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Flood-Induced Geomorphological Changes and Displacement of Informal Settlements: A Remote Sensing-Based Assessment of the Rapidly Urbanizing Msimbazi River Basin, Dar es Salaam, Tanzania

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ABSTRACT

Urban flooding is a major socio-economic challenge in many cities of the Global South. Inadequate and unequal urban planning often excludes the poor majority, while rapid urban change makes it difficult to obtain reliable, up-to-date data for flood management. This study investigates changes in the river channel and informal settlements along the Msimbazi River in Dar es Salaam, one of the world's fastest-growing cities, which faces increasingly severe annual flooding. We use high-resolution satellite imagery, open elevation data, and a relative elevation model approach to map flood-prone areas and analyze flood-induced transformations between 2013 and 2022. Our findings show that even a small change in the Msimbazi River's water level leads to significant shifts in flood zones, with risk areas evolving during each flood event. During the study period, flooding also triggered substantial geomorphological changes in areas not included in existing flood risk maps. These changes would have remained undetected without high-resolution imagery or field investigations. Informal settlements underwent considerable spatial shifts following floods, disproportionately affecting the most vulnerable populations. Informal settlements were also expanding further away from the city center, where flood risks are primarily geomorphological rather than driven by overbank flooding and thus overlooked in the local flood risk assessments. The results of this study emphasize the need to integrate geomorphological insights and vulnerability indicators into flood risk assessments and to engage civil society in the process. Additionally, they highlight the importance of making high-resolution satellite data widely accessible, ensuring that its benefits extend beyond wealthier groups.

1 | Introduction

Urban flooding is one of the most pressing socio-economic challenges in many cities of the Global South, posing a frequent and severe threat to residents (IPCC 2022). The flood risk is exacerbated by rapid and unplanned urbanization and combined with climate change and biodiversity loss, it creates profound social, economic, and environmental pressures (Ngcamu 2023). Population growth, particularly in informal settlements, places strain on inadequate planning systems, leaving vulnerable areas increasingly at risk (Adegun 2023). Policy responses are further constrained by the scarcity and inaccessibility of reliable spatial data, especially on fast-changing informal areas (Abascal et al. 2022).

Urbanization alters local hydrological dynamics by expanding impervious surfaces, reducing natural infiltration, and increasing stormwater runoff (Chen et al. 2023; Walsh et al. 2005; Smith and Petley 2008). With limited drainage infrastructure, runoff is funneled quickly into rivers, raising peak flows and increasing flood frequency (Santillan et al. 2019). This rapid runoff reshapes river morphology, driving erosion and channel migration, which can damage infrastructure and reduce usable urban land (Chin 2006; Vietz et al. 2016). Poor waste management exacerbates these risks, both by polluting stormwater and by blocking rivers and drains with solid waste (van Leeuwen et al. 2019; Beard et al. 2022; Abubakar et al. 2022).

In Global South cities, many rural-to-urban migrants settle in informal areas, which often lack planning and infrastructure (Hooli 2016; United Nations 2016; Douglas et al. 2008; UN-Habitat 2022). These settlements expand in a spatially informal manner, often spreading to marginal and environmentally hazardous land, such as floodplains (Abascal et al. 2022). Additionally, unplanned areas are systematically excluded from flood management strategies, and the vulnerability of residents is largely ignored. The combined effect of informality and environmental risk leave these areas particularly vulnerable. Consequently, preparedness remains inadequate, and flood damages in these regions are sidelined politically, enabling harmful and unjust development to persist (Mishra and Sinha 2020).

Inappropriate decision-making processes further disempower communities, restricting their ability to shape their living environments or to demand safer, more sustainable management (Douglas et al. 2008). At the same time, the current pushes for transformative land use management risk centralizing resource control in the hands of states and corporations, further undermining local rights and deepening existing inequalities (McDermott et al. 2023). Previous studies show that informal settlements often depend on strong social ties and community trust, while formal settlements benefit from greater access to consolidated resources and technical knowledge (Shahid et al. 2022). This contrast underlines the need to account for both social and material factors in urban flood risk governance.

Advancing socially and environmentally sustainable land use requires understanding local urbanization dynamics in both planned and unplanned areas, as well as the broader environmental and climatic conditions (Rana et al. 2021; Shahid et al. 2022). This requires more context-specific research using spatially comprehensive, high-accuracy data with sufficient temporal resolution to capture rapidly changing phenomena (Li et al. 2022; McDermott et al. 2023; Nguyen et al. 2023). Even though increasingly precise and long satellite data time series and cloud computing make studying river environments in remote or low resource areas more feasible (Papa et al. 2023; Wu et al. 2023), the resolution of freely available datasets (such as Landsat and Sentinel) is 10 m at best, which is still insufficient to capture localized processes like flood dynamics in informal settlements. In addition, many analytical methods require specialized expertise, which often results in data-driven, site-specific analyses being left undone. For example, flood management usually focuses on drainage and overbank flooding, neglecting geomorphological processes, such as erosion, channel migration, and sediment accumulation, that also create severe risks for these communities (Naylor et al. 2016; Mishra and Sinha 2020).

To overcome the challenges posed by uncontrolled urbanization, data scarcity, and inadequate water management, there is a need for deeper understanding of how flood management and preparedness can be developed in cost-effective ways that prioritize human wellbeing. This requires evidence on cost-efficient data and analytical methods which enable the detection of local flood impacts, including human vulnerability, and reveal processes in understudied areas, such as informal settlements (Islam et al. 2024). Moreover, research is needed to demonstrate the significant role that geomorphic changes can play in shaping the destructiveness of floods, to ensure it is better considered in future flood protection. Such examples would help steer flood management in the Global South toward more equitable and sustainable approaches.

In this study, we analyze the flood-related dynamics of geomorphology and human settlements along the rapidly urbanizing Msimbazi River basin in Dar es Salaam, Tanzania, which is persistently affected by flooding. We utilize an open Digital Terrain Model (DTM) with 5-m resolution and high-resolution satellite imagery (0.5 m) from CNES' Pléiades program to define the most flood-prone areas along Msimbazi River. We map the changes in the river's geomorphology and human settlements along the riverbanks between 2013 and 2022 and demonstrate how existing datasets and simple methods can provide highly detailed understanding of flood impacts, thereby contributing to improve the quality of flood protection.

2 | Study Area: Msimbazi River Basin in Dar es Salaam

This study focuses on the Msimbazi River basin, which covers ~270 km^2, and is heavily impacted by human activities (Wambura 2024; World Bank 2019a). The Msimbazi River flows through Dar es Salaam, the largest city in East Africa with a population of 8 million (World Population Review 2025) that is increasing rapidly (Figure 1). The area has a tropical savanna climate, receiving around 1100 mm of rainfall annually, with two rainy seasons: short rains from October to December (Vuli) and long rains from March to May (Masika) (Kottek et al. 2006). The rainfall has historically fluctuated in response to teleconnection patterns such as El Niño and the Indian Ocean Dipole (Saji et al. 1999; Kijazi and Reason 2005), with El Niño causing more frequent heavy rains, leading to severe flooding (World Bank 2019a; van Aardenne and Pasquini 2017). Located along the coast, the flood risk is amplified by the combined effects of intense rainfall and storm surges (Qi et al. 2023).

Situated on the Indian Ocean with its economic center, the Central Business District (CBD), around the port, Dar es Salaam has experienced urban densification. A large share of the population and infrastructure is concentrated in the lower reaches of the river, often built directly on floodplains or along the riverbanks. Due to its rapid growth, approximately 70%–80% of the residents of Dar es Salaam live in informal settlements without adequate infrastructure and services, such as drainage systems (Anande and Luhunga 2019). Recently, substantial settlement growth also near rivers has been reported, with impervious surfaces expanding 3.9% annually between 2000 and 2019 (Yuan et al. 2023), reducing natural drainage and increasing surface runoff (Mkilima 2021).

Climate change is intensifying the rainfall fluctuations caused by teleconnection patterns, increasing heavy rains and flood risk (Chen et al. 2023). In the 21st century, seasonal flooding in Dar es Salaam has escalated into a severe socio-economic crisis. Recent analyses indicate that Tanzania experienced approximately a 45% increase in flood frequency between 2010 and 2020, with flooding representing the most severe climate change-related risk in the country (IMF 2023). In addition to the explosive urban growth and climate variability (Anande and Luhunga 2019; Erman et al. 2019), the vulnerability to flooding stems from colonial-era spatial planning, with roads and drainage implemented without sufficient consideration of flood risk (Edward 2022). Since then, decision-making has failed to improve drainage infrastructure and solid waste management, or to restrict construction in unplanned areas (Vietz et al. 2016; Wantzen et al. 2019; Sakijege and Dakyaga 2023; Figure 2), while large-scale modernization projects have continued to

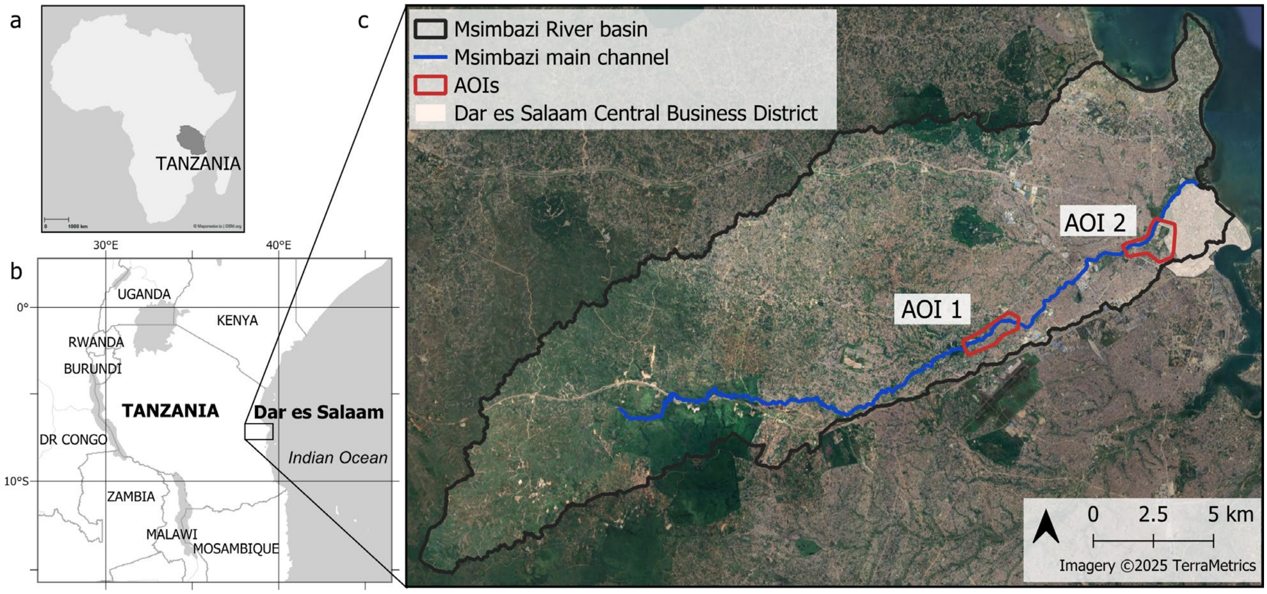

FIGURE 1 | (a) Tanzania is located in Eastern Africa, on the coast of the Indian Ocean, (b) Dar es Salaam is the economical center of Tanzania, and (c) the Msimbazi River flows through the city, discharging into the Indian Ocean.

FIGURE 2 | Sediments and waste transported downstream along the Msimbazi River. Photo by Chris Morgan, World Bank (2018).

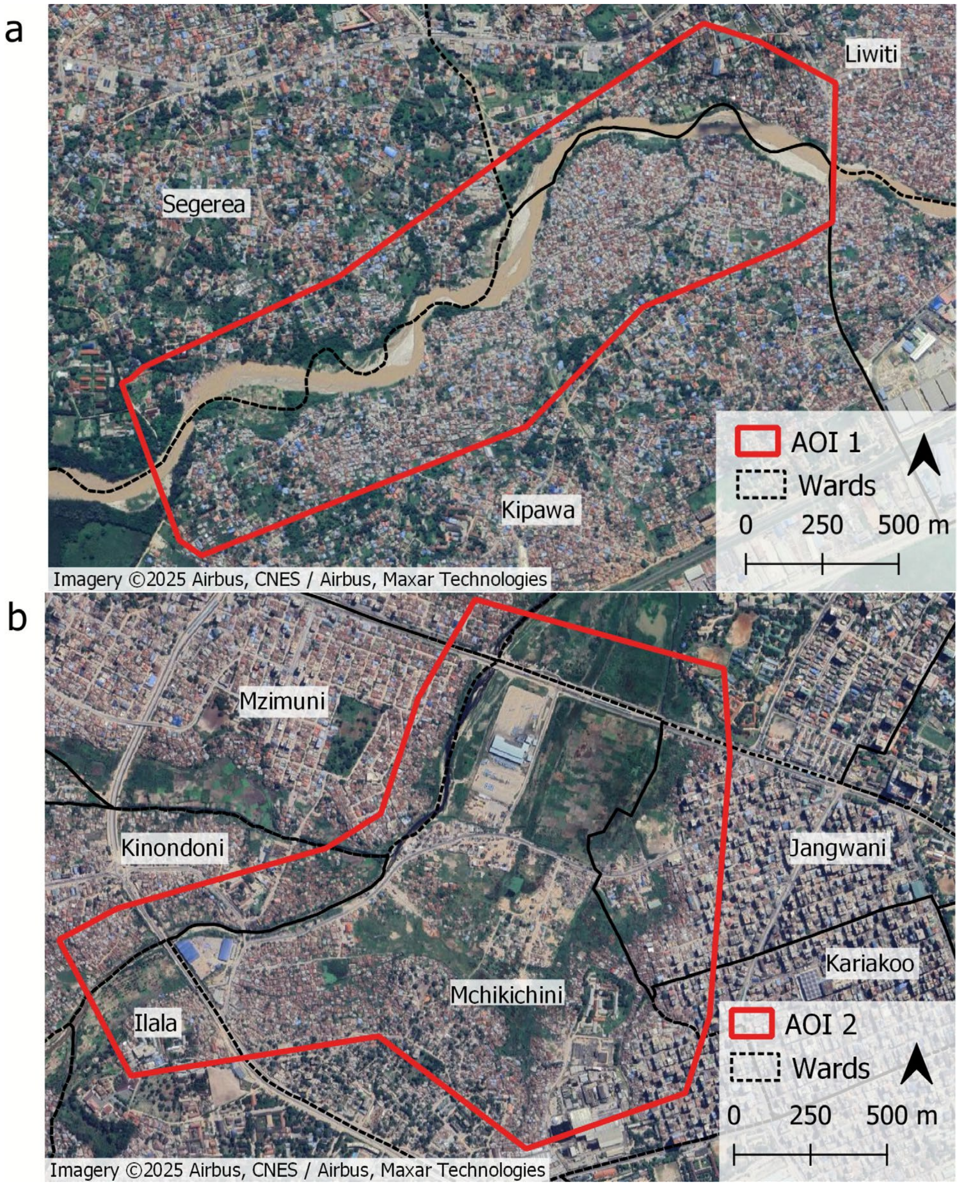

FIGURE 3 | Our study focuses on two areas of interest (AOIs). (a) AOI 1 is located in the middle reach of the Msimbazi River and (b) AOI 2 is located downstream, right next to the city center. See location of the areas in Figure 2.

introduce structures that obstruct natural waterways. The IMF country report (2023) estimates that the population displaced by floods has risen dramatically, from 182 per million inhabitants in 2016 to 22,680 per million in 2020.

The Msimbazi River typically floods two to three times annually, with the most intense episodes occurring during the Masika rains (World Bank 2019a). Typically, the river water level rises 1–2 m during a flood, but higher events have also been reported (Izdori et al. 2022; World Bank 2019a; Global Publishers 2017). Recent severe flood events occurred in April 2023 and in January 2024, causing severe economic and social damages displacing thousands of people from their homes (Tanzania Meteorological Authority 2024; Lasteck and Salla 2024). During our study period (2013–2022), the river experienced annual flooding during Masika. In 2019, 2021, and 2022, floods also occurred during the Vuli. In most flood events, the water level rose between 2 and 3 m.

Despite the recurrent flooding, flood management and infrastructure resilience in Dar es Salaam remain insufficient, largely due to challenges in identifying flood risk (Valimba and Mahé 2020). An insufficient monitoring network and outdated elevation models result in incomplete information on flood extent and depth, leaving many severe flood impacts unreported or their exact locations unknown.

In this study, we focus on flood impacts in two specific areas of interest (AOIs) along the Msimbazi River that are particularly vulnerable to flooding or flood-driven geomorphological changes (see, e.g., World Bank 2018) (Figure 3). The AOIs differ from each other both socio-economically and environmentally, but both are predominantly composed of informal settlements (Table 1). AOI 1 is situated in the middle reaches of the river, further from the CBD, and extends over the wards of Kipawa, Segerea, and Liwiti. AOI 2 lies in the lower reaches, directly adjacent to the CBD, and covers parts of Ilala, Kigogo, Mzimuni, Mchikichini, Jangwani, and Kariakoo (Figure 1). The CBD itself is the commercial and administrative core of Dar es Salaam, spanning the wards of Ilala, Upanga, Kariakoo, and surrounding areas. Inadequate planning exacerbates the flood risks both in the erosion-prone areas of AIO 1, such as Kipawa, and the low-lying areas of AOI 2 such as Jangwani and Mchikichini (Figures 2 and 3) (Erman et al. 2019).

3 | Data and Methods

3.1 | Overall Methodological Approach and Data Description

We exploited a DTM and Relative Elevation Model (REM) approach to identify flood-prone areas and satellite images to examine changes in geomorphology and informal settlements in two flood-prone areas of interest (AOI 1 and AOI 2) along the Msimbazi River between 2013 and 2022. Community-based flood survey data was used to validate estimates of the REM model. During the study period, the river flooded every year at least during the April–May period, but often also during the smaller rains later in the year. The analysis followed a sequential process (Table 2): first, openly available elevation data were used to generate REMs for different flood scenarios, and the results were compared to community-reported flood data; second, high-resolution satellite imagery was analyzed to document geomorphological transformations and the expansion or disappearance of informal settlements (Table 2).

The DTM employed was an open, 5 m resolution data set from 2016 (COWI 2016). The DTM was produced through photogrammetry from an airplane and analyzed by COWI (2016), as reported in Winsemius and Verhoeven (2018). The DTM was produced as part of the World Bank-funded Tanzania Urban Resilience Program, which aimed to increase the country's ability to manage urban climate risk (World Bank 2019b). The DTM has earlier been used for example in hydrological modeling of

TABLE 1 | Characteristics of the two areas of interest.

	AOI 1: middle reach	AOI 2: lower reach
Wards (administrative districts)	Extends over Kipawa, Segerea, and Liwiti.	Extends over Ilala, Kigogo, Mzimuni, Mchikichini, Jangwani, and Kariakoo.
Topography and flooding	Steep, erosion-prone riverbanks with significant elevation differences. The water flows through the residential area toward lower reach (Izdori et al. 2022; Alexander et al. 2024).	A flat floodplain where water tends to remain stagnant for long periods of time. Accumulation of sediments and human waste is typical (Izdori et al. 2022; Alexander et al. 2024).
Socio-economy	Situated far from the CBD without proper public transport connection with it. Economic activities vary.	Situated near the CBD (such as Ilala and Kariakoo), with economic and administrative activities closely tied to it.
Settlement structure	A densely populated, unplanned settlement lacking designated flood protection zones.	Densely built, unplanned settlements coexist with new formal buildings (e.g., Jangwani bus depot built in 2015), frequently damaged by floods.

TABLE 2 | Summary of the data and methods used in this study.

Data source	Data processing/analysis	Output
Digital Terrain Model (DTM, 5 m) (COWI 2016) Dar es Salaam River Basins (JBA Consulting 2018)	Flood modeling using Relative Elevation Model (REM): digitize river centerline; interpolate water surface for 0.5, 1, 2, and 3.5 m water level rise; generate REMs by subtracting the water levels from the DTM, which was clipped to cover the river basin	Flood-prone area maps for 0.5, 1, 2, and 3.5 m water level rise scenarios
Community-based flood survey data (Ramani Huria 2018)	Comparing the flood models with community flood survey data	Flood scenarios validated
Pléiades satellite imagery (0.5 m) (CNES 2013–2022, Distribution Airbus DS)	Mapping geomorphological changes (centerline shifts, channel widening and erosion) Digitizing informal settlements of each time-step and calculating the change	Geomorphological activity in 2013–2022 Informal settlement dynamics in 2013–2022

TABLE 3 | Pléiades satellite imagery used in the study.

Date	AOI 1	AOI 2
01 March 2013	x	x
05 July 2016	x	x
21 March 2018	—	x
22 August 2019	x	—
05 November 2022	x	x

the Msimbazi River (Winsemius and Verhoeven 2018). The DTM does not include bathymetric data of the river channel. In our analysis, we assume that the elevation values in the channel area do not represent the riverbed itself but rather the water surface level at the time of measurement, when the water volume in the channel was low (Winsemius and Verhoeven 2018). Therefore, while the DTM provides a detailed representation of the floodplain, it may not accurately capture the river channels.

The community-based flood survey data, used for REM validation, was also openly available, based on a survey by the community-based mapping project Ramani Huria (2018), reporting the community's experiences of flood extents and depths at the lower reaches of the river. The survey was conducted in 2017–2018 as part of the Tanzania Urban Resilience Program. The digital terrain model, extents of Dar es Salaam's river basins and community-based flood survey data were obtained from the Climate Risk Database, hosted by the Tanzania Resilience Academy (https://crd.resilienceacademy.ac.tz).

The high-resolution satellite imagery exploited was produced by CNES' Pléiades program (CNES 2013–2022) and distributed by Airbus DS. We employed images from five occasions between the years 2013 and 2022 (Table 3). Images were selected for their minimal cloud cover and extensive spatial coverage. The 0.5-m spatial resolution made it possible to identify individual buildings, roads, and geomorphological features. This level of detail enabled the distinction between informal and formal settlements based on building size, density, and spatial arrangement.

3.2 | Defining the Flood-Prone Areas Using the REM Approach

We identified flood-prone areas using the REM, a widely used and cost-effective method for flood mapping in regions with limited hydrological data (Samela et al. 2018). The REMs were generated by subtracting estimates of the river surface elevations from the 5-m resolution DTM.

To estimate the water surface elevations, we digitized the centerline of the Msimbazi River and transformed it into a chain of points, each of which got an elevation value from the DTM. These point elevations were interpolated into a continuous surface using the IDW method, resulting in a raster where pixel values represent the gradient of the river across the river valley. This raster was clipped to the Msimbazi River basin boundary (JBA Consulting 2018). Subtracting this interpolated surface from the original DEM produced the REM, where each pixel indicates relative elevation above the river under low-flow conditions.

Flood scenarios were derived by extracting pixels with REM values below set thresholds of 0.5, 1, 2, and 3.5 m, corresponding to areas likely to be inundated under increasing water levels. These raster layers were then converted into vector format and cleaned of artifacts to create polygons representing flood extents. The process was repeated for each water level scenario. Based on earlier studies and reports, the 0.5- and 1-m scenarios represent frequent floods occurring approximately annually in the area. The 2- and 3.5-m scenarios reflect more extreme events expected roughly every 5 years (Winsemius and Verhoeven 2018; Global Publishers 2017). Areas with REM values below these thresholds were classified as flood-prone.

The resulting flood extent maps were compared with community-reported flood events at the lower reach (Ramani Huria 2018) using GIS. The REM approach reproduced reported flood zones and depths such as knee- and chest-high water levels. Some events had been reported also outside of the REM-based flood maps, which is most likely due to local pluvial flooding rather than riverine flooding. In this study, however, the main emphasis is on morphodynamic and settlement changes, and therefore the analysis does not depend on exact flood depths but rather on the delineation of relative flood-prone areas.

3.3 | Analysis of River Channel and Settlement Dynamics From Satellite Imagery (2013–2022)

3.3.1 | Geomorphological Changes

We assessed geomorphological changes in the areas of interest during the nine-year study period through visual interpretation of the Pléiades images (see Table 3). We manually digitized the river's centerline for each available image, and shifts in position greater than 10 m were recorded as significant channel changes. We also documented variations in river width, evidence of bank erosion, and sediment deposition patterns. Particular attention was given to areas near bridges and built infrastructure, where human interventions often alter flow dynamics. These observations were marked directly on maps to spatially track the most prominent changes between 2013 and 2022.

3.3.2 | Evolvement of Informal Settlements

We mapped the evolution of informal settlements within the areas of interest using the same set of satellite images. Unplanned settlement areas were identified based on their irregular street patterns, high building density, and small building sizes (Kuffer et al. 2016). The settlement boundaries were digitized using GIS software and total areas were calculated for each year. By comparing the digitized extents across the selected images, we quantified both expansions and reductions in settlement areas, paying particular attention to whether new settlements appeared in flood-prone zones. We also paid attention to the changes in building density and structure to capture shifts in settlement patterns.

4 | Results

4.1 | Flood-Prone Areas Within the Msimbazi River Basin

Based on the analysis of the REMs calculated for four different flood water levels, large areas of Dar es Salaam are inundated when the Msimbazi River overflows. Even a 0.5-m rise in water level, which is reported almost annually, can inundate nearly 2 km^2 (Figure 4). A flood event with water level rising 3.5 m above normal would cover up to 7.4 km^2. These flooded areas contain significant amounts of housing, critical infrastructure such as main roads, a public transit terminal and industry.

Out of the two AOIs of this study, the upper area (AOI 1) features steeper topography, meaning a small rise in water level (0.5–1 m scenarios) has little impact on the extent of the inundated area (Figure 5a). In the lower reaches of the river (AOI 2), even a small rise in water level results in widespread lateral flooding—a 0.5-m rise in water level can cause 30% of the area to flood. In AOI 2, further increases in water level (scenarios 1–3.5 m) gradually increase the extent of the flooded area (Figure 5b).

4.2 | The Morphological Changes of the Msimbazi River and their Relation to Flooding

In the middle reaches of the river (AOI 1), the riverbed changed notably during the nine-year study period (2013–2022) both by its land cover and shape (Figure 6). The amount and extent of the exposed riverbed and sandbars increased while vegetation and farmland decreased from 2013 to 2022. The river's centerline shifted significantly along almost the entire studied river reach. The most pronounced changes occurred upstream, where the meandering of the river is active. In some places, the river's centerline moved almost 150 m and one meander cut-off occurred between August 2019 and November 2022 (Point C, Figure 6). There are also some buildings that are inundated by the 2 m flood (Point D, Figure 6).

A closer examination of this upstream section reveals that at the beginning of the section, there is a road crossing the river without a bridge (Point A, Figure 6). Downstream from this crossing, there has been cultivation within the riverbed (Point B, Figure 6), which may have restricted or redirected water flow, ultimately causing the river to cut through the meander bend.

In AOI 2, the low elevation profile causes a more extensive area to be inundated according to the 2m flood scenario, but the lateral shift of the riverbed has been moderate compared to the upstream area (Figure 7). The centerline of the riverbed shifted by up to 40 m at most between 2013 and 2022 (Point E, Figure 7), but on average, the shift was less than 10 m. In some areas, this movement caused damage to residential areas by eroding away land where houses were located (Point F, Figure 7). Additionally, the riverbed widened year by year, with the widest point observed in 2022. This widening is particularly noticeable near the bridge (Point G, Figure 7), where the river is significantly broader, especially upstream of the bridge.

4.3 | Dynamics of the Informal Settlements in Flood-Prone and Geomorphologically Active Areas

In 2013, approximately 58% (0.9 km^2) of AOI 1 was covered by informal settlements (Table 4, Figure 8). These settlements

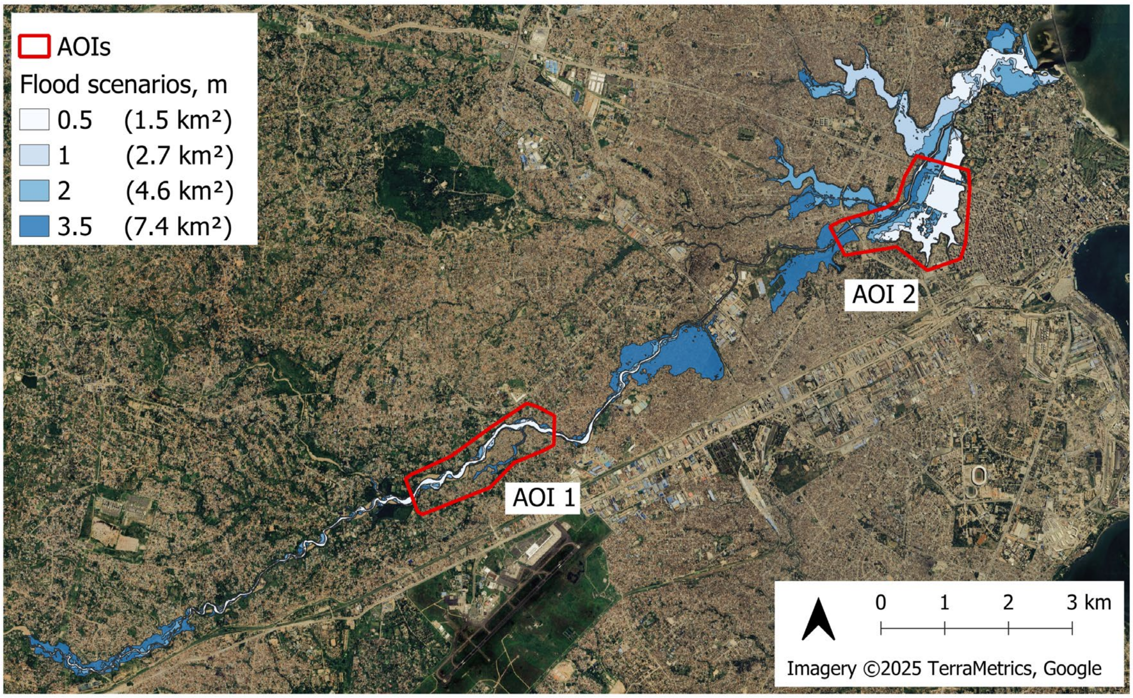

FIGURE 4 | Flood scenarios of Dar es Salaam for water levels of 0.5, 1, 2, and 3.5 m above reference level, based on the relative elevation model approach utilizing a DEM from 2016. The extent of the inundated area (km^2) is specified alongside each scenario.

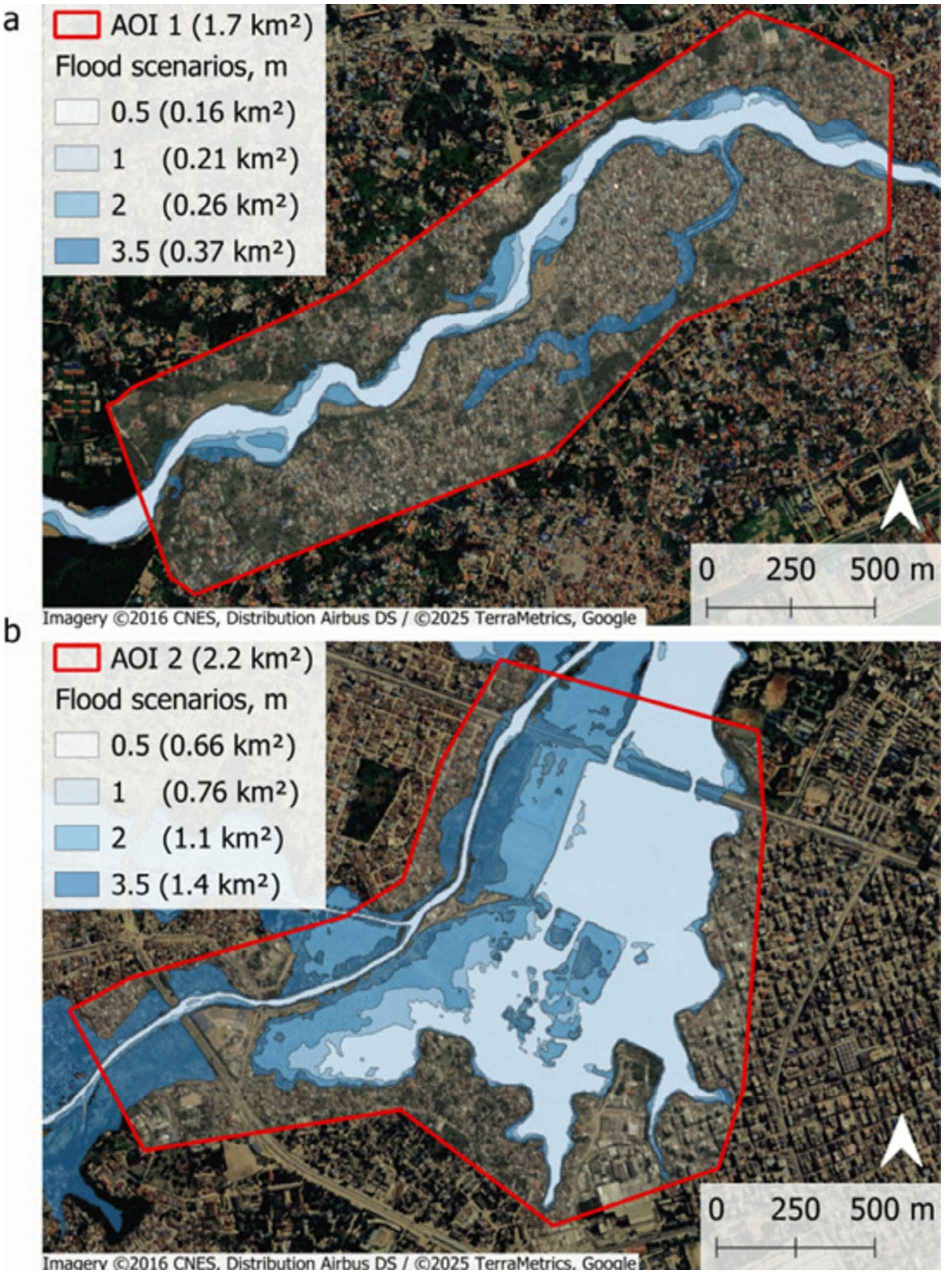

FIGURE 5 | The inundated area according to four different scenarios in (a) AOI 1 located on the middle reach and (b) AOI 2 on lower reach of Msimbazi River. The extent of the inundated area (km 2) is specified alongside each scenario. See location of the areas in Figures 1 and 4.

were primarily concentrated on the southern side of the river and the southeastern part of the AOI, where housing density was relatively high. In contrast, the northern side of the river featured noticeably less dense settlements with larger buildings, making their classification as informal settlements somewhat ambiguous. In some areas, settlements were situated extremely close to the river, directly along its banks (Points I, K, L, and M, Figure 8).

In AOI 1, the patterns of informal settlements changed significantly between 2013 and 2022. By 2022, the settlement area in AOI 1 had expanded substantially compared to 2013, with 0.21 km^2 of new settlements representing a 21% increase compared to 2013 (Table 4). On the south side of the river, the settlements expanded primarily by filling in vacant land among the 2013 residential areas (Point H, Figure 8). On the north side, the settlement area also grew, with increased density leading to their classification as informal settlements (Point J). However, overall, the settlements did not encroach closer to the river. Housing density increased, and some buildings that were in ruins in 2013 had been repaired by 2022.

River course changes between 2013 and 2022 caused the destruction of some settlements near the river (Points I, K, L, and M, Figure 8). Approximately 0.08 km^2 (8%) of the area settled in 2013 was no longer populated by 2022. Most of these areas were close to the river (Points J, K, L, and M), with about 25% located in flood-prone zones (2-m scenario). The 2022 satellite image clearly shows that the river had shifted its course, flowing through areas that were populated in 2013 (Points I and L), or

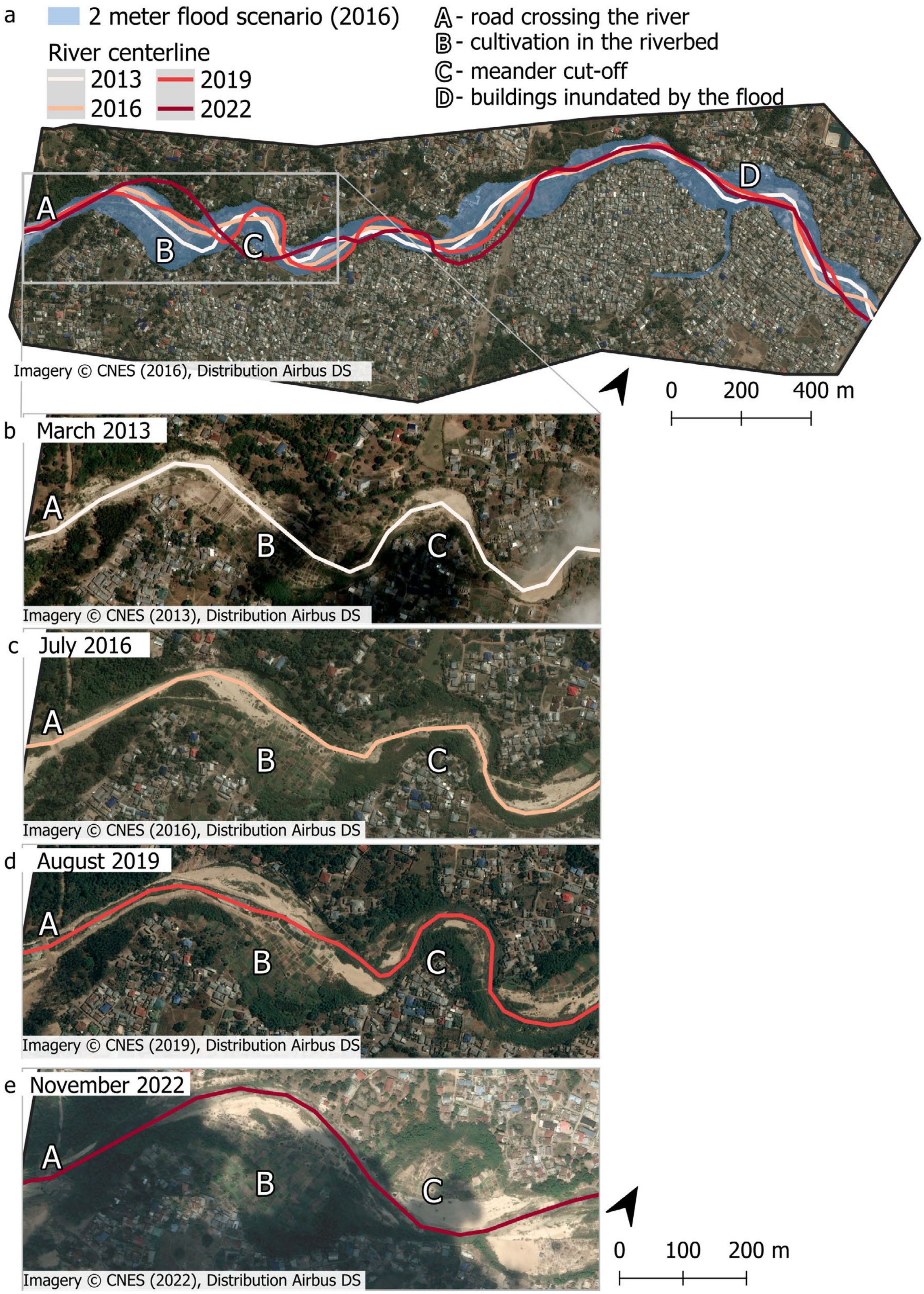

FIGURE 6 | (a) The inundated area in the 2 m flood scenario based on the DEM of 2016 and the river centerlines in years 2013, 2016, 2019, and 2022 in AOI 1 (see Figures 1 and 4 for location). The area experienced notable geomorphological changes during the study period of 2013–2022, especially in the eastern part (points B, C, D). The flood-prone area derived from a 2016 elevation model doesn't even match the path of the river anymore in 2022. The locations of most dramatic changes are marked with letters A, B, C, and D. The dates of the satellite images are marked in each of the figures b, c, d, and e.

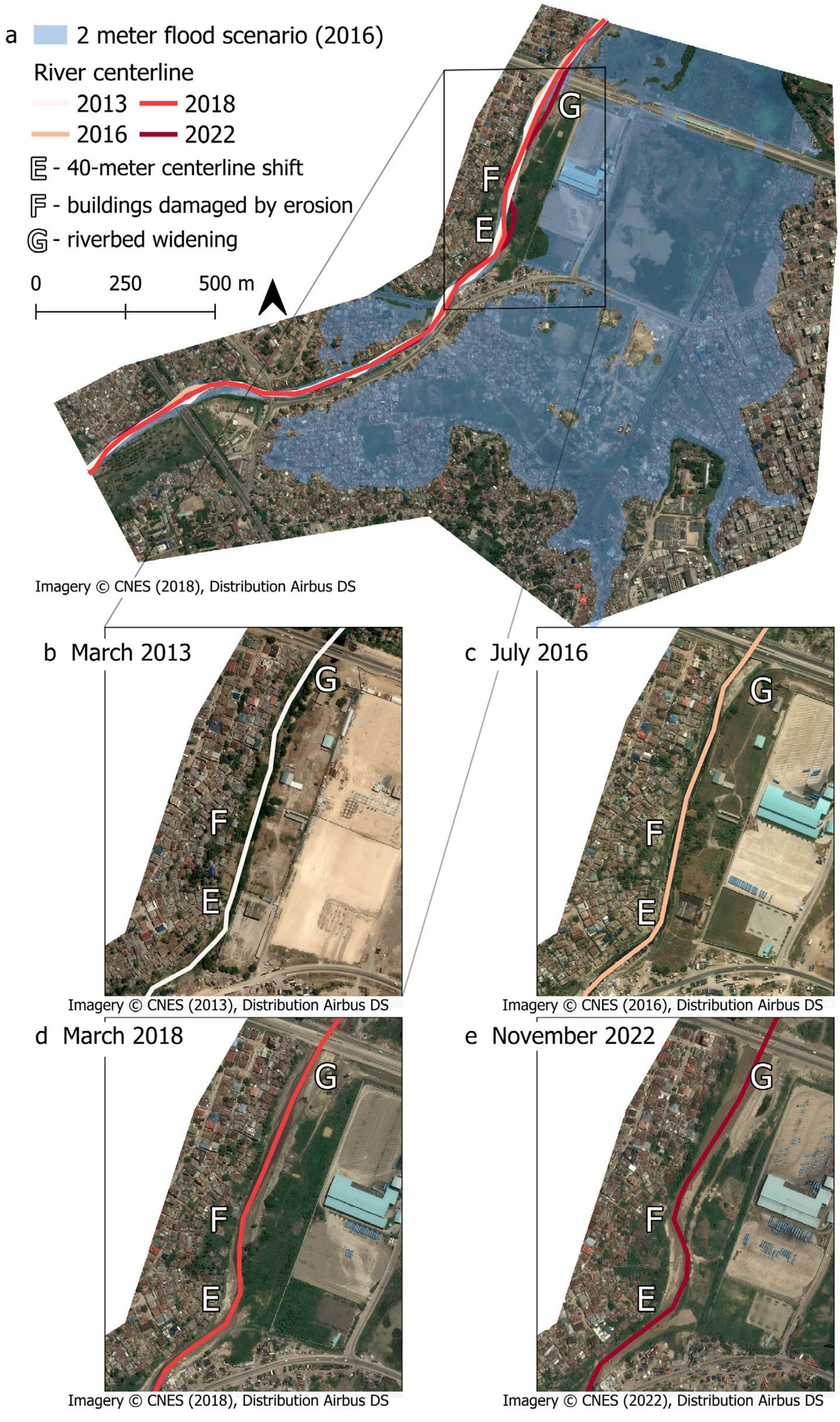

FIGURE 7 | (a) The inundated area in AOI 2 in the 2 m flood scenario based on elevation model from 2016 and river centerlines in 2013, 2016, 2018, and 2022. The points E, F, and G represent locations with dramatic changes. The dates of the satellite images are marked in each of the figures b, c, d, and e. See Figures 1 and 4 for location of AOI 2.

had eroded its banks to the point where habitation was no longer possible (Points K and M).

In the lower study site (AOI 2), extensive areas of informal settlements in 2013 were no longer apparent in 2022 (Figure 9). Approximately 37% of the downstream study area was covered by informal settlements in 2013 (Table 4). The 2.2 km^2 study area, particularly on the south side of the river, is low-lying, and even minor floods can extend far from the river. The eastern portion of the area, which features a formal planned

TABLE 4 | Flood-prone extents under the 2-m scenario and settlement dynamics (expansion, reduction and persistence) in the two areas of interest between 2013 and 2022.

	AOI 1	AOI 2
Total area	1.72 km^2	2.21 km^2
Flood-prone area according to the 2-m scenario (% of total)	0.26 km^2 (15%)	1.1 km^2 (50%)
Total settlement area 2013 (% of total)	0.99 km^2 (58%)	0.81 km^2 (37%)
Total settlement area 2022 (% of total)	1.12 km^2 (65%)	0.71 km^2 (32%)
New settlements (2013–2022) (% of total area)	0.21 km^2 (21%)	0.04 km^2 (5%)
New settlements in flood-prone areas according to the 2-m scenario (% of total area)	0.006 km^2 (3%)	0.001 km^2 (3%)
Settlement loss (2013–2022) (% of total area)	0.08 km^2 (8%)	0.14 km^2 (17%)
Settlement loss in flood-prone areas (% of total area)	0.02 km^2 (25%)	0.13 km^2 (93%)

Note: The 2022 flood scenario is less accurate for AOI 1 due to significant river course changes since 2016.

grid pattern, is situated on elevated ground and remains less vulnerable to flooding (Point S, Figure 9). Conversely, informal housing tends to occupy lower elevations where flooding is more frequent (Point R). In 2013, large, continuous, and densely built informal settlements were present on both sides of the river, some very close to the riverbanks. The public transportation terminal area, however, had no residential settlements (Point N).

By 2022, some informal settlements farther from the river had spread into new areas (Point Q, Figure 9), but this accounted for only 0.04 km^2 of newly settled land. In contrast, a significant portion of the informal settlements from 2013 had disappeared or become uninhabitable. The areas no longer classified as dense informal settlements covered 0.14 km^2, representing a 17% decrease in settlement area. Of these lost areas, 93% were located in flood-prone zones (2-m scenario). These abandoned areas were predominantly on the southern side of the river, both very close to the river (Point O) and over 500 m from the main channel (Point P). The remaining inhabited areas by 2022 were already so densely built in 2013 that there was no room for further construction.

5 | Discussion

The urbanization of many megacities in the Global South is both rapid and uncontrolled, resulting in a lack of reliable and up-to-date data, which complicates efforts to manage socio-environmental hazards such as flooding (Nygren et al. 2024; Lin et al. 2023). In Dar es Salaam, the combined effects of climate change and uncontrolled urbanization have significantly increased flood risk, particularly among the poorest communities (Todd-Burkeley et al. 2021; Wantzen et al. 2019). Researchers have found similar dynamics in many other megacities across the Global South, underscoring the urgent need for context-sensitive planning that integrates both environmental risk and social vulnerability (Islam et al. 2024).

This study demonstrates the potential of combining high-resolution satellite imagery with a DTM to map flood-prone areas and flood-induced changes in fluvial geomorphology and informal settlements along the Msimbazi River between 2013 and 2022. Our results show that even small increases in water levels lead to significant shifts in flood zones, and each flood event triggered resettlement and geomorphological transformations that would not have been detectable with coarser-resolution imagery.

In the lower reaches, closer to the commercial city center, low-lying floodplains and widening channels made the area highly susceptible to rapid inundation and erosion. Local reports confirm that heavy rainfall can raise the water level by 0.5–1 m within an hour, leading to swift flooding (World Bank 2018). The river channel in this area has widened considerably due to floods, especially near informal settlements, exacerbating inundation and erosion risks. In the upper study area, the river flows through a steep, narrow valley where rising water generally remains confined within the banks. This geomorphology reduces exposure to traditional overbank flooding but leaves the area highly vulnerable to erosion and channel shifts. Flood-induced erosion has displaced communities and shifted the river channel by up to 150 m in only a few years. Despite these risks, the area, located further from the city center and inhabited primarily by economically disadvantaged communities, has been largely ignored in flood risk management plans.

These findings support previous research by highlighting the need to integrate geomorphological understanding into flood risk assessments. Areas not susceptible to traditional overbank flooding are often excluded from official flood risk maps, leaving erosion dynamics and community vulnerability unconsidered (Mishra and Sinha 2020; Naylor et al. 2016). Earlier research has warned that focusing solely on predicted flood extents creates a false sense of security for areas outside the modeled limits (Thompson and Clayton 2002), yet this remains common practice. Adopting geomorphologically informed adaptation strategies could strengthen the resilience of socio-geomorphological systems to climate extremes (Naylor et al. 2016). However, predicting geomorphic responses to floods remains challenging due to numerous influencing factors (Hooke 2015). Emerging approaches, such as machine learning, offer promising ways to integrate geomorphological and socio-economic factors while requiring minimal data and resources (Deroliya et al. 2022; Nygren et al. 2024).

Urbanization and displacement dynamics differed markedly between localities. In the middle reach, informal settlements have expanded rapidly along the riverbanks and across flood-prone areas and are frequently displaced by flood-induced erosion. By contrast, in the lower area near the city center, where the

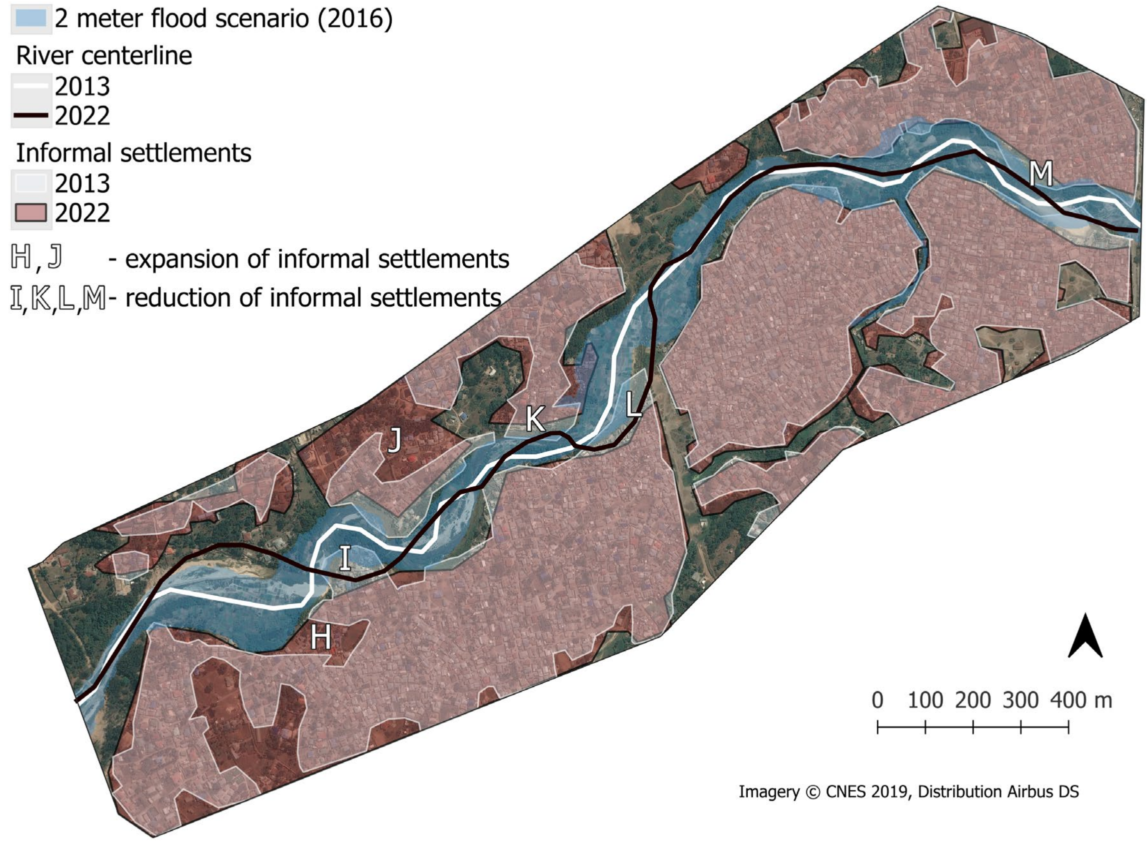

FIGURE 8 | Informal settlements and the Msimbazi River's centerlines in AOI 1 in 2013 and 2022. The points H, I, J, K, L, and M represent locations with the most dramatic changes. The background satellite image is from 2019 and the 2 m flood scenario is based on DEM of 2016. See location in Figures 1 and 4.

floodwaters persist longer, has experienced more long-term settlement and urbanization, with some efforts of urban planning and control measures in place, although informal settlements continue to persist and rebuild (Kombe and Muheirwe 2024). The temporal analysis confirmed that urbanization in the middle reach has been faster than in the lower reach, reflecting socio-economic pressures, land competition, and weaker regulation. Since the middle reaches are not considered in the flood risk management plans, settlements proliferate along the riverbank and across flood-prone areas, ultimately being displaced due to flood-induced erosion. Therefore, in line with previous research (i.e., Rana et al. 2021), we stress the importance of developing more context-specific knowledge to capture the local nuances shaped by diverse socio-economic structures and geomorphological conditions.

These governance inconsistencies are exemplified by the 2015 construction of the Jangwani bus depot, which cost over 15 million USD and was built in a flood-prone zone. This top-down policy decision, promoted as a development initiative and partially funded by the World Bank, an organization also involved in the city's flood risk management, directly led to forced evictions and the displacement of residents. Meanwhile, other flood-prone areas were simultaneously promoted as “safe” through selective infrastructure investments. Such contradictory approaches highlight the disconnect between policy design and on-the-ground risk, reinforcing earlier findings that the psychological distance communities feel from disasters significantly affects preparedness (Rana et al. 2023). The Jangwani example illustrates how inconsistent, top-down policies not only distort local perceptions of risk but also erode trust in governance, weakening community resilience and undermining adaptive capacity.

In many rapidly growing cities in the Global South, land use planning is often inconsistent, responsibilities are poorly defined, and the marginalized majority of the population are frequently excluded or overlooked in decision-making processes (Watson 2009; Bidandi and Williams 2020). As a result, areas with high population density, poor infrastructure, and limited disaster preparedness plans are especially vulnerable to hazards (Mishra and Sinha 2020). For these reasons, flood risk mapping needs to place greater emphasis on vulnerability, as it partly determines the extent of harm a flood event can cause to people. Our findings suggest that these challenges are also relevant to our study area, despite the absence of social, economic, and political dynamics in the analysis. Gaining a deeper understanding of the flood-induced dynamics in informal settlements would require additional qualitative evidence on the factors influencing urbanization, land use dynamics, and vulnerability.

The satellite imagery used in this study provided accurate, temporally high-resolution data, enabling detailed observation of the dynamics of human settlements and fluvial geomorphology. However, disadvantaged communities often cannot leverage these resources due to prohibitive costs. In addition, rapid

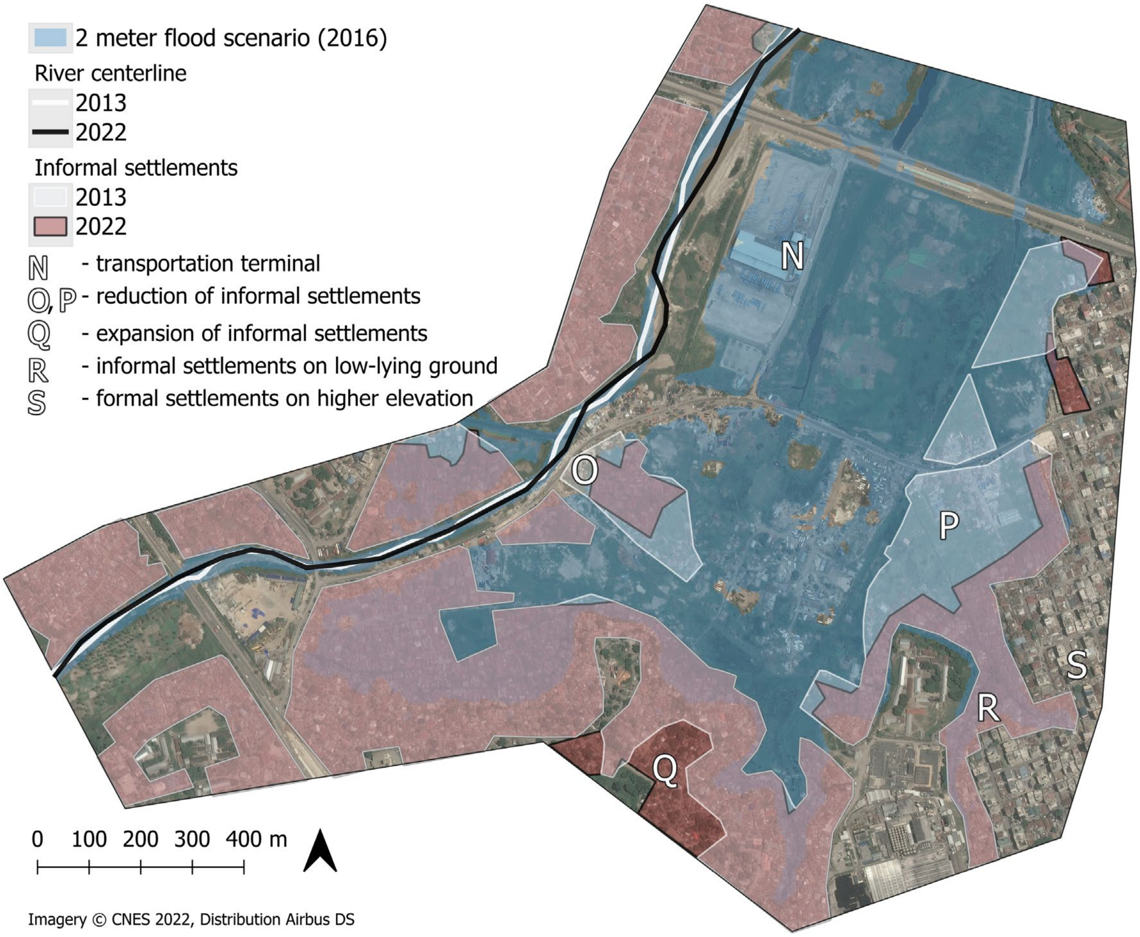

FIGURE 9 | Informal settlements and the Msimbazi River's centerlines in AOI 2 in 2013 and 2022. The points N, O, P, Q, R, and S highlight locations of interest. The background satellite image is from 2022, and the 2 m flood scenario is based on DEM of 2016. See location in Figures 1 and 4.

changes in riverine topography further complicate flood risk assessments; in our study area the most recent terrain model dates back to 2016, complicating analysis and limiting the accuracy of effective flood preparedness.

In summary, our results underscore the urgent need to incorporate geomorphological understanding and vulnerability indicators into flood risk assessments, especially in areas of unplanned urbanization. Active participation of local communities should be ensured in the flood risk management processes. Furthermore, we emphasize that the benefits of high-resolution satellite imagery should not be limited to wealthier groups, but instead, this valuable data should be made freely accessible to all.

6 | Conclusions

Urban flooding in the Global South, particularly in rapidly growing cities like Dar es Salaam, presents significant socio-economic challenges and is likely to intensify due to climate change. This study utilized high-resolution satellite imagery, open elevation data, and a REM approach to map flood-prone areas and analyze flood-induced changes in riverbanks and informal settlements along the Msimbazi River, one of the world's fastest-growing urban areas. Our analysis showed how even minor changes in water levels can lead to substantial variations in flood risk, depending on location, and highlighted the impact of geomorphological changes caused by river flooding on communities.

The results provided actionable insights that can support the development of sustainable flood risk management strategies, identifying key areas where interventions are most needed. The study underscores the disproportionate impact of flooding on informal settlements, which are often located on the urban periphery and excluded from urban flood risk management. The findings also revealed the need to consider the flood damages driven by geomorphological changes, which are frequently overlooked in local flood risk assessments, and should be incorporated into all flood management planning. The results further highlight the critical role of open, up-to-date data in understanding and managing flood risks in rapidly changing urban environments. Using high-resolution satellite imagery and simple analytical approaches, we were able to investigate significant flood risk areas that had been neglected in planning. Ensuring that the benefits of such high-resolution data are accessible to all, not just wealthier groups, is essential for equitable and effective flood management.

This study relied almost solely on remote sensing and did not incorporate local residents' perspectives to a large extent. Broader field-based evidence would strengthen the findings. In addition to documenting experienced flood events and risks, future research should consider how communities perceive floods, whether as part of daily life or as a hazard. Integrating vulnerability indicators into flood risk assessments and engaging all segments of civil society will be crucial for more inclusive and effective flood management.

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Data Availability Statement

Data used in this study are obtainable in the Climate Risk Database, hosted by the Tanzania Resilience Academy at https://crd.resilienceacademy.ac.tz/: Dar es Salaam Digital Terrain Model, 5m 2016, https://crd.resilienceacademy.ac.tz/catalogue/#/dataset/889; Dar es Salaam Historical Flood Depths, https://crd.resilienceacademy.ac.tz/catalogue/#/dataset/733; Dar es Salaam River Basins, https://crd.resilienceacademy.ac.tz/catalogue/#/dataset/817.

The CNES Pléiades satellite imagery was provided by Airbus Defence and Space as a free research sample and cannot be publicly redistributed.

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