Re-evaluating Urban Flood Causality: Integrating InSAR Time-Series and Multi-Sensor Satellite Observations for the 2024 Makassar Flood

Agustan Agustan[1,2*], Mukhsan Putra Hatta[3], Ilham Alimuddin[3], Takeo ITO[1]
[1*] Earthquake and Volcano Research Center, Nagoya University, JAPAN
[2] National Research and Innovation Agency (BRIN) – Jakarta, INDONESIA
[3] Universitas Hasanuddin, INDONESIA
* agustan@ieee.org

ABSTRACT

Urban flooding in coastal Southeast Asia is often attributed to land subsidence from excessive groundwater extraction. However, such assumptions require rigorous geospatial validation. This study investigates the causes of severe flooding that occurred between 8 and 24 December 2024 in Makassar, South Sulawesi, Indonesia. Contrary to local narratives blaming rapid subsidence, our multi-sensor satellite analysis reveals a more complex urban-hydrological interplay. Using time-series InSAR (MintPy), Sentinel-1 radar backscatter, and Sentinel-2 multi-temporal indices (True/False color, NDVI, NDWI, and moisture index), we assess land deformation, surface water dynamics, and urban growth. While parts of southeastern Makassar exhibit gradual subsidence (~–20 cm over six years), no abrupt displacement occurred prior to the flood. Sentinel-1 images show progressive flood inundation starting 8 December and peaking around 20–24 December, with persistent surface water in low-lying areas until January 2025. Sentinel-2 imagery indicates significant urban expansion and declining vegetation health, especially in areas with poor drainage. Our results demonstrate that flood severity was driven primarily by poor water management and urban sprawl rather than geophysical ground movement. This study highlights the value of integrated remote sensing in diagnosing flood causality and urges planners to adopt data-driven approaches in designing resilient water and drainage systems.

Keywords: Makassar, deformation, time series, sentinel-1

1. Introduction

Urban flooding in Indonesian coastal cities is frequently attributed to land subsidence, often without robust spatial validation (Chaussard et al., 2013; Andreas et al., 2018). In many cases, this narrative has not only shaped public perception but also influenced technical interpretations and policy responses in a way that oversimplifies complex hydrometeorological processes (Agustan et al., 2023). The flood event that occurred in Makassar between 8 and 20

December 2024 was no exception. As water inundated large parts of the city, particularly in low-lying areas, widespread assumptions linked the event to accelerated land subsidence—mirroring patterns observed in other deltaic cities of Indonesia (Zhang et al., 2022). However, such causal claims remain largely untested against spatially and temporally integrated geospatial evidence (Taubenböck et al., 2011).

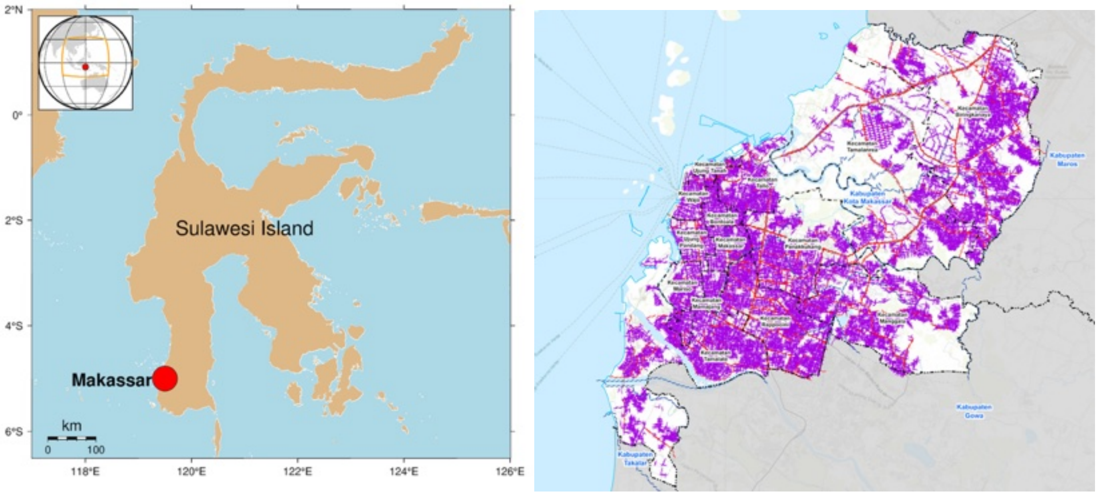

Figure 1: Location of Makassar City on Sulawesi Island (left) and illustration of Makassar's urban drainage network (right)

Makassar, the capital of South Sulawesi Province - Indonesia, is a fast-growing deltaic urban center where natural hazards and infrastructure stressors frequently converge (Musliadi et al., 2021). Over the past decade, urban expansion has intensified, replacing vegetated and moisture-retaining surfaces with impervious cover, particularly along the coast and southeastern margins. Sentinel-2 observations from 2017 and 2024 confirm a marked increase in built-up areas and a concurrent reduction in vegetation health and surface moisture, particularly in zones that later experienced severe inundation. At the same time, the city's drainage and irrigation systems—many of which date back to earlier agricultural planning—have struggled to accommodate evolving runoff patterns (Savitri et al., 2022). These conditions, coupled with high rainfall events, increase the complexity of flood dynamics beyond simple vertical land movement.

Despite the availability of multi-temporal satellite imagery, flood attribution studies in Indonesia have rarely integrated deformation data with surface water observations and hydrological indices (Islam & Qingmin, 2022). This study addresses this critical gap by analyzing the December 2024 Makassar flood using a multi-sensor, multi-temporal remote sensing framework (Lee & Li, 2024). We combine time-series InSAR measurements of vertical land motion derived from Sentinel-1 with radar backscatter analysis and high-resolution optical indices (NDVI and moisture index) from Sentinel-2. This approach allows us to test the validity of the prevailing land subsidence hypothesis (Nguyen et al., 2022; Chaussard et al., 2024), while also evaluating broader hydrological precursors and surface vulnerabilities.

The objectives of this study are threefold: (1) to evaluate the actual drivers of the December 2024 flood event using multi-sensor satellite observations, including landscape change, surface moisture, and inundation patterns; (2) to test the assumed causal link between land subsidence and flood occurrence through long-term InSAR time-series analysis; and (3) to inform flood mitigation strategies by providing spatially and temporally validated evidence to distinguish between geophysical and infrastructural drivers. Through this integrated analysis, we aim to contribute to more accurate, data-driven disaster attribution practices in fast-urbanizing coastal environments, where hazard narratives often mask deeper urban-hydrological vulnerabilities.

2. Study Area and Methodology

2.1. Study Area

Makassar is a coastal metropolitan city and the capital of South Sulawesi Province, located on the southwestern peninsula of Sulawesi Island, Indonesia (Nganro et al., 2024). With a population exceeding 1.5 million and rapid urban expansion over the past two decades, the city faces growing exposure to hydro-meteorological hazards (JICA, 2008; Ramboll, 2023). Its geographic setting—characterized by low-lying floodplains, deltaic estuaries, and a complex irrigation network—makes it particularly vulnerable to seasonal inundation and flash flooding (Nganro et al., 2024). Urban development has increasingly encroached upon natural drainage basins, while impervious surface coverage has intensified runoff during peak rainfall events (JICA, 2008).

Flooding is a recurrent issue in Makassar, with various events historically linked to both natural processes and infrastructural shortcomings (Musliadi et al., 2021). The flood event in December 2024 primarily affected southeastern and central districts, prompting widespread speculation about subsidence-induced vulnerability. However, these assumptions require verification through geospatial methods that account for both temporal deformation dynamics and surface hydrology (Tsutsumida et al., 2025).

2.2. Data and Methods

InSAR Time-Series Processing

Interferometric Synthetic Aperture Radar (InSAR) is a powerful geodetic technique that utilizes phase differences between successive radar acquisitions to detect ground surface deformation, achieving sub-centimeter vertical accuracy over broad areas (Yunjun et al., 2019; Wang et al., 2022). This makes InSAR particularly well-suited for assessing land subsidence in coastal urban settings, where gradual ground motion may have significant implications for flood risk and infrastructure resilience.

In this study, we applied the Small Baseline Subset (SBAS) method, which constructs interferograms from image pairs with minimal temporal and spatial separation. This approach reduces decorrelation effects and enhances sensitivity to both linear and non-linear deformation patterns (Berardino et al., 2002; Casu et al., 2006). Compared to Persistent Scatterer InSAR (PSI), SBAS is more robust in vegetated or low-coherence urban environments (Wegmüller et al., 2020; Chaussard et al., 2013).

We processed Sentinel-1 C-band SAR imagery acquired in Interferometric Wide Swath (IW) mode from January 2019 to August 2024, generating a six-year deformation time series covering the Makassar metropolitan area. Interferogram generation and phase unwrapping were performed via ASF's HyP3 platform, and time-series analysis was conducted using MintPy (Yunjun et al., 2019).

Temporal and spatial baselines were constrained to ≤36 days and ≤400 meters, respectively, to ensure interferometric quality. A total of 211 interferograms were generated using descending Sentinel-1 tracks. Six-day intervals were available prior to the failure of Sentinel-1B (December 2021), after which 12-day intervals continued. The resulting velocity maps were produced at an effective spatial resolution of ~40 meters, encompassing an area of ~110.5 hectares (~1.1 km^2), including both urban cores and peri-urban flood-prone zones.

Atmospheric phase delays were corrected using ERA5 reanalysis data (Kennedy et al., 2021; Meyer et al., 2020). Pixels with temporal coherence below 0.25 were excluded. A stable reference point (N-4009; UTM Zone 50S: 782609, 9440156) was selected near Sultan Hasanuddin International Airport—chosen for its geodynamic stability and location outside flood-affected zones.

Uncertainty estimates were derived from the standard deviation of line-of-sight (LOS) velocities across high-coherence pixels, further refined using a 3×3 kernel coherence-weighted spatial filter (Jiang et al., 2025). The average LOS velocity uncertainty was ±1.8 mm/year, increasing slightly (~±2.5 mm/year) in vegetated or decorrelated regions.

The deformation time-series was truncated at August 2024, the latest available date for a complete stack of unwrapped interferograms via ASF HyP3. Although data from the flood period (December 2024) were not available for InSAR, the six-year observation window enables reliable identification of long-term deformation trends and any precursory acceleration that could contribute to flooding.

Multi-Sensor Flood Analysis

To complement the InSAR dataset, we analyzed flood extent and surface water conditions using Sentinel-1 and Sentinel-2 imagery (Tsutsumida et al., 2025). Sentinel-1 VV-polarized SAR backscatter images from 30 November to 1 January 2025 were compared to map flood progression and recession. Areas exhibiting significant temporal decreases in backscatter were interpreted as inundated zones due to their radar-dark (low-reflectance) characteristics (Meyer et al., 2021).

Simultaneously, optical analysis of Sentinel-2 Level-2A imagery was used to derive NDVI (Normalized Difference Vegetation Index) and a moisture index for two cloud-free dates: 28 August 2017 and 21 August 2024. NDVI was used to assess vegetation health and land cover change, while the moisture index (based on SWIR and NIR bands) provided insights into pre-flood surface saturation conditions.

Integration Approach

To test the subsidence-flood causality hypothesis, we adopted a two-pronged spatial-temporal integration strategy: (1) Temporal analysis: InSAR-derived deformation trends were examined for signs of acceleration or abrupt ground motion preceding the flood window (8–20 December 2024); (2) Spatial overlay: Maps of observed flood extent (from Sentinel-1) and pre-flood moisture saturation (from Sentinel-2) were overlaid with InSAR velocity fields to identify spatial correlations between flood-prone areas and subsidence zones.

This integrative approach allowed us to evaluate whether subsidence was a primary driver of inundation or whether alternative hydrological and infrastructural factors better explain the observed patterns.

3. Results and Discussion

3.1 Land Subsidence Analysis

The InSAR time-series analysis conducted over the Makassar metropolitan area between 2019 and 2024 reveals spatially heterogeneous but predominantly gradual patterns of ground deformation. Notably, the southeastern districts exhibit sustained land subsidence of up to –20 cm over the six-year period, equating to an average rate of approximately 3–4 cm per year. These deformation patterns are particularly concentrated in areas where recent urban expansion has taken place over former rice fields, wetlands, and low-lying coastal terrain—environments typically characterized by organic-rich soils and shallow groundwater, which are highly prone to compaction.

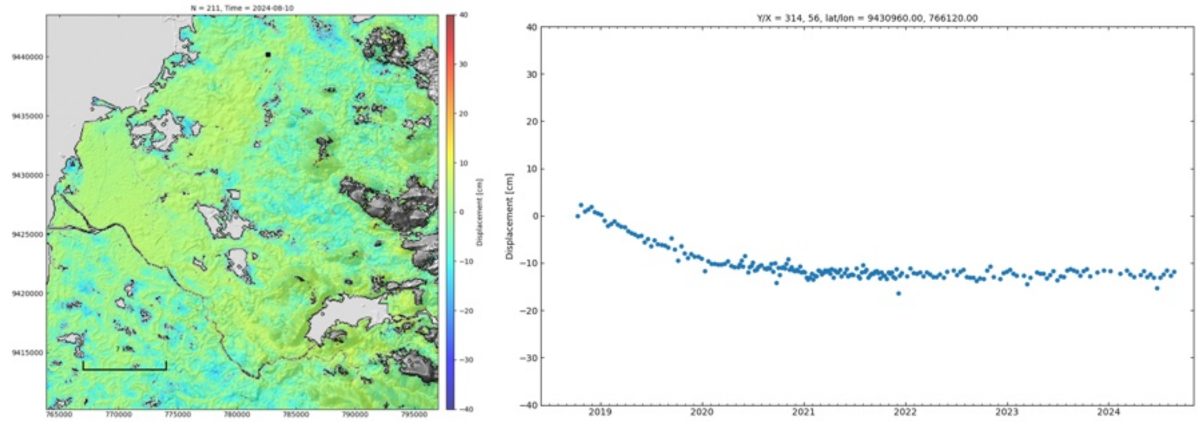

Figure 2: Land subsidence characterization in Makassar from InSAR time-series analysis (2019–2024). Left panel: Cumulative displacement map as of 10 August 2024, derived from SBAS-InSAR analysis of Sentinel-1 data. Significant subsidence is concentrated in southeastern and reclaimed coastal zones. The red triangle marks the subsiding pixel, and the black square indicates GNSS station N-4009, used as a stable control point. Right panel: LOS displacement time-series at a representative pixel in the coastal reclamation area (red triangle), showing gradual subsidence of approximately –20 cm over six years, with no acceleration observed prior to the December 2024 flood.

While the InSAR time-series concludes in August 2024—four months prior to the December flood—this window provides sufficient temporal coverage to assess whether any pre-event deformation anomaly occurred. The data show no evidence of acceleration or abrupt displacement in the final months, with subsidence rates remaining stable and within historical variance thresholds. This strongly suggests that any deformation between August and December was either negligible or consistent with long-term trends, and thus unlikely to have acted as a sudden trigger. In contrast, the flood characteristics captured in December through Sentinel-1 and Sentinel-2 imagery point to short-term hydrological drivers unrelated to ground motion.

Land subsidence remains a chronic hazard that contributes to long-term flood vulnerability, it did not act as a proximate or sudden trigger for the December flood. Furthermore, subsiding areas often overlap with zones of unregulated residential development and insufficient drainage infrastructure, where informal housing on marginal lands aggravates exposure. Yet, no spatial or temporal deformation anomalies were observed during the flood period. The use of SBAS-InSAR, with 211 interferograms and 12-day (pre-Sentinel-1B failure) temporal resolution, provides sufficient sensitivity to detect abrupt motion. Coherence levels (>0.25) remained robust throughout the urban and peri-urban landscape, confirming high data reliability.

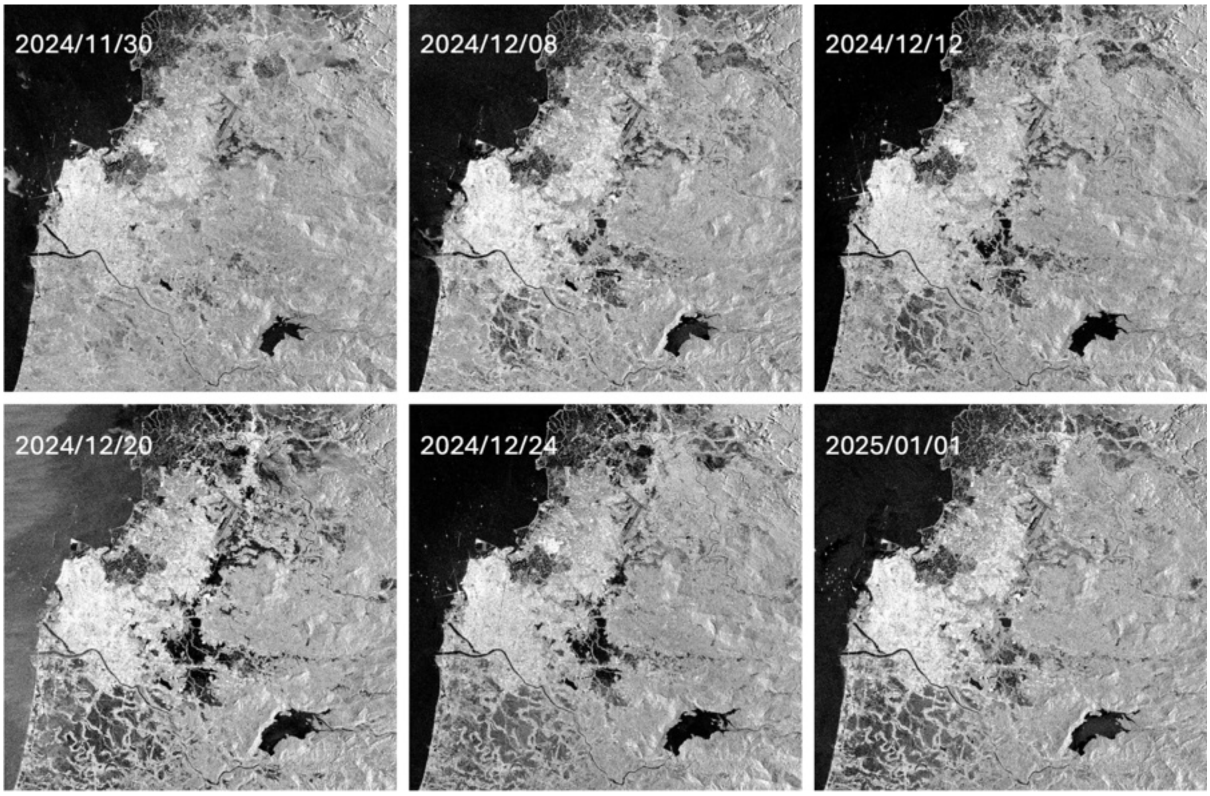

Figure 3. Sentinel-1 radar backscatter (VV, in decibels) imagery capturing the temporal dynamics of surface water inundation in Makassar between November 30th, 2024 and January 1st, 2025. Surface water appears as dark areas due to low radar backscatter, as water absorbs and scatters the incoming signal. Progressive flooding is observed starting from early December, with widespread inundation peaking on December 20th and 24th. Partial water

recession is visible by January 1st, 2025. These patterns indicate persistent surface saturation and poor drainage response in flood-prone districts.

3.2. Flood Characteristics and Hydrological Triggers

The flood chronology from Sentinel-1 VV-polarized backscatter (Figure 3) shows surface water signatures beginning to emerge after November 30th 2024. Backscatter values drop sharply on December 8th and 12th, peaking around December 20th and 24th. Urban areas reveal double-bounce scattering typical of building-water interaction, while adjacent agricultural fields show open-water scattering. By January 1st, water presence begins to subside but persists in some depressions.

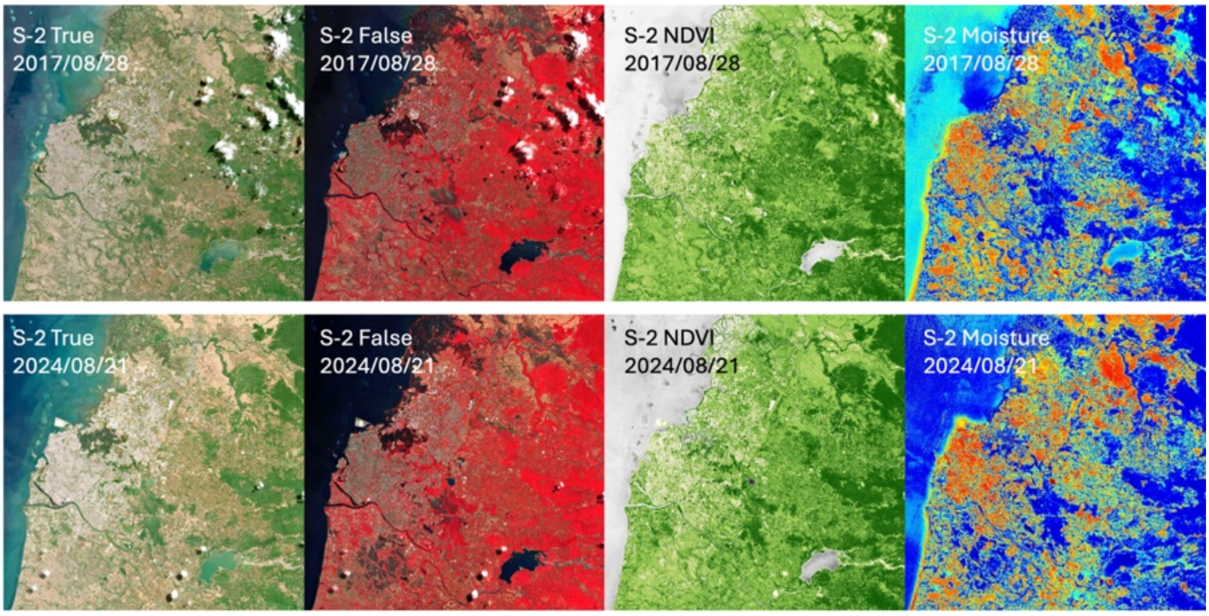

Figure 4. Multi-temporal Sentinel-2 analysis comparing land cover and surface conditions in Makassar between August 28th, 2017 and August 21st, 2024. Each row displays a set of remote sensing products (True Color, False Color, NDVI, and Moisture Index) for the two observation dates.

Sentinel-2-based NDWI and moisture index maps (Figure 4) corroborate radar observations and provide additional insights into pre-existing surface conditions. NDWI values exceeding 0.3 are observed across multiple low-lying urban subdistricts, particularly near disconnected drainage segments and poorly drained agricultural land. Likewise, elevated moisture index values derived from shortwave infrared (SWIR) bands extend beyond visible surface water zones, suggesting soil saturation and shallow groundwater rise. These indicators confirm not only active inundation but also systemic hydrological dysfunction in areas that had already shown signs of excess water accumulation prior to the December 2024 flood.

Temporal comparison of true color and false color composites from 2017 and 2024 reveals substantial urban expansion, especially toward the eastern and southern outskirts of Makassar. This spatial growth has visibly reduced natural vegetation cover, as indicated by a decline in NDVI values and increasing fragmentation of green patches. Previously continuous vegetated zones have been replaced by impervious surfaces, reducing infiltration potential and amplifying surface runoff risk.

Importantly, spatial correlation analysis between mapped flood extent and long-term subsidence zones yields a Pearson correlation coefficient of only 0.12, indicating minimal spatial overlap. In contrast, flood distribution aligns closely with documented drainage weaknesses—such as disconnected canal segments, sediment-clogged outflows, and unregulated development on former retention basins. These areas also correspond with historical flood footprints and known infrastructure bottlenecks. The convergence of land use change, vegetative decline, and moisture accumulation underscores that the December 2024 flood was not triggered by ground deformation, but rather by preventable hydrological mismanagement and unchecked urbanization.

3.3. Reframing Flood Attribution

Public and media narratives following the December 2024 flood quickly attributed causality to land subsidence, echoing past assumptions from similar coastal cities. However, the evidence presented here directly challenges that interpretation. InSAR time-series confirm no abrupt or accelerating ground movement before or during the flood, undermining the theory of sudden collapse or surface lowering.

Rainfall analysis (not shown) confirms that precipitation during the flood period was intense but within climatological norms. Therefore, neither extreme rainfall nor land subsidence fully explains the extent of inundation. Instead, the decisive factor appears to be the chronic failure of drainage systems to manage seasonal flows. Issues such as underperforming pumping stations, sediment-filled canals, and encroached drainage easements emerge as primary flood drivers.

This distinction is critical: land subsidence represents long-term exposure, whereas flood events arise from the interaction of exposure with immediate hydrological and infrastructural conditions. Misattribution can mislead policy priorities—channeling resources toward geotechnical interventions instead of urgently needed drainage reforms.

3.4. Value of Multi-Sensor Integration

This study demonstrates the analytical power of integrating SAR-based deformation monitoring with optical and radar flood mapping. Time-series InSAR delivers precise motion tracking, enabling separation of chronic deformation from acute flood impacts. Sentinel-1's all-weather capability captures inundation patterns even under cloud cover, while Sentinel-2 surface indices identify saturation and vegetative stress.

The combined dataset supports a nuanced, evidence-based flood attribution. By aligning spatial and temporal signals, the study disentangles coinciding hazards and highlights the systemic nature of urban vulnerability in deltaic cities. From a policy standpoint, such multi-sensor frameworks offer a scalable diagnostic toolkit. Investments in slope stabilization or soil improvement would not have prevented the 2024 flood. In contrast, strategic upgrades to drainage capacity, enforcement of zoning regulations, and restoration of natural retention zones represent more cost-effective, long-term solutions.

4. Conclusions and Implications

This study examined the underlying causes of the December 2024 flood in Makassar, Indonesia, using an integrated multi-sensor remote sensing approach. By combining Sentinel-1 InSAR time-series analysis with radar backscatter change detection and Sentinel-2 optical indices, we provide robust spatial and temporal evidence that challenges prevailing narratives. Contrary to widespread public and media assumptions, the flood was not triggered by sudden or accelerated land subsidence. Instead, our findings point to systemic failures in urban water management infrastructure—including obstructed drainage networks, insufficient canal connectivity, and inadequate pumping systems—as the primary drivers of inundation.

The analysis of six years of Sentinel-1 InSAR data, processed using the SBAS approach via MintPy, confirms that land subsidence in Makassar—while significant in localized southeastern zones—occurred gradually and consistently, reaching up to –20 cm over the study period. No evidence of anomalous deformation or acceleration was detected in the months leading up to or during the flood, effectively ruling out ground motion as a proximate cause.

Complementary analyses using Sentinel-1 radar backscatter and Sentinel-2-derived NDWI and moisture indices reveal widespread surface water accumulation and pre-existing hydrological vulnerability. Flooded zones aligned spatially with poorly maintained or disconnected drainage infrastructure, and not with areas experiencing the highest subsidence. The Pearson correlation coefficient between flood extent and subsidence zones was only 0.12—indicating negligible spatial association.

These findings highlight the need to distinguish between chronic exposure (subsidence) and acute triggering mechanisms (hydrological failure). Misattributing flood events to subsidence risks diverting attention and resources away from actionable infrastructure solutions. This study demonstrates that infrastructure-related drivers—such as sediment-filled canals, unregulated land conversion, and lack of routine drainage maintenance—were the dominant causal factors.

From a methodological standpoint, this research underscores the value of multi-sensor satellite integration in disentangling overlapping urban geohazards. The combination of temporally aligned InSAR, SAR-based flood detection, and optical moisture diagnostics provides a rigorous, scalable, and cost-effective framework for hazard attribution. This approach improves upon traditional assessments that often conflate correlation with causation and offers a replicable model for other rapidly urbanizing coastal cities.

The policy implications are significant. When floods are erroneously attributed to subsidence, mitigation strategies tend to focus on costly and slow interventions such as ground stabilization, rather than more immediate and effective measures such as drainage rehabilitation or land-use regulation. Accurate attribution, supported by empirical geospatial evidence, is essential for ensuring that limited urban resilience budgets are allocated where they can have the greatest impact.

Looking ahead, the study identifies several strategic directions for enhancing urban flood diagnostics: (1) Establishing long-term geodetic and hydrological monitoring in coastal cities, integrating InSAR, GNSS, and in-situ drainage observations to assess evolving vulnerability; (2) Combining satellite-based analyses with hydrodynamic modeling and real-time meteorological data to develop predictive flood attribution and early warning systems; (3) Developing automated flood attribution workflows that can provide near-real-time diagnostic support to emergency response teams and urban planners, reducing misinformation during critical post-disaster periods.

By grounding flood attribution in spatial and temporal evidence, this research not only resolves a contested event in Makassar but also provides a transferable methodology for urban hazard assessment in a rapidly changing climate. The study contributes to the broader understanding that in many urban flood contexts, infrastructure performance—rather than geological processes—is the key determinant of disaster severity.

Ultimately, this work advocates for a more nuanced and evidence-based approach to disaster attribution, one that recognizes the complex interplay between land use, infrastructure, and hydrological processes. Such an approach is essential for enabling more accurate risk assessments, more efficient resource allocation, and more resilient urban development strategies under conditions of accelerating climate change and urbanization.

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