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Regional Case Study

Flood Hazard Mapping via High-Resolution Imagery

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Abstract

Urban flooding in low-lying coastal zones like Way Lunik, Bandar Lampung, presents a growing challenge driven by rapid land use change, degraded infrastructure, and limited hydrological planning. This study combines high-resolution UAV-derived Digital Surface Models (DSM), national elevation data (DEMNAS), satellite imagery, and field-based drainage surveys to analyze flood risk in the Way Lunik watershed. Hydrological modeling shows that the watershed acts as a terminal catchment with low slopes and only two main discharge points, making it prone to runoff accumulation and tidal backflow. Significant mismatches between modeled and observed drainage patterns stem from blocked channels, informal settlements, and outdated infrastructure. Land cover analysis (2017–2023) reveals substantial growth in impervious surfaces, especially over former green or agricultural areas, increasing runoff and decreasing infiltration. Field surveys confirm drainage blind spots, unplanned flow paths, and encroached outlets in industrial and residential zones. The study also maps building types and clusters of flood-prone areas, often overlapping with marginalized neighborhoods and public facilities. By integrating elevation data, UAV imagery, and ground mapping, this research provides a spatially detailed assessment of urban flood hazards, emphasizing the importance of watershed-scale planning, infrastructure renewal, and the role of UAVs in adaptive flood risk management.

Keywords: Digital surface models; flood risk management; hydrological modelling; impervious surfaces; urban flooding

1. Introduction

Flooding stands as the most pervasive hydrometeorological disaster in Indonesia, with coastal urban regions such as Bandar Lampung increasingly affected by both the frequency and severity of flood events (Chayyani et al., 2020). In particular, Way Lunik Village, situated in the Panjang District, has become a persistent hotspot for recurrent urban flooding, especially during the peak rainy season. In early 2025, an extreme rainfall event triggered catastrophic flooding in Way Lunik, with inundation depths reaching up to two metres. The event submerged hundreds of homes brought the Trans-Sumatra Highway to a standstill, and resulted in the loss of human life, reflecting not just a recurring hazard, but a growing crisis with multidimensional impacts (Cambodia et al., 2023).

Despite the growing frequency of such disasters, there remains a critical gap in localized spatial analysis and risk-based planning that integrates upstream-downstream hydrological processes, urban infrastructure mapping, and real-time flood vulnerability assessments (Gumelar, 2020). Previous responses have largely been reactive and infrastructural, overlooking the complex spatial and environmental drivers that continue to amplify flood exposure in Way Lunik. The area suffers from a combination of natural and anthropogenic stressors, including sedimentation from upstream stone mining (e.g., Way Gubak and Way Laga), rapid and unregulated land use change, and severely degraded drainage infrastructure (Suni et al., 2023). Compounding the physical damage are social consequences schools like SDN 01 Way Lunik have been forced to close temporarily, while mobility and economic activity are routinely paralyzed during flood events.

Recent studies in other urban zones within Bandar Lampung, such as Rajabasa, have demonstrated how land cover change significantly increases surface runoff by raising Curve Number (CN) values (Rohman et al., 2019; Rohman and Prasetya, 2019), leading to near-total conversion of rainfall into direct runoff (Rohman et al., 2024). A parallel process is underway in Way Lunik, where vegetated or open lands have been replaced by residential and industrial development, but without corresponding improvements in drainage capacity or retention infrastructure (Sumiharni and Afriani, 2021). Despite the well-documented risks, the area remains underrepresented in high-resolution spatial flood assessments.

There is an urgent need for innovative and rapid flood mapping techniques that can bridge the data and response gap. Drone-based photogrammetry, especially when combined with Ground Control Points (GCPs), has been shown to produce accurate, high-resolution elevation models within a single day, enabling detailed hydrological analysis and rapid flood-prone area identification (Ramadhani et al., 2023). This technology, coupled with participatory mapping and community engagement, not only enhances the spatial understanding of flood risks but also aligns with the Sendai Framework for Disaster Risk Reduction (DRR), which calls for evidence-based, inclusive, and proactive risk governance.

Therefore, this study seeks to integrate high resolution digital elevation models, drainage line analysis, land use change detection, and ground verification to systematically assess the spatial dynamics of flooding in Way Lunik. The results are expected to inform targeted flood mitigation strategies and serve as a model for flood risk management in other rapidly urbanizing coastal regions. By emphasizing spatial precision, cross-sector collaboration, and community involvement, the study contributes to the development of locally grounded yet scalable flood resilience strategies.

2. Materials and Methods

2.1 Data Acquisition and Processing

This study employed a combination of primary and secondary spatial datasets to conduct hydrological modelling, and drainage network analysis in the Way Lunik Subdistrict. The methodological framework is illustrated in Figure 2, which outlines the integration of administrative, elevation, and drainage data for comprehensive spatial analysis. The difference is, the elevation model from DEMNAS is changed to high resolution elevation model.

2.2 Methodology

2.2.1 Elevation Data Collection and Processing

High-resolution elevation data were obtained using Unmanned Aerial Vehicle (UAV) photogrammetry. UAV flights were conducted with pre-planned trajectories and a ground sampling distance (GSD) of approximately 5–10 cm. To enhance the spatial accuracy of the generated Digital Surface Model (DSM) and Digital Terrain Model (DTM), a total of 10 Ground Control Points (GCPs) were measured using dual-frequency geodetic GPS and referenced to the Indonesian Geospatial Standard (Sistem Referensi Geospasial Nasional – SRGI 2013). Post-processing of UAV imagery was carried out using structure-from-motion (SfM) photogrammetry workflows. The elevation data were validated against DEMNAS, Indonesia's national elevation dataset, to assess vertical accuracy and resolution differences.

2.2.2. Drainage Line and River Network Mapping

Existing river shapefiles at a 1:50,000 scale were sourced from the Indonesian Geospatial Information Agency (BIG). The tracked drainage points were overlaid with the DEM to verify flow direction and catchment delineation. A standard hydrological modelling procedure was performed using GIS software. The following processes were applied sequentially to the elevation data: (1) Fill sinks to remove surface depressions; (2) Flow direction and flow accumulation mapping; (3) Stream definition and segmentation; (4) Catchment delineation using the Strahler method; (5) Drainage line processing to extract flow paths aligned with topography. These steps produced drainage network overlaid on the DEMNAS and UAV-derived elevation map. Field-based tracking of the drainage system was conducted using handheld GPS devices and camera to show the drainage condition in the field.

2.3.3 Land Use Mapping

Land use changes were analysed using satellite imagery for the years 2017, 2020, and 2023, classified using supervised classification methods. Urban expansion and the emergence of impervious surfaces were quantified to explain runoff intensification trends.

3. Result and Discussion

3.1 Study Area

The study was conducted in Way Lunik Basin, located in Bandar Lampung City, Indonesia, situated along the coastal zone of Lampung Bay. This area is characterised by rapid urban development, a complex drainage network, and frequent occurrences of tidal and runoff-induced flooding. The area encompasses residential, industrial, and commercial zones, making it particularly sensitive to hydrometeorological hazards. Way Lunik lies at the downstream terminus of several small watersheds, receiving surface runoff from elevated regions in the north. The elevation ranges between 0 to 350 metres above sea level, with a predominantly southward slope toward the coastline, contributing to water stagnation and overflow during extreme rainfall events.

To support spatial hydrological analysis, high-resolution topographic data were obtained using UAV-based photogrammetry, enhanced with geodetic GPS ground control points (GCPs) to ensure geometric accuracy. The elevation model (Figure 1a) and field observations (Figure 1b) clearly show that flood-prone areas in Way Lunik correspond with densely developed low-lying urban pockets. The broader study design is outlined in Figure 2, derived from Digital Elevation Model Nasional (DEMNAS) which includes basin boundary, drainage lines network, and the field-mapped situation of drainage lines. The study then used spatial analysis for hydrological and flood risk assessment. The selection of Way Lunik as the study site was based on its documented flood vulnerability and dynamic land use changes, especially in the context of rapid urbanisation and limited drainage infrastructure. These characteristics make the area ideal for evaluating the interplay between topography, flood exposure, and urban building typologies in a coastal watershed setting.

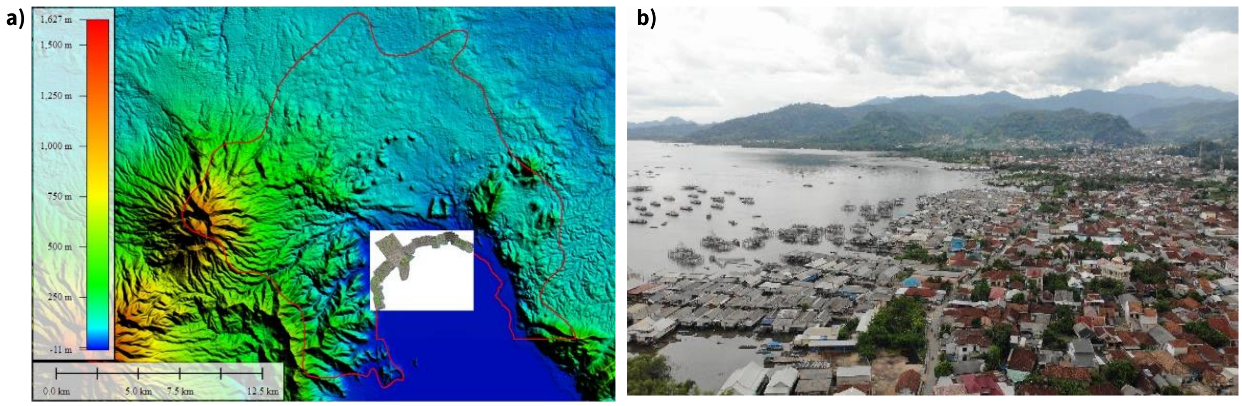

Figure 1. Topographic and field visualization of the study area (a) Elevation map of Lampung Bay and the high-resolution image from UAV-derived data, showing low-lying coastal areas prone to flooding; (b) Drone-view image of Lampung Bay and surrounding residential zones illustrating urban density and proximity to the coastline.

Figure 2 presents a comprehensive visualization of the hydrological setting and flood-prone conditions in Way Lunik Subdistrict, combining digital elevation modelling, satellite imagery, and field-based validation (Rohman et al., 2024). The delineated watershed boundary (Figure 2a) confirms that Way Lunik lies at the terminus of a regional catchment area, where surface runoff from upstream zones converges. This positional disadvantage inherently subjects the subdistrict to high flood risk, especially during extreme rainfall events when flow volumes exceed channel capacity (Sumiharni and Afriani, 2021).

The 3D terrain models in Figures 2b and 2c further emphasize the critical role of topography in shaping flood behaviour. The stark contrast between the steep upstream slopes and the low-lying coastal floodplain illustrates a classic "convergent basin" dynamic, where runoff accelerates from the highlands and accumulates rapidly in the flatter, downstream urban core (Kurniawan, 2017). This lack of slope gradient in the Way Lunik basin not only reduces the speed of water evacuation but also heightens the potential for backflow during tidal surges from Lampung Bay, particularly in areas without backflow prevention structures (Wulandari et al., 2023). Figure 2d overlays the drainage network on high-resolution satellite imagery, showing that the existing urban fabric is densely interwoven with the main flow paths. This spatial entanglement creates multiple conflict zones where roads, industrial estates, and informal housing interfere with natural or planned drainage lines (Zhou et al., 2019). The situation is worsened in segments where drainage lines are either disconnected or not maintained, leading to ineffective surface runoff discharge and increased vulnerability to flooding.

This analysis is reinforced by the field observation in Figure 2e, which shows a critical drainage outlet completely obstructed by waste and sediment. Such blockages are symptomatic of chronic maintenance neglect and inadequate waste management systems. They also highlight the mismatch between the theoretical performance of the drainage system as modelled in GIS and elevation data and the actual field conditions. Even well-designed networks can fail if not regularly cleaned or integrated with solid waste strategies (Kusumastuti et al., 2014).

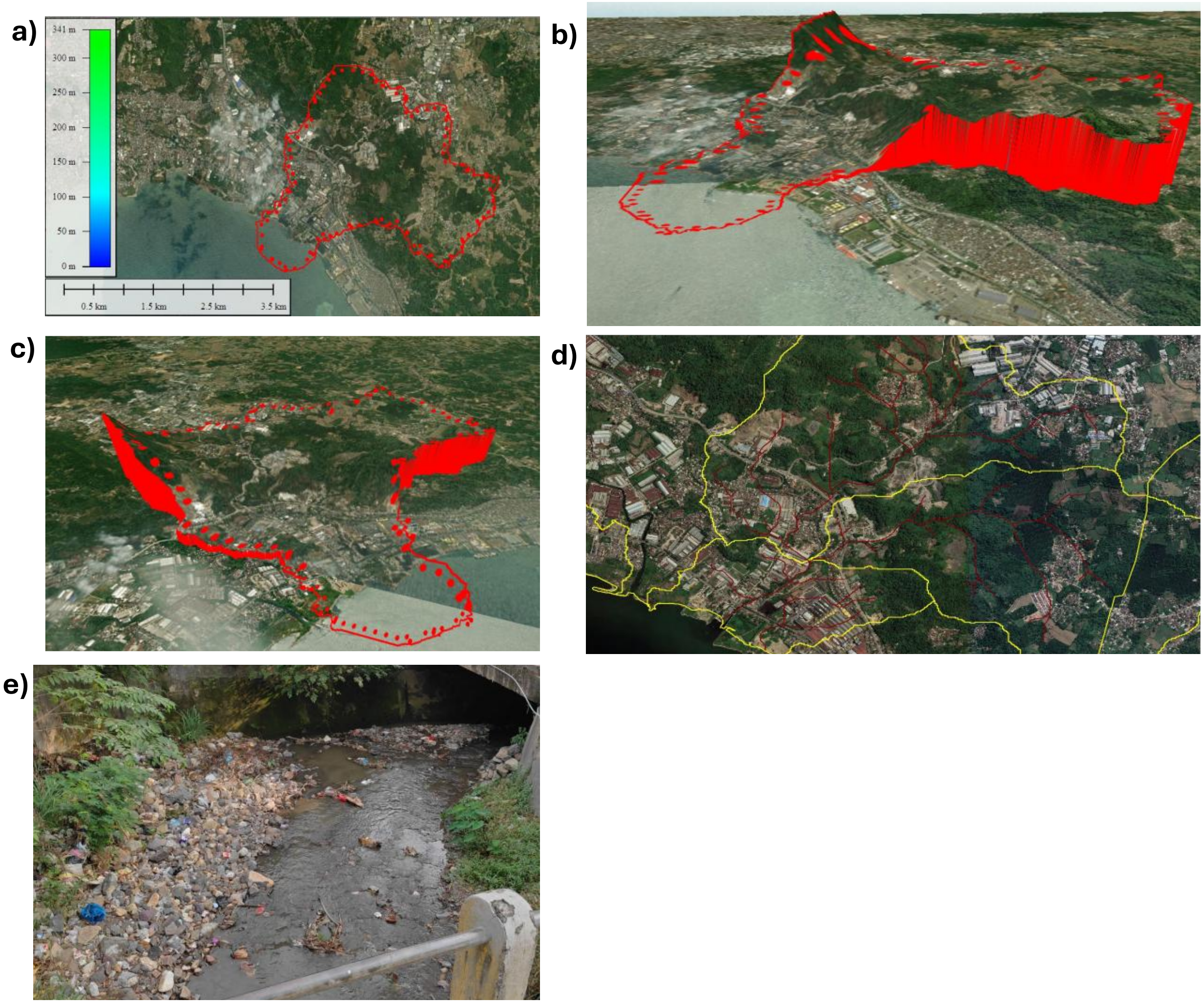

Figure 2. Visualization of flood-prone conditions and hydrological vulnerabilities in Way Lunik Subdistrict (a) Watershed boundary delineation using elevation data; (b–c) 3D terrain model illustrating steep upstream terrain and flat downstream coastal basin; (d) Planimetric drainage analysis over satellite imagery; (e) Field observation showing a blocked drainage outlet with accumulated waste and sediment. The composite visualization reveals the convergence of topographic, infrastructural, and environmental factors contributing to flooding in Way Lunik.

Figure 3 provides a three-dimensional representation of the Way Lunik watershed, highlighting the topographical gradient from the upstream regions to the coastal outlet at Lampung Bay. This visualization underscores the watershed's steep upstream terrain transitioning into low-lying downstream areas, a configuration that significantly influences hydrological responses during precipitation events. The pronounced elevation drop facilitates rapid surface runoff, reducing infiltration opportunities and increasing the velocity of water flow towards the basin's outlet. Such topographical characteristics are critical in understanding flood dynamics, as areas with steep slopes and minimal elevation variation are more susceptible to flash flooding due to the accelerated convergence of runoff (Guo et al., 2021).

Moreover, the proximity of the watershed's outlet to Lampung Bay introduces the potential for compound flooding events. Compound flooding occurs when fluvial floods coincide with coastal high tides or storm surges, leading to exacerbated flood conditions in coastal urban areas (Tang, 2025). In regions like

Way Lunik, where urban development encroaches upon natural floodplains, the risk of such events is amplified, necessitating integrated flood risk management approaches that consider both inland and coastal flood drivers. The utilization of 3D visualization tools in this context enhances the comprehension of complex watershed dynamics, allowing for more effective communication of flood risks to stakeholders and aiding in the development of targeted mitigation strategies. By visualizing the spatial relationships between topography, hydrological pathways, and urban infrastructure, planners and decision makers can better identify vulnerable areas and prioritize interventions.

Figure 3. Three Dimension visualization of the Way Lunik watershed and its outlet toward Lampung Bay

3.2. Morphometric and Hydrological Analysis

Figure S1 illustrates the delineated catchment areas that drain towards Lampung Bay, with the Way Lunik catchment discharging near the Port of Panjang. These catchments differ in both spatial extent and hydrological influence, reflecting variations in runoff contribution and flood potential across the region. Catchment 1 covers an area of approximately 2,215 hectares, while Catchment 2 is the largest, spanning 5,981 hectares. Catchment 3 occupies 548 hectares, followed by Catchment 4 with 441 hectares. Catchment 5, another large basin, comprises 5,527 hectares. Catchment 6 identified as the Way Lunik catchment covers 810 hectares, and finally, Catchment 7 extends over 683 hectares.

The range of catchment sizes offers important insights into the regional hydrological dynamics. Larger basins, such as Catchments 2 and 5, have the capacity to collect significant upstream runoff and may exert increased pressure on downstream drainage systems, particularly during periods of extreme rainfall. In contrast, smaller catchments, such as Catchments 3, 4, and 7, are more likely to produce localised flood effects, especially in areas with dense development or limited permeability.

Catchment 6, in which Way Lunik is situated, plays a pivotal role due to its mid-range size and its location at the downstream confluence of several urban runoff pathways. Although not the largest in extent, its position near the coastal outfall makes it particularly vulnerable to the cumulative impact of surface water from adjacent sub-catchments. This spatial configuration highlights the importance of adopting an integrated catchment-based flood management approach, recognising the interdependence of upstream land use, catchment capacity, and downstream exposure.

A comparative analysis of the catchments reveals significant differences in their flood typologies. There are catchments are characterised by mountainous upstream zones (1 and 2), resulting in longitudinal water flow patterns that increase the risk of flash flooding due to the steep slopes and rapid runoff. In contrast, there are catchments that has an upstream area dominated by urban development (3, 4, and 5) rather than natural highlands. This absence of steep gradients, coupled with dense built-up zones, gives rise to a different flood regime, namely, pluvial flooding or ponding, primarily driven by slow-moving runoff and impaired drainage systems. The last is the combination of the two types, hilly upstream (around 200 m above sea level) with short river (catchment 6 – Way Lunik, and 7).

Moreover, morphometric characteristics such as drainage density, bifurcation ratio, and relief ratio further contextualise the flood susceptibility of Way Lunik. Previous research indicates that areas with high drainage density and low relief are particularly prone to inundation due to the rapid concentration of runoff and limited dispersal capacity (Raja Shekar and Mathew, 2024). In this context, Way Lunik's relatively flat terrain and expanding but fragmented drainage network presents a critical hydrological challenge. Water tends to accumulate rapidly during peak rainfall events but is unable to evacuate efficiently, leading to widespread urban flooding.

Furthermore, the proximity to the coast introduces additional challenges, such as tidal influences and sea-level rise, which can exacerbate flooding conditions. Coastal areas with low elevation are particularly vulnerable to storm surges and tidal inundation, which, when combined with fluvial flooding, can lead to compound flood events (Guo et al., 2021). Thus, the elevation model underscores the critical role of topography in flood dynamics within Lampung Province. The natural slope directs runoff towards the southern lowlands, where urban expansion and coastal proximity converge to elevate flood risks. Effective flood management strategies in Way Lunik must consider these topographical and hydrological factors to mitigate future flood events.

Figure S2 presents the drainage network and hydrological outlets in Way Lunik Subdistrict, derived from the DEMNAS dataset. The delineated drainage lines exhibit a dendritic pattern, characteristic of homogeneous substrates and gentle slopes, which is typical in coastal plains. This pattern facilitates efficient surface runoff collection but can also lead to rapid concentration of flow, increasing flood susceptibility in downstream areas. The analysis identifies two primary hydrological outlets that serve as the main discharge points for surface runoff. However, their limited number and capacity may not suffice during extreme weather conditions, leading to waterlogging and flooding in the surrounding urban areas.

The drainage density, calculated from the network, is a vital morphometric parameter influencing flood potential. High drainage density indicates a well-developed network capable of quickly conveying runoff, but it also suggests a higher potential for flash flooding due to rapid water movement. In Way Lunik, the combination of high drainage density and limited outlet capacity underscores the area's vulnerability to flood events. Furthermore, the relief ratio, representing the elevation difference between the highest and lowest points in the watershed, affects the velocity of surface runoff. A higher relief ratio implies steeper slopes, leading to faster water flow and reduced infiltration time. In the context of Way Lunik, the relatively low relief ratio contributes to slower runoff movement, causing prolonged water retention and increasing flood risk. The integration of morphometric parameters such as drainage density and relief ratio provides a comprehensive understanding of the hydrological behaviour in Way Lunik. These insights are crucial for urban planners and disaster management authorities to develop effective flood mitigation strategies, including the enhancement of drainage infrastructure and the implementation of sustainable land use practices.

Figure S3 illustrates the hydrogeological framework of Lampung Province, emphasizing the intricate network of river systems and their influence on the region's flood dynamics. The province's topography, characterized by the Bukit Barisan Mountain range in the west and low-lying coastal plains in the east, plays a pivotal role in directing surface water flow and determining flood susceptibility. The major rivers, including the Way Sekampung, Way Seputih, and Way Tulang Bawang, originate from the highlands and traverse the province before discharging into the Java Sea. These rivers are integral to the province's irrigation infrastructure, supporting agricultural activities across extensive areas. For instance, aacording to the World Bank in 2013 the Way Sekampung River supplies irrigation water to approximately 35,000 hectares of agricultural land, highlighting its significance in regional water resource management.

However, the convergence of these river systems in the eastern lowlands, combined with the province's high annual rainfall, contributes to frequent flooding events, particularly in downstream areas. As can be seen in the Figure 6, Lampung has two bays, one is the Lampung Bay located in City of Bandar Lampung, and the other is Semaka Bay in Tanggamus. Both bays experienced riverine flood from mountainous area. The interesting thing is, the bay also has local hilly area with small catchment and short river stream that end up in the flat terrain coast. The flat terrain and limited drainage capacity in these regions exacerbate flood risks, necessitating comprehensive flood management strategies. Furthermore, land-use changes, such as deforestation and urban expansion, have altered the natural hydrological balance, increasing surface runoff and sedimentation in river channels. These changes underscore the importance of integrating hydrogeological assessments into urban planning and disaster risk reduction efforts to enhance the resilience of vulnerable communities.

Figure S5 displays the modelled drainage line network of Way Lunik Subdistrict, delineated using DEMNAS data. This map reveals the intricate system of minor and major flow paths that define the hydrological behaviour of the area. The model identifies three principal catchment subzones, all converging toward the southern outlet into Lampung Bay, aligning with topographic flow directions and gravity-induced accumulation zones. The hydrological delineation illustrates that the subdistrict functions as a terminal basin, receiving runoff from both inland slopes and urbanized catchments. As the flow accumulation paths converge, the modelled drainage lines serve as essential indicators of potential flood zones, particularly where topographic convergence meets impervious urban surfaces. Similar digital elevation-based drainage modelling approaches have been widely applied for urban flood risk mapping and have shown high accuracy in identifying surface runoff hotspots (Preisser et al., 2022; Storch and Downes, 2011).

While the model provides a useful base layer, field verification reveals discrepancies in some drainage paths due to anthropogenic alteration, such as channel realignment, blockage, or urban encroachment. This reflects findings from regional studies where the alignment of DEM-based modelled drainage lines can differ significantly from actual field conditions due to infrastructure development and sedimentation (Akbar et al., 2024; Nie et al., 2024). Moreover, the low gradient across much of Way Lunik means that the global DEMNAS data (scale approx to 1:50.000), can't capture the real problem. A small-scale topographic depressions or unmaintained channels can substantially influence surface water routing, reinforcing the importance of high resolution topographic and ground survey validation. The hydrological behaviour of these micro-catchments, when unmanaged, can lead to localised inundation and long ponding duration during heavy rainfall, especially near residential and industrial zones.

Figure S6 presents a series of field photographs documenting the current conditions of the drainage infrastructure in Way Lunik Subdistrict. These images illustrate multiple issues that significantly impair the drainage system's performance, particularly during peak rainfall events. Among the most critical problems observed are clogged inlets and culverts filled with solid waste and vegetation, which obstruct water flow and contribute to surface water accumulation in residential and commercial zones. Many of the drainage channels are shallow, narrow, and lack structural lining, making them susceptible to erosion and sedimentation. These physical limitations reduce the capacity of the channels to transport runoff efficiently and increase the risk of overbank flow. Additionally, some drainage paths show abrupt directional changes and elevation inconsistencies, which impede natural hydraulic flow and promote localized flooding.

Another prominent issue is the fragmentation and discontinuity of the drainage network. Several pipes and open channels are unconnected, leading to backflow and standing water, especially in low-lying urban pockets. Encroachment by informal settlements and industrial infrastructure further complicates maintenance and reduces the effective width of drainage channels, compromising their function. The conditions captured in these field observations underscore the gap between modelled hydrological systems and on-the-ground realities. While spatial analysis and DEM-based mapping can identify theoretical flow paths, the actual state of physical infrastructure often deviates due to neglect, inadequate design, or unplanned urban development. These findings emphasize the need for a comprehensive and integrated drainage improvement program in Way Lunik, combining structural upgrades, regular maintenance, and urban planning measures to ensure proper water management and flood risk reduction.

Figure S7 presents field-based evidence of drainage infrastructure dysfunction across several critical zones within and around Way Lunik Subdistrict. These real-world observations provide valuable ground truth validation of the spatial modelling results, illustrating how hydrological flow is severely disrupted by physical blockages, infrastructural encroachment, and poor maintenance practices (Yudhistira and Putri, 2024). Figure S7(a) shows a drainage channel adjacent to a railway line, where the accumulation of solid waste has nearly filled the channel. This condition severely restricts the conveyance of stormwater, particularly during high-intensity rainfall events. The proximity to transport infrastructure such as railways introduces additional risks, as overflowing drains in this context can interfere with rail operations and pose safety hazards to nearby communities.

In Figure S7(b), the drainage line is overtaken by dense vegetation and sediment buildup, indicating prolonged neglect. Such vegetative overgrowth is not merely an aesthetic issueit actively impedes flow, reduces hydraulic efficiency, and increases the potential for upstream ponding and overflow. Without regular clearing and desilting, even structurally sound channels like this can become functionally obsolete. Figure S7(c) highlights a more structural concern: the physical obstruction of a drainage outlet by industrial fencing and multiple utility pipes. This reflects a broader problem of uncoordinated land use, where critical drainage corridors are co-opted by industrial or private developments without consideration for water management. The interference not only limits flow but also creates localized turbulence and backflow risks (Sumiharni and Afriani, 2021).

Figure S7(d) captures the condition of a roadside channel filled with silt and debris, rendering it ineffective in conveying runoff. The stagnant nature of the drain suggests a chronic problem with upstream blockage or insufficient slope, leading to long-standing water retention and potential breeding grounds for disease vectors (Siregar et al., 2025). Together, the panels in Figure 9 illustrate the systemic breakdown of the drainage network in Way Lunik, reinforcing the conclusion that technical modelling must be supported by field validation. The images reveal how even minor obstructions, if widespread and unaddressed, can accumulate into significant flood hazards. These findings emphasize the need for sustained maintenance programs, regulatory enforcement to prevent encroachment, and the integration of drainage audits into urban infrastructure planning.

3.2 Flood Mapping and Spatial Overlay

Figure S8 provides a regional perspective on flood distribution patterns across Lampung Province, identifying key areas prone to recurrent inundation. The mapped data show that flood events are not isolated to low-lying coastal zones but are also widespread in upstream catchments and urban peripheries. The circled locations Tubaba, Metro, Pringsewu, Tanggamus, and Bandar Lampung represent flood-prone clusters where hydrological, topographical, and anthropogenic factors intersect to amplify flood risk. The Tubaba and Metro regions, situated in broad alluvial plains, exhibit dense drainage networks and limited elevation variation. These lowland areas are particularly susceptible to overbank flooding due to the accumulation of upstream runoff and reduced outflow efficiency. Urban expansion without adequate drainage infrastructure further contributes to waterlogging during extreme rainfall events. Similar patterns are observed in Pringsewu, where topography channels runoff from hilly terrain toward the urban core, often exceeding the capacity of existing drainage systems. Tanggamus, while predominantly highland, also shows flood vulnerability in valley basins where steep slopes generate rapid runoff that converges in flatter downstream zones. Flash flooding is common in such transitional landscapes, particularly in areas affected by deforestation or land cover change, which reduce infiltration and accelerate overland flow. Bandar Lampung, including Way Lunik Subdistrict, is highlighted as a critical hotspot due to its dual exposure to inland and coastal hydrological pressures. As a terminal basin receiving water from multiple upstream sources, combined with its low elevation and high population density, Bandar Lampung faces compound flooding risks from both fluvial and tidal influences.

Figure S9 illustrates the progressive transformation of land cover in Bandar Lampung between 2017 and 2023, with a particular emphasis on the expansion of built-up areas. The red zones, which represent urban and industrial development, show a noticeable increase over the six-year period, particularly in the central and southern parts of the city. This trend reflects the ongoing urbanization of the region, driven by population growth, industrial expansion, and infrastructure development. The visual comparison between Figure S9(a), (b), and (c) reveals a marked reduction in green spaces and agricultural land, especially along the urban fringes. As vegetated areas are replaced with impervious surfaces such as concrete, asphalt, and rooftops, the city's natural capacity to absorb rainfall is significantly reduced. This leads to an increase in surface runoff, which overwhelms the drainage infrastructure particularly in low-lying areas like Way Lunik. The correlation between land cover change and increased flood incidence is well-documented, as the loss of permeable ground surfaces accelerates runoff velocity and reduces groundwater recharge. Furthermore, the spread of built-up areas toward the coastal and downstream catchments suggests a growing exposure of vulnerable communities and critical infrastructure to flood hazards. The land use change also alters the hydrological response of the catchment by reducing lag time and increasing peak discharge, which contributes to the intensity and frequency of urban flooding. This transformation reinforces the need for land use planning that considers hydrological functions (Ait Zamzami et al., 2024), particularly through the integration of green infrastructure, buffer zones, and sustainable drainage systems.

Figure S10 presents a detailed spatial representation of flood-prone zones within Way Lunik Subdistrict, developed through the integration of field data, drainage line tracking, and UAV based imagery. The flood locations, highlighted in blue, follow the course of the existing drainage network, particularly in areas where the channels intersect industrial zones, densely built neighborhoods, and low-lying terrain. These segments mark the critical hotspots where stormwater frequently exceeds the conveyance capacity of the local drainage system. The map reveals a distinct spatial pattern where flood incidents cluster near key drainage junctions and poorly maintained channels, especially in the southern and central parts of the subdistrict. The proximity to the coastline further exacerbates flooding due to limited slope gradients, tidal influences, and constrained outflow into the bay. In addition, urban sprawl into previously undeveloped floodplains has altered natural runoff pathways, forcing water into confined artificial drainage systems that are often fragmented or blocked. This spatial analysis confirms that flood vulnerability in Way Lunik is not evenly distributed but rather concentrated in specific zones with compounding risk factors namely, inadequate infrastructure, impervious surfaces, and hydrological bottlenecks. The data also suggest that the risk is systemic, affecting not only residential areas but also industrial corridors, thereby posing threats to both livelihoods and economic activity.

Figure S11 presents a detailed spatial comparison between observed and modelled drainage systems within the Way Lunik Subdistrict, highlighting the complexities and challenges of urban flood mapping in rapidly changing environments. Figure S11(a) shows drainage features captured through aerial mapping and field tracking, representing the current surface drainage network shaped by both engineered structures and informal channels. These observed lines reflect real hydrological responses to rainfall under existing land use and infrastructure conditions (Rimba et al., 2023). Figure S11(b), on the other hand, displays drainage flowlines derived from DEMNAS topographic data, which simulate surface runoff based solely on elevation and slope gradients. While effective in natural or semi-natural landscapes, DEM-based hydrological models often fail to capture the influence of urban infrastructure, such as culverts, roads, buildings, or drainage redirection systems (Konadu and Fosu, 2009; Legowo, 2019). The integrated map in Figure S11(c) reveals both spatial agreement and critical misalignment between the two datasets. In less-developed, vegetated areas, the cyan (modelled) and red (observed) lines align reasonably well, indicating that elevation-based modelling can reliably predict flow paths in minimally disturbed terrain. However, in built-up zones, especially around industrial estates, road corridors, and dense housing, significant mismatches emerge. Here, the DEM-derived drainage lines either oversimplify or misrepresent actual flow, often routing water through inaccessible or blocked areas due to unaccounted man-made modifications. Furthermore, the visualized discrepancies identify key drainage "blind spots" areas where modelled lines exist, but field surveys reveal no functioning drainage, and vice versa. These inconsistencies highlight where potential flood risks are underestimated in spatial planning and underscore the limitations of relying on DEM-derived models alone in urban environments (Alrajhi et al., 2016).

By overlaying all layers, Figure S11 provides a diagnostic view of the drainage system's performance and spatial accuracy. It offers valuable guidance for infrastructure improvement, such as prioritizing rehabilitation in areas where modelled and observed drainage paths diverge or ensuring connectivity where disjointed flowlines occur. Ultimately, this figure demonstrates the importance of integrating remote sensing, field validation, and GIS-based hydrological analysis to ensure that flood modelling reflects the real, functional drainage landscape particularly in vulnerable, fast-growing coastal areas like Way Lunik.

3.3 Land Use Problem

The hydrological analysis derived from high-resolution DSM data enabled the delineation of stream networks, which were subsequently overlaid with high-resolution aerial imagery captured by Unmanned Aerial Vehicles (UAVs), as described in the previous sections. A key strength of this approach lies in the temporal alignment of the elevation data and the imagery both were acquired simultaneously during the same UAV mission. As a result, the hydrological modelling conducted using these datasets offers an accurate and up-to-date representation of the current flood conditions on the ground.

This contrasts significantly with more conventional flood analysis workflows, which often rely on archived elevation datasets such as the DEMNAS, or any contour data capture a long while ago. While such national datasets may still be paired with recent satellite imagery, they typically do not capture topographical changes resulting from recent land use activities. Consequently, the derived drainage lines may not reflect the actual surface flow dynamics, particularly in rapidly evolving urban or semi-urban environments. In contrast, the UAV-derived data used in this study incorporate both real-time elevation surfaces and contemporary land cover, enabling a far more nuanced and dynamic understanding of the hydrological system.

The results of this integrated approach reveal several critical findings in the upper section of the Way Lunik catchment, as shown in Figure S11. First, land use change, particularly mining activity in the upstream area, has led to the formation of a new flow path (Figure 11(a)), which terminates without a defined outlet. This isolated drainage feature suggests incomplete or artificial channeling, which may increase the risk of localized ponding or erosion. Secondly, more detailed data layers reveal that the main outlet located in the residential downstream area does not only receive runoff from the primary upstream stream channel (depicted in magenta), but also from surrounding impervious surfaces, including adjacent road infrastructure (Figure 11(b) and (c)). This indicates that unplanned urban runoff convergence is occurring, potentially overwhelming the drainage capacity and intensifying flood risks in populated zones.

These findings underscore the added value of integrating UAV-derived DSMs and orthophotos in hydrological modelling, particularly in urban areas where land use is dynamic and frequently unrecorded in official spatial datasets. Such real-time integration of elevation and imagery allows for the identification of undocumented flow paths, anthropogenic drainage disruptions, and mismatches between planned infrastructure and actual hydrological function.

3.4 Impact of Lampung Flood

Flooding in Lampung has resulted in both direct and indirect economic and social losses, significantly affecting critical infrastructure, livelihoods, and public health. Direct losses refer to the immediate physical damage to infrastructure, property, and productive assets caused by the floodwaters. In Bandar Lampung, extensive damage was reported to roads, bridges, and drainage systems manifesting in pothole-ridden streets, structurally compromised bridges, and clogged or malfunctioning drainage channels. These failures have impaired basic mobility and public service delivery. The agricultural and fisheries sectors have also sustained substantial direct losses. Inundation of farmland across several regions led to crop failure and reduced yields, directly affecting farmers' incomes and local food availability (Ilyas et al., 2025). Likewise, small and medium-sized enterprises (SMEs) experienced direct damage to business premises, equipment, and inventory, particularly in low-lying commercial areas.

Indirect losses, in contrast, capture the broader economic and social disruptions resulting from the aftermath of flooding. For example, damaged transport infrastructure delayed supply chains and restricted access to markets and services, thereby reducing productivity across various sectors. Many SMEs reported declining revenues due to prolonged closures and customer inaccessibility, with some businesses forced into permanent shutdown. In highly exposed urban centers such as Jakarta and Semarang, SMEs often underinsured and lacking institutional support struggle to recover, relying solely on individual coping mechanisms (Neise et al., 2021).

On a social level, floods have disrupted community life through mass evacuations, the destruction of homes, and the displacement of residents. These disruptions have heightened the risk of disease outbreaks, mental health disorders, and reduced access to education and healthcare, particularly among vulnerable groups in informal settlements (Kurniawan et al., 2024). In Metro City, flood-induced economic losses were significant, with commercial damages totaling approximately IDR 101.7 million and agricultural losses reaching IDR 587.98 million. These figures exemplify the compound nature of flood impacts where immediate physical destruction is followed by longer-term economic stagnation and increased poverty. Such patterns are consistent with national trends, where floods are not only a recurring hazard but also a structural impediment to inclusive development and resilience (Ilyas et al., 2025).

3.5 Recommendation for The Policymaker and Researcher

Based on the findings of this study, several targeted strategies are proposed to address flood risk in Way Lunik. First, there is an urgent need to adopt a catchment-based planning approach that aligns development policies with watershed boundaries. Hydrological delineation has shown that upstream activities, particularly unregulated land conversion and mining, contribute directly to downstream flood hazards. Urban planning must therefore consider flow direction and surface hydrology to avoid disrupting natural drainage networks.

Second, the study identified critical weaknesses in existing drainage infrastructure, including blocked, fragmented, and misaligned flow paths. These findings, derived from UAV-based elevation modelling and field verification, highlight the importance of rehabilitating drainage systems. Priority actions include re-connecting severed flowlines, improving discharge capacity, and incorporating sustainable urban drainage elements such as infiltration basins and retention ponds.

Third, land use regulation must address the rapid expansion of impervious surfaces, especially in areas formerly designated as green or agricultural land. Without intervention, continued urbanization will increase surface runoff and further stress the drainage system. Zoning should therefore integrate flood risk and preserve open space in high-risk areas.

Finally, community participation should be strengthened through awareness campaigns and improved waste management. Clogged drains caused by solid waste were repeatedly observed in flood-prone locations. Empowering local communities to maintain drainage infrastructure will complement structural measures and enhance long-term flood resilience.

4. Conclusions

This study highlights the complex and multifactorial nature of urban flooding in Way Lunik Subdistrict, Bandar Lampung. By integrating high-resolution UAV imagery, DEMNAS-based hydrological modelling, land use change analysis, and field validation, we identified critical spatial and infrastructural drivers of flood vulnerability in the region. The research reveals that Way Lunik functions as a terminal catchment with a low-lying topography, making it a natural accumulation point for runoff from upstream watersheds. This positional disadvantage is exacerbated by rapid urbanization, poorly maintained drainage infrastructure, and unregulated land use changes. The overlay of modelled and observed drainage networks reveals clear discrepancies, particularly in densely developed zones where natural flow paths are obstructed or redirected by human intervention. Field investigations further confirm the presence of clogged, disconnected, and encroached drainage systems that fail to manage surface runoff effectively. These structural deficiencies, alongside the widespread conversion of permeable surfaces to built-up areas between 2017 and 2023, significantly increase both the frequency and severity of flooding events.

Moreover, spatial analysis indicates that flood risk is not evenly distributed across the subdistrict. Instead, it is concentrated in distinct clusters especially near industrial zones, major road corridors, and poorly planned residential areas. The co-location of vulnerable building typologies such as vacant properties, informal housing, and flood-exposed public facilities further reinforces the socio-economic dimension of urban flood vulnerability. This research demonstrates that accurate flood mapping in urban coastal environments requires a hybrid and site-specific approach one that combines elevation data, remote sensing technologies, participatory ground surveys, and field-based validation. The synchronization of high-resolution DSMs and aerial imagery acquired in real-time proved particularly valuable in identifying emerging flow paths and drainage inconsistencies that would otherwise remain undetected in archive-based modelling.

Ultimately, the spatial datasets and hydrological insights produced in this study contribute not only to more reliable flood risk assessments but also to the design of evidence-based planning, infrastructure investment, and community preparedness strategies. Future studies are encouraged to build on this framework by incorporating temporal flood simulation, climate projections, and nature-based solutions to enhance adaptive capacity in similarly vulnerable urban watersheds

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