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Social Sensing and Urban Flooding: Socio-Spatial Insights from Citizen-Generated Data in Makassar City, Indonesia

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ABSTRACT

Urban flooding in rapidly urbanizing coastal cities increasingly exceeds the capacity of conventional monitoring and response systems to capture its localized, time-sensitive, and socially differentiated impacts. This study examines the potential of social sensing as a complementary approach for understanding urban flooding as a socio-spatial process shaped by everyday experiences, digital participation, and governance practices, with an empirical focus on Makassar City, Indonesia. Drawing on citizen-generated Instagram content collected between January 2019 and March 2024 (retained posts: n = [N]; geotagged posts used for spatial analysis: [P%]), the research integrates spatial, temporal, and qualitative signals derived from geotagged locations, posting timestamps, and visual–narrative materials to analyze flood dynamics. Social sensing outputs are triangulated with institutional flood information (incident logs, response records, and hazard layers) to assess correspondence, gaps, and governance relevance. The findings indicate that social sensing captures impact-oriented flood information in locations where inundation disrupts everyday urban activities, provides early temporal signals associated with flood onset and escalation, and reveals qualitative dimensions of lived flood experience that are not represented in hydrological or administrative data alone. While spatial and temporal patterns broadly align with institutional records, citizen-generated reports can precede formal documentation and highlight highly localized effects (e.g., temporary road closures or neighborhood-scale ponding) that remain underreported in official datasets. Methodologically, the study advances a human-centered analytical framework that bridges digital geographic analysis with qualitative interpretation, prioritizing transparency, interpretability, and ethical handling of publicly available social media data (e.g., de-identification and quotation minimization). From a governance perspective, the results demonstrate the value of integrating social sensing into hybrid urban flood governance to support more adaptive, context-sensitive, and inclusive approaches to flood risk management.

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1. Introduction

Urban flooding has become one of the most persistent and socially disruptive hazards in contemporary cities, particularly in rapidly urbanising coastal environments. Recent assessments have shown that intensified precipitation, sea-level rise, and land-use transformation increasingly interact to amplify flood frequency and severity in urban areas worldwide (IPCC, 2023; Tellman et al., 2021). In this context, flooding cannot be understood solely as a hydrological event. Rather, it represents a socio-spatial process through which environmental dynamics intersect with urban development trajectories, infrastructure systems, and governance arrangements (Di Baldassarre et al., 2013; O'Donnell and Thorne, 2020). Flood impacts materialise unevenly across space and society, reflecting structural inequalities, institutional capacities, and differential access to protective resources (Cutter et al., 2003).

Geographical scholarship increasingly emphasises that flood risk is co-produced through physical processes and social relations embedded in places. Work in urban and political ecology highlights how historical urbanisation patterns, planning regimes, and socioeconomic marginalisation shape uneven flood exposure and vulnerability, particularly in coastal cities (Douglas et al., 2008; Satterthwaite, 2013). In rapidly growing urban regions of the Global South, flood risk is often intensified by the expansion of informal settlements, insufficient drainage infrastructure, and fragmented land governance, creating persistent risk landscapes rather than isolated disaster events (Hallegatte et al., 2017). In Makassar, Indonesia, recurrent pluvial flooding on low-lying coastal terrain interacts with drainage constraints

and rapid land-use change, creating recurring disruptions to everyday urban life, including mobility, livelihood security, and access to basic services.

Despite these complexities, operational flood risk management remains largely dependent on conventional monitoring infrastructure, such as rainfall gauges, river-stage sensors, and numerical forecasts. While indispensable for measuring physical hazards, evidence from rapidly growing cities shows that these systems can remain spatially uneven, costly to maintain, and limited in their ability to support real-time street-level responses, particularly in resource-constrained settings (Jha et al., 2012). More critically, instrument-based systems are designed to capture hydrological variables rather than the lived and immediate impacts of flooding on people and infrastructure. Consequently, information on street-level inundation, transport disruption, and household impacts often emerges too late to inform rapid decision-making and prioritisation during response operations (Fohringer et al., 2015; de Albuquerque et al., 2015).

The proliferation of digital technologies and social media platforms has introduced new opportunities for observing environmental events through everyday social practices. Social sensing—defined as the use of citizen-generated digital traces to detect and interpret real-world phenomena—has attracted growing attention as a complementary approach to traditional environmental monitoring (Imran et al., 2016). Urban residents collectively generate spatially and temporally explicit information that can function as a distributed sensing network through routine actions such as sharing images, tagging locations, and narrating experiences (Goodchild, 2007). Unlike technical sensors, social sensing can capture situated knowledge, perceptions, and experiential dimensions of flooding, offering insights into how risk is encountered and communicated in daily urban life.

Conceptually, social sensing overlaps with but is distinct from volunteered geographic information (VGI) and public participation GIS (PPGIS). VGI broadly refers to voluntarily contributed geographic content (Elwood et al., 2012), whereas PPGIS is typically designed as an intentional participatory process to inform planning and policy (Sieber, 2006; Brown and Kyttä, 2014). In contrast, social sensing leverages 'found' digital traces produced for everyday communication (e.g., images, captions, and place tags) and repurposes them for environmental understanding. This distinction matters because it foregrounds platform-mediated participation, positional uncertainty, and representativeness constraints that must be explicitly addressed in analysis and governance use.

Recent disaster studies have demonstrated that social media–based sensing can play a significant role in rapid event detection, situational awareness, and crisis response. Empirical work has shown that spikes in social media activity can align closely with hazard onset and impacts, and, in some contexts, provide early indications of disruption patterns (Kryvasheyeu et al., 2016). Geotagged imagery and narrative content have been used to map flooded streets, assess damage severity, and identify urgent needs during response operations. These findings underscore the role of citizens not only as information consumers but also as active producers of flood-relevant knowledge.

From a geographical perspective, social sensing intersects with broader debates on volunteered geographic information, public participation GIS, and the co-production of spatial knowledge. Long-standing scholarship highlights how digital participation reshapes whose knowledge enters decision-making processes and how spatial data are produced, valued, and governed. However, participation in social sensing remains uneven, shaped by platform algorithms, differential access to devices and connectivity, and socioeconomic inequalities, resulting in partial and biased representations of flood impacts (Shelton et al., 2015; Taylor, 2017). These challenges highlight the importance of interpreting social sensing data within its sociospacial and institutional contexts.

Despite the rapid growth in the literature, important gaps remain. First, many studies focus on large-scale flood disasters or technologically advanced urban regions, leaving recurrent, smaller-scale flooding in developing coastal cities underexamined. Second, social sensing is frequently analysed as an isolated data stream rather than as part of an integrated governance process involving validation, interpretation, and institutional response. Third, while methodological advances in GIScience have improved event detection, fewer studies explicitly integrate qualitative signals, such as urgency, experiential descriptions, and visual evidence, into response-oriented analytical frameworks that can support decision-making (Cash et al., 2003).

Coastal cities in the Global South provide a particularly important context for addressing these gaps. Compound flood drivers, including extreme rainfall, river overflow, sea-level rise, and land subsidence, interact to create persistent risks in coastal urban environments. At the same time, institutional constraints and limited data infrastructure can hinder the expansion of conventional monitoring

systems, increasing reliance on informal information flows during flood events. Social media platforms have thus become critical channels through which residents report flooding, share visual evidence, and coordinate responses, effectively forming informal yet extensive sensing networks.

This study conceptualises social sensing not simply as an alternative data source but as a socio-spatial process embedded within urban flood governance. Using Instagram-derived social media content, the analysis examines how geotagged locations, posting times, images, and user narratives function as indicators of flood occurrence and impact. These citizen-generated signals are triangulated with institutional information from local disaster management authorities to assess their reliability, complementarities, and limitations in supporting rapid response.

Based on these gaps, this study addresses three research questions (RQs):

(RQ1) How do the spatial patterns of geotagged Instagram flood reports correspond with institutional flood information in Makassar City?
(RQ2) To what extent do temporal peaks in social media data lead or lag official flood documentation during discrete flood events?
(RQ3) What qualitative themes of lived flood experience emerge from social media images and narratives, and how can these insights support hybrid flood governance?

This study makes three primary contributions. First, it extends the empirical understanding of social sensing for urban flooding in coastal cities of the Global South, where recurrent flood events intersect with rapid urbanisation and limited formal monitoring infrastructure. Second, it advances a methodological approach that integrates spatial, temporal, and qualitative dimensions of social media–derived data, responding to calls for more context-sensitive, human-centred analyses of digital traces in disaster studies. Third, the study contributes to urban flood governance debates by demonstrating how citizen-generated information can complement institutional response systems while foregrounding questions of representativeness, equity, and data justice in contemporary risk management.

2. Method

2.1 Research Design

The research design follows a staged analytical workflow that transforms raw social media content into governance-relevant flood information. The workflow comprises data collection, relevance filtering, spatial and temporal analysis, qualitative interpretation, and institutional triangulation. This sequential yet iterative process allows insights emerging at one stage to inform subsequent analytical steps, reflecting co-production approaches to environmental knowledge (Jasanoff, 2004). Figure 1 illustrates how citizen-generated signals are progressively refined and validated through this workflow, emphasising the translation of lived flood experiences into interpretable information that supports situational awareness and flood response within hybrid governance systems.

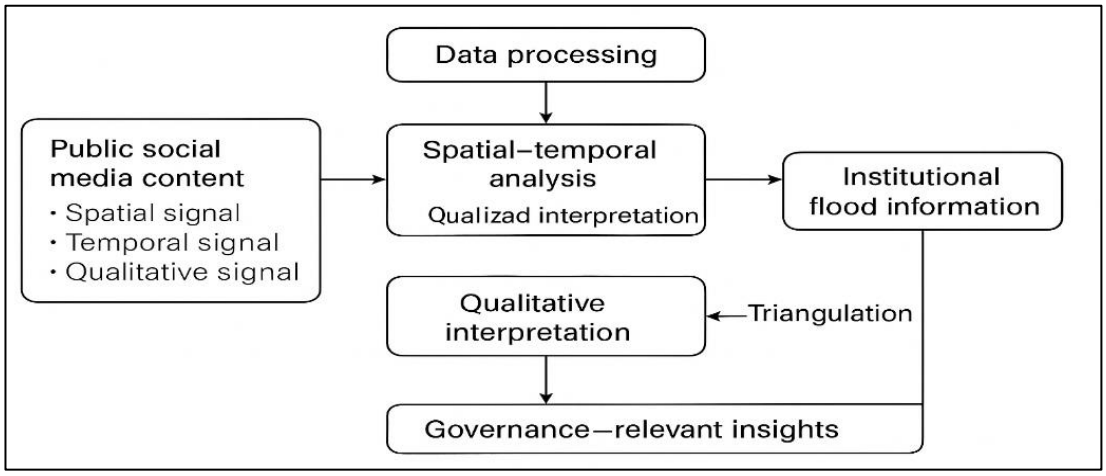

Figure 1. Conceptual workflow of social sensing-based flood analysis

The methodology outlines the stages of research conducted in a structured and integrated manner to achieve the research objectives. It provides concise yet comprehensive information on the research process, including materials and data sources, analytical tools and environments, sampling strategies, measurement procedures, research design and workflow stages, analytical parameters, and data analysis techniques. The methodological framework is designed to ensure analytical rigor while maintaining interpretability within a socio-spatial perspective on urban flooding, consistent with recent developments in digital geography and disaster risk research (de Bruijn et al., 2019).

This study employs a socio-spatial analytical approach to investigate social sensing as a mechanism for understanding urban flood dynamics in a coastal urban environment. Rather than treating social media outputs as isolated digital records, citizen-generated content is conceptualised as part of a distributed social sensing process embedded in everyday urban practices and institutional flood governance structures (Arthur et al., 2018). The overall methodological logic integrates spatial, temporal, and qualitative dimensions of social media activity with institutional triangulation, enabling flood events to be interpreted as lived socio-environmental processes rather than solely hydrological occurrences. An overview of the analytical workflow is illustrated in Figure 1.

2.2. Materials and Data Sources

The primary data source for this study consists of citizen-generated social media content obtained from Instagram, a visual-oriented platform increasingly recognised for disaster and risk research because of its widespread use, support for geotagging, and emphasis on rapid image sharing (Barker & Macleod, 2019). Posts were collected through systematic keyword/hashtag searches related to urban flooding in Makassar City. The observation window covered January 2019 to March 2024, and the data were downloaded in April 2024 using a manual platform-based search and archival procedure that complied with publicly accessible content and platform terms of use. These characteristics enable the capture of fine-scale, street-level representations of flood impacts that are often absent from conventional monitoring systems.

Flood-related posts were identified using combinations of event-relevant keywords and hashtags commonly associated with urban flooding. Only publicly accessible content was included, and all data were handled in accordance with ethical guidelines for social media research (Section 2.6), including de-identification and avoidance of reproducing usernames. For each post, four core attributes were documented: (i) geographic location (geotag/place tag), (ii) posting timestamp (local time), (iii) visual content (images or videos), and (iv) accompanying narrative text. Because explicit geotags are not uniformly available across social media posts, posts without a usable location tag were excluded from the spatial analysis and retained solely for qualitative interpretation when their visual or textual content clearly referred to flood conditions within the study area. These attributes constitute the fundamental social sensing signals used in subsequent analytical stages, reflecting spatial presence, temporal immediacy, and experiential meaning (Crooks et al., 2013).

Institutional data were used as complementary sources for validation and triangulation. These data included (i) official incident logs and response records provided by the local disaster management authority (BPBD) covering reported flood occurrences, the timing of notifications, and response actions; and (ii) flood hazard information from the national inaRISK platform (BNPB) to contextualise modelled flood susceptibility. All institutional datasets were harmonised to the same administrative and spatial reference system as the social sensing data. The institutional records support a hybrid approach to flood risk governance that combines citizen-generated and authoritative information for situational awareness and response prioritisation.

Study area context: Makassar City is a coastal urban system where low-lying terrain and limited gradients constrain drainage during intense rainfall. To describe the physical exposure conditions, we used SRTM-derived elevation data to classify the topography into elevation bands relevant for surface ponding and coastal backwater effects. Figure 2 summarizes the elevation classes used in this study (0-4 m, 4-7 m, 7-11 m, 11-15 m, 15-18 m, 18-22 m, 22-25 m, 25-30 m, and 30-40 m), which provide a physiographic baseline for interpreting spatial clustering of flood-related posts.

The SRTM-derived elevation classes indicate that large portions of Makassar lie in low-lying terrain (0–7 m) along the coastal plain and river corridors (Figure 2). Elevation increases gradually inland, with higher classes (7–15 m and above) concentrated toward the northeastern parts of the city. Low gradients in the coastal and fluvial belts constrain drainage during intense rainfall, promoting ponding and slow recession. For interpretation, lower-elevation bands were treated as being more prone to

surface inundation, providing a physiographic baseline for explaining recurring impact-reporting clusters.

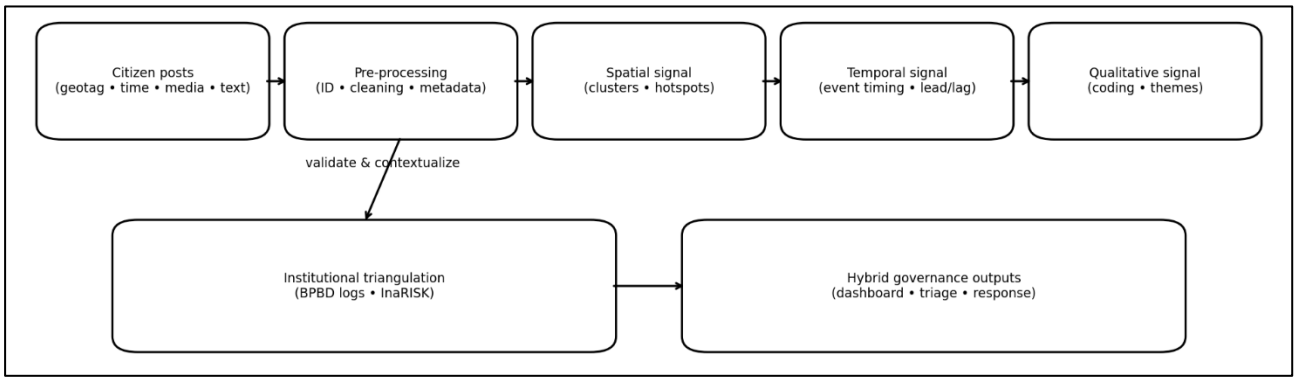

Figure 2. Topographic elevation classes in Makassar City (SRTM-derived).

2.3. Tools and Analytical Environment

Data organisation, spatial visualisation, and analytical processing were conducted using a combination of geographic information system (GIS) software and qualitative content analysis tools. GIS was employed to map and visualise the spatial distribution of geotagged social media posts, identify reporting clusters, and examine their correspondence with known flood-prone areas and urban infrastructure (Resch et al., 2018).

A qualitative interpretation of visual and textual materials was conducted through an iterative review and coding process, enabling a contextual understanding of flood impacts and the lived experiences communicated through images and narratives. Rather than relying on automated sentiment or image classification, the analytical environment prioritised interpretability and human-centred analysis to reduce misclassification and preserve contextual nuance, responding to critiques of overly technocratic digital disaster research.

2.4. Sampling and Data Collection

Sampling followed a purposive strategy focused on posts that explicitly referenced flood conditions, impacts, or responses within the study area. An initial keyword-based screening was conducted, followed by manual inspection to exclude irrelevant, ambiguous, or metaphorical uses of flood-related terms. Posts that could not be reasonably associated with the geographic extent of the study area were removed, following established practices in social media–based hazard research. This hybrid sampling approach balances coverage and precision, reducing false positives commonly associated with fully automated filtering while ensuring that the retained data reflect localised flood experiences and situational relevance (Vieweg et al., 2010).

2.5. Measurement Procedures and Parameters

Social sensing signals were operationalised through three complementary dimensions: spatial, temporal, and qualitative. Spatial signals were measured using geotagged coordinates and interpreted as indicators of locations where flooding was reported and experienced, rather than as direct proxies for hazard intensity. Spatial concentration was assessed using [specify method: point-density/KDE or clustering algorithm] with a spatial aggregation unit of [grid size or bandwidth]. Temporal signals were derived from posting timestamps, aggregated to [time bin, e.g., 10-minute or hourly] intervals, to identify peaks of flood-related communication. A relative activity threshold (tau = 0.1) was used to delineate periods of intensified reporting, where tau represents the normalised activity level above which a time window is classified as an event-related peak. Qualitative signals were extracted from visual materials and narrative descriptions, capturing experiential aspects such as perceived water depth, accessibility constraints, infrastructure disruption, and urgency of impacts. These dimensions were treated as interconnected indicators that collectively enhance interpretability and governance relevance (Meadow et al., 2015). The key dimensions, data sources, and analytical roles are summarised in Table 1.

Table 1. The key dimensions of social sensing data and their analytical roles

Indicator dimension	Data source	Analytical role	Relevance for flood response
Spatial signal	Geotagged social media posts	Identify flood-affected locations and reporting clusters	Support spatial prioritization of response actions
Temporal signal	Posting timestamps	Examine timing and progression of flood events	Enhance situational awareness and response timing
Qualitative signal	Images, videos, and narrative text	Interpret flood depth, accessibility, and perceived urgency	Inform impact assessment and resource allocation
Institutional data	Official flood records and response logs	Validation and triangulation of citizen-generated reports	Reduce uncertainty and strengthen governance integration

2.6. Data Quality Control, Uncertainty, and Ethics

To improve validity and transparency, this study applied multiple quality control steps. Relevance screening combined keyword filtering with manual inspection to reduce false positives and exclude metaphorical or non-local uses of flood terminology. Duplicate or near-duplicate posts (e.g., reposts of the same image/video) were identified using a combination of URL matching, identical visual content, and close textual similarity and removed from the quantitative analyses. Spatial uncertainty was addressed by distinguishing precise geotags (coordinate level) from coarse place tags (neighborhood/city level) and by interpreting clusters as impact-reporting hotspots rather than exact flood boundaries. Temporal uncertainty was acknowledged by treating posting time as a proxy for the timing of observation/communication, which may lag the actual onset of inundation; therefore, lead-lag results were interpreted as indicative rather than deterministic. For qualitative coding, an initial codebook was developed from a subset of posts, refined iteratively, and applied to the full corpus. To enhance reliability, a second coder independently coded a subsample (%), and inter-coder agreement was assessed using [metric, e.g., Cohen's kappa =...]. Ethical considerations: Only publicly accessible posts were analysed. Personally identifying information was removed during data handling; quotations were minimised and paraphrased where necessary; and images were described analytically rather than reproduced unless explicit permission was available. This study followed the principles of data minimisation, contextual integrity, and harm reduction when using citizen-generated digital traces for disaster research.

2.7. Data Analysis

Spatial analysis was used to identify concentrations of flood-related reported activity across the urban landscape. Clusters of posts were interpreted as indicators of areas where flooding disrupted everyday urban activities, mobility, or access to services, rather than as direct measures of hydrological magnitude. Temporal analysis examined fluctuations in posting frequency to identify periods of intensified flooding and potential early signals relative to institutional reporting timelines. For institutional triangulation, an official flood event was defined as a distinct institutional incident log entry with a recorded report time (and, where available, a location descriptor). For institutional triangulation, each official flood incident was paired with the nearest local maximum in social sensing activity within a ±[window] time window, and the lead-lag time was computed as (peak social sensing time–official report time) in minutes (Table 2).

Qualitative analysis interpreted visual and narrative content to contextualise spatial–temporal patterns. Images and videos were examined for observable flood characteristics (e.g., visible inundation depth cues, vehicle passability, debris, and infrastructure damage), while narrative text was coded to identify themes such as urgency, mobility disruption, and immediate response needs. Coding followed an iterative process of open coding and thematic consolidation, guided by the codebook described in Section 2.6. Institutional triangulation compared citizen-generated signals with official flood records to assess correspondence, information gaps, and the operational relevance of citizen reports for rapid response.

3. Results and Discussion

3.1. Spatial Distribution of Social Sensing Flood Reports

A spatial analysis of geotagged Instagram posts reveals a distinctly non-random distribution of flood-related reports across the urban landscape. Flood reports are spatially clustered in low-lying districts, heavily urbanised neighbourhoods, and areas characterised by dense transportation networks. These spatial concentrations indicate recurrent locations where flooding intersects with everyday urban activities, including commuting, residential mobility, and access to public facilities.

Rather than reflecting hydrological intensity alone, the spatial pattern of social-sensing reports emphasises locations where flood impacts are experienced and communicated by residents. High reporting densities frequently correspond to streets, intersections, and residential corridors where inundation disrupts mobility and accessibility. In contrast, areas with limited reporting activity tend to coincide with zones of lower population density or reduced social-media usage, highlighting the socially mediated nature of spatial signal generation. These findings suggest that social sensing captures impact-oriented flood dynamics rather than purely physical flood extents.

These spatial patterns should be interpreted alongside representativeness and positional uncertainty. Social sensing is shaped by who uses Instagram, who posts during disruptive events, and which posts include usable geotags or place tags. Consequently, areas with low reporting density may reflect under-participation rather than low flood impacts. Moreover, place tags can vary in granularity; therefore, mapped points may represent approximate locations (e.g., neighborhood-level) rather than the precise site of inundation. These limitations motivate cautious interpretation and reinforce the need for institutional triangulation.

The topographic context further reinforces this spatial pattern. As described in Section 2.1 and visualised in Figure 2, extensive low-lying terrain along the coastal plain and river corridors constrains drainage efficiency during intense rainfall, which helps explain recurring impact-reporting clusters in several western and coastal neighbourhoods.

3.2. Temporal Dynamics of Flood Reporting

A temporal analysis reveals distinct patterns in the timing of social media posts in relation to flood events. The posting frequency increases during periods of heavy rainfall and surface inundation, with peak activity typically occurring around the most disruptive phases. In several cases, social media reports emerged before official flood notifications, indicating potential value as early situational signals; however, posting time may lag the actual onset of inundation because users report after observing impacts, reaching safe conditions, or regaining connectivity.

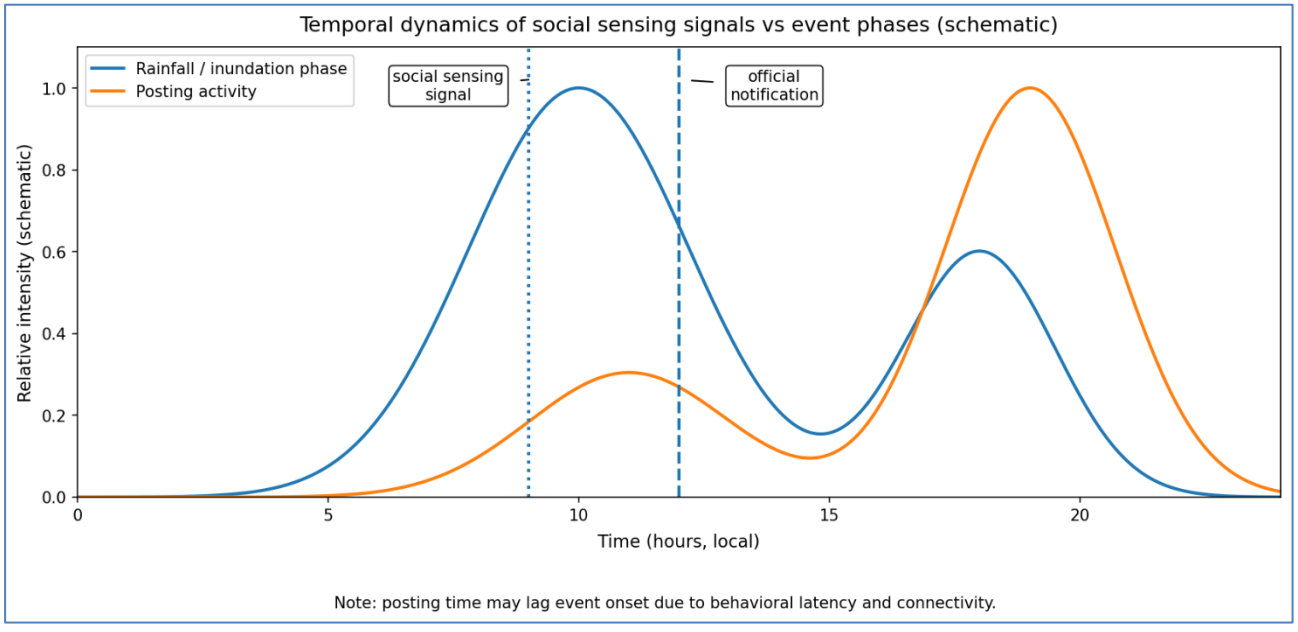

Figure 3. Temporal dynamics of flood reporting and event phases (schematic).

The temporal distribution of posts indicates that residents tend to communicate flood conditions most actively once everyday routines are disrupted—particularly when mobility becomes constrained (e.g., roads are impassable, public transport is suspended, or commuting is delayed) or when access to essential services is affected (e.g., power outages, blocked drainage, interruptions to market activity, or limited access to health facilities). In this sense, social media activity captures not only the physical presence of flooding but also the moment when flooding becomes socially consequential and actionable in daily life. Posting intensity typically declines as floodwaters recede and movement resumes, further underscoring that social sensing responds to lived flood experiences rather than continuously tracking hydrological conditions. At the same time, these temporal patterns are shaped by behavioural and infrastructural factors, such as delayed posting when residents prioritise safety, intermittent connectivity during heavy rainfall, and platform-specific usage rhythms (night-time activity, work-hour cycles, or weekend effects). Therefore, while these dynamics can complement institutional reporting cycles by offering near-real-time situational cues and potential early warning signals, they should be interpreted as indicative timing signals (i.e., relative lead–lag relationships) rather than exact event timestamps. A schematic summary of these timing relationships, including the expected latency between flood onset, posting peaks, and official notification windows, is provided in Figure 3.

3.3. Qualitative Characteristics of Flood-Related Content

The analysis of visual and narrative content highlights the qualitative richness of social-sensing data. Images and videos frequently depict water depth relative to recognisable urban features, such as vehicles, curbs, sidewalks, and building entrances. These visual cues provide contextual indicators of flood severity and accessibility constraints that are not captured by conventional hydrological measurements.

Narrative descriptions and comments often reference disrupted mobility, impassable roads, damaged property, and requests for assistance. Expressions of urgency and warnings to other residents are common, indicating that social media functions not only as a reporting channel but also as a medium for peer-to-peer risk communication. Together, the visual and textual elements convey the experiential dimensions of flooding, revealing how residents interpret and respond to flood impacts in real-time.

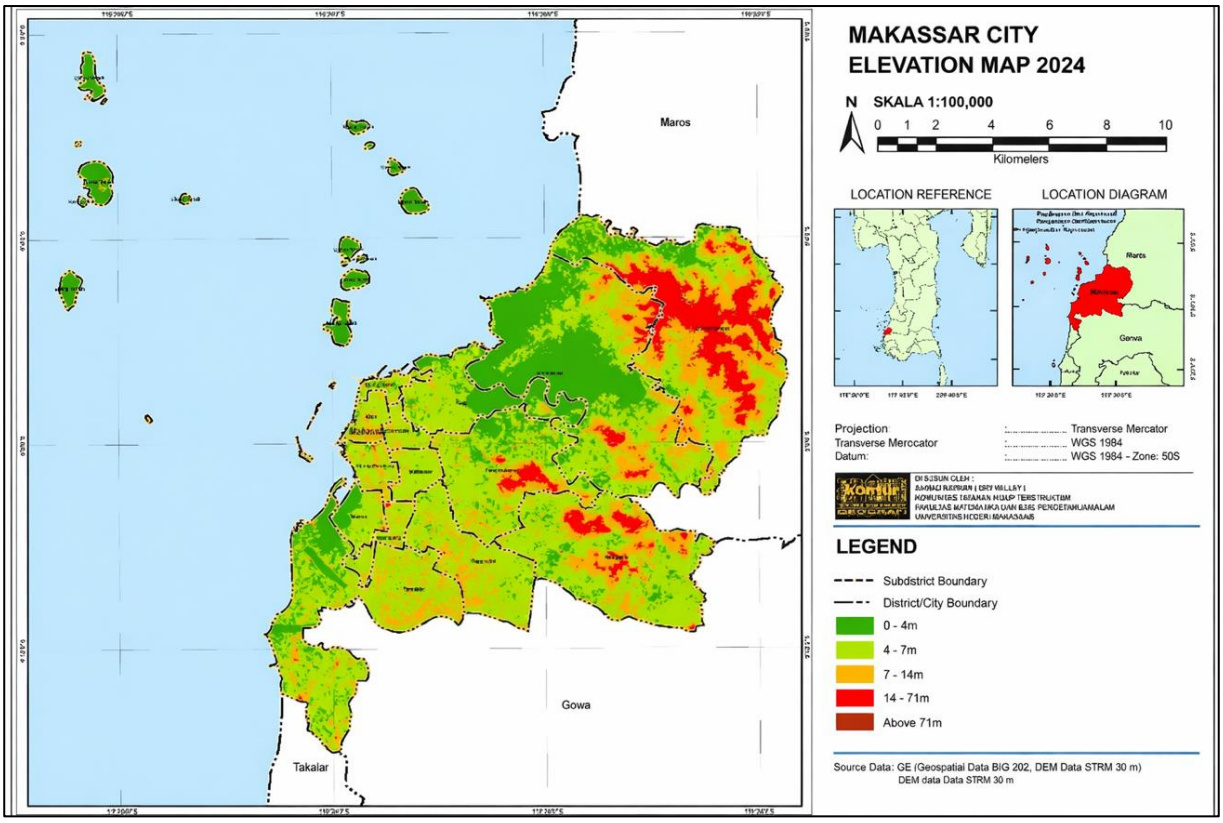

Figure 4. Topographic elevation classes in Makassar City (2024).

SRTM-derived elevation classes reveal extensive lowlands of 0–4 m and 4–7 m along the coastal plain and river corridors (see Figure 4). The terrain gradually rises to 7–14 m and 14–71 m toward the northeast. Low gradients in the coastal and fluvial belts constrain drainage efficiency under intense rainfall. These conditions promote ponding and slow recession during storms. Therefore, an elevation indicator was assigned ascending vulnerability scores for lower terrain. The areal dominance of the 0–7 m belt exerts strong control over the final zonation pattern. This topographic signal complements the spatial pattern found in the rainfall layer. Together, they explain much of the clustering of high vulnerability in the city's western half.

3.4. Integration of Spatial, Temporal, and Qualitative Signals

When spatial, temporal, and qualitative dimensions are examined jointly, social-sensing signals provide a coherent and interpretable representation of flood dynamics across the city. Spatial clusters of reports align with temporal peaks in posting activity. At the same time, qualitative content contextualises these patterns by revealing the nature and severity of flood impacts experienced at specific locations and times. The analytical roles of each signal dimension are summarised in Table 2.

This integrated perspective demonstrates that social sensing captures flood events as dynamic processes rather than static occurrences. Locations with repeated reporting across multiple events emerge as persistent impact zones, whereas temporal patterns indicate that residents rapidly respond to changing flood conditions through digital communication. Integrating multiple signal dimensions enhances interpretability and reduces reliance on any single indicator that may be subject to bias or incompleteness.

Table 2. Dimensions of social sensing signals and their analytical and governance roles.

Dimension	Data attribute	Analytical focus	Governance relevance
Spatial	Geotagged locations	Impact clustering	Identification of priority response zones
Temporal	Posting timestamps	Event progression	Early situational awareness
Qualitative	Images and narratives	Lived flood experience	Context-sensitive response planning

3.5. Correspondence with Institutional Flood Information

A comparison between social sensing reports and institutional flood information reveals a substantial degree of spatial and temporal correspondence. Locations identified through clustered social media activity frequently align with areas documented in official flood records. Similarly, periods of heightened social media reporting correspond with documented response intervals by disaster management authorities (Table 3). In this dataset, all three institutional flood incidents within the observation window exhibited a corresponding social sensing peak, yielding an event-detection correspondence rate of 3/3. Lead-lag values range from -5 to +45 min (mean = 26.7 min; median = 40 min), indicating that citizen reports can precede or closely track formal documentation.

Despite this alignment, discrepancies are evident. In several instances, social media reports precede institutional documentation, particularly during the early stages of flood events. In other cases, citizen-generated content highlights highly localised impacts, such as temporary road closures or neighborhood-scale inundation, that are not recorded in official datasets. These findings indicate that social sensing provides complementary, impact-focused information that enriches institutional flood knowledge rather than duplicating it.

Table 3. Temporal correspondence between social sensing reports and institutional flood documentation.

Flood event	Peak social sensing time	Official report time	Lead–lag (minutes)
Event 1	08:30	09:10	+40
Event 2	14:05	14:00	–5
Event 3	21:15	22:00	+45

Note: Lead-lag is computed as (peak social sensing time - official report time), and positive values indicate earlier citizen reporting.

3.6. Implications for Rapid Flood Detection and Response

The empirical results demonstrate that social sensing offers a timely and context-sensitive source of flood information. Spatial clustering highlights priority areas for response, temporal dynamics reveal early signals of flood onset, and qualitative content conveys the lived impacts that shape response needs.

When triangulated with institutional information, social sensing enhances situational awareness and supports adaptive decision-making during flood events.

Additionally, the results underscore the limitations of social sensing. The reporting density varies across space and is influenced by population distribution and social media usage patterns. Consequently, social sensing signals should be interpreted as indicative representations of flood impacts rather than exhaustive measurements. Nevertheless, the combination of spatial, temporal, and qualitative signals provides a robust empirical foundation for integrating citizen-generated data into urban flood response frameworks.

4. Discussion

4.1. Social Sensing and the Socio-Spatial Nature of Urban Flooding

The spatial concentration of flood-related social media reports underscores the inherently socio-spatial character of urban flooding. Rather than depicting flood processes only through biophysical parameters, such as water depth, flow accumulation, or precipitation intensity, social sensing foregrounds the places where flooding is experienced, interpreted, and managed in everyday urban life. In this framing, clusters of posts do not simply mark where water is present; they also reveal where flooding becomes socially consequential: where movement is disrupted, household coping strategies are mobilised, infrastructure failures are noted, and requests for assistance or information circulate. In other words, the spatial signal captured through citizen-generated reports is closer to a geography of reported impacts and situational urgency than to a hydrological delineation of flood extent.

As shown in Figure 4, areas identified as having an elevated institutional flood hazard provide an important contextual baseline for interpreting where reports might be expected to occur, particularly in low-lying terrain and locations historically associated with drainage bottlenecks. However, institutional hazard layers do not fully account for the observed spatial clustering of reported impacts. Social media concentrations are also shaped by sociotechnical and urban factors that condition who can report and which places become visible in digital traces, such as population density, land-use intensity, proximity to major roads and commercial corridors, differential access to smartphones and connectivity, and the likelihood that residents perceive a location as noteworthy or shareable. Consequently, clusters may be amplified in areas with high activity and digital participation, whereas impacts in peripheral or underserved neighbourhoods may be underrepresented despite potentially severe conditions. Therefore, interpreting these spatial patterns requires reading Figure 5 not as a one-to-one validation of hazard intensity but as a complementary lens: institutional hazard maps indicate where flooding is plausible from a technical standpoint, whereas social sensing highlights where flooding becomes reported and actionable within the sociospacial fabric of the city.

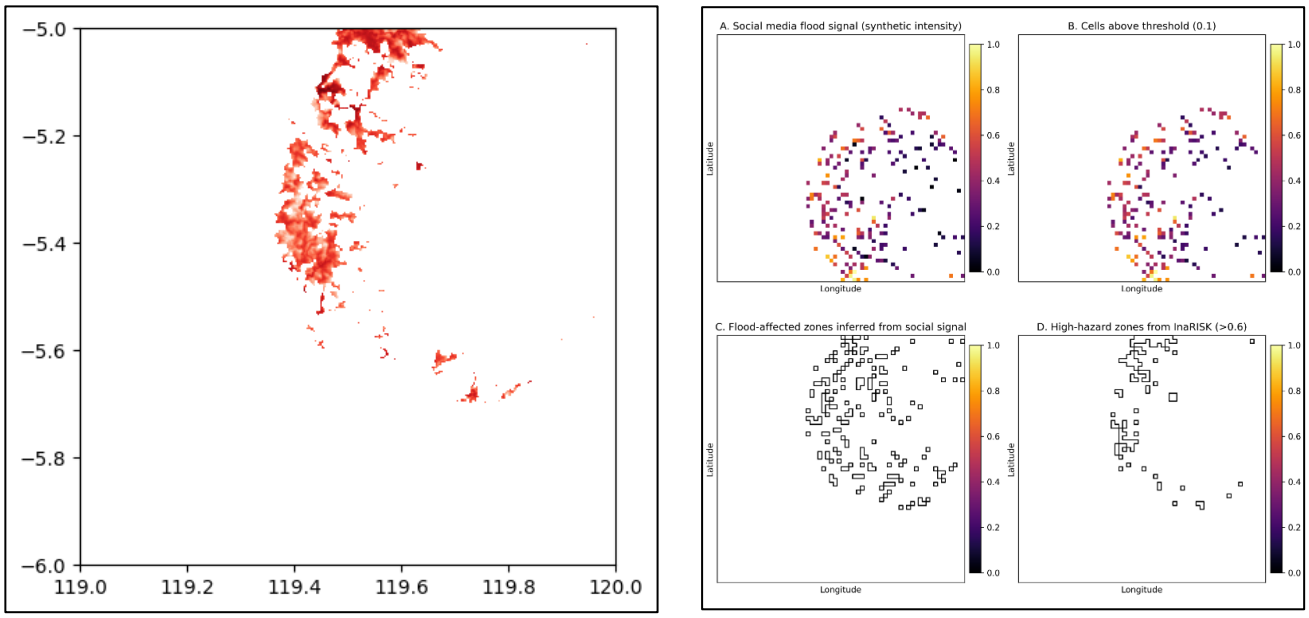

Figure 5. Flood hazard context in urban areas based on citizen-generated flood reports and spatial emergence.

The modelled social sensing signal indicates that citizen-generated flood reports are not uniformly distributed across the wider hazard landscape but instead cluster selectively within it. As illustrated in Figure 6A, the spatial intensity of social media signals concentrates in particular parts of the urban area rather than reproducing the continuous surface implied by modelled flood hazards. This divergence is analytically important: it suggests that social sensing does not simply "map hazard" but highlights where flooding becomes repeatedly noted, reported, and socially consequential—often where impacts intersect with densely used infrastructures, residential concentrations, or routine mobility corridors.

To distinguish diffuse, sporadic reporting from more persistent patterns, we apply a minimum signal threshold ($\tau = 0.1$). This step isolates a subset of grid cells where reporting density is sufficiently high to plausibly reflect recurrent flood-related experiences rather than one-off mentions or incidental chatter (Figure 6B). Conceptually, the threshold functions as a conservative filter: it reduces noise by retaining only locations with sustained digital traces of flood impact. At the same time, it should be interpreted as an operational criterion rather than a physical flood boundary because signal strength can be shaped by uneven participation, connectivity, and posting practices.

The retained cells are then aggregated into contiguous zones (Figure 6C) to provide a more interpretable representation of spatial patterns. This aggregation translates a pixel-level signal into neighborhood-scale "impact zones" inferred from social sensing—areas where multiple adjacent cells jointly exhibit elevated reporting activity. Importantly, these zones should be interpreted as reported flood-affected areas; they emphasise locations where flooding repeatedly disrupts everyday urban activities (e.g., commuting, access to markets and services, household mobility, or local road connectivity), rather than depicting the hydrological extent. In this way, Figures 6A–6C operationalise the core contribution of social sensing: converting uneven, citizen-generated digital traces into actionable spatial insights that complement institutional hazard assessments by foregrounding the geography of lived disruption.

Panel A shows the gridded spatial intensity of flood-related social media signals. Panel B displays grid cells exceeding a minimum reporting threshold (tau = 0.1). Panel C aggregates threshold-exceeding cells into inferred flood-affected zones based on social sensing. Panel D presents high-hazard zones derived from InaRISK (normalized hazard > 0.6) for contextual comparison between modeled hazard and citizen-reported flood impacts.

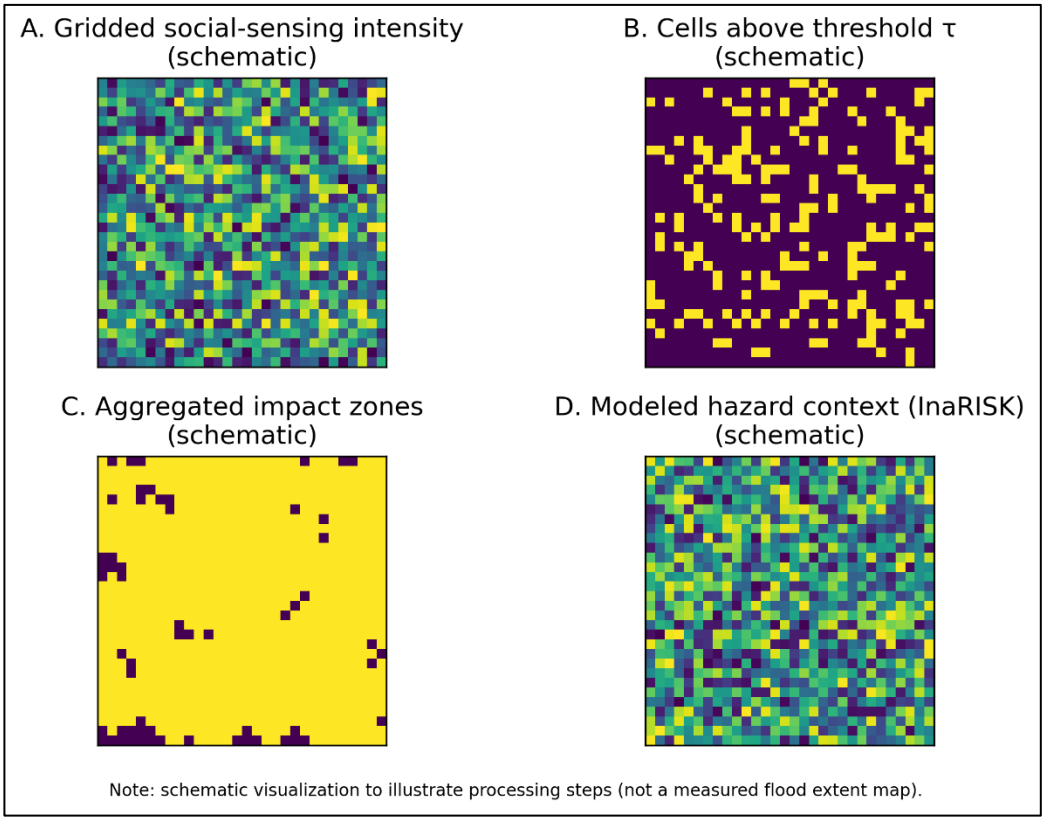

Figure 6. Transformation of social sensing flood signals into spatially interpretable impact zones.

A comparison between the inferred social sensing impact zones and high-hazard areas derived from the InaRISK (Figure 6D) reveals both overlap and divergence. Although several social sensing zones correspond spatially with areas of elevated modelled hazard, other reported impact zones fall outside the highest hazard classes. This pattern indicates that social sensing captures not only physical exposure but also the social conditions under which flooding becomes disruptive and noteworthy to residents. Flood impacts emerge most strongly at the intersection of physical exposure and social activity, particularly in areas of high mobility, dense land use, and everyday infrastructural dependence.

These spatial patterns align with long-standing arguments in human geography that environmental risks are not evenly distributed but are produced through sociospatial configurations of urban development, infrastructure, and daily practices (Harvey, 1996). From the perspectives of political ecology and sociohydrology, the repeated appearance of streets, transport corridors, and residential neighbourhoods in social sensing outputs reflects historically shaped vulnerabilities rooted in infrastructural investment, land-use decisions, and socioeconomic differentiation. Social sensing thus complements institutional flood maps by revealing how flood risk is socially produced and spatially experienced, rather than merely where flood hazards are modelled to occur.

Rather than replacing hydrological representations of flooding, social sensing adds a layer of socio-spatial meaning that captures how residents encounter and respond to flood events. This finding resonates with socio-hydrological perspectives that emphasise feedback between human behaviour and environmental processes. By identifying locations where flooding disrupts mobility, access to services, and everyday routines, social sensing provides empirically grounded insights into the lived spatial consequences of flooding that often remain invisible in sensor-based or model-driven assessments.

4.2. Temporal Social Signals and the Dynamics of Everyday Flood Governance

The temporal patterns observed in social media reporting highlight citizens' responsiveness to rapidly evolving flood conditions. The near-real-time emergence of flood-related posts during event onset illustrates how residents function as distributed observers embedded within affected environments. This finding supports arguments in disaster studies that citizen-generated data can provide early situational awareness, particularly when institutional monitoring systems face temporal or spatial constraints (Morss et al., 2017).

From a geographical standpoint, these temporal signals reflect the relational nature of time and space in urban risk contexts. Space and time are not separate dimensions; rather, they are mutually constituted through events and practices. Social sensing captures this relationality by documenting how flood impacts unfold across space as time-sensitive disruptions to everyday routines. Posting activity spikes when residents experience immediate constraints on movement and safety, indicating that digital communication is closely tied to the lived temporal rhythms of flooding.

The implications for flood governance are significant. Institutional response systems often operate on formal reporting cycles that rapidly change with on-the-ground conditions. Social sensing provides a complementary temporal perspective that reflects when flooding becomes socially consequential, rather than merely when hydrological thresholds are exceeded. Recent work on situational awareness and crisis informatics highlights the importance of time-sensitive, user-generated information for enhancing responsiveness under uncertainty.

However, the value of temporal social signals lies not in speed alone, but in their interpretation within governance frameworks. Without contextualisation and validation, rapid signals risk being dismissed or misused. This underscores the need for institutional protocols that can interpret social sensing data as indicators of emerging impact rather than definitive measurements, supporting timely yet cautious decision-making.

4.3. Qualitative Flood Narratives and the Lived Experience of Risk

Methodologically, the qualitative findings reported here are grounded in the codebook and reliability steps described in Section 2.6. Rather than treating narratives as illustrative anecdotes, the analysis applies systematic coding to identify recurring themes, actors, and response needs, and then links these themes back to the spatial–temporal patterns of reporting.

One of the most distinctive contributions of social sensing is its ability to capture qualitative narratives of flood experiences. Visual content and textual descriptions offer insights into how residents perceive flood severity, navigate inundated areas, and convey urgency to others. Such experiential knowledge aligns with humanistic geography's emphasis on place, meaning, and lived experience in

shaping human–environment relations (Cresswell, 2015; Tuan, 1977). Qualitative flood narratives reveal dimensions of risk that are otherwise difficult to capture through technical monitoring. Images showing water levels relative to vehicles or buildings, for example, communicate accessibility constraints and perceived danger more effectively than numerical indicators. Narrative descriptions often underscore the conveyance of frustration, warnings, or calls for assistance, highlighting the emotional and social aspects of flooding. These findings align with research that emphasises the importance of experiential data in understanding environmental risk as a lived condition, rather than an abstract probability. From a governance perspective, such qualitative signals are particularly valuable for response planning. Emergency decisions often depend on understanding not only where flooding occurs but also how it affects residents' ability to move, communicate, and access essential services. Social media narratives provide context-rich information that can inform prioritisation during responses, supporting more people-centered interventions.

Simultaneously, qualitative social-sensing data require careful interpretation. Social norms, digital literacy, and the affordances of various platforms influence the expression of urgency and impact. Consequently, these narratives should be read as situated accounts rather than objective representations. Recognising this interpretive dimension is essential to avoid misrepresentation while still benefiting from the rich contextual insights that qualitative data provide. Figure 7 summarises the coded qualitative themes and links them to a usable-knowledge framing for governance interpretation.

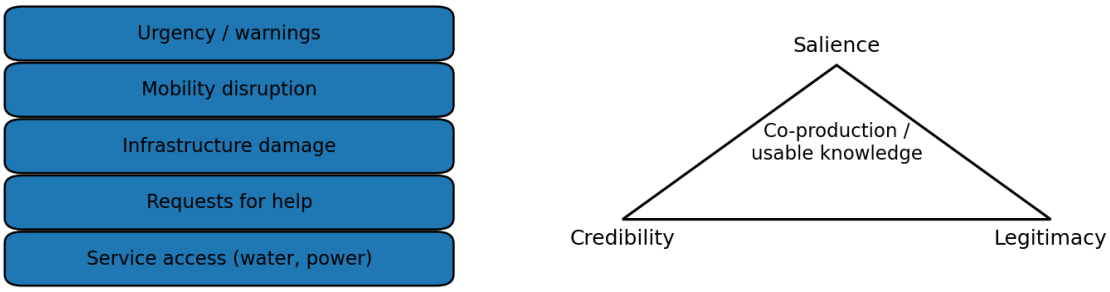

Figure 7. Qualitative themes and usable-knowledge framing for governance interpretation

4.4. Social Sensing within Hybrid Flood Governance Systems

The correspondence between citizen-generated flood reports and institutional records highlights the potential for social sensing to function as part of a hybrid governance system. Rather than existing in opposition to formal monitoring, social sensing complements institutional data by filling temporal and spatial gaps and foregrounding impact-oriented information. This aligns with scholarship on data hybridity, which emphasises the integration of diverse knowledge sources in environmental decision-making.

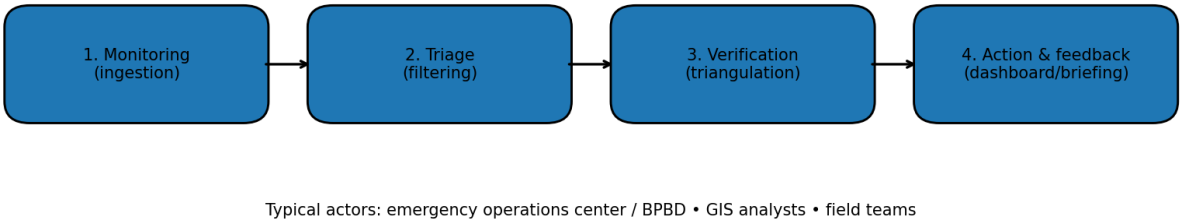

Figure 8. Operational pathway for integrating social sensing into hybrid flood response workflows (schematic).

Operationally, integrating social sensing into hybrid flood governance can be structured as a four-step pipeline: (1) Ingestion: continuous collection of public posts using a transparent keyword/hashtag list, with automated de-identification and metadata extraction. (2) Filtering and validation: relevance screening, duplicate removal, and cross-checking against official incident logs and hazard layers. (3) Synthesis: production of near-real-time hotspot maps and event timelines, complemented by coded qualitative indicators (e.g., mobility disruption, requests for help, infrastructure failure). (4) Action and feedback: dissemination to emergency operations centers through dashboards or briefings, followed by feedback loops that refine queries, thresholds (tau), and response protocols. Such a pipeline emphasizes that social sensing is not a stand-alone substitute for institutional data, but a complementary layer that

can improve situational awareness, prioritization, and communication during rapidly evolving flood events. Figure 8 provides a schematic overview of this operational integration pathway.

The concept of co-production further illuminates this relationship. Knowledge about flooding is produced not solely by experts or institutions, but through interactions among citizens, technologies, and governance structures. Social sensing exemplifies this process by translating everyday experiences into actionable information that informs institutional responses. When appropriately triangulated, these citizen-generated signals strengthen situational awareness without undermining formal authority.

The policy implications emerge clearly from this hybrid perspective. Effective integration of social sensing requires institutional openness, clear protocols for validation, and recognition of citizen-generated data as complementary rather than secondary. Recent work on usable science underscores that knowledge becomes impactful when it is salient, credible, and legitimate to decision-makers. Social sensing has the potential to meet these criteria when embedded within governance mechanisms that value participatory inputs and engagement.

However, hybrid governance also presents challenges. Institutional actors must navigate issues of trust, data overload, and uncertainty. Social sensing should therefore be strategically integrated into response workflows to support, and not overwhelm, existing systems.

4.5 Limitations, Ethics, and Power in Social Sensing

Despite its potential, social sensing is shaped by uneven participation and digital inequality. Not all residents have equal access to social media or choose to report flood experiences online, leading to partial representations of risk. Critical data studies remind us that absences in data often mirror existing social and spatial inequalities. Ethical considerations further complicate the use of citizen-generated data. While publicly available content was used in this study, questions of consent, representation, and potential misuse remain salient. Feminist and critical data scholarship emphasises the need to consider power relations embedded in data practices and to resist treating digital traces as neutral artefacts (D'Ignazio and Klein, 2020). Recognising these limitations does not diminish the value of social sensing; rather, it highlights the importance of understanding its limitations. Rather, it underscores the need for transparent, ethically grounded frameworks that acknowledge uncertainty and bias. Such reflexive engagement strengthens the credibility and responsibility of social sensing in flood governance.

5. Conclusion

Urban flooding in rapidly growing coastal cities demands approaches to risk assessment and response that move beyond hazard-centric and instrument-dependent frameworks. This study demonstrates that social sensing, conceptualised as a socio-spatial process through which citizens collectively generate spatial, temporal, and experiential information, can significantly enrich our understanding of urban flooding as a lived and governed phenomenon. By integrating citizen-generated social media data with institutional flood information, the research highlights how social sensing complements conventional monitoring systems by providing timely, localised, and impact-oriented insights into flood dynamics. Methodologically, the study advances an interpretive framework that bridges GIS-based spatial analysis with a qualitative understanding of lived experience, contributing to ongoing debates in human geography and digital geographic research. From a governance perspective, the findings underscore the value of hybrid approaches that recognise citizens as active participants in environmental monitoring and response while maintaining institutional rigor through validation and triangulation. As coastal cities confront intensifying flood risk under climate change and urbanisation pressures, ethically grounded and context-sensitive integration of social sensing into flood governance holds significant potential to support more adaptive, inclusive, and responsive approaches to urban resilience.

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Conflict of interest. The authors declare no conflict of interest regarding the publication of this article.

Data availability. Owing to ethical considerations and platform terms of use, the social media data analysed in this study cannot be publicly shared. The dataset consists of publicly accessible posts collected for research purposes, and personally identifiable information was removed during data processing. Aggregated data and analytical procedures supporting the findings of this study are available from the corresponding author upon reasonable request.

AI Use Declaration. The authors used ChatGPT (OpenAI, GPT-5) for language editing, structural refinement of academic writing, and limited assistance in outlining sections of the manuscript.

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