Flood Dynamics and Floodplain Alterations Over Two Decades: A Hydrogeomorphological Study of the Larbaâ River, Northern Morocco

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Abstract. Proactive tracking of flood dynamics is essential for identifying floodplain alterations, anticipating newly vulnerable areas, and ultimately updating flood hazard maps. This study inspected changes along the Larbaâ River pathway in Taza City using the hydrogeomorphological method over a two-decade period (2006–2025). We commenced by elaborating initial flood maps based on aerial photographs from 1982 and recent satellite images from 2025. We then relied on observational insights from field campaigns in 2006 and 2025 to identify changes in natural riverland. We supplemented the initial maps with on-site evidence, including sedimentary deposits, flood marks on structures and vegetation, and eyewitness reports from community members. The results showed that floodplain sections are divided into three riverbeds (the minor bed, middle bed, and major bed), arranging them according to a hierarchy of flood risk categories: high, moderate, and low. Certain floodplain sections near the Al Malha neighborhood are significantly modified through embankment construction and urban encroachment, altering natural landforms and consequently reinforcing flood effects. Field investigations revealed that human activities have intensified flooding impacts more than natural factors. Historical analysis and eyewitness data enriched understanding of extreme flood magnitude. Our flood risk maps represent flood limits, from non-overflowing events to exceptional incidents. The maps do not explicitly depict future flooding; rather, they highlight areas that have experienced inundation in the past. While effective for tracking historical flood zones, the method encounters limitations in heavily modified urban sections, suggesting the need for integrated approaches combining geomorphological analysis with hydrodynamic modelling

Keywords: Taza City, Larbaâ River, hydrogeomorphological method, floodplain alterations, flood risk maps.

1 Introduction

While natural floodplains possess inherent capacity to accommodate overflow events, anthropogenic modifications to riverine landforms can fundamentally alter fluvial dynamics [1,2]. These alterations frequently disregard the geomorphological and hydrological characteristics of drainage basins and lack comprehensive frameworks for flood risk management [3,4,5], thereby amplifying inundation hazards rather than mitigating them.

The anthropogenic occupation of floodplains for residential, agricultural, and industrial purposes necessitates systematic monitoring of riverine conditions and proactive flood risk assessment [6]. Longitudinal tracking of flood dynamics is essential for understanding spatio-temporal evolution of flood hazards and informing evidence-based management strategies. Such monitoring enables evaluation of how climate variability, land use change, and hydrological processes influence flood frequency, magnitude, and duration. Furthermore, reanalysis facilitates identification of anthropogenic factors that obstruct water conveyance during flood events, assessment of mitigation measure effectiveness, and refinement of flood hazard mapping [7,8]. These efforts ultimately enhance community resilience, support sustainable development, and protect vulnerable populations.

Contemporary flood research employs diverse methodological approaches, including quantitative hydrological modeling and comprehensive field-based investigations. Recent decades have witnessed significant advances in flood analysis capabilities through developments in remote sensing, geographic information systems (GIS), and computational modeling [7,9]. Hydrodynamic modeling enables prediction of potential flood scenarios under varying conditions, while field-based geomorphological methods facilitate characterization of floodplain units and identification of inundation-prone zones [10].

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Hydrodynamic modeling approaches primarily focus on quantifying peak discharge rates and their spatial propagation, enabling flood forecasting under diverse hydrological scenarios [1,8]. Model implementation requires observed or estimated flow rates, surveyed channel cross-sections, and hydraulic parameters derived from empirical relationships [11]. High-resolution models with extended computational domains are generally recommended for accurate representation of hydraulics fluvial [12]. This methodology has demonstrated effectiveness in flood magnitude assessment across diverse environments [13, 14, 15].

In contrast, the hydrogeomorphological method relies on physical field evidence to delineate flood-prone zones. Originating in France, this approach utilizes sedimentological indicators, botanical evidence, and geomorphological features preserved in the landscape [2,16]. The method integrates knowledge of morphogenetic processes, field observations, and sedimentological analysis [17] to establish a comprehensive framework for understanding fluvial systems [18]. Officially endorsed by the French government for regulatory flood mapping [10], this approach has been extensively applied throughout North Africa, particularly in Morocco [5, 19]. Compared to modeling approaches, the hydro-geomorphological method is relatively straight-forward and cost-effective [20, 21], though its reliability depends critically on the rigor and expertise applied during field investigations.

This study applies the hydro-geomorphological method to track flood hazard evolution along the Larbaâ River, which flows through Taza City and represents a significant flood risk to urban and agricultural areas. The research focuses on densely occupied alluvial plain sections where residential and agricultural activities intersect with flood-prone areas. Specific objectives include (1) developing flood hazard maps for two distinct time periods spanning two decades (2006–2025); (2) documenting floodplain modifications, including riverbed encroachment and wetland conversion; (3) identifying flow obstructions and anthropogenic factors influencing flood behavior; and (4) evaluating the efficacy of the hydro-geomorphological method for tracking flood dynamics.

The methodology employs systematic field observations to document floodplain evolution through identification of flood indicators, including sedimentary deposits, erosional features, botanical evidence (damaged vegetation), and structural damage to buildings. Geomorphological analysis characterizes functional floodplain units, while integration of archival data, historical imagery, and field evidence produces comprehensive flood hazard maps delineating inundation-prone areas with associated uncertainty assessment.

This research contributes to flood hazard assessment literature by (1) demonstrating temporal tracking capabilities of the hydrogeomorphological method; (2) characterizing functional floodplain units and their evolution under anthropogenic pressure; and (3) identifying specific human factors that exacerbate flood risk in semi-arid Mediterranean environments. The findings provide evidence-based guidance for flood risk management and land use planning in the Larbaâ River basin.

2 Study area

The study area is in northern Taza City, where tributaries of the Larbaâ River converge (Figure 1). The Larbaâ drainage basin covers 780 km² within Taza Province and is mapped by four 1:50,000 scale topographic sheets: Taza, Bab Mrouj, Ain Boukellal, and Ain Al Bahera. The catchment has two distinct geomorphological sections. The northern region consists of pre-Rif Oriental Hills with soft rocks, mainly marls and marly limestones from the Cretaceous and late Tertiary periods. Erosion of these vulnerable lands has created a hilly landscape with rounded peaks (locally called "Koudias") exceeding 1,300 meters in elevation [22]. The southern part goes into the eastern Middle Atlas Mountains, which are made up of solid limestone and dolomite from the Lias period. These resistant rocks limit water erosion, creating steep terrain with the highest point reaching 1,400 meters in the Bab Bouidir area [1, 4]. Vegetation is sparse throughout the watershed except for scattered perennial plants in the southern section. The Taza region experiences a semi-arid climate with frequent, intense, short-duration rainstorms [23]. These powerful convective storms often trigger erosion, driving land degradation that threatens agriculture, ecosystems, and community stability across the pre-Rif region [1,7,23]. While water quality in the upper Larbaâ River remains within acceptable physicochemical standards, urban expansion and agricultural intensification pose ongoing threats downstream [24].

Furthermore, thunderstorms regularly cause the Larbaâ River and its tributaries (Bouljraf, Laâzib, Jouana, Rhouireg, Dfali, and Taza) to overflow, generating floods in both urban and rural areas [4, 5, 19, 25]. Over the past thirty years, Taza City has experienced numerous flood-related fatalities and substantial property damage. The September 27, 2000, flood destroyed 47 houses, damaged 126 additional structures [26], and caused crop losses for 349 farmers [27]. The same event damaged the railway system with estimated costs of 4 million dirhams, displacing track sections by several meters and disrupting the Rabat-Oujda line for two days [28]. The 2010 flood damaged road networks, interrupting traffic in various sections and causing estimated losses of approximately 8 million dirhams [26]. These recurring catastrophic events underscore the persistent threat flooding poses to human safety, infrastructure, and economic activities in the region.

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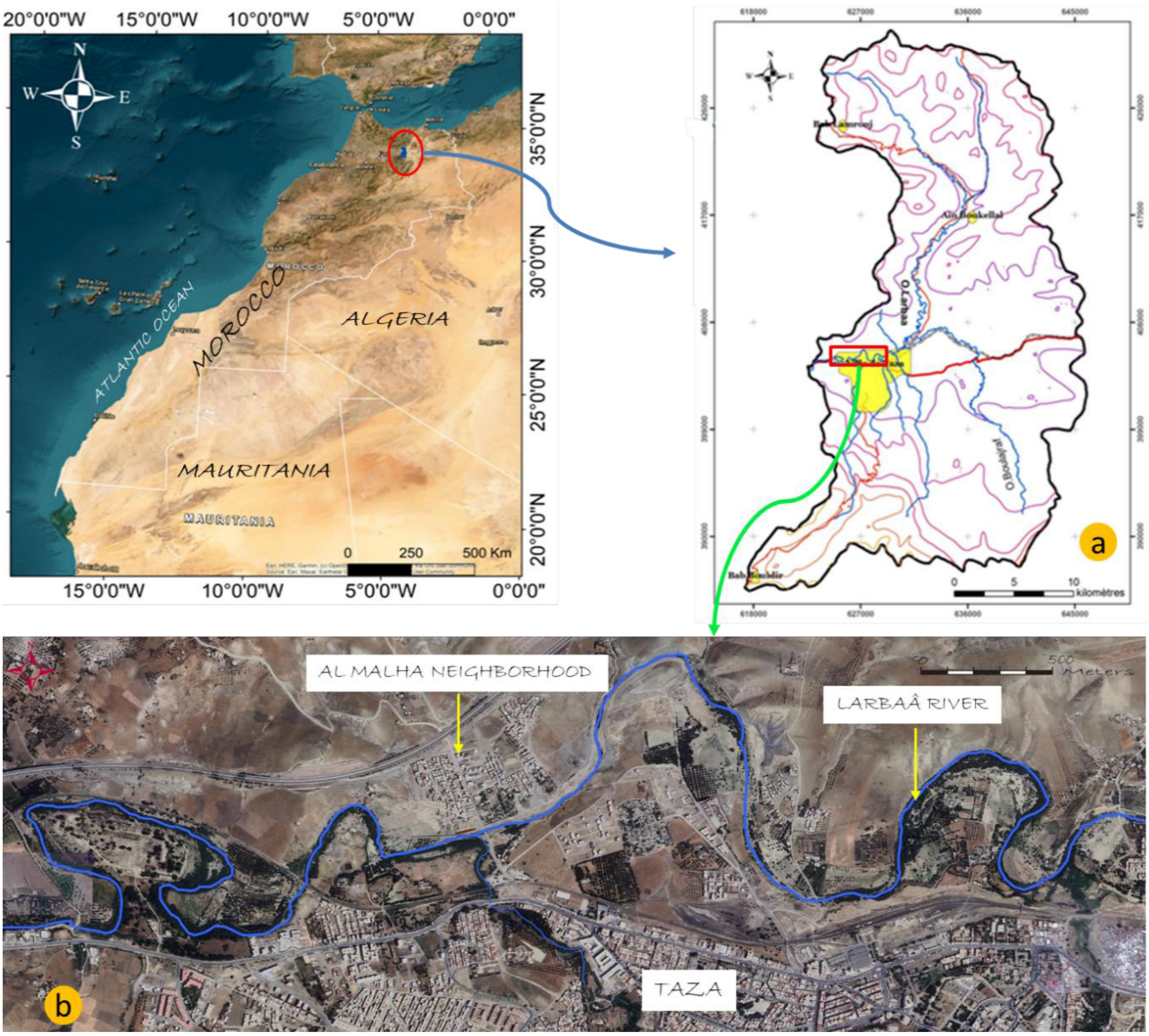

Fig. 1. Study area. (a), Larbaâ watershed, (b), case study along Larbaâ river in Taza city.

3 Materials and methods

To track flood dynamics and develop inundation risk maps for the Larbaâ River, we integrated multiple data sources including aerial photographs (1982), satellite imagery (2025), official archives, eyewitness accounts, and field observations. The methodology consisted of three interconnected stages. All findings were synthesized and integrated into a comprehensive flood risk map (Figure 2).

3.1 Interpretation of Aerial Photographs and Satellite Imagery

Here, we compared historical and current landscape conditions to assess how human activities have modified the river environment and altered natural landforms. We began by interpreting aerial photographs from 1982, provided by the Polydisciplinary Faculty of Taza, to identify and analyze river landforms. These photographs cover the downstream section of the Larbaâ River and align well with our study area, though they do not capture a river meander section where a landfill was later established. We then analyzed a 2025 satellite image (10-meter resolution) obtained from Google Earth to assess current landform conditions. This imagery source is widely used in contemporary flood research for identifying and tracking inundation zones [29]. Modern computational capabilities enable extraction of precise topographic features from such imagery [30].

3.2 Archival Data and Eyewitness Accounts

The second stage involved analyzing technical reports and academic literature. Technical documents included reports from the Taza Urban Agency [26, 31], National Office of Railways [28], Technical Service of Taza Municipality [32], Provincial Service of Taza Equipment [33], and Hydraulic Basin Agency of Sebou [25, 34]. Academic sources included studies addressing hydrological hazards and flood-prone zone delineation in the Taza region [4, 5, 19]. We supplemented archival analysis with interviews of residents who experienced past flood events. These eyewitness accounts provided valuable context that complemented information derived from aerial photographs and satellite imagery.

3.3 Field Investigations

Ca Field investigations focused on identifying morpho-sedimentary features and documenting floodplain alterations. We analyzed sediment particle size and shape to characterize and classify floodplain units. This analysis enabled riverbed description based on alluvial material characteristics. We established transversal topographic profiles to identify and delineate flood-prone areas. Riverbed classification considered bank height and slope within the floodplain. Field surveys were essential for documenting floodplain changes over the 20-year study period (2006–2025).

Flood mapping utilized Taza's 1:10,000 topographic base map. Previous research recommends scales of 1:10,000 or larger for accurate flood mapping [2,35]. While the 1:10,000 scale was the only available scale, it provided sufficient spatial detail for depicting morphological units. The topographic base map was essential for delineating floodplain and fluvial terrace characteristics. Map development followed a systematic two-step approach: (1) defining primary channel boundaries as reference features for subsequent mapping, and (2) delineating riverbed boundaries and fluvial terrace margins. Locations exhibiting floodplain modifications were labeled with letters (A, B, C, and D for 2006; A', B', C', and D' for 2025) to facilitate temporal comparison of observational data.

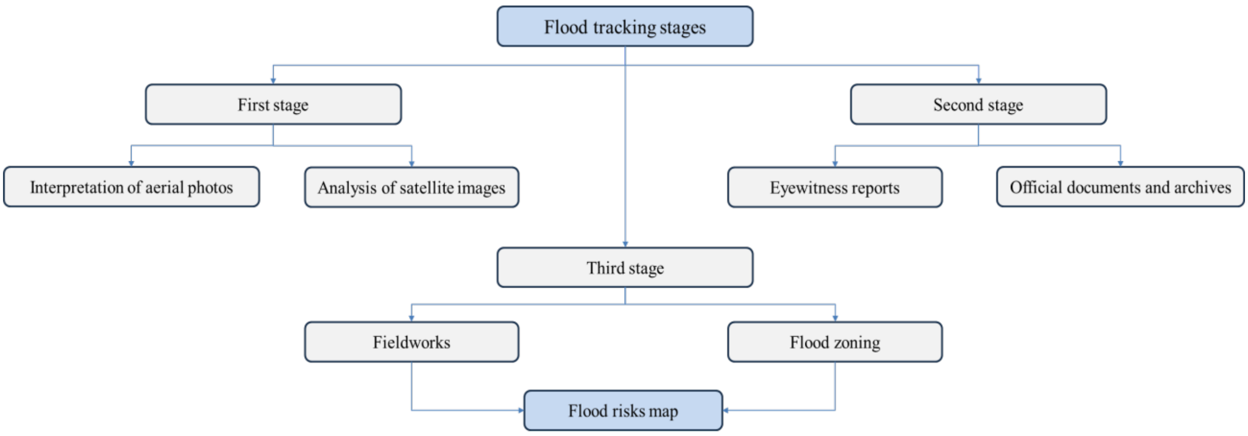

Fig. 2. Methodological framework for tracking flood dynamics and developing inundation risk maps.

4 Results

4.1 Floodplain delineation

4.1.1 Aerial photograph analysis

Aerial photograph interpretation enabled delineation of floodplain units and reconstruction of historical river dynamics. Photographs taken during non-flood periods revealed erosional and depositional patterns, with lighter tones indicating alluvial deposits and darker tones representing olive and fig tree orchards that dominated floodplain agriculture in 1982. Except for scattered houses in the Al Malha neighborhood, the alluvial plain was largely uninhabited, providing insights into historical land use patterns along the river (Figure 4). Stereoscopic analysis enhanced identify-cation of floodplain features including channel margins, riverbanks, bank erosion zones, riverbeds, and terraces (Figure 3).

4.1.2 Satellite imagery analysis

Satellite imagery (2025) enabled precise landform delineation and identification of flood-prone areas (Figure 4). The imagery clearly depicts current land use including residential properties, olive groves, and fruit orchards near the river. Light-toned areas indicate bare ground representing either natural alluvium or anthropogenic embankments, distinctions subsequently verified through field investigations. Dark-toned areas on fluvial terraces indicate well-developed soils with high organic matter content (Figure 4). Comparison between 1982 aerial photographs and 2025 satellite imagery reveals substantial morphological changes in the alluvial plain over the study period.

4.1.3 Field-based floodplain classification

Field investigations, combined with aerial photograph and satellite imagery analysis, enabled classification of the Larbaâ River floodplain into three distinct riverbeds: the minor bed, middle bed, and major bed (Figure 5). These riverbeds were organized hierarchically according to flood risk (high, moderate, and low, respectively) consistent with previous studies [5, 19]. Each riverbed exhibits sub-horizontal surfaces with gentle downstream gradients. Banks ranging from less than one meter to over five meters in height separate the riverbeds along the floodplain. Bank morphology varies with lithological composition (Figure 5). Where channels erode alluvial terrace conglomerate or marl hill bases, banks are steep to vertical. Within the floodplain proper, banks exhibit gentler slopes (Figure 5). The minor bed experiences frequent flow, indicating high inundation risk. Sparse hydrophilic vegetation reflects ongoing fluvial activity. Sediments consist primarily of sand, silt, gravel, and minor coarse material. In some locations, the minor bed extends laterally to directly contact fluvial terraces (Figure 5). The middle bed exhibits irregular topography affecting surface roughness, resulting from erosional processes originating in the minor bed. This unit carries moderate inundation risk. During flood events, water inundates this partially urbanized zone supporting hydrophilic vegetation and olive groves.

The major bed, in contrast, consists of fragmented sub-horizontal surfaces resembling isolated elevated platforms. These areas experience inundation only during rare floods following exceptional rainfall events, justifying their classification as low flood risk zones (Figure 5). The major bed's lower inundation frequency makes it suitable for permanent human activities. Sediments consist primarily of sand, silt, and clay, indicating low-energy depositional conditions. These fine-grained sediments produce fertile soils highly valued by local farmers who extensively cultivate the major bed (Figure 5). Soil development varies across the floodplain terraces: lower terraces exhibit weakly developed soils with incipient coloration, while higher terraces display well-developed soils reflecting prolonged pedogenic processes.

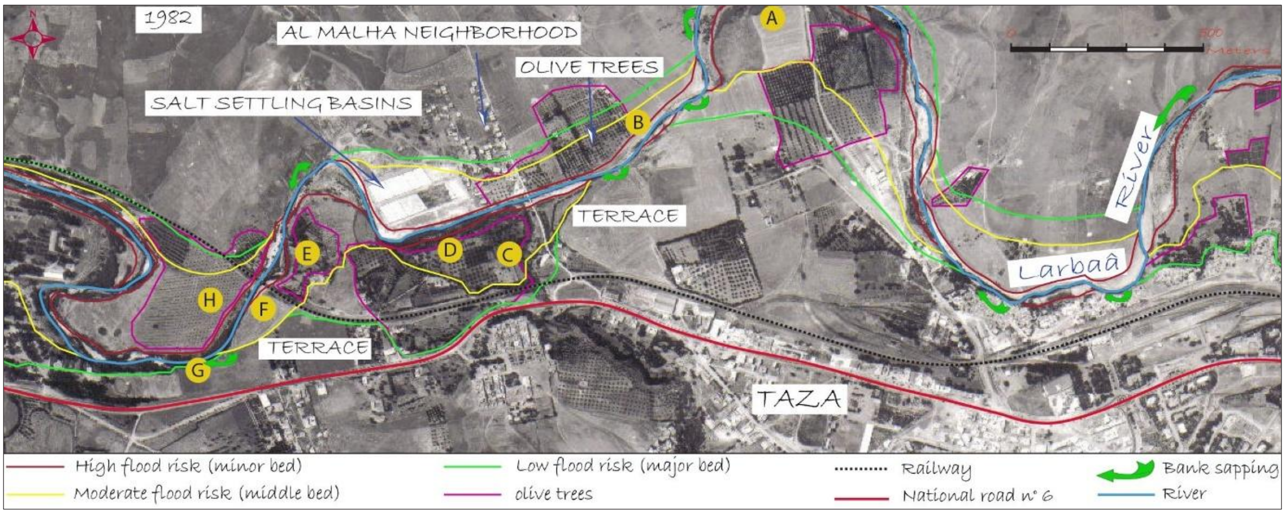

Fig.3. Initial floodplain delineation using 1982 aerial photographs. Light areas indicate alluvial deposits; dark areas represent orchards and vegetation.

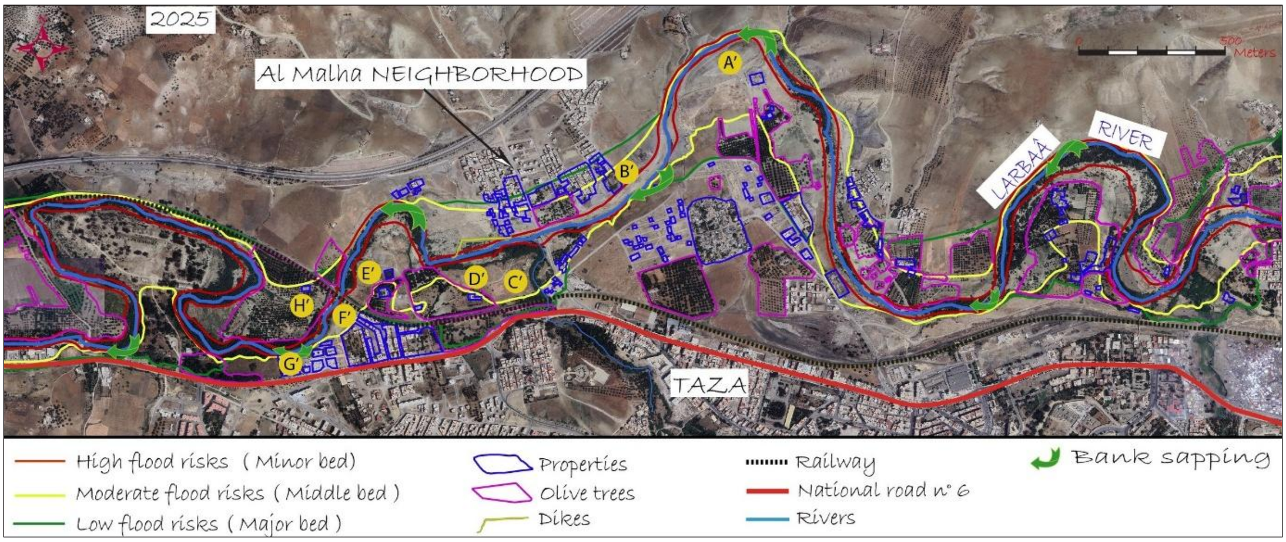

Fig. 4. Floodplain delineation and land use patterns from 2025 satellite imagery (Google Earth).

4.2 Floodplain modifications over two decades

Vegetation and sediment accumulation obstruct the Larbaâ River, disrupting its ecological and hydrological functions and increasing flood risk to residents and properties. Moreover, several floodplain locations exhibit significant human alterations that have changed the river's natural form and intensified flooding impacts.

Field investigations revealed that human activities are the primary driver of altered river behavior. Major problematic interventions include undersized bridges, extensive embankments in the floodplain, inadequate flood protection structures, and residential properties built dangerously close to the river.

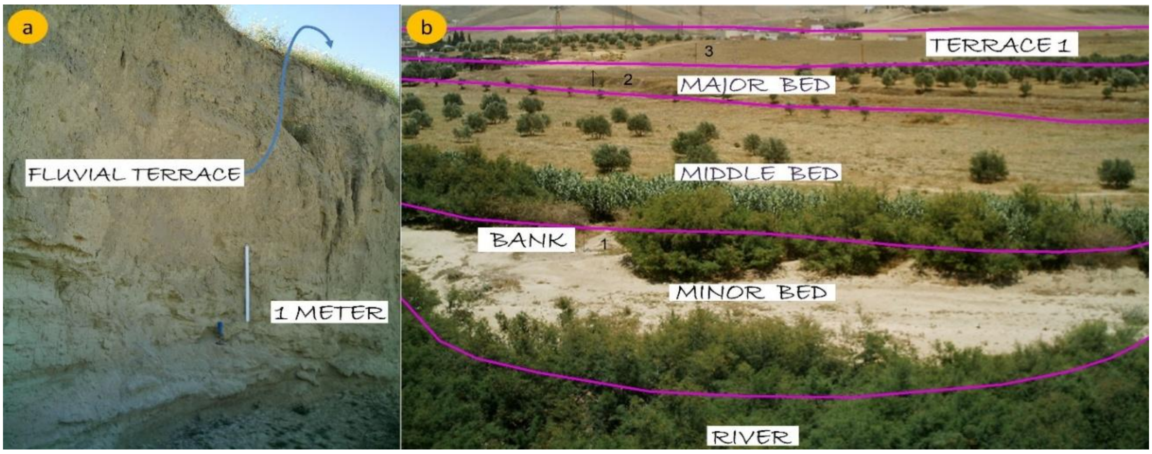

Fig. 5. Bank types along the Larbaâ River. (a) Steep bank where channel erodes terrace. (b) Gentle bank within the floodplain separating riverbeds.

4.2.1 Embankment Construction in the Floodplain

Construction debris—including rubble from demolished buildings and excavated foundation soil—is regularly dumped along the Larbaâ River (Figure 6). This material is typically deposited near the channel, creating risks of downstream transport toward the Idris First Dam. Residents perceive the river corridor as unused space, leading to waste disposal without consideration of consequences (Figure 6). Over time, accumulated debris has created artificial landforms that fundamentally alter the natural floodplain configuration (Figures 6B, B', C, C', D, D').

In some areas, farmers cover embankments with topsoil to enable cultivation (Figure 6C, C'). In other sections, residents consider these embankments effective flood barriers, leading to continued deposition and compaction of material in the riverbed. These practices have changed the shape of the floodplain (Figure 6B, B'), making the floodable area narrower and less able to handle large floods. Section F exhibits the most severe alterations, where the embankment has raised the floodplain to terrace elevation, creating a continuous surface extending to the active channel (Figure 7F, F′). Section E experiences ongoing embankment deposition over fruit orchards, including olive and fig trees (Figure 8).

Taza City Hall recently announced plans to convert the former landfill site into a public park to enhance green space and community well-being. To implement this project, the city deposited and compacted large volumes of fill material in the riverbed to cover the landfill area. This intervention has substantially altered natural landforms (Figure 9A, A') and modified the landscape. The filling material disrupts river flow patterns and creates barriers that obstruct water conveyance. By partially blocking the natural flood-plain, this intervention increases flood risk. These modifications raise concerns about the park's long-term sustainability, safety, and potential impacts on surrounding communities.

4.2.2 Inadequate Flood Protection Structures

Dikes were constructed to reduce flood impacts, particularly in densely populated areas along the river [32]. In the Al Malha neighborhood, protective barriers consist of longitudinal embankments forming a continuous levee extending hundreds of meters (Figure 10). After the big flood on September 27, 2000, the Taza municipality quickly built these structures to keep water from overflowing and to protect people and their property (Figure 10). Construction materials were extracted directly from the channel and placed within the floodplain (Figure 10). While these levees confine flow and limit inundation extent, they also obstruct natural water conveyance, potentially creating unexpected flooding patterns. Field investigations revealed that these dikes altered natural landforms and modified flow dynamics, ultimately worsening flood conditions rather than improving them.

4.2.3 Undersized Hydraulic Structures

Field investigations identified inadequate hydraulic structures throughout the study reach. During major flood events (2000, 2002, 2010, and 2026), the river regularly overtops bridges in the urban area. These cross-structures act as barriers that hinder water conveyance and worsen flood impacts both upstream and downstream [7]. Hydraulic modeling and historical flood observations confirm that existing structures are undersized for discharges exceeding the 20-year return period [1]. Historical records, technical reports, and academic studies document how these structures have intensified flood impacts [1, 5, 19, 25].

The railway bridge at kilometer point 116 represents the largest structure and has experienced repeated flooding over the past two decades (Figure 12a). Since its construction in 1934, sediment has progressively accumulated beneath the bridge. Currently, sediment deposits and trapped wood debris partially obstruct the bridge opening, reducing its hydraulic capacity (Figure 11).

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Fig. 6. Floodplain alterations over two decades: 2006 (B, C, D) and 2025 (B', C', D').

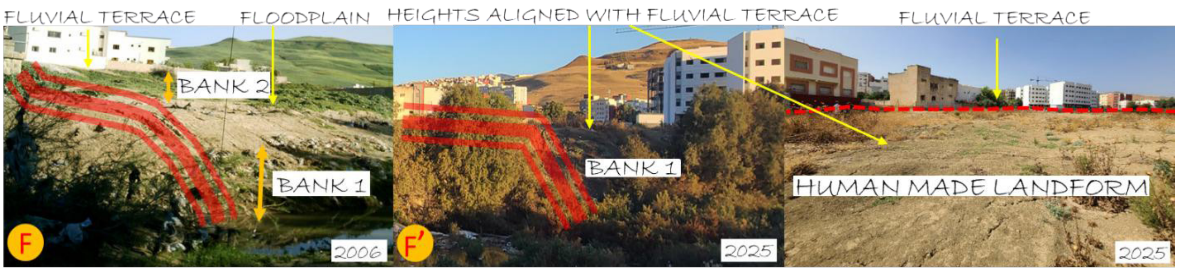

Fig. 7. Embankment over floodplain at section F. (F) 2006 conditions; (F') 2025 conditions showing terrace-level fill.

Fig. 8. Construction debris deposited over fruit trees in the floodplain at section E.

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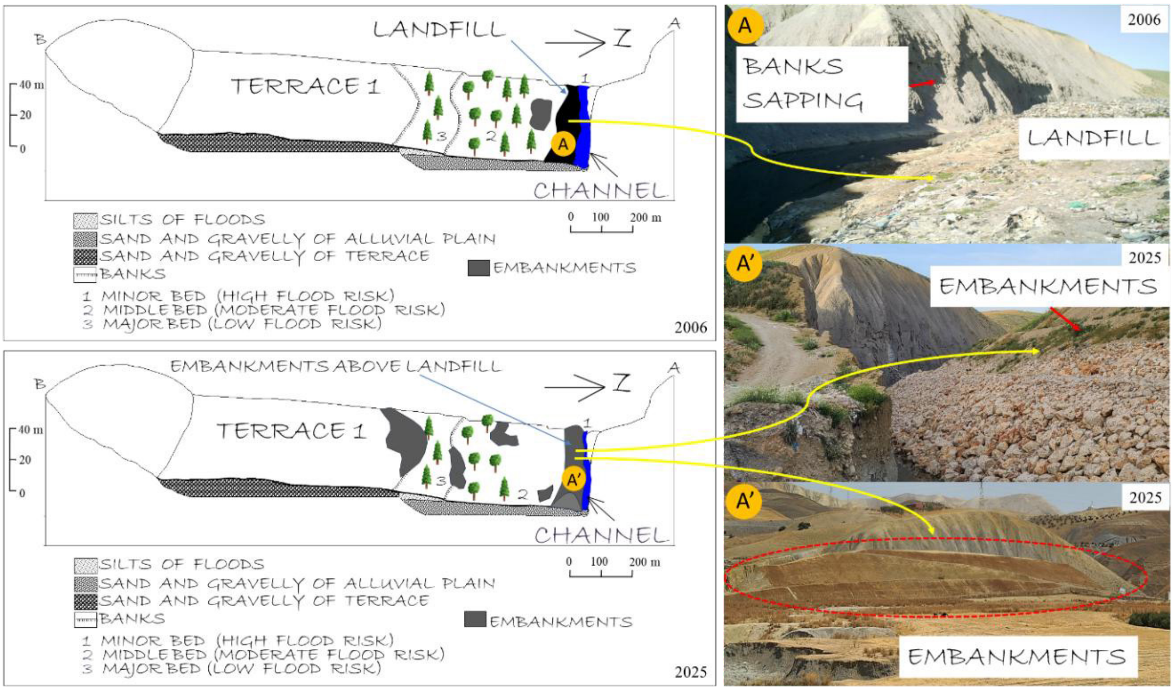

Fig. 9. Floodplain modifications at section A. (A) Landfill site, 2006 ; (A') embankment construction, 2025.

Fig. 10. Dikes alongside Al Malha neighborhood, (a), dikes during its construction stage on the left riverbank (TUA, 2000); (b), improper dikes constructed in the right bank in 2002 (TUA, 2002); (c), current state of dikes along the right and left riverbanks.

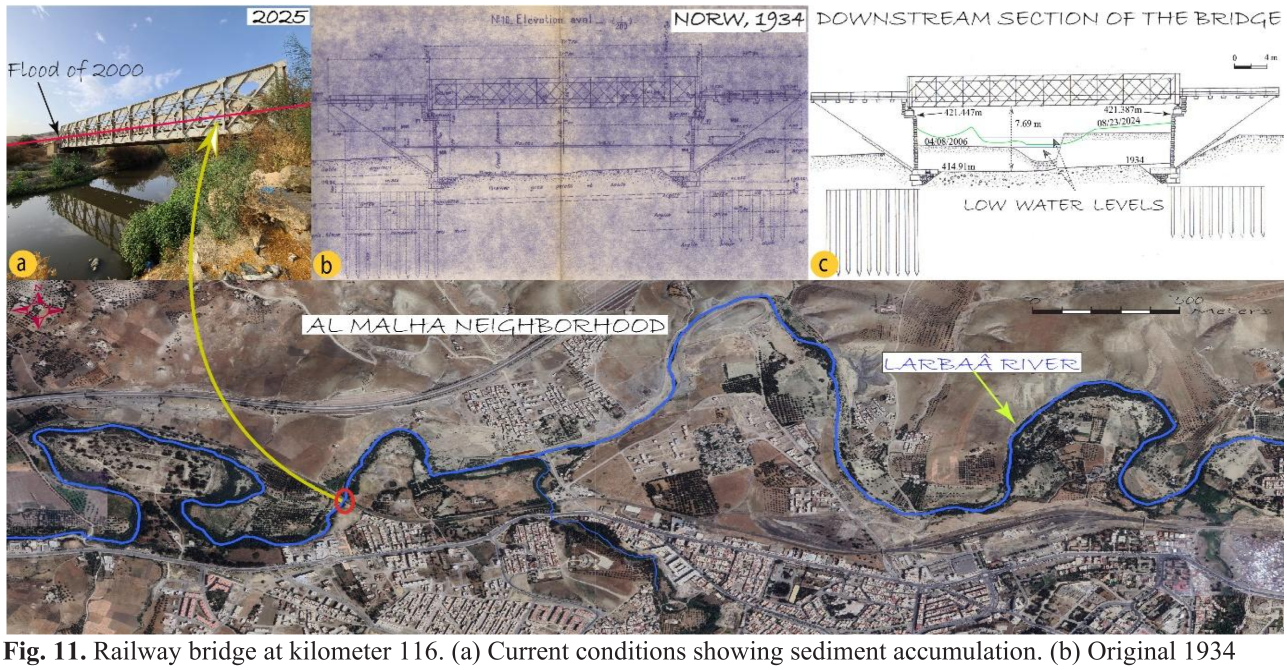

Fig. 11. Railway bridge at kilometer 116. (a) Current conditions showing sediment accumulation. (b) Original 1934 construction plan (NORW, 2000). (c) Channel bed elevation changes over the past century.

4.2.4 Bank Stabilization with Gabions

At section G, the river flows directly against the fluvial terrace, an area that has recently undergone extensive development. The river has actively eroded this bank for decades, causing progressive cliff retreat (Figure 12G). To enable development, gabion walls were installed at the bank base, and trees were planted along the cliff edge to stabilize the riverbank (Figure 12G). This intervention has stabilized the area sufficiently to permit urban development adjacent to the river. However, this stability may be temporary. Water passes through the gabion structure, saturating the terrace base and creating persistent moisture conditions (Figure 12G'). This continuous wetting promotes groundwater circulation within the terrace, potentially increasing long-term terrain instability despite the apparent surface resilience.

4.2.5 Residential Development in Flood-Prone Zones

Extensive residential development has encroached into the floodplain along the riverbank (Figure 14). Previous studies identified human settlements extending into flood-prone areas, with the Al Malha neighborhood being the most vulnerable [4, 5, 19, 25, 26]. Property development in this area has modified natural landforms and disrupted floodplain dynamics. The neighborhood experiences recurring catastrophic floods with lasting community impacts, including major events in 2000, 2002, 2010, and recently in February 2026 [7]. The Larbaâ River now regularly inundates residential areas following substantial rainfall. Hydrodynamic simulations indicate the floodplain cannot convey 50-year and 100-year flood discharges [1]. Consequently, the Al Malha neighborhood and other settlements remain highly vulnerable to flooding.

Fig. 12. Riverbank stabilization at section G. (G) Active bank erosion, 2006. (G') Gabion-reinforced bank with residential.

5 Discussion

Our flood hazard maps document the river's flooding history in Taza City. Importantly, these maps do not predict future flooding; rather, they show areas where flooding has already occurred. Comparison of the 2006 and 2025 maps reveals dramatic changes near the Al Malha neighborhood (Figures 13 and 14). The most significant transformation involves extensive embankment construction within the floodplain, which has progressively narrowed the river channels. The 2025 map shows a more confined river system compared to the relatively natural configuration visible in 2006. The updated map also documents recent urban development encroaching onto the floodplain and river terraces.

Field investigations revealed clear evidence of past flood events. We documented the size of transported sediment and identified deposits of fine material left by floodwaters. Flood marks on walls, trees, and ground surfaces allowed us to reconstruct previous flood events' extent. Our observations identified serious deficiencies in flood protection infrastructure. Bridges crossing the Larbaâ River and protective levees designed to prevent water overflow into residential areas are inadequate for current conditions. Field surveys further pinpointed vulnerable zones requiring immediate protection measures, structural reinforcement, or possible evacuation planning. The evidence shows that human activities have intensified flooding more than natural factors alone. Urgent intervention is needed to prevent further degradation.

Furthermore, fieldwork proved essential for interpreting satellite imagery and aerial photographs accurately. Direct observation allowed us to distinguish artificial features from natural landforms. We identified bright patches in satellite images as embankments (Figure 4B', C', D', E'). Earlier aerial photographs showed these same areas as cultivated land, but over time, vegetation was removed and embankments were built over former orchards (Figures 3B, C, D, E, and 5B', C', D', E'). At Section F, property owners constructed embankments to protect homes and belongings from flooding. Rather than clearing riverbeds and banks to maintain flow capacity, residents focused on building barriers to block floodwaters. These interventions have disrupted natural river processes and worsened flooding (Figure 14F').

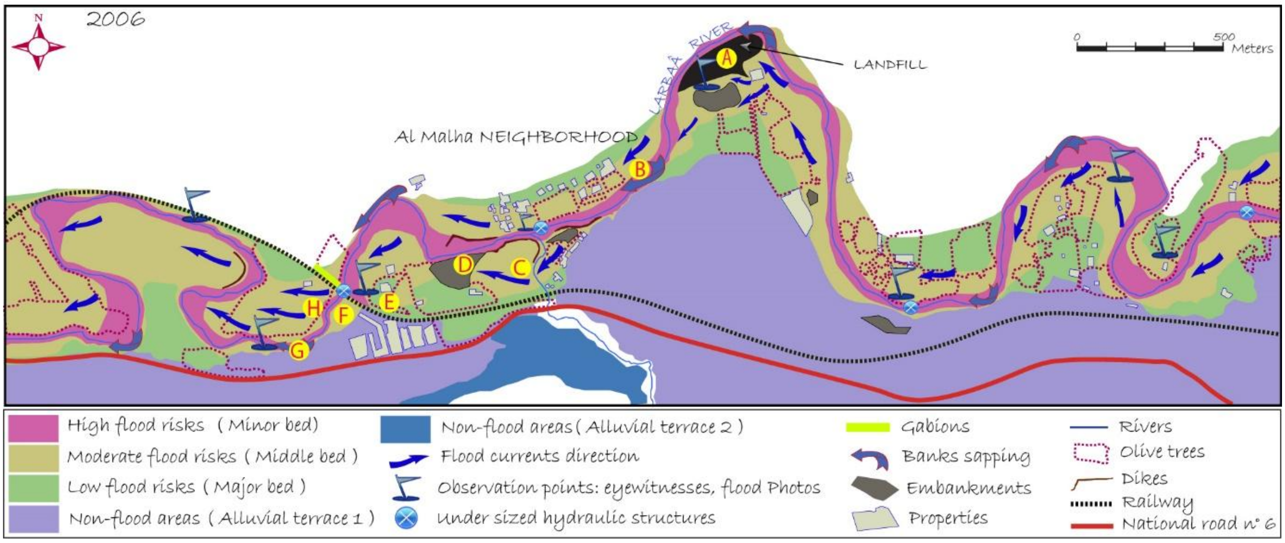

Fig. 13. Flood risk map of 2006.

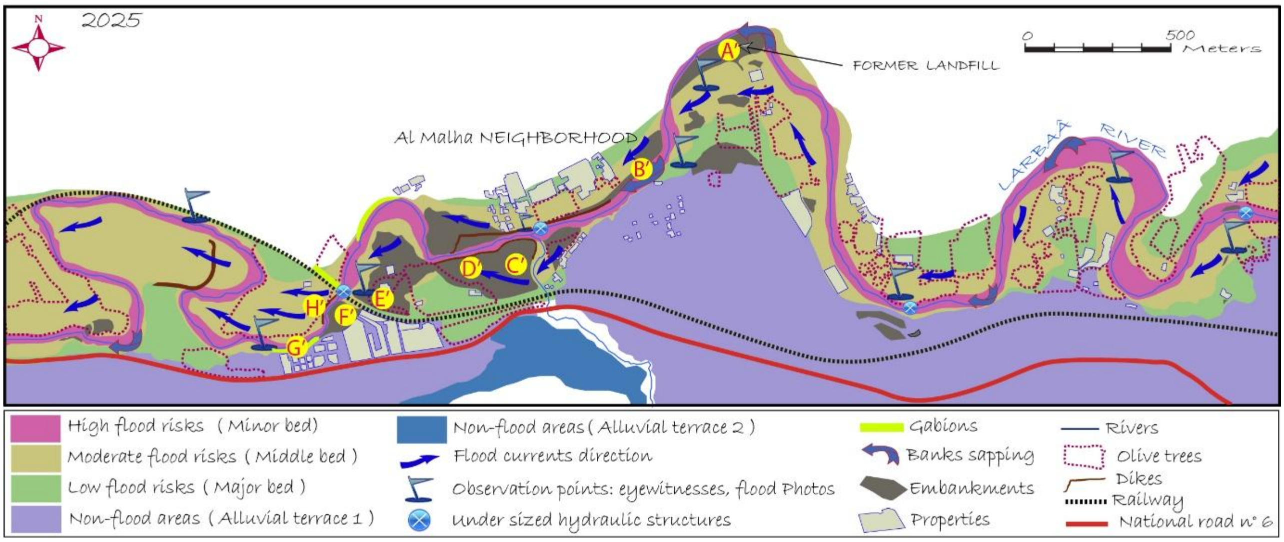

Fig. 14. Flood risk map of 2025.

During major floods like those in 2000 and 2010, these modified riverbanks obstruct natural flowing expansion, forcing water toward the right bank, where agricultural fields and olive groves are located. One farmer even built levees to protect his cultivated land (Figure 14H). Residents building or farming in the floodplain actively resist the river's natural behavior, attempting to redirect flow away from their properties. This mutual constriction from both banks reduces the river's ability to safely convey floodwaters. These findings emphasize the necessity of hydraulic modeling tools. While field investigations identify flow obstructions, computer models are necessary to simulate flooding dynamics and predict how the river will respond to these barriers.

Historical documents and previous studies improved our initial flood zone mapping. Archives including old flood maps and data from government agencies and researchers helped complete and validate the floodplain delineation. Additionally, eyewitness testimony provided valuable information about flood severity. Conversations with long-time residents revealed that memories of the 1969 flood remain vivid in the community. According to one elderly resident, this event was even more severe than the major floods of 2000, 2002, and 2010. This establishes the 1969 flood as the most significant in the Larbaâ River's recorded history, despite the absence of official documentation. Experts consider it an extraordinary event with a return period exceeding 100 years. Fortunately, the alluvial plain was uninhabited in the early 1970s, preventing major loss of life and property.

Despite using multiple data sources and analytical tools, mapping floodplain features proved difficult in certain areas, particularly where human activities have altered riverbanks and changed the river's shape. In developed areas like the Al Malha zone, we had to infer the natural extension of riverbanks through built-up areas. Agricultural activities also complicated mapping—plowing and cultivation often obscure riverbed boundaries, making floodplain delineation challenging. To overcome these obstacles, we used aerial photographs and satellite imagery to analyze floodplain geometry. In locations with dense water-loving vegetation, extensive field surveys were necessary to distinguish human-made features from natural landforms.

Climate change presents another major challenge for flood tracking in Morocco. Over the past two decades, the Taza region has experienced increasingly severe weather patterns. Residents frequently observe unpredictable events, particularly intense rainfall that arrives suddenly and causes devastating floods. These occurrences have become more common, affecting both urban and natural environments [7]. Agriculture, essential to the local economy, struggles to adapt to these changing conditions. Farmers face shifting growing seasons and unexpected crop failures, leading to reduced harvests and economic hardship. Additionally, more frequent heatwaves and extended dry periods damage topsoil. These conditions reduce soil moisture and decrease the land's resistance to degradation. When rain finally arrives, initial storms can destroy the soil structure, creating a smooth, impermeable surface layer that increases runoff. This process amplifies water erosion, ultimately producing severe muddy floods. Under these circumstances, peak flows may rise unexpectedly, and the time water takes to concentrate in channels becomes unpredictable.

Addressing these challenges requires adaptive measures from community leaders and residents. Essential improvements include better water management through rainwater harvesting and wetland restoration. Educational programs should raise awareness about sustainable practices and promote environmental stewardship. Local governments should collaborate with environmental organizations to develop comprehensive climate action plans. These efforts will strengthen resilience, helping both human communities and wildlife withstand future climate impacts.

6 Conclusion

The hydrogeomorphological method effectively tracked flood dynamics along the Larbaâ River over two decades. However, the approach encounters limitations in heavily urbanized areas where human activities have substantially altered natural river morphology. While our flood hazard maps accurately represent historical inundation zones based on geomorphological evidence, they cannot fully account for how recent modifications redirect flood pathways. These anthropogenic alterations fundamentally change flood behavior, potentially causing inundation in areas that geomorphological features alone would classify as safe. To address these limitations, we recommend an integrated methodological framework combining hydrogeomorphological analysis with hydrological and hydraulic modeling. This complementary approach leverages the strengths of each method: field-based geomorphological assessment provides spatial context and historical evidence of flood incidences, while computational models simulate flood propagation under modified conditions. Hydrodynamic models have demonstrated effectiveness in urban environments where structural features dominate flood behavior. Integrating geomorphological field evidence with hydraulic simulation enables more robust hazard assessment and improved delineation of flood-prone zones in complex urban settings. Future research should incorporate remotely sensed flood observations from satellite platforms to further enhance flood tracking methodologies. This multi-method integration offers the most comprehensive approach to flood hazard assessment in human-modified fluvial systems. Such integrated methodologies will strengthen strategies for managing flood risk, support evidence-based urban planning decisions, and ultimately enhance community resilience against flood hazards in vulnerable areas.

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