



# Comprehensive investigation of flood-resilient neighborhoods: the case of Adama City, Ethiopia

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## Abstract

Adama is the second most populous city in Ethiopia and experiences frequent flash floods that have a detrimental impact on the community's livelihood. To this effect, this study emphasizes the significance of conducting a comprehensive investigation to identify flood-resilient neighborhoods in Adama City. By considering the existing spatial pattern and morphology that are resilient to urban flooding, the city can enhance its flood management strategies in the future. The findings of this study demonstrate varying levels of spatial connectivity within Adama City. Detailed examination of two neighborhoods identified through space syntax analysis with high and low spatial connectivity revealed important insights into flood resilience. The high-connective neighborhoods exhibited well-interconnected street systems with manageable street spacing, facilitating efficient runoff flow and effective flood management during flooding events. These neighborhoods also had shorter block sizes with frequent intersections, promoting better water drainage and reducing the risk of flooding during heavy rain events. The grid pattern observed in these areas allowed for efficient water runoff through multiple drainage paths, including the street surfaces. On the contrary, neighborhoods with low spatial connectivity exacerbated urban flooding. The lack of connectivity and abundance of dead-end streets posed challenges for flood evacuation during emergencies. Irregular block arrangements disrupted the natural drainage system, aggravating the potential for urban flooding. These findings have implications for other flood-prone areas of neighborhoods in Adama City and similar urban areas in the global south on how human settlements are arranged spatially to mitigate urban flood vulnerability.

**Keywords** Urban flood · Spatial morphology · Space syntax · Resilience · Adama · Ethiopia

## Introduction

Urban flood vulnerability is a global issue that requires attention and action. It is a major natural global hazard that is becoming increasingly frequent and serious worldwide due to the acceleration of urbanization processes and dramatic urban physical forms changes (Wang et al. 2022; Ziegler

et al. 2012). Human and natural factors affect vulnerability to flooding, such as agricultural activity, urbanization, deforestation, and land degradation. Devastating flood risk increases due to climate change, heavier rainfall, and deforestation (Baky et al. 2020; Tagnani et al. 2015; Tanoue et al. 2016; Williams et al. 2019a, b). Urban areas are vulnerable to extreme hydrologic events such as heavy precipitation and floods. This is due to the concentration of population, rising runoff volume, increase in built-up infrastructure, and other human activities (Chang and Franczyk 2008; Chen and Leandro 2019; Waghwal and Agnihotri 2019).

Urban flood vulnerability varies across regions of the world, with some areas being more vulnerable than others. Rapid urbanization in developing countries, particularly in Africa and Asia, is a challenge for flood risk management (Duc 2013; Kovacs et al. 2017; Wang et al. 2022). Due to the interconnection between flood exposure and poverty, low and middle-income countries are particularly vulnerable to flood risks given the challenges associated

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with social safety nets and infrastructure quality, with 89% of the world's flood-exposed population residing in these countries (McDermott 2022; Rentschler and Salhab 2020; Rentschler et al. 2022). In addition, informal settlements in various global southern nations face enormous challenges that contribute to their vulnerability to flooding (Anwana and Owojori 2023; Tietjen et al. 2023). These settlements often lack proper infrastructure, including adequate drainage systems, which increases their susceptibility to flood hazards (Dickson-Gomez et al. 2023; Peters et al. 2022; Ramiamanana and Teller 2021). In contrast, formal and well-planned settlements with appropriate drainage systems demonstrate a reduced vulnerability to flooding (Adegun 2023; Williams et al. 2019a, b).

Achieving urban flood resilience is considered the best technique for dealing with urban flood vulnerability (Schelfaut et al. 2011; Yin et al. 2022). Urban flood resilience refers to a city's ability to withstand and recover from flooding, effectively managing the physical damage and socioeconomic disruptions that arise, to prevent casualties and injuries, and preserve the existing social, economic, and environmental fabric (Rözer et al. 2022). Within a city, certain neighborhoods may be more vulnerable to flooding than others, while some areas may be more resilient to flooding due to the physical urban form. Neighborhood-level considerations play a crucial role in community resilience planning in urban locations (Bukvic et al. 2021).

Investigating flood-resilient neighborhoods is important for flood mitigation and sustainable spatial planning and contribute to increasing flood resilience in neighborhoods (Bukvic et al. 2021; Fitriyati et al. 2022; Serre et al. 2018; Truu et al. 2021). It is important to consider the specific context and scale of the community when identifying and implementing strategies to increase resilience to flooding. Implementing flood-resilient neighborhoods was challenging due to different factors such as rapid urbanization and climate change (Serre et al. 2018); flood-prone areas are often subject to climate change and socioeconomic development, which can contribute to increasing flooding (Hemmati et al. 2020); and the need for coordination between different stakeholders and the potential for conflicts between different interests (Serre et al. 2018).

Following pioneering research conducted by Holling who coined the term “resilience” in the study of ecology in 1973 (Holling 1973), many studies were used in various fields such as disaster management, psychiatry, and social science (McClymont et al. 2020). They are used as a part and combination of interdisciplinary frameworks (*engineering, systems, and complex adaptive systems resilience*) (Martin-Breen and Anderies 2011). Recently, the concept of Social-Ecological-Technological Systems (SETS) resilience provides frameworks for optimizing human–environment interactions and addressing risks posed by natural and

climate-induced hazards (Kim et al. 2022; Sharifi 2023). By analyzing the intricate interplay between environment, infrastructure, and equity considerations, SETS allows us to explore how hazards impact society and their distribution across different domains (Chang et al. 2021). In the urban planning concept, urban resilience pertains to the capacities of the urban system that are essential to the proper functioning of urban services (Rus et al. 2018) and promotes ‘living with floods’ (Batica and Gourbesville 2016). In this study, flood resilience is defined as the ability of urban areas to withstand and recover from the impacts of flooding. It involves a comprehensive approach that considers various aspects of urban morphological elements such as street networks/connectivity, buildings, and block arrangements. By considering these various aspects and their interdependencies, cities can develop comprehensive approaches to mitigate the impacts of flooding and enhance their resilience in the face of future flood events.

Extensive research has been conducted by Aroca-Jiménez et al. (2018), Bottazzi et al. (2018), Mugume and Butler (2017), Newman et al. (2020) to examine the components of urban flood resilience, including physical infrastructure such as drainage systems, transportation, green infrastructure, housing, and community resilience, as well as social and economic factors. However, given the complex and dynamic nature of urban areas, it is essential to delve into different themes and their interconnectedness to develop a comprehensive understanding of urban flood resilience, as highlighted by Barreiro et al. (2020), Rezende et al. (2019). In line with this, Prashar et al. (2023) stress the importance of uncovering these various themes and connections to enhance our knowledge in this area. Therefore, it is crucial to expand our research scope and explore the multifaceted aspects of urban flood resilience to effectively address the challenges faced by urban communities in the face of flooding events.

Abshirini et al. (2017) examined the resilience of cities based on similarity and sameness measures and focused on the accessibility of street networks to different amenities before and after flooding. He et al. (2022) investigated the resilience of urban road networks, considering their exposure to flood hazards and the indirect effects caused by travel disruptions and cascading failures throughout the city. Martin et al. (2021) conducted a study that measured the resilience of road networks in terms of territorial accessibility, evaluating different orders of network damage using deterministic and random approaches.

Recent research has emphasized the crucial role of spatial morphology in urban flood resilience, highlighting its significance in enhancing cities' ability to withstand and recover from flooding (Marcus and Colding 2014; Maulana and Nordin 2019). This concept of integrating resilience with urban morphology has garnered increasing interest among researchers, recognizing the importance of considering the

physical layout and structure of urban areas in developing strategies to enhance flood resilience (Stangl 2018). This includes understanding the spatial arrangement of infrastructure, such as street networks, building composition, and block arrangements, for effectively managing flood risks. By exploring the interconnectedness between spatial morphology and resilience, cities can develop comprehensive approaches that address the complex and dynamic nature of urban flood resilience (Shukla et al. 2023). For example, Serre et al. (2018) evaluated the capacity of urban drainage systems and strategies to reduce building exposure to flood hazards. Feng et al. (2021) also highlighted the importance of the spatial distribution of impervious surface coverage, which is closely related to flood risk. Additionally, Wijayawardana et al. (2023) utilized urban density-based runoff simulation to project and enhance the flood resilience of cities. However, these studies did not explicitly examine other essential urban elements such as road connectivity and spatial morphologies.

Road connectivity plays a critical role in ensuring that public infrastructure facilities including community flood relief centers, primary health care centers, emergency response managers, and disaster response forces are adequate during floods (Tachaudomdach et al. 2021; Watson and Ahn 2022; Xu et al. 2022). Connectivity refers to the direct connections that a street has with its neighboring streets within a specific area. A high connectivity value indicates that a street has numerous connections with its side streets, while a low value suggests fewer connections. This static measurement is essential in determining the level of connectivity and its impact on flood resilience in a particular urban area. Unfortunately, during the inundation, the mobility of cities and flood-affected neighborhoods deteriorates, worsening the situation (Asiedu 2020). Disruption of road network connectivity brings cities to a standstill, leading to substantial emotional trauma and economic losses for those affected (He et al. 2022). The impact of floods on roads is categorized into direct effects such as physical damage to infrastructure and transport facilities, and indirect impacts like disruption to traffic movement, and loss of business, and life (Brown and Dawson 2016; Hammond et al. 2015; Kadaverugu et al. 2021). During urban flooding, inundated road becomes inaccessible and risky for movement, negatively impacting essential services and emergency operations. This disruption increases resilience time, further exacerbating the impact on the city's overall resilience (Mukesh et al. 2022).

Spatial morphology has developed frameworks for studying urban form that can be used to organize data on resilience, on smaller and larger-scale units of analysis using GIS applications to examine the impact of forces and responses at multiple scales (Stangl 2018). Gauthier and Gilliland (2006) provided an exhaustive survey of various scientific studies focusing on spatial morphology, from the empirical

analysis of the city as a spatial entity, to normative propositions in multiple fields including urban planning, urban design, architecture, economics, archeology, and urban history. The methodologies range from general concepts suited for wider application, such as Kevin Lynch's studies, to very specific topics with notation systems, as exemplified by Satoh (1997) to examine various dimensions of threats to urban life and property, such as earthquakes, fires, and flooding (Stangl 2018). Nowadays, four prominent schools of thought in urban morphology exist, each offering distinct theories, concepts, and methodologies to comprehend the physical structure of cities. These theories have profound implications for the societal, economic, and environmental aspects of urban life (Kropf 2009; Sima and Zhang 2009). The four schools are as follows: morphological analysis, which explores the arrangement of streets, plots, and buildings within a city; philosophical process, which examines the social dimension of urban space; typo-morphological analysis, which scrutinizes the overall organization of towns, buildings, and systems; and space syntax, which investigates the intricate relationship between society and spatial configurations. This study adopts a historico-geographical and space syntax framework to investigate flood-resilient neighborhoods in relation to urban form. Through this approach, it reveals a better understanding how city layouts impact resilience in the face of flooding events.

Therefore, the present study focuses on operationalizing road connectivity, flood event observations, key informants and Municipality interviews, and spatial morphology to investigate urban flood-resilient neighborhood areas that could help reduce impacts, enable evacuation or provide safe havens, or facilitate recovery at the neighborhood level to achieve sustainable urban development to build resilience to urban flooding. Investigating the flood resilience of Adama, a flood-prone city in Ethiopia, at the neighborhood level is crucial for understanding and mitigating flood hazards, highlighting the significance of integrating accessibility and spatial morphology concerns at the urban scale.

## Methodology

### Description of the study area

The present study was conducted in Adama City, Ethiopia. Adama is the second-most populous city in Ethiopia and has experienced rapid growth since its establishment in 1916. Situated within the Awash River Watershed and the East African Rift Valley, Adama is characterized by its flat terrain surrounded by plateaus, mountain ranges, and ridged topography. The city's geographical coordinates are between 8026'15"–80 37'00" N and 390 12'15"–39,019'45" E.

The altitude of the study area ranges from 1489 to 1976 m above sea level, and it is located 99 km southeast of Addis Ababa, the capital of Ethiopia. Adama covers a total area of 30,865.4 hectares and has its highest and lowest points at the northern tip and eastern border, respectively. The lowest point is a flat, low-lying area that collects floodwater from Borticha Ridge and the eastern edge of Migira Ridges, forming seasonal ponds. On the other hand, the highest elevation point is found at the northern tip of the Wind Farm II substation.

According to the 2007 census carried out by the Central Statistics Agency of Ethiopia (CSA), Adama City had a population of 222,035, growing at a rate of 5.4%, which is higher than the national urban growth average of 2.5%. In their Adama City Structure Plan Report (ACSPR) of 2018, it was reported that the total population within the administrative boundary of 30,865.4 hectares was 431,202. The doubling rate was found to be 13 years, faster than the national doubling time of 23 years. This rapid growth can be attributed to the city's strategic location along the Addis Ababa—Djibouti railway and its proximity to Addis Ababa. However, the influx of people has resulted in overcrowding near floodplains, increasing the risk of recurring floods due to the city's landscapes. The growth rates from 2004 to 2016 indicate that Adama has experienced an annual change rate of nearly 9%, making it one of Ethiopia's fastest-growing cities (Bulti and Assefa 2019).

Adama experiences a hot semi-arid climate, with an average annual temperature of 20.7 °C. Rainfall occurs from June to September, with an average annual rainfall of 866.25 mm. May is the warmest month, with an average temperature of 22.7 °C, while December is the coldest and driest month, with an average temperature of 18.3 °C (National Meteorology Agency (NMA), 2022). Figure 1 shows the location of the map of the study area.

## Data sources

The data for the existing street network, administration boundary, block arrangements, and land use in Adama City were acquired from the Adama City Administration (ACA). To fill in any gaps in the existing road network, digital mapping techniques were employed using Google Earth Pro-Satellite imagery (Version 7.3.6) within the ArcGIS software (Version 10.8). This method ensured an accurate and comprehensive representation of the road infrastructure in Adama City. The combination of data obtained from ACA and the digitization process facilitated the creation of a reliable and up-to-date road network dataset.

Similarly, buildings were digitized from high-resolution Google Earth Pro-Satellite imagery (Version 7.3.6) in ArcGIS software (Version 10.8). The acquisition of the existing blocks from the esteemed Adama City Administration

(ACA) was undertaken to bridge the gaps in the current inventory, necessitating the utilization of digital mapping methods. Specifically, Google Earth Pro-Satellite imagery (Version 7.3.6) supported by the ArcGIS software (Version 10.8) was employed. This approach not only ensured high precision but also provided a comprehensive depiction of the blocks within Adama City. By combining the data procured from ACA with the digitization process, a dependable and contemporary dataset of blocks was successfully generated.

Furthermore, the land use data were used to interpret the function concerning street connectivity. Finally, flood event observations, key informants, and professionals from the municipality actively participated in the research process, providing valuable insights and perspectives.

## Methods

This study aimed to investigate flood-resilient neighborhoods in the study area using a combination of Space syntax (DepthmapX version 0.8.0) for spatial connectivity analysis and GIS (version 10.8)-based morphological analysis. The research methodology involved flood events observations, utilization of the depth-map model, insights from experts and key informants, and an extensive review of relevant literature. This comprehensive framework allowed for the investigation of the complex relationship between urban morphology and flood resilience, ultimately informing urban planning and design strategies to create more resilient settlements and communities.

The first step in the research methodology was to use the DepthmapX model output to identify areas in the study area with varying levels of connectivity. Then, flood event observations were conducted during heavy rainfall in the rainy seasons of June, July, and August. Two sites were selected for further morphological analysis: one with low connectivity and one with high connectivity. These sites were chosen due to their proximity to each other, regular inundation with floods, similar landforms, and soil types, and their status as long-standing settlements. Both sites have a history of being heavily impacted by floods during the rainy season, causing significant damage to the local community and affecting their daily livelihoods. The morphological analysis involved the examination of the street system (street hierarchy and material), buildings, land use, and block arrangements.

To gather comprehensive insights, key informant elders who have lived in the area for over 35 years were consulted about flood events situations in their neighborhoods. These elders represented organized local community leaders from religious, women's, security facilitators, and business sectors, with 10 elders from site "a" and 10 from site "b". Additionally, professionals from the municipality were also consulted regarding flood events in the study area. The general workflow followed by this study is represented in Fig. 2.



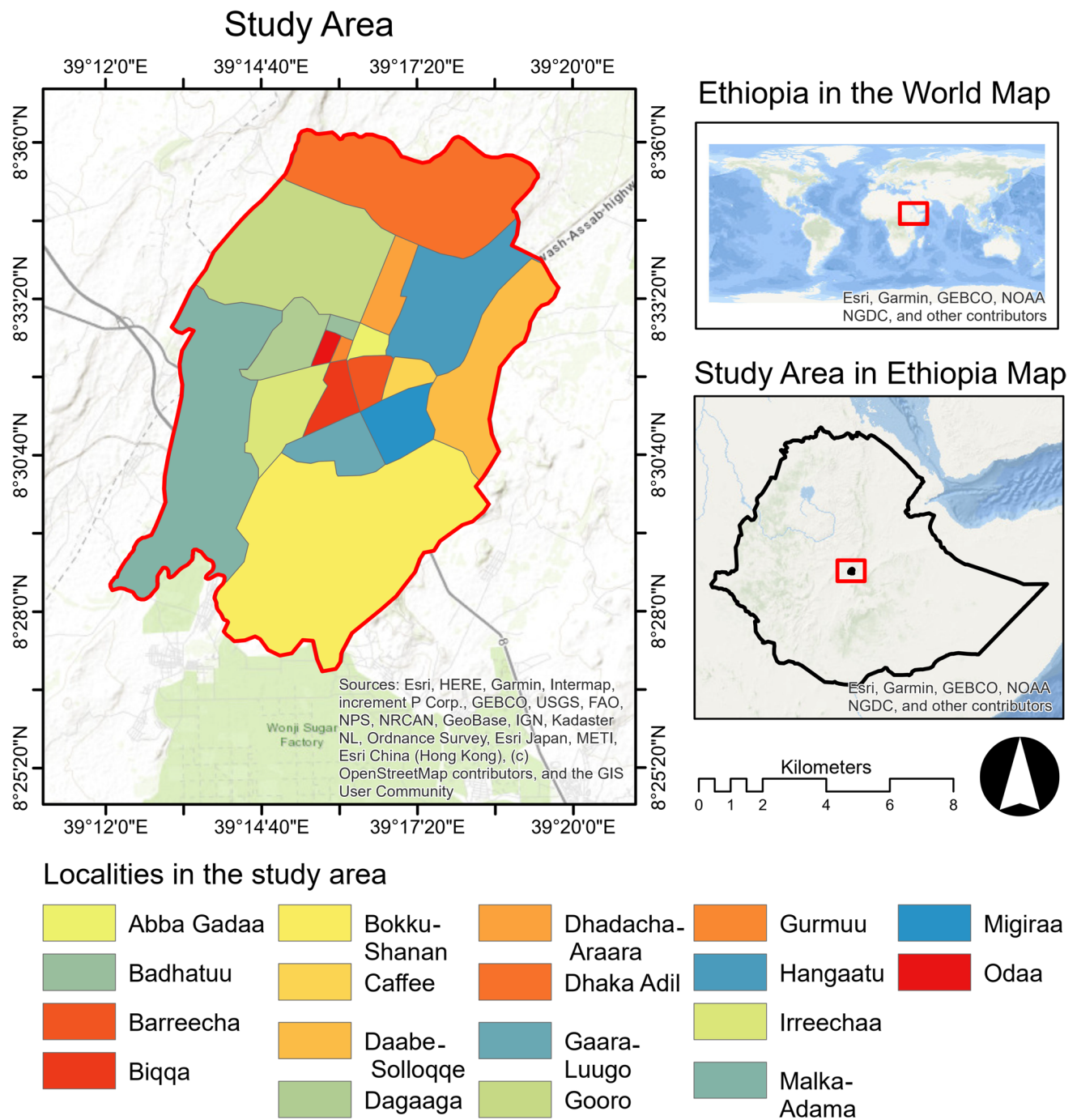


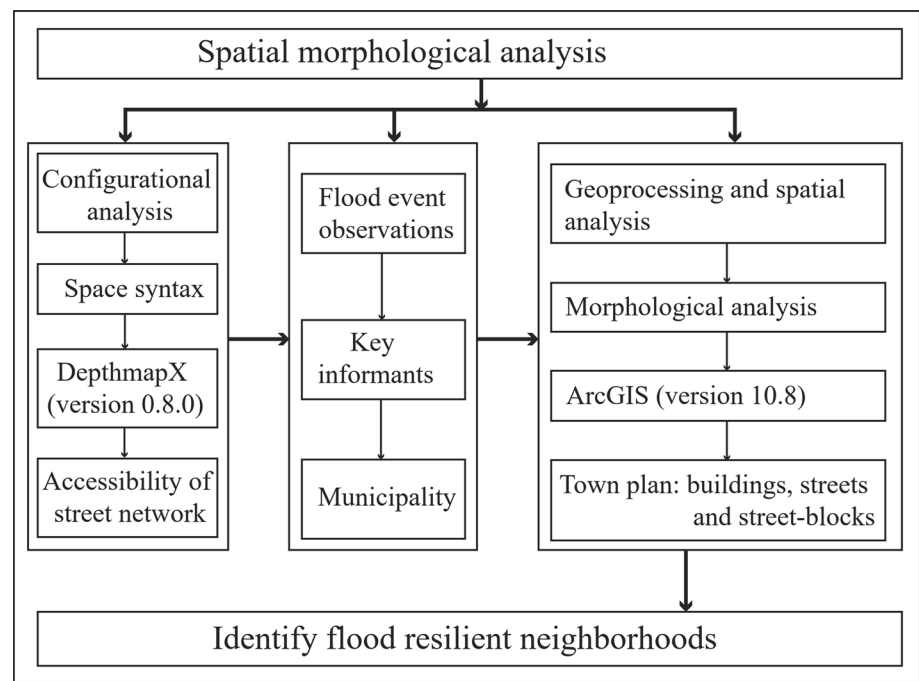
Fig. 1 Location map of the study area

### Methods of analyzing configurational analysis

Space syntax is a set of analytical techniques used to examine the spatial arrangement of various environments, particularly those in which spatial configuration plays a crucial role in human affairs, such as buildings and cities (Hillier et al. 1984). This approach scrutinizes diverse phenomena including patterns of movement, spatial layout, awareness,

interaction, density, land value, urban growth, societal differentiation, safety, and crime distribution. To conduct the analysis, the research employed DepthmapX software (version 0.8.0), which facilitated the assessment of axial accessibility (Behmanesh and Brown 2019; Turner 2007; Varoudis 2012). By utilizing this software, areas with high and low accessibility were identified and subsequently selected for further morphological analysis.

**Fig. 2** Flow chart to identify flood-resilient neighborhoods of Adama City



### Geoprocessing and spatial analysis

The analysis of the town plan for two specific areas, namely high and least-accessible areas, was conducted using ArcGIS 10.8. This software tool enabled the examination of morphological aspects, which encompassed the study of street layout, buildings, and block distribution within the urban setting. The primary focus of this investigation was to identify flood-resilient areas within the city.

## Result

### Configurational analysis of Adama City

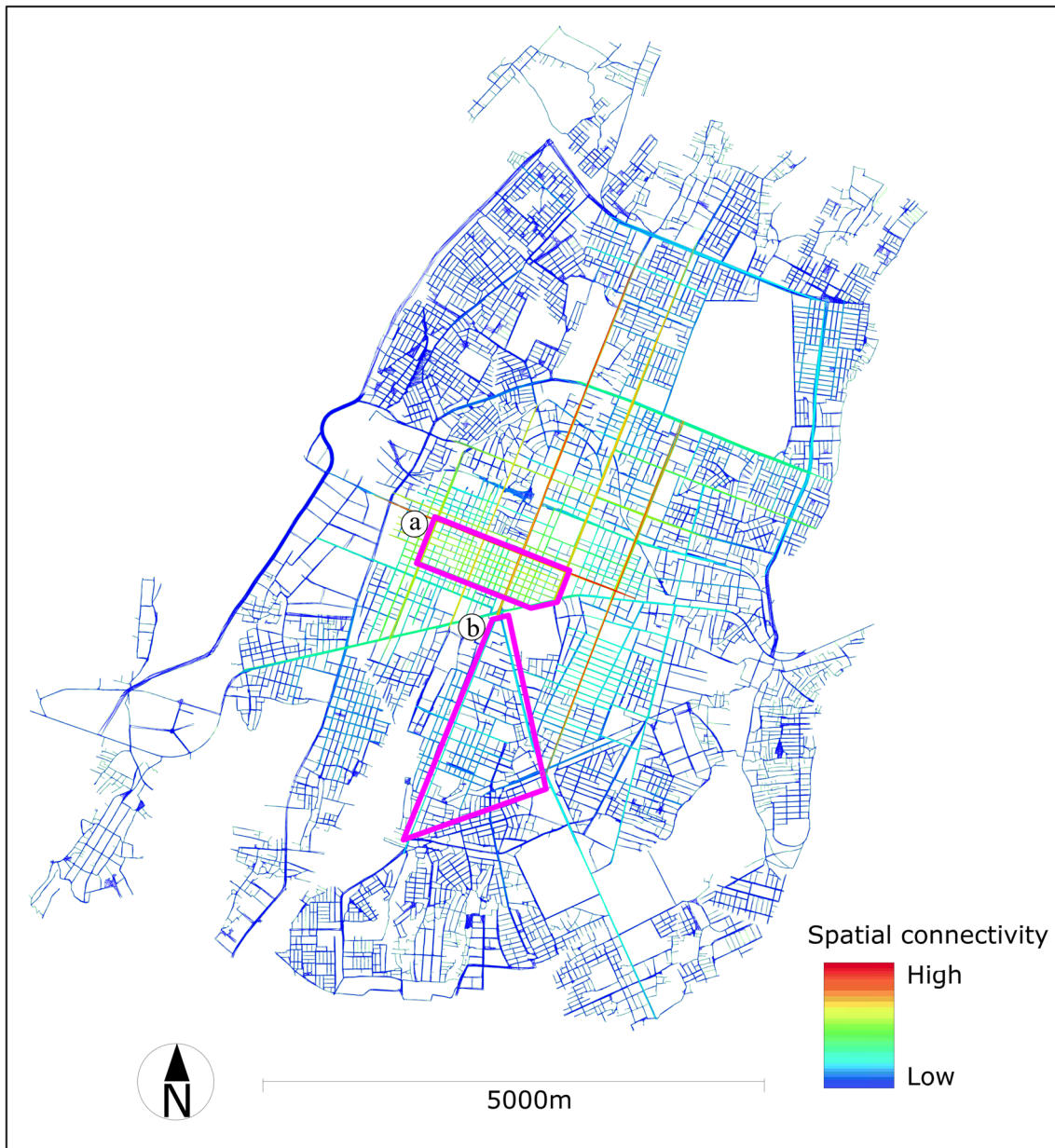
The analysis of Adama City's configuration using DepthmapX (version 0.8.0) revealed varying levels of connectivity across different areas in the city as shown in Fig. 3. DepthmapX (version 0.8.0) calculates DepthmapX (version 0.8.0) as a tool that calculates the spatial integration of a street axis, or axial line, concerning all other streets in the system. Essentially, it measures how many changes of direction, or syntactic steps, are needed to reach all locations in the system from a particular street. Streets with fewer changes of direction have higher integration values, while those with many changes of direction tend to have lower values and are considered spatially segregated.

These integration values can be represented on a map using a color range. For example, in Fig. 3, we can see the degree of connectivity for each street in the study area. The streets marked in red and yellow have the highest number of

connections to adjacent streets, while those with dark blue colors only have one or two connections nearby. The city center has high connectivity values, and one of the main shopping areas, "site a", also has a high connectivity value. On the other hand, "site b", which is an informal residential area, has low street connectivity.

It is worth noting that the localities of Oda, Badhaatu, Abba Gadaa, and Gurmū exhibit high accessibility, indicating a well-connected and easily navigable street network in the study area. This suggests that these areas may have a better chance of receiving aid and emergency assistance due to their accessibility. In contrast, Dagaaga, Dhadacha Araara, Hangaatu, and Caffee demonstrate moderate accessibility, suggesting a relatively less developed road infrastructure compared to the aforementioned areas. This can make it more challenging for people to move around within these areas. Moreover, the remaining parts of the city have lower levels of accessibility, which could make them more vulnerable to urban flooding. Inaccessibility in these areas can hinder the movement of people and resources during flood events, making it more difficult to provide assistance and mitigate the impacts of flooding.

The DepthmapX dataset showed an average connectivity attribute value of 291.96, ranging from a minimum of 2 to a maximum of 4527. The standard deviation was calculated to be 466.48. Furthermore, the total count of line length in the dataset was 116,464, representing the overall extent of the street network of the study area. Based on the information presented in Table 1 and Fig. 4, neighborhoods that exhibited connectivity values below 454.5 and above 4074.5 were selected for further morphological analysis. These specific



**Fig. 3** Spatial connectivity Map of Adama City

thresholds were chosen to identify areas with significantly low and high connectivity, respectively, which may indicate distinct characteristics or patterns within the street network. By focusing on these neighborhoods, further morphology and structure of the network, potentially uncovering valuable insights and understanding how connectivity attributes contribute to the overall functionality and efficiency of flood resilience during heavy rainfall.

Figure 5 shows the two sites chosen for the study, referred to as site “a” and site “b”, which displayed varying degrees of connectivity. Site “a” was identified as having a high level of connectivity, while site “b” was characterized by a low

level of connectivity. Site “a” was found to have a vibrant and well-developed central area of the city, with 41.52% of its land use designated for commercial and mixed purposes. On the other hand, site “b” was considered an informal settlement, with only 8% of its land use allocated for commercial and mixed purposes, and primarily consisting of residential quarters, as illustrated in Table 2 and Fig. 6.

### Flood event observations

Flood events that occurred during the rainy season in the study area were conducted, with a particular emphasis on the

**Table 1** Connectivity attributes of the study area using DepthmapX (version 0.8.0) model output

Value	Average	Min	Max	Std Dev	Count	<454.5	454.5–907	907–1359.5	1359.5–2264	2264.5–3169.5	3169.5–3622	3622–4074.5	>4074.5
Attribute	291.96	2	4527	466.48	116,464	95,316	11,448	4910	3,370	1,121	208	57	34
Remarks on the level of spatial connectivity						Low	Medium						High

months of June, July, and August. These floods had substantial consequences for the economic, social, environmental, and health aspects of the community. Many neighborhoods within the city experienced inundation, resulting in road closures and widespread flooding. To gain a better understanding of these events, the researchers analyzed historical rainfall patterns in Adama City over a span of 33 years and conducted on-site observations during the rainy seasons. The flooding of roads and neighborhoods during these periods had detrimental effects on the well-being of the communities, affecting them socially, economically, environmentally, and psychologically. The occurrence of these flood events was corroborated by cross-referencing the data with information from the National Meteorological Agency, as demonstrated in Fig. 7. Additionally, visual evidence of the inundation was captured through recorded videos and photographs. In site "a," the floodwaters receded swiftly, allowing for a prompt recovery, as depicted in Fig. 8. However, in site "b," the floodwaters remained stagnant for a prolonged period, significantly impacting the daily lives of the community, as illustrated in Fig. 9. In site "a," floods were observed as overtopping through drainage manholes, resulting in neighborhood inundation. However, due to efficient water removal measures, the floodwaters receded quickly. In contrast, site "b" experienced issues such as clogging and siltation, causing the floodwaters to linger for an extended duration.

### Key informants and municipality

To gather information on the historical flood situation in the study area, insights were obtained from 20 key informant elders who have resided there for over 35 years. These informants were evenly distributed, with 10 from site "a" and 10 from site "b". In addition, professionals from the municipality were consulted regarding flood incidents in Adama City, specifically focusing on sites "a" and "b".

According to the key informants, the study area experiences flooding during each rainy season (June to August). However, the extent of damage varies over time and depends on the intensity of rainfall. They attributed the cause of these floods to a lack of drainage infrastructure and inadequate maintenance of existing systems. As a result, waste accumulates and blocks the drainage lines, leading to waterlogging, overflow onto roads and settlements, and detrimental impacts on the community's economy, social fabric, psychological well-being, environment, and health.

The municipality acknowledges the concerns raised by the key informants and expands further on their insights. The study area is considered a flood-prone area due to its geographical location on a flat terrain surrounded by plateaus, mountain ranges, and ridged topography. It is situated within the Awash River Watershed and the East African Rift Valley, which are known as the most flood-affected watersheds in



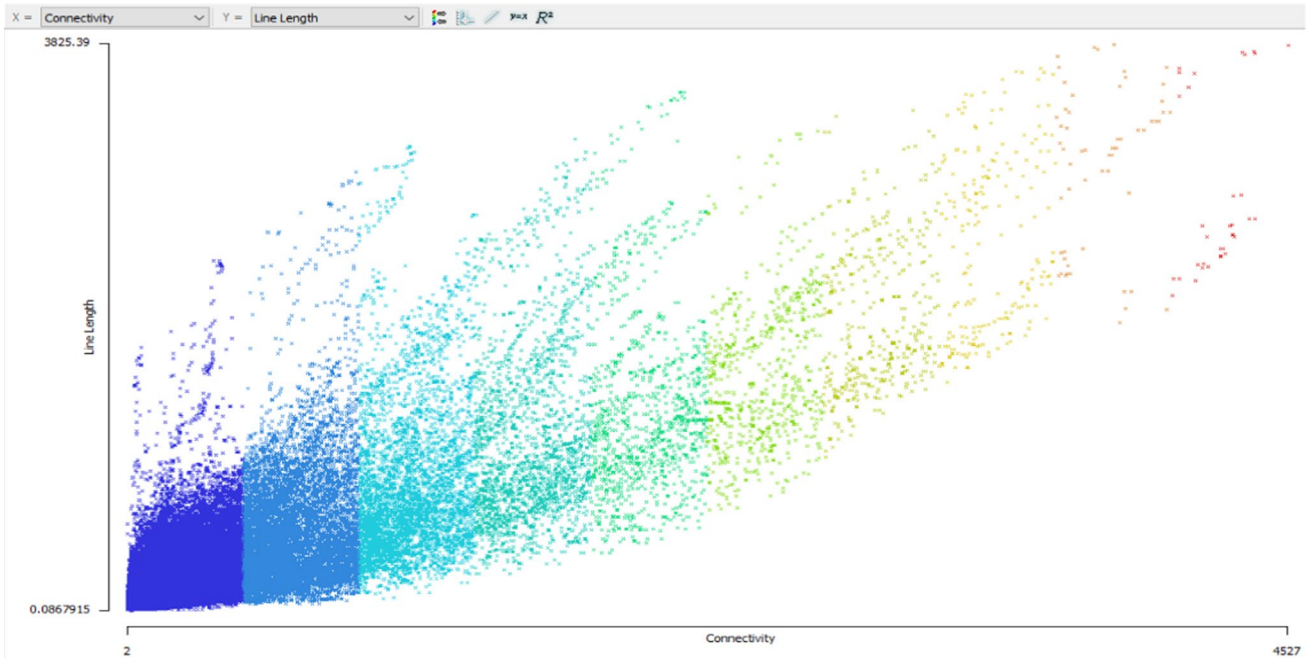


Fig. 4 Scatter plot of street line length to connectivity for the study area



Fig. 5 Selected sites with high connectivity (a) and low connectivity (b) parts of Adama City

**Table 2** Comparative analysis of land use of the two sites

Land use types	Area (ha)		Percent (%)	
	Site a	Site b	Site a	Site b
Residential	22.83	60.67	47.31	63
Commercial	10.43	2.78	21.6	3
Service	1.89	8.72	3.92	9
Open and green space	0.46	5.43	0.95	6
Administration	0.66	0.97	1.38	1
Industry and Manufacturing	1.66	11.54	3.43	12
Under construction	0.72	0.73	1.5	1
Mixed-use	9.61	4.69	19.92	5
Vacant land	–	1.38	–	1

Ethiopia. Furthermore, rapid urbanization, informal settlement aggregation, and deforestation exacerbate the flooding situation in the study area. This highlights the need for prompt action to address these issues and mitigate the impact of floods on the community's daily activities.

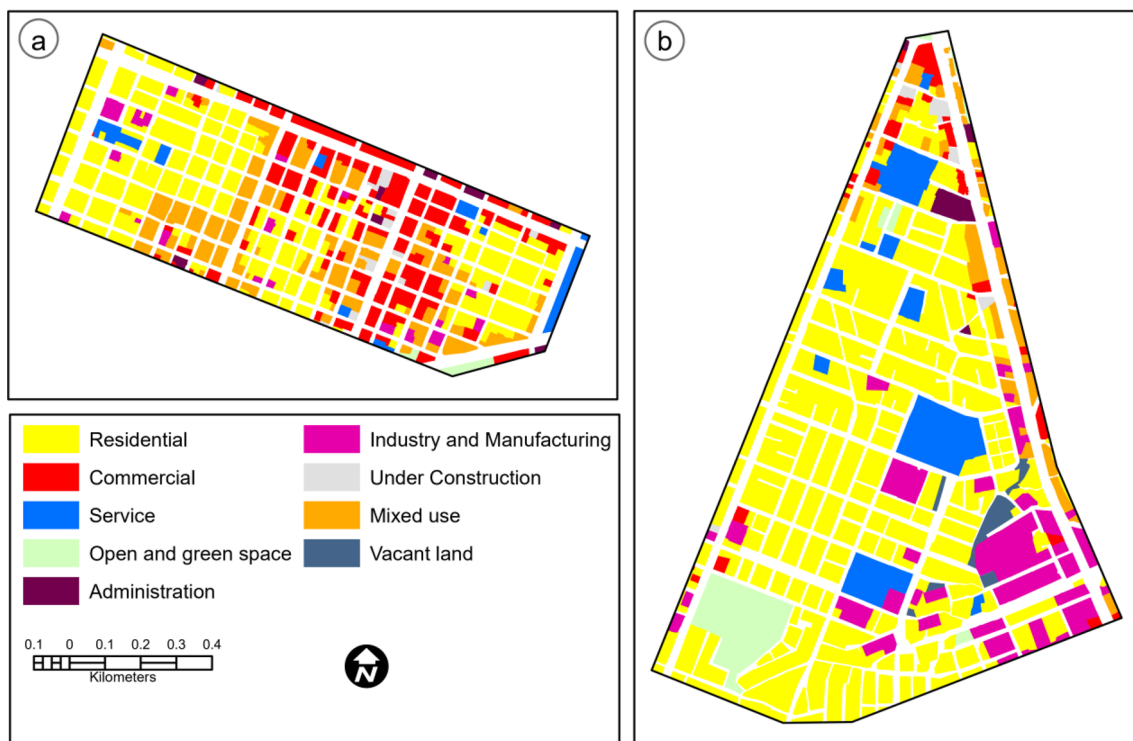
### Morphological analysis of the selected areas

#### Building configurations

Building configurations in planned and unplanned neighborhoods within a block can have both positive and

negative effects on flooding. In site “a”, building configurations are meticulously designed to mitigate flood risks. This includes the incorporation of proper drainage systems, open spaces, and permeable surfaces that facilitate better water absorption. Despite being exposed to floods, these neighborhoods can quickly redirect water to other areas, allowing for a faster return to normal conditions. Consequently, planned neighborhoods are less susceptible to flooding due to the strategic placement of buildings and street systems, which minimize runoff and promote effective water management.

In contrast to planned neighborhoods, unplanned neighborhoods, often characterized as informal settlements, lack proper consideration for flood mitigation in their building configurations. Buildings are placed randomly without functional open spaces, resulting in the area being inundated by floods during each rainy season. The informal buildings obstruct the movement of floodwaters, causing water to remain stagnant for longer periods and negatively impacting the socioeconomic and health conditions of the community. The haphazard placement of buildings in unplanned neighborhoods exacerbates flooding by increasing runoff on sealed surfaces and reducing the available area for water absorption. Furthermore, the absence of proper drainage systems further contributes to flooding issues in these areas, as shown in Fig. 10.



**Fig. 6** Land use map of the two sites

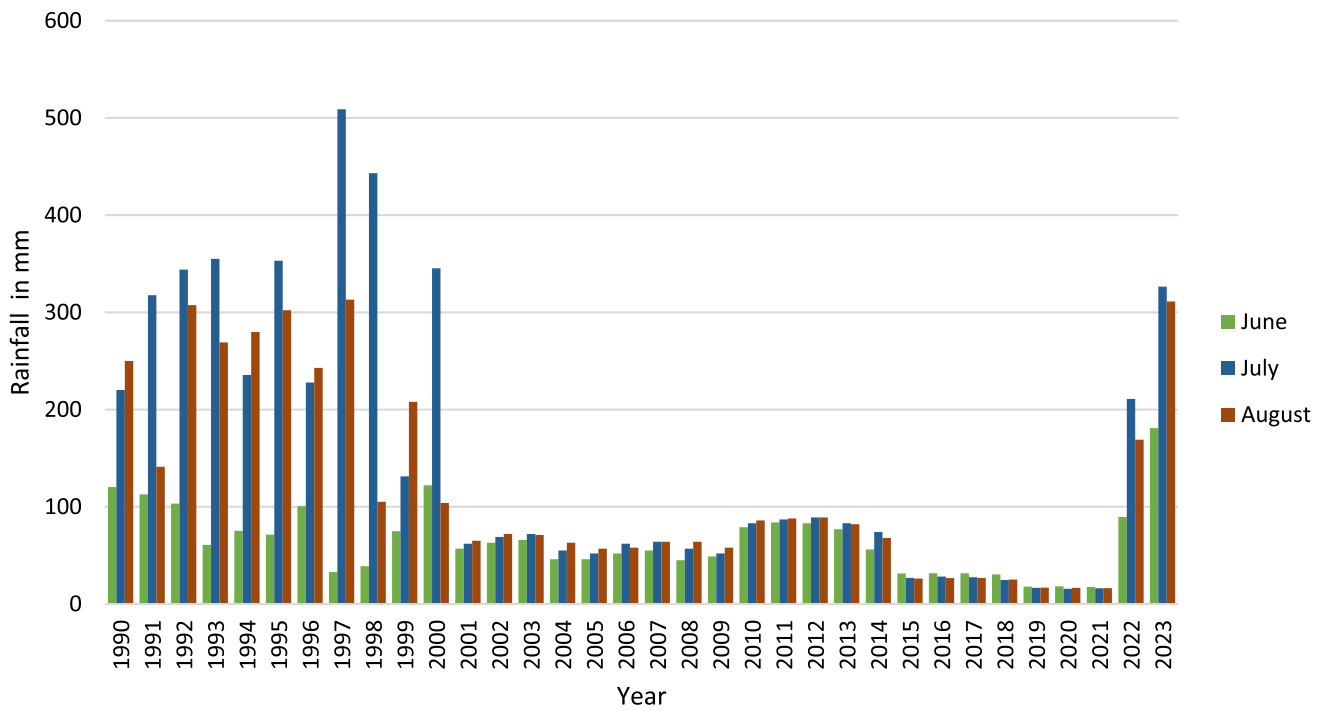


Fig. 7 Historical rainfall of Adama City. Source: National Meteorological Agency



Fig. 8 Flood event observations in site “a”, July 2023

**Street hierarchy**

The street hierarchy analysis revealed distinct differences between site a and site b in terms of their street network characteristics. Site “a” has a well-designed and interconnected street system, featuring seven principal arterial streets ranging from 25 to 40 m in width, as well as local streets measuring 6–10 m, and access roads less than 4 m wide. Such well-designed street spacing and coverage significantly enhance traffic efficiency and facilitate seamless navigation

within the vicinity. Moreover, during extreme rainfall occurrences, these characteristics aid in the smooth flow of water, ensuring effective flood mitigation measures are in place.

In contrast, the street network in site “b” is characterized by a lack of connectivity and a disjointed layout. The area primarily consists of two main arterial streets, one with a width of 25 m and the other 30 m, while the rest is covered by access roads. This configuration presents challenges for flood evacuation, as well as impedes the smooth flow of water, and hampers the timely delivery of aid to affected





**Fig. 9** Flood event observations in site “b”, July 2023

communities during emergencies. The limited connectivity and abundance of dead-end streets in site “b” create obstacles that need to be addressed for effective disaster response and mitigation efforts. Furthermore, due to the absence of adequate cross-drainage infrastructure, coupled with insufficient solid waste disposal practices and infrequent maintenance of drainage lines, stormwater accumulates and causes blockages during flash floods. Consequently, urban roads in the surrounding area become overwhelmed and overflowing, exacerbating the impact of flooding events, as depicted in Fig. 11.

#### Street surface material

The analysis of street surface materials revealed significant disparities between site “a” and site “b” in terms of their road infrastructure. Site a boasts a well-maintained and

interconnected street system, with seven asphalted roads ranging from 25 to 40 m in width, complemented by cobblestones and gravel on the remaining streets. This careful selection of surface materials contributes to the efficient flow of stormwater during extreme rain events, traffic flow, and ease of navigation within the area.

In contrast, site “b” exhibits a less developed road network, with only two asphalted roads, some cobblestones, and a predominance of earthen roads. The lack of asphalted surfaces and the dominance of earthen roads in site “b” pose serious challenges during urban flooding events. Earthen roads are more susceptible to damage and erosion caused by heavy rainfall, leading to increased surface runoff and potential blockages, as shown in Fig. 12. This not only hinders the evacuation of flood-affected communities but also impedes the delivery of essential aid and emergency services.



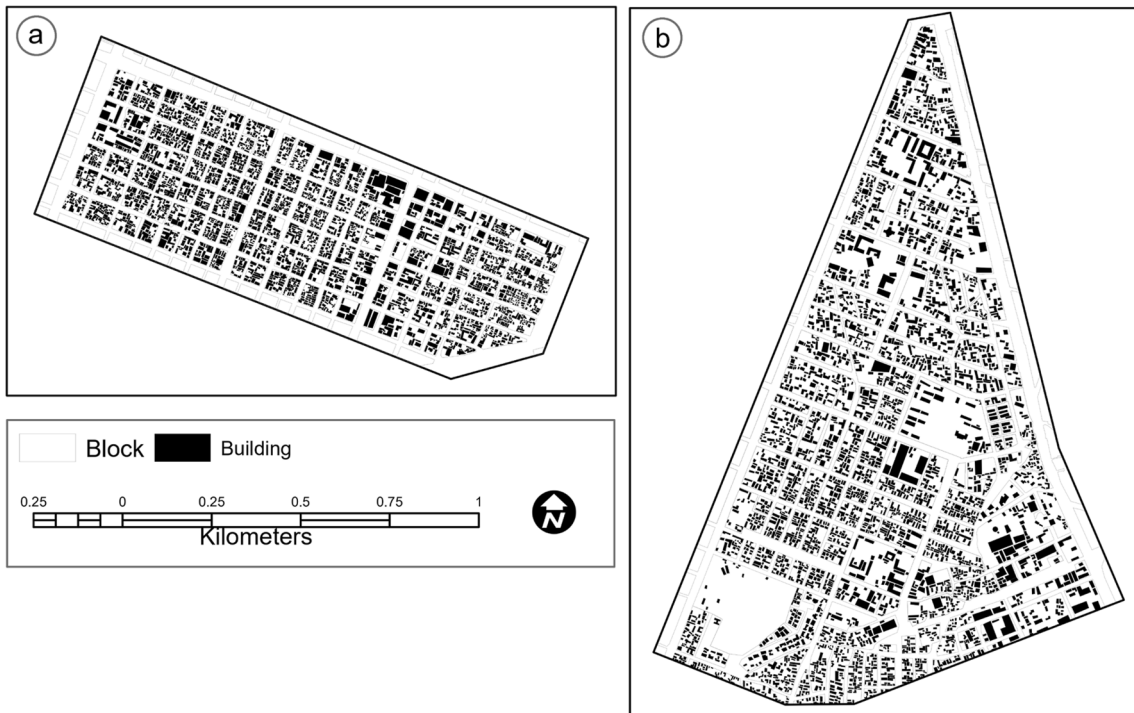


Fig. 10 Building configurations



Fig. 11 Street hierarchy

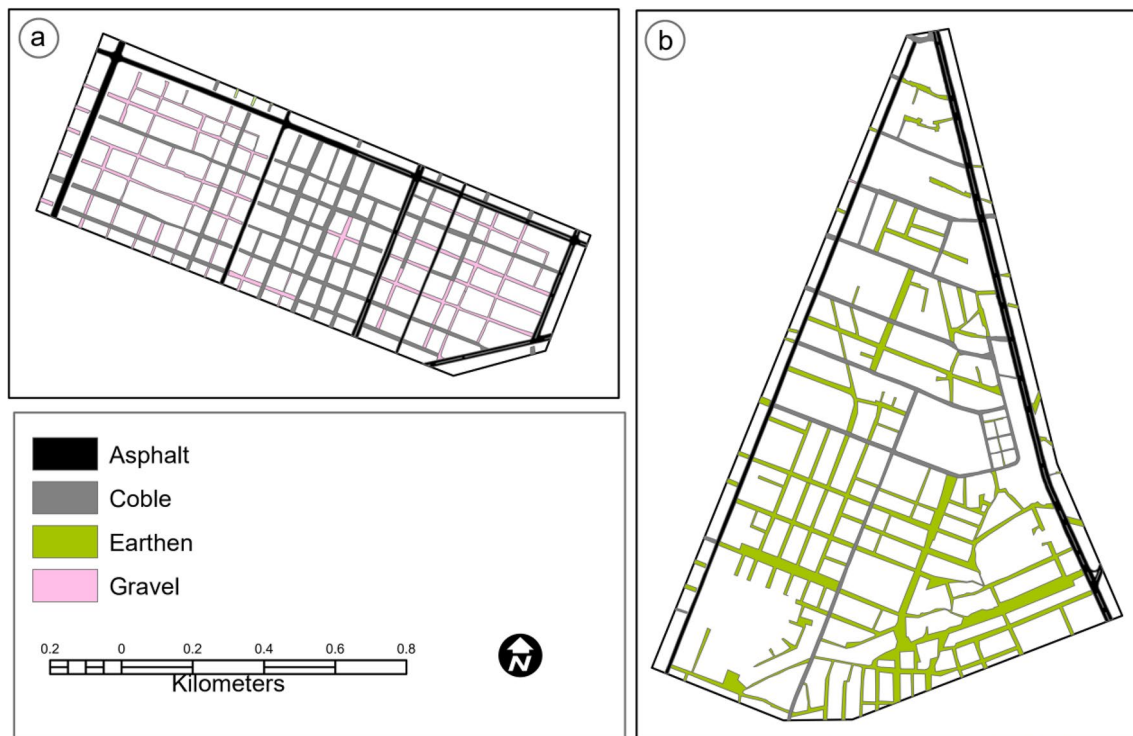


Fig. 12 Street surface material

## Blocks

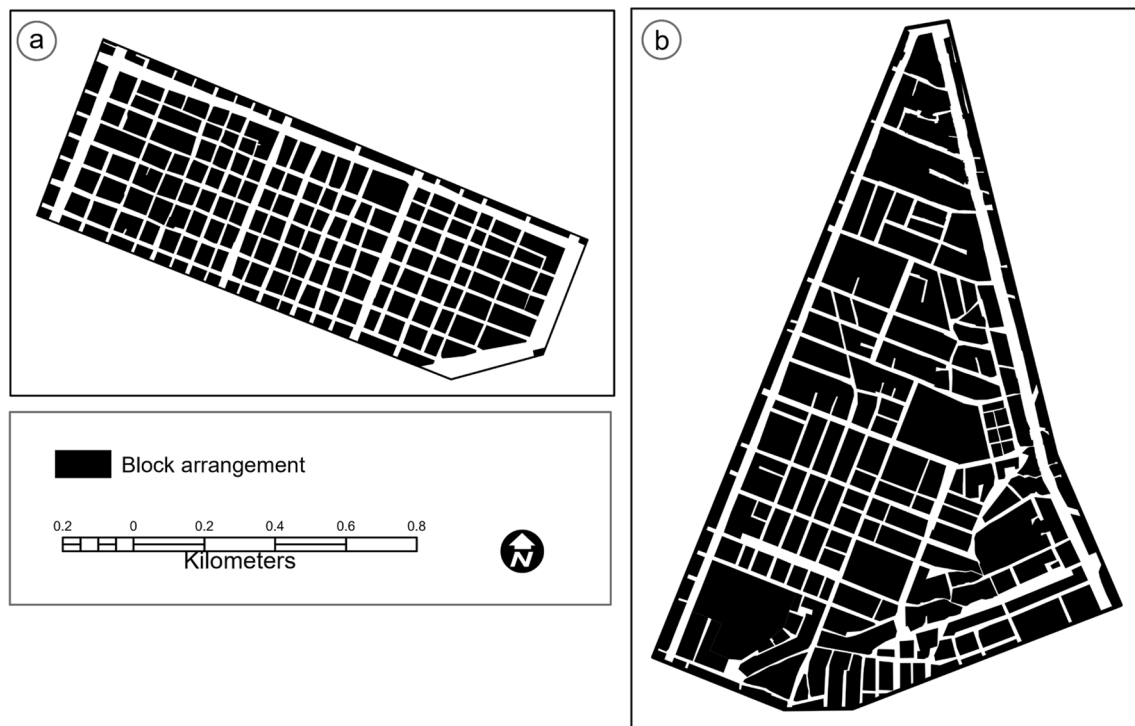
Site “a” has short block sizes, with smaller dimensions and more frequent intersections, which tend to promote better water drainage and reduce the risk of flooding. On the other hand, site “b” has long block sizes that hinder the natural flow of water, increasing the likelihood of water accumulation during heavy rainfall events. Similarly, site “a” has a grid pattern that allows for efficient water runoff, as it provides multiple drainage paths. In contrast, site b has irregular block arrangements that disrupt the natural drainage system, impeding water flow and exacerbating the potential for urban flooding, as shown in Fig. 13.

## Discussions

It is crucial to identify flood-resilient neighborhoods in Adama City through a comprehensive analysis that includes configurational analysis, flood event observations, insights from key informants and the municipality, and morphological analysis (Safiah Yusmah et al. 2020; Wang et al. 2022; Zhou et al. 2022). This approach allows for a cascaded analysis that considers the overall spatial connectivity of the city, as well as specific aspects such as street and block arrangements. By integrating flood event observations and input from key informants and the municipality, a more holistic

understanding of the city's flood-resilient neighborhoods can be identified (Eric et al. 2021; Mohammadtaghi et al. 2023; Tanoue et al. 2016). This type of analysis is particularly important in developing countries like Ethiopia, where limited information and resources exacerbate the severity of flooding impacts in rapidly urbanizing contexts (Deria et al. 2020; Rentschler et al. 2022; Salami et al. 2017). Therefore, a combination of spatial and morphological analysis, coupled with flood event observations, and key informants is essential for effectively addressing the challenges posed by flooding in Adama City.

The depth map of analysis of Adama City revealed varying levels of accessibility across different areas. Specifically, the localities of Oda, Badhaatu, Abba Gadaa, and Gurmu demonstrate high accessibility, indicating a well-connected and easily navigable street network in these regions. This suggests that these areas are more likely convenient for flood event action, emergency aid, and evacuation due to their accessibility. In contrast, Dagaaga, Dhadacha Araara, Hangaatu, and Caffee exhibit moderate accessibility, suggesting a relatively less developed road infrastructure compared to the aforementioned areas. This implies that these areas may face challenges in terms of road connectivity and ease of movement within them. Additionally, the remaining parts of the city display lower levels of accessibility, indicating potential vulnerability to urban flooding. The inaccessibility in these areas can



**Fig. 13** Block arrangements

hinder the movement of people and resources during flood events, making it more difficult to provide assistance and mitigate the impacts of flooding. The results of this study align with previous research conducted by Gangwal et al. (2023), He et al. (2021), Lee et al. (2023), Zhou et al. (2022), which suggests that areas with high accessibility and well-connected street networks are more capable of effectively managing flood vulnerability compared to less accessible areas in facilitating flood event actions, aid distribution, and evacuation efforts.

According to the findings of the present study, neighborhoods that had well-designed and interconnected street systems with manageable street spacing demonstrated a higher level of resilience to urban flooding. These features facilitated efficient runoff flow and effective flood management during flooding events. Conversely, neighborhoods with poor spatial connectivity, such as dead-end streets and irregular block arrangements, exacerbated urban flooding by impeding water flow and disrupting the natural drainage system. These findings emphasize the importance of considering flood mitigation measures in building configurations to mitigate flooding risks. Neglecting proper flood mitigation in building configurations can contribute to the worsening of urban flooding. This finding aligns with previous studies conducted by Der Sarkissian et al. (2022), Talbot et al. (2018), who highlighted that urban areas that have an appropriate building configuration can effectively reduce flood

risk due to the presence of a variety of land cover that allows for greater water absorption and reducing surface runoff.

The present study findings indicated that the design and connectivity of the street system play a crucial role in both efficient traffic flow and flood management. Specifically, areas with a well-planned and interconnected street network, featuring manageable street spacing coverage, were found to contribute to smooth traffic movement and easy navigation. Additionally, such areas were able to effectively manage flood inundation damage during urban flooding events. On the other hand, neighborhoods characterized by a lack of street connectivity and an abundance of dead-end streets, as observed in site b, presented significant challenges for flood evacuation and hindered the delivery of aid to affected communities during emergencies. The absence of adequate road space hampers the smooth, unobstructed flow of runoff into downstream areas, coupled with insufficient solid waste disposal practices and infrequent maintenance of drainage lines, resulting in the accumulation of stormwater and subsequent blockages during flash floods. Consequently, the surrounding urban roads became overwhelmed and overflowed, exacerbating the impact of flooding events. These findings are consistent with a previous study conducted by Farahmand et al. (2021), Karley (2009), La Rosa and Pappalardo (2020), Li et al. (2020), which emphasizes the importance of street connectivity and proper drainage systems in mitigating flood risks.

The selection of street surface materials plays a crucial role in ensuring efficient traffic flow and easy navigation in urban areas. However, the prevalence of earthen roads and the absence of asphalted surfaces pose significant challenges during urban flooding events. Earthen roads are more susceptible to damage and erosion caused by heavy rainfall, leading to increased surface runoff and potential blockages. This not only hampers the evacuation of flood-affected communities but also delays the delivery of essential aid and emergency services. Previous studies have shown that permeable pavements, such as porous asphalt, pervious concrete, permeable interlocking concrete pavers, and grid pavers, can enhance traffic flow and facilitate easy navigation (Sansalone et al. 2012; Xie et al. 2017). Nevertheless, the absence of asphalted surfaces and the dominance of earthen roads remain major obstacles during urban flooding events (Ahlmer et al. 2018; Konrad and Booth 2005). Earthen roads are particularly vulnerable to damage and erosion caused by heavy rainfall, resulting in increased surface runoff and potential blockages (Eisenberg et al. 2015; National Association of City Transportation Officials 2017).

Research has shown that neighborhoods with shorter block sizes, smaller dimensions, and more frequent intersections are beneficial for water drainage and reducing the risk of flooding. Conversely, neighborhoods with longer block sizes impede the natural flow of water, increasing the chances of water accumulation during heavy rainfall. Furthermore, a grid pattern in neighborhood design allows for efficient water runoff by providing multiple drainage paths. On the other hand, irregular block arrangements disrupt the natural drainage system, hinder water flow, and worsen the potential for urban flooding. These findings align with a previous study that emphasized the positive impact of smaller urban blocks on water drainage and flood risk reduction (Feng et al. 2021). Additionally, the presence of more frequent intersections in these neighborhoods can improve traffic flow and ease navigation (Mejía-Morales et al. 2021). In contrast, larger urban blocks hinder the natural flow of water and are more likely to lead to water accumulation during heavy rainfall events (Zhang et al. 2022). Regular grids are more effective in reducing the risk of flooding as they provide multiple drainage paths, while irregular grids are less effective and contribute to the exacerbation of urban flooding (Feng et al. 2021; Sharifi et al. 2021).

The analysis of floods relies heavily on the observations of flood events, as they offer valuable insights that can aid in mitigating flood risks. Recent studies have emphasized the pivotal role played by flood event observations in reducing flood risk. These observations have proven to be instrumental in identifying areas that are susceptible to economic losses and ecosystem vulnerability. Flood event observations are an essential component of flood analysis, providing valuable information that can be utilized to reduce

flood risk. Studies conducted by Kang et al. (2023), Zhang et al. (2021) have highlighted the crucial role of flood event observations in flood risk reduction. These observations have been instrumental in identifying areas at high risk of economic failure and ecosystem vulnerability. By integrating flood event observations with input from key informants and the municipality, a more holistic understanding of the city's flood resilience can be achieved, which is essential for effectively addressing the challenges posed by flooding (Coeur and Lang 2008; Haltas et al. 2021; Zhang et al. 2021).

## Conclusions

This study emphasizes the importance of conducting a comprehensive analysis of various factors, such as configurational analysis, flood event observations, key informants, municipality information, and morphological analysis, to identify flood-resilient neighborhoods in Adama City. By considering the existing spatial pattern and morphology that are resilient to urban flooding, the city can improve its flood management strategies and enhance its overall resilience to flooding in the future.

The findings of this study indicate that Adama City exhibits its varying levels of spatial connectivity. Two neighborhoods with high and low spatial connectivity were selected for further analysis. The high-connective neighborhoods were characterized by well-designed and interconnected street systems with manageable street spacing coverage. These features contributed to efficient traffic flow, smooth flow of stormwater, and effective management of flood inundation damage during rain events. The use of different street surface materials also played a role in facilitating traffic flow and reducing flood damage and erosion caused by heavy rainfall. Additionally, the presence of short block sizes with smaller dimensions and more frequent intersections helped promote better water drainage and reduce the risk of flooding. The grid pattern observed in these neighborhoods allowed for efficient water runoff by providing multiple drainage paths that aided in the mitigation of flooding risks during inundation.

On the other hand, neighborhoods with low spatial connectivity were found to exacerbate urban flooding. The lack of connectivity and abundance of dead-end streets posed challenges for flood evacuation and hindered the delivery of aid to affected communities during emergencies. Long block sizes impeded the natural flow of water, increasing the likelihood of water accumulation during heavy rainfall events. Irregular block arrangements disrupted the natural drainage system, impeding water flow and exacerbating the potential for urban flooding.

This study provides valuable insights into the spatial pattern and morphology of the study area, focusing on the factors that contribute to resilience against flooding events.



The research highlights the importance of well-connected street networks, careful selection of street surface materials, strategic building placement, shorter block sizes, and a grid pattern with frequent intersections in mitigating the impact of flooding. These findings can be applied to other flood-prone areas within the city and inform the enhancement of informal settlements in flood-prone areas across the city and similar urban areas in the global south on how human settlements are arranged spatially to mitigate flood vulnerabilities. In addition to analyzing the spatial pattern and morphology, the study also incorporates flood event observations, key informant interviews, and municipality information to provide a comprehensive understanding of the flood management challenges faced by Adama City. The research outcomes have significant implications for urban planning and design, not only in Adama City but also in other urban areas in the global south confronting similar flooding issues. Policymakers and urban practitioners can utilize these findings to develop effective flood management strategies that take into account the spatial morphology of the city. This can include incorporating space syntax analysis into existing urban planning and design processes to identify areas that are more vulnerable to floods and develop targeted interventions to mitigate their impact. Additionally, this study highlights the need to consider flood risk in building design and construction, settlement development, and neighborhood design. By incorporating space syntax analysis into these processes, cities can enhance their resilience to flooding and promote sustainable urban development.

### Limitation of the study

One of the limitations of this study is the lack of sufficient literature on the link between space syntax and spatial morphology to urban floods. Despite our best efforts, we were unable to find a significant amount of existing research on this topic. This implies that there is a gap in the literature and our study may be one of the first to explore this connection. As a result, the comparison of our findings to other studies may be limited due to the lack of related research in this context.

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**Data availability** No additional information is available for this paper.

### Declarations

**Conflict of interest** There are no conflicts of interest.

**Ethical approval** We did not conduct any animal studies for this manuscript; therefore, an ethical standards statement is not applicable.

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