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2 **Review article: Climate hazards ~~and risk~~ in African**
3 **cities – knowledge gaps and research needs**

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Abstract

This study conducts a semi-systematic assessment of the scientific literature published between 2015 and 2025 to examine the current state of knowledge on climate risk in African cities. An initial search using broad climate and urban-related keywords yielded 1,832 records, which were conservatively screened based on title and abstract, resulting in a sample of 272 articles. The corpus was analysed using a mixed-methods approach. Quantitative mapping assessed the geographic distribution of case studies across climate zones and city size categories, examined keyword co-occurrence networks, evaluated trends in methodological approaches, and classified articles according to dominant climate hazards and related methodological aspects. This analysis was complemented by expert review and supported by AI-assisted synthesis of research gaps to test the robustness of the interpretation. The analysis reveals a rapidly expanding but structurally uneven knowledge base. Research is geographically concentrated in a limited number of regions, with Central Africa and fast-growing secondary cities underrepresented. Authorship patterns show that less than half of the authors are affiliated with African institutions. Certain hazards dominate the literature, while multi-hazard or cascading risk frameworks remain uncommon. Earth Observation forms an important pillar of the field, yet its broader potential remains underutilised. High-resolution urban climate modelling with explicit representation of urban morphology remains limited, and many studies rely on coarse climate projections or sparse observations, constraining the assessment of intra-urban variability. Social vulnerability, informality, governance capacity and health impacts are frequently acknowledged but rarely integrated into risk frameworks. Most studies remain retrospective, and few couple future climate scenarios to projected urban growth. Overall, the literature is characterised by single-city case studies, limited cross-city comparability, and a persistent gap between scientific insights and urban planning practice. Addressing these limitations is essential to support robust, evidence-based adaptation and resilience planning in one of the world's most climate-vulnerable regions.

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39 2025 to examine the current state of knowledge on climate hazards in African cities. A broad
40 literature search yielded 1,832 records, which were conservatively screened to a final sample of 272
41 articles. The corpus was analysed using quantitative mapping and a qualitative hazard-based expert
42 review. The analysis reveals a rapidly expanding but structurally uneven knowledge base. Research is
43 geographically concentrated, with Central Africa and small and fast-growing secondary cities
44 underrepresented. Flooding and heat-related topics dominate the literature, whereas sea-level rise,
45 windstorms and urban water stress receive comparatively limited attention. Consideration of multiple
46 hazards remains limited and uneven, while explicit analysis of interactions between hazards is rare.
47 Earth Observation is widely used, but its broader potential remains underexploited, while high-
48 resolution urban climate modelling and observations remain limited. Most studies focus on historical
49 or present-day conditions, and few combine future climate scenarios with projected urban growth.
50 Overall, broader geographic and thematic coverage, improved high-resolution observations and
51 urban-scale modelling, and stronger integration of future climate and urban development are needed
52 to provide a more representative evidence base for adaptation and resilience planning in African
53 cities.

1 Introduction

Although the African continent has played only a modest role in driving global warming, it remains among the regions most exposed and vulnerable to climate change impacts (Ayompe et al., 2020). This imbalance raises fundamental issues of climate justice, as populations that have contributed least to the problem face some of its most severe consequences. Under continued global warming, climate-related hazards are projected to intensify markedly across the continent (IPCC, 2023). Cities are at the centre of this challenge. Urban areas concentrate people and assets, while local characteristics such as impervious surfaces and anthropogenic materials aggravate heat and flood risks. Rising temperatures also interact with health issues, for example by expanding the habitat of malaria-carrying mosquitoes (Sinka et al., 2020). At the same time, floods and storms continue to expose the fragility of urban infrastructure, particularly in informal settlements, where homes may easily overheat, collapse in storms, or be swept away in floods (UN-Habitat, 2022). More than half of Africa's urban residents, around 230 million people, live in such settlements, and their number is rising.

The speed of urbanisation adds another layer of urgency, as can be seen from Figure 1. Africa is projected to host some of the world's largest megacities by the end of this century (Hoorweg and Pope, 2017). Much of this growth is informal and unplanned, which increases exposure to hazards and limits adaptive capacity (Mukim and Roberts, 2023). This creates a triple risk: (1) the concentration of resources and people in cities, (2) structural vulnerability and limited adaptation options, and (3) urban features that amplify climate impacts. Despite these realities, fast-growing secondary cities in Africa remain substantially underrepresented in urban climate studies (Montfort et al., 2025).

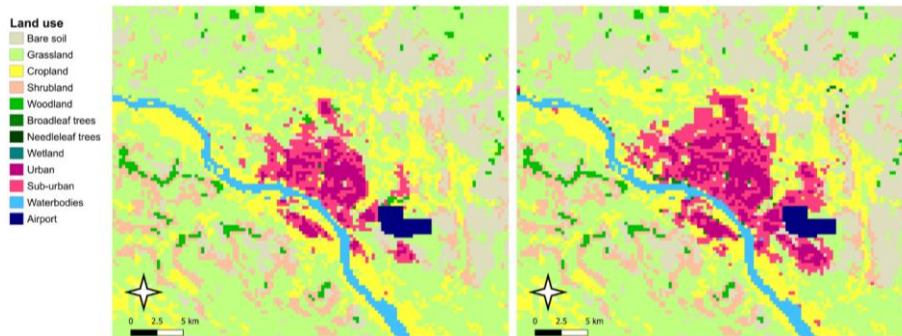


Figure 1. Land-use maps of Niamey, Niger, for 2005 (left) and 2020 (right) at 300 m resolution, generated by integrating ESA CCI Land Cover, Global Human Settlement Layer built-up fractions, ESA WorldCover, and OpenStreetMap data. The comparison illustrates the urban growth of Niamey over just 15 years, which is exemplary of the rapid expansion seen in many African cities.

Climate research in Africa has traditionally focused more on rural concerns, such as agriculture and water resources, than on urban challenges (Carr et al., 2020). Funding flows are also skewed, with most climate research funds directed to institutions outside Africa, leaving African researchers with limited resources to generate locally relevant knowledge (Overland et al., 2022). As a result, decision-relevant climate information at the city scale remains scarce, undermining efforts to support adaptation and limiting access to international climate finance.

Model-based climate information at the urban scale also remains limited. Global and regional climate models typically operate at spatial resolutions too coarse to capture city-level processes, creating a mismatch between research outputs and local adaptation needs (Graça et al., 2022; Hamdi et al., 2020).

Earth Observation (EO) provides an important complementary source of climate-relevant information, particularly in regions where ground-based monitoring networks are sparse, as in much of Africa. Satellite observations offer spatially consistent measurements of environmental conditions over large areas and multi-decadal time periods, enabling the analysis of land-cover change, urban

95 expansion and surface temperature patterns at spatial resolutions of tens of metres (Li et al., 2022a;
96 Wulder et al., 2019). Satellite-derived land surface temperature provides spatially distributed
97 information on urban thermal patterns, with observations at different spatial and temporal
98 resolutions offering complementary insights into urban thermal dynamics (Keramitsoglou et al.,
99 2012). In recent years, the European Space Agency (ESA) and the Copernicus programme have
100 substantially expanded the availability of such datasets through missions such as Sentinel and
101 initiatives including the Climate Change Initiative (CCI) and the Global Human Settlement Layer
102 (GHSL), which provide harmonised global information on land cover and urbanisation (Buchhorn et
103 al., 2020; Melchiorri, 2022).

104 While these advances have improved the availability of climate-relevant data, important knowledge
105 gaps remain regarding climate risks in African cities. African cities are growing rapidly while facing
106 intensifying climate risks, but the knowledge base needed to support adaptation planning and
107 financing remains underdeveloped.

108 Despite a growing body of literature on climate change in African cities, existing reviews have
109 generally addressed specific aspects, including adaptation (Hunter et al., 2020), research trends
110 (Mhedhbi et al., 2023), multi-risk perspectives (Fekete and Subramanian, 2024), or climate
111 vulnerability and adaptation (Ansah et al., 2024). To the best of our knowledge, a broad, quantitative,
112 hazard-centred synthesis across African cities remains lacking.

113 This study addresses this gap by synthesising ~~This study synthesises~~ what is currently known and
114 unknown about climate risks in African cities. This is addressed through both quantitative and
115 qualitative analyses of a sample of scientific publications on urban climate in Africa. The assessment
116 follows a semi-systematic approach, combining automated procedures with expert evaluation of the
117 literature. An overview of the data and methods is provided next, including the method used to
118 establish the sample of scientific articles. Subsequently, results are presented stemming from
119 quantitative and qualitative assessments, which are followed by the conclusions.

120 **2 Data and methods**

121 **2.1 Selection of articles**

122 Given the broad scope of the research question, the study was designed as a semi-systematic review
123 (Snyder, 2019), combining quantitative mapping of the literature with qualitative thematic synthesis.
124 The initial step consisted of a selection of scientific articles in the Web of Science (WoS) archive
125 records, using the set of keywords provided in Table 1~~Table 1~~. A final search update was conducted ~~in~~
126 ~~January~~ on 17 February 2026, focusing on the period 2015-2025, possibly entailing that some articles
127 with a publication date in late 2025 might not be included yet.
128 The aim was to choose keywords in such a way as to keep as many avenues open as possible, i.e.,
129 keeping the restrictions limited to not miss potentially relevant articles. Still, in order to keep a
130 sufficient and necessary focus, we demanded that variants of ‘urban’ appear as a part of the title. The
131 only topical keyword specified was ‘climat*’ (to cover ‘climate’, ‘climatic’, ‘climatological’, etc.), i.e., we
132 refrained from pre-defining topical terms referring explicitly to hazards such as heat, flooding,
133 drought – or to methods, such as modelling, remote sensing – in order to avoid creating a bias from
134 the start. Conversely, we specified the geographic context as completely as possible, both at the
135 continental level (“Africa*”) and at the national level by including all 54 African country names,
136 following the United Nations Department for General Assembly and Conference Management,
137 according to which 54 countries belong to the African Group and are Members of the United Nations.
138 *Table 1. Keywords used for the selection of articles in the Web of Science records. The asterisk (“*”) denotes a*
139 *wildcard. The ‘Topic’ category contains the Title, Abstract, and Keywords.*

Keyword		In
urban* OR city OR cities OR metropol*		Title
AND	climat*	Topic

AND	Africa* OR Algeria* OR Angola* OR Benin* OR Botswana* OR "Burkina Faso" OR Burkinabé OR Burundi* OR "Cabo Verde" OR "Cape Verdean" OR Cameroon* OR "Central Africa*" OR Chad* OR Comoros OR Comorian* OR Congo* OR DRC OR Djibouti* OR Egypt* OR "Equatorial Guinea" OR Eritrea* OR Eswatini OR Swazi* OR Ethiopia* OR Gabon* OR Gambia* OR Ghana* OR Guinea* OR "Guinea-Bissau" OR "Ivory Coast" OR Ivorian OR Kenya* OR Lesotho OR Basotho OR Liberia* OR Libya* OR Madagascar OR Malagasy OR Malawi* OR Mali* OR Mauritania* OR Mauritius OR Mauritian* OR Morocco* OR Mozambique* OR Namibia* OR Niger* OR Nigeria* OR Rwanda* OR "São Tomé and Príncipe" OR "São Toméan" OR Senegal* OR Seychell* OR "Sierra Leone*" OR Somalia* OR "South Africa*" OR Sudan* OR Tanzania* OR Togo* OR Tunisia* OR Uganda* OR Zambia* OR Zimbabwe*	Topic
AND	years 2015-2025	Date

No explicit hazard-related terms (e.g. heat, flooding or drought) or methodological terms (e.g. modelling or remote sensing) were prescribed in advance. This was deliberate, as the hazards and methodological approaches represented in the literature were intended to be outcomes of the analysis. Prescribing such terms at the search stage would have required defining these categories a priori and could have biased their observed representation in the resulting corpus. A consequence of requiring climat* as a search term is that studies addressing individual urban hazards without explicitly referring to climate may not be retrieved. The resulting corpus therefore represents literature that explicitly connects hazards affecting African cities to a climate context, rather than the complete literature on urban hazards.

~~The selection based on the above list of keywords initially led to a large number (N = 1832) of articles. The list of articles was exported as an MS Excel file, which was then used as a basis for further~~

screening. This screening for relevance was done in a subjective manner, considering all 1832 article titles, and referring to the abstract when required.

As before, we adopted a conservative approach, preferring to keep an article of uncertain relevance within the list rather than discard potentially useful articles. This exercise led to the selection of 272 articles, still in the same WoS Excel format, containing a fairly complete description of each article.

Apart from the authors, journal title, volume, page range, month and year of publication, it contained a full abstract, keywords (both author keywords and 'keywords plus'), DOI identifiers and links to the articles on the publishers' website.

The literature search was conducted using the Web of Science Core Collection (state of 17 February 2026) and was restricted to English-language records published between 2015 and 2025. No restrictions were applied by Web of Science Category, and all document types were considered except books, book chapters and book reviews. The search returned a list containing 1,832 records, which was subjected to manual relevance screening. Because the broad search deliberately omitted hazard-specific terms, a large proportion of the retrieved records were clearly outside the scope of the review, and the screening consisted primarily of removing these records (Figure 2).

All titles were screened first, and where relevance could not be established from the title alone, the abstract was consulted. Records were retained where a climate hazard affecting an African urban setting constituted a substantive focus of the study. Records were excluded where the African or urban context was incidental, or where climate change or climatic hazards primarily provided context for another research topic without substantive analysis of the underlying hazard. Examples include studies focusing on urban crime or conflict following climatic shocks, climate-induced migration, adaptation planning and governance, greenhouse-gas mitigation, urban agriculture, building energy performance, and environmental issues such as pollution or waste management.

Screening was conducted by a single author. We considered this appropriate for our semi-systematic review because the broad search retrieved a large proportion of clearly out-of-scope records, making

most exclusion decisions straightforward. Where relevance could not be established from the title alone, the abstract was consulted, and where uncertainty remained after consulting the abstract, the record was retained, this conservative approach being intended to minimize the risk of excluding potentially relevant studies. This screening procedure resulted in a final corpus of 272 articles. The bibliographic details of the articles constituting the final review corpus are provided as Supplementary Material S1. Full-text PDFs were obtained for all papers retained in the final corpus, including through institutional subscriptions where articles were not openly accessible.

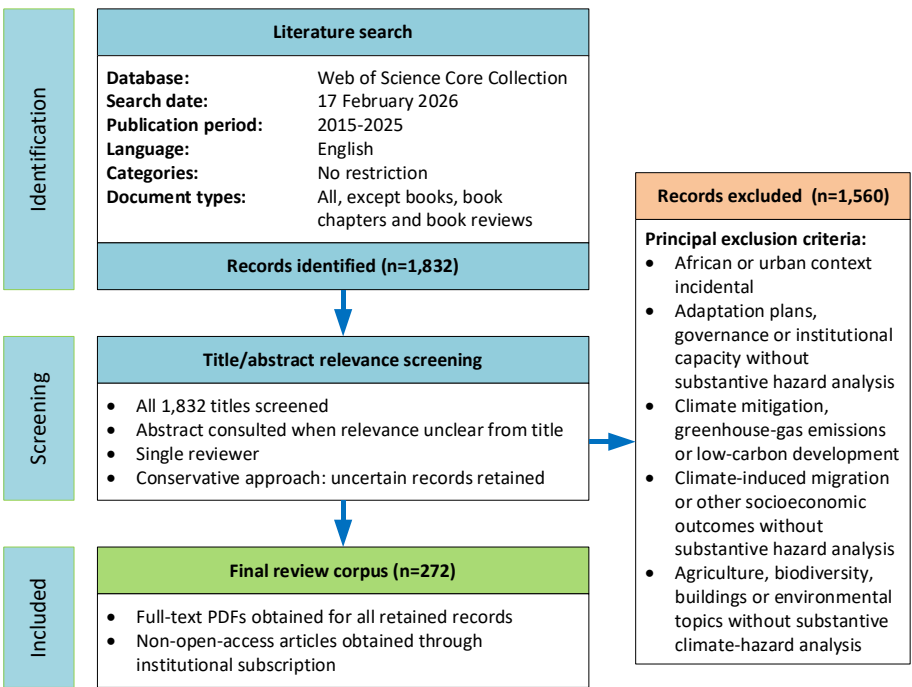


Figure 2. Literature search and screening process used to identify the final review corpus. Records were identified through the Web of Science Core Collection and screened for title and abstract relevance according to the predefined inclusion and exclusion criteria. Of the 1,832 records identified, 1,560 were excluded, resulting in a final review corpus of 272 publications.

Applying the WoS ‘Analyse’ function to the selected body of articles revealed that authors with an African affiliation account for 48.1% in the sample. The countries contributing most to the publication record were found to be non-African (UK and US). The highest-ranking African countries in the sample were, in order, South Africa, Nigeria, Ethiopia and Ghana.

2.2 Brief overview of analysis steps

The method to conduct the analysis of the 2723 selected articles is outlined in [Figure 3](#)[Figure-2](#). The upper row of the figure shows, from left to right, the progression from the WoS export list towards bibliographic (Zotero) and PDF files-archive for each of the article records.

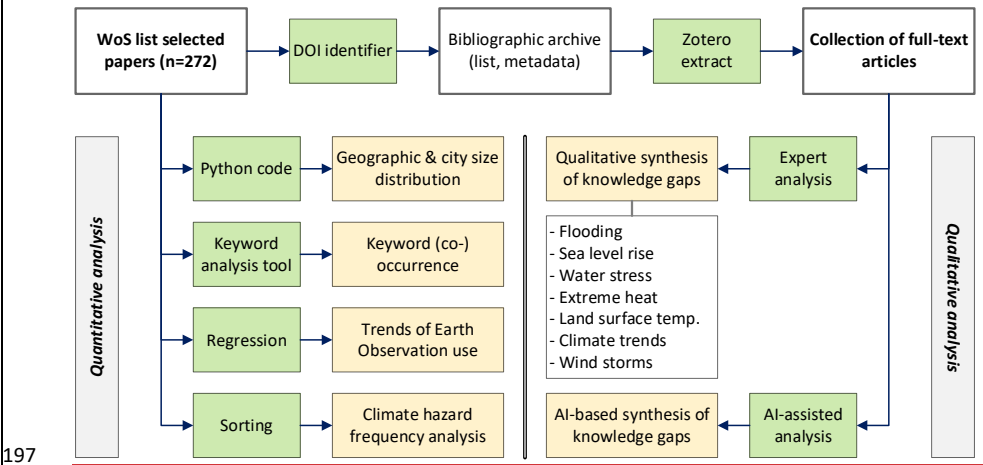


Figure 3. Schematic representation of the analysis steps used in this article. The left half covers the quantitative analysis, the right half covers the qualitative analysis.

The WoS article list was analysed quantitatively with respect to (left half of [Figure 3](#)[Figure-3](#))

- the representativeness of the sampled cities in terms of (1) Köppen-Geiger climate zone and (2) population size
- keyword (co-)occurrence in the selected articles;
- trends of Earth Observation (EO) use;

- climate hazard frequency analysis.

The PDF archive containing all 2723 articles was analysed qualitatively (right half of [Figure 3](#)~~Figure 2~~) by conducting an expert-based thematic analysis organised by climatic hazard.

~~• running an AI-assisted assessment of knowledge gaps occurring in the scientific articles.~~

3 Quantitative mapping of the literature

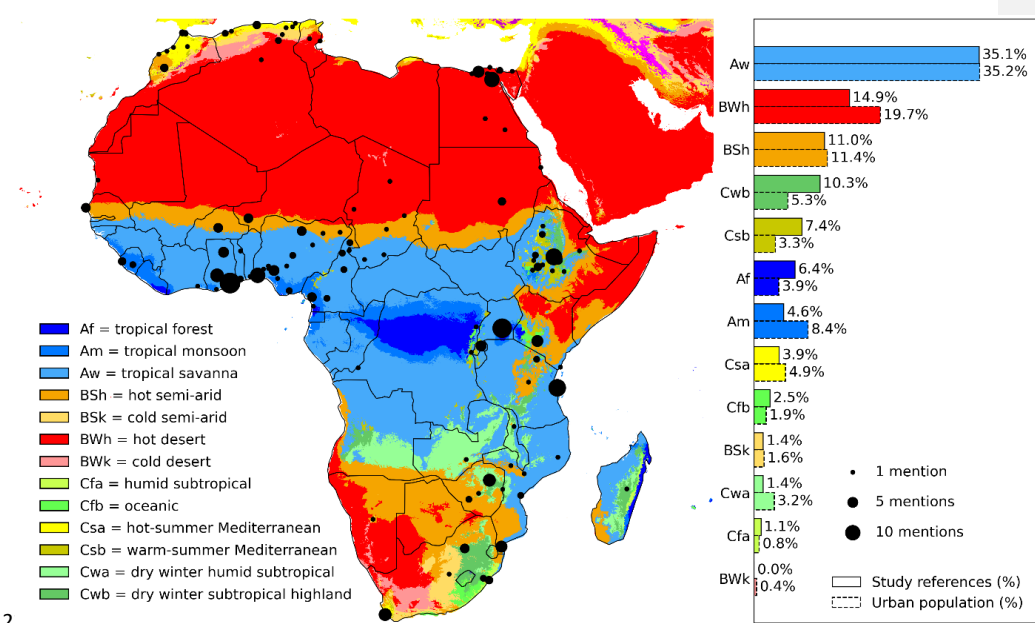
3.1 Climate zone representation

The WoS list of 272 selected articles was examined for city names in the Title and Abstract fields by extracting all capitalised words from these texts, enabling rapid identification of potential city names. This was implemented in MS Excel using a Visual Basic for Applications (VBA) function that identifies and extracts words starting with a capital letter and stores them in a separate column.

This column was then reviewed to identify city names, by comparing city names occurring in the GHS Urban Centre Database (GHS-UCDB) R2024A from the Copernicus Global Human Settlement Layer (GHSL), which includes population estimates for each city (Melchiorri, 2022). If an extracted name from a selected article matched a city in the list, it was retained. If the same city had already been identified earlier, its occurrence count was increased by one. Nouns that resembled city names but were not present in the GHS-UCDB list were further checked using Wikipedia and Google Maps to determine whether they referred to neighbourhoods or sub-units of larger cities. In such cases, the names were assigned to the corresponding host urban agglomeration.

The analysis focused on urban agglomerations as defined in the GHS-UCDB list rather than on smaller units such as sub-cities or neighbourhoods. This choice was made for reasons of cross-country consistency, as the administrative subdivision of cities differs between countries. For example, a large city in one country may be recorded as a single entity, while in another it may be subdivided into multiple smaller administrative units.

228 The cities thus identified are shown in [Figure 4](#) as solid dots, scaled to the number of
 229 mentions (references) in the literature sample. For each of the cities, the Köppen-Geiger climate zone
 230 (Beck et al., 2023) was determined. This enabled a comparison of the frequency of climate zones
 231 represented in the literature sample with the baseline distribution of African urban populations
 232 across climate zones.



234 *Figure 4. Distribution of the reviewed literature across Köppen–Geiger climate zones compared with the*
 235 *baseline distribution of African urban populations. The bars representing the literature correspond to the*
 236 *number of reviewed articles referring to cities located within each climate zone. Cities may appear in multiple*
 237 *articles, so counts represent occurrences in the literature rather than unique cities. The baseline population*
 238 *distribution was derived from the GHSL Urban Centre Database (GHS-UCDB R2024A), aggregated by Köppen–*
 239 *Geiger climate (Beck et al., 2023). The comparison illustrates the extent to which research attention across*
 240 *climate zones reflects (or diverges from) the distribution of urban populations across Africa.*

The comparison (Figure 4) shows that the climate zones represented in the sample of urban climate studies reflect the actual distribution of African agglomerations fairly well. The tropical savanna (Aw) zone, for instance, dominates both the literature sample and the population baseline. Some imbalances are nevertheless apparent. Cities in highland (Cwb) and Mediterranean (Csa, Csb) climates receive disproportionately high attention relative to their urban population share, likely reflecting the visibility of climate impacts (e.g., flooding, landslides) and/or the presence of strong local research infrastructures. Conversely, urban populations in monsoon (Am), tropical forest (Af), and hot desert (BWh) climates are somewhat underrepresented, despite their demographic significance. These patterns highlight that while the overall distribution across climate zones is well captured, there remains a tendency for research to concentrate in hazard-prone or research-intensive regions, leaving important populations in other climate zones relatively less studied.

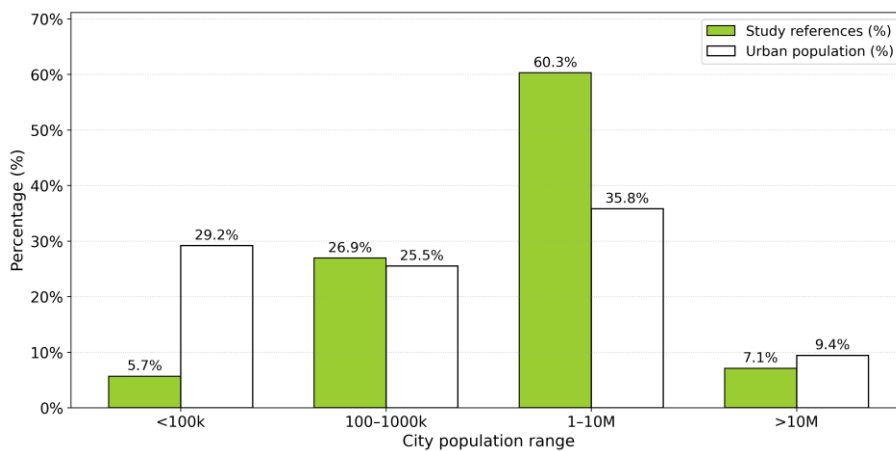
From a geographical point of view, Figure 4 shows a relatively higher coverage of referenced cities (1) near the Gulf of Guinea (West Africa), (2) along an axis extending from East to Southern Africa, and (3) in North Africa along the Mediterranean. Such a pattern is consistent with findings by other researchers (Leal Filho et al., 2023; Montfort et al., 2025). From Figure 4 it also emerges that a considerable number of the frequently studied cities are located along the coast.

3.2 City size representation

We compared the city size distribution (measured by number of inhabitants) of the city sample with the actual population distribution across different size categories:

- small cities (< 100,000 inhabitants)
- medium-sized cities (100,000 – 1,000,000)
- large cities (1,000,000 – 10,000,000), and
- megacities (> 10,000,000).

264 [Figure 5](#) shows the distribution of the sampled cities (green bars) compared with the actual
265 city size distribution (white bars). A most striking feature resides in the strong underrepresentation of
266 small cities in the sample, whereas large cities are overrepresented. This lesser inclusion of smaller
267 cities was also noticed by other researchers (e.g., (Montfort et al., 2025)). In contrast, medium-size
268 and megacities are represented at proportions that closely match the actual distribution.



269
270 *Figure 5. Comparison of the proportion of study references (green bars) with the distribution of the urban*
271 *population (outlined bars) across city population ranges in Africa.*

272 We also examined the distinction between capital and non-capital cities in the sample. Out of 112
273 cities, 28 (25%) are capitals. However, when weighting by the number of times each city is referenced
274 in the selected articles (as represented by dot size in [Figure 4](#)[Figure 3](#)), the share of capital cities rises
275 to nearly 45%. This reflects the tendency for capital cities to appear in multiple studies, while smaller
276 cities are typically mentioned only once.

277 3.3 Keyword (co-)occurrence analysis

278 A keyword analysis was conducted using VOSviewer, a software tool for constructing and visualizing
279 bibliometric networks (www.vosviewer.com) (Van Eck and Waltman, 2017). Using VOSviewer, a

280 network map (Figure 6Figure-6) was created from the bibliographic data contained in the WoS output
281 file, based on a co-occurrence analysis of both author keywords and Keywords Plus.

282 The terms 'climate (change)' and 'urban/city' were excluded from the keywords, given they were the
283 primary search keywords (hence should not re-appear on the network map). Our focus was on
284 identifying *additional* keywords that emerged from the search. To reduce clutter and avoid less
285 relevant terms, only keywords appearing at least nine times were retained, resulting in a final list of

286 47 keywords. This threshold of 47 was determined through trial and error, aiming for a balance

287 between including as many relevant terms as possible while maintaining a clear visualization. A

288 VOSviewer 'thesaurus' file (see (Van Eck and Waltman, 2017)) was developed and applied to (1) filter
289 out non-relevant keywords (e.g., city names); (2) merge spelling variants (e.g., 'heat island' vs. 'heat-
290 island'); (3) unify conceptually similar terms (e.g., 'earth observation' and 'remote sensing').

291 For visualization, the VOSviewer *Scale* parameter was set to 100%, fully allowing circle sizes to reflect
292 keyword frequency (larger circles representing more frequent keywords); the *Size Variation*
293 parameter was set to 50%, in order to avoid excessively small labels for less frequent keywords.

294 Figure 6Figure-6 shows the keyword co-occurrence network generated by VOSviewer. Node size
295 reflects the frequency of keyword occurrence, while the thickness of the connecting lines indicates
296 the strength of co-occurrence. Colours represent clusters, the algorithm positioning related terms

297 closer together to reveal strong internal relationships. The occurrence and connectivity of keywords is
298 also provided as a ranked table in Supplementary Material S2, including keyword occurrence
299 frequencies and Total Link Strength (TLS) values.

300 In Figure 6Figure-6, four clusters emerge. The red cluster is dense and cohesive around heat-related
301 terms: UHI (urban heat island), LST (land surface temperature), and ~~(UHI, LST,~~ thermal comfort). Note
302 that LST refers to the radiative temperature of the Earth's surface, as inferred from emitted thermal
303 radiation, and is distinct from near-surface air temperature. The green cluster centres on flooding and
304 social aspects (risk, vulnerability, poverty). Smaller clusters focus on hydrological extremes (blue) and

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also links to flooding and land-use studies. *Modelling* serves as another methodological bridge, connecting the flooding and vulnerability literature with research on precipitation and variability. Peripheral nodes represent less frequent or more isolated keywords. Strikingly, many of these are impact-related, such as *mortality*, *vector-borne disease*, *malaria*, or the aggregated term *soil impacts* (covering landslides, soil erosion, and subsidence). Broader socio-economic dimensions like *poverty*, *informality*, and *hazard* also appear in the periphery. Their position suggests that explicit links to concrete societal impacts remain less developed and relatively fragmented. Emerging methodological terms, such as *machine learning*, are also visible at the margins, indicating directions that are beginning to enter the field but have not yet reached central importance.

Taken together, [Figure 6](#) demonstrates that hazard-specific research (e.g., heat, flooding) forms the structural backbone of the network, while methodological concepts such as remote sensing and modelling provide essential connections across themes. At the same time, the peripheral position of impact-related keywords highlights a gap in the literature: despite frequent references to hazards and methods, systematic integration of health, poverty, and other vulnerability dimensions into the research is still relatively limited. This suggests an important direction for future work, namely the stronger linkage of urban climate hazard research to the societal impacts most directly affecting populations.

3.4 Trends of EO data use

Considering that Earth Observation (EO) constitutes a rapidly evolving field, the selected articles were analysed with respect to the trend of the use of EO data. The regression was done over the time span 2015-2024, i.e., excluding articles published in 2025 as that might not be complete (the sampling of

the 2015-2025 articles having been finalised in February 2026), which could introduce a bias.

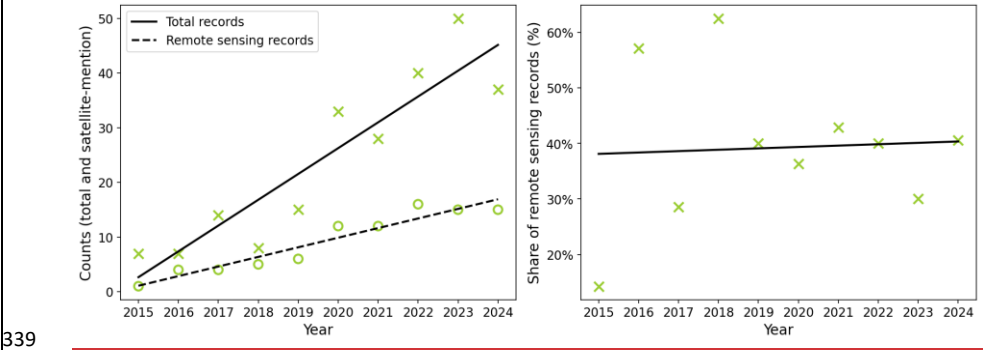


Figure 7. Left: total number of articles (crosses and solid regression line) and EO-using articles (circles and dashed regression line) published per year throughout the period 2015-2024. Right: share of the number of EO using articles (crosses and solid regression line).

The total annual output of articles shows a strong and statistically significant upward trend (Figure 6, left), with publications increasing from only a few articles in 2015 to more than 40 in 2024. Both the overall corpus ($R^2 = 0.83$, $p < 0.001$) and the subset of studies using satellite remote sensing ($R^2 = 0.92$, $p < 0.001$) exhibit robust growth. However, the relative share of remote sensing studies has remained statistically stable over the decade (Figure 6, right), fluctuating around 40%, without a significant trend ($R^2 = 0.003$, $p = 0.88$). This indicates that while EO is increasingly used in the studied articles, its proportional contribution to the field has not expanded in recent years.

The total annual output of articles shows a clear upward trend over the period 2015–2024 (Figure 7, left), increasing from only a few articles in 2015 to more than 40 in 2024. The number of studies using satellite remote sensing similarly increases over this period. In contrast, the relative share of remote-sensing studies varies substantially during the first years of the period but remains relatively stable at around 40% in the later years (Figure 7, right). This indicates that, while the absolute number of studies using remote sensing has increased alongside the overall growth of the literature, its proportional contribution to the field has not markedly increased in recent years.

3.5 Climate hazard frequency

The list of 272 articles was further analysed in terms of the climate hazards covered. This was done by experts in the respective hazard domains, screening the title and abstracts of each article, labelling them with a hazard indication, including wind-storms, sea level rise, water stress, extreme heat, ~~climate-trends~~slow-onset events, land surface temperature (LST), and flooding. Here, slow-onset events refer to gradual changes in climatic conditions, such as increasing mean temperatures or changing precipitation patterns, consistent with the IPCC framing of slow-onset events (Calvin et al., 2023).

In cases where an article covered multiple hazards, the dominant hazard was identified, obviously inducing a certain level of subjectivity. In addition, each article was labelled for the occurrence of (or reference to) one or more conceptual or methodological aspects, including urbanisation (including such terms as urban growth, or urban dynamics), modelling, informality, data science, future climate, remote sensing.

The outcome of this exercise is shown in ~~Figure 8~~Figure 8. A close look at the distribution of hazards reveals clear thematic imbalances. Research on flooding and LST dominate the field, together accounting for nearly half of all publications. Studies on slow-onset ~~climate-trends~~events and extreme heat are also well represented, underlining the importance of both gradual climate variability and acute heat extremes in African cities. It is worth noting that the two heat-related categories (extreme heat and LST) were separated in our classification. While this provides analytical clarity, it may also dilute the apparent weight of heat-related hazards in the dataset: taken together, these account for well over a hundred articles, confirming heat as one of the most prominently studied urban climate risks in Africa. The prominence of land surface temperature in particular reflects the reliance on remote sensing, which offers a consistent and widely accessible data source in data-sparse regions such as Africa. By contrast, water stress, sea level rise, and wind-storms are covered only sparsely,

despite their known relevance for urban vulnerability. This thematic skew suggests a concentration of research attention on hazards that are both visible in cities and relatively straightforward to monitor, while other critical but less studied risks remain underexplored.

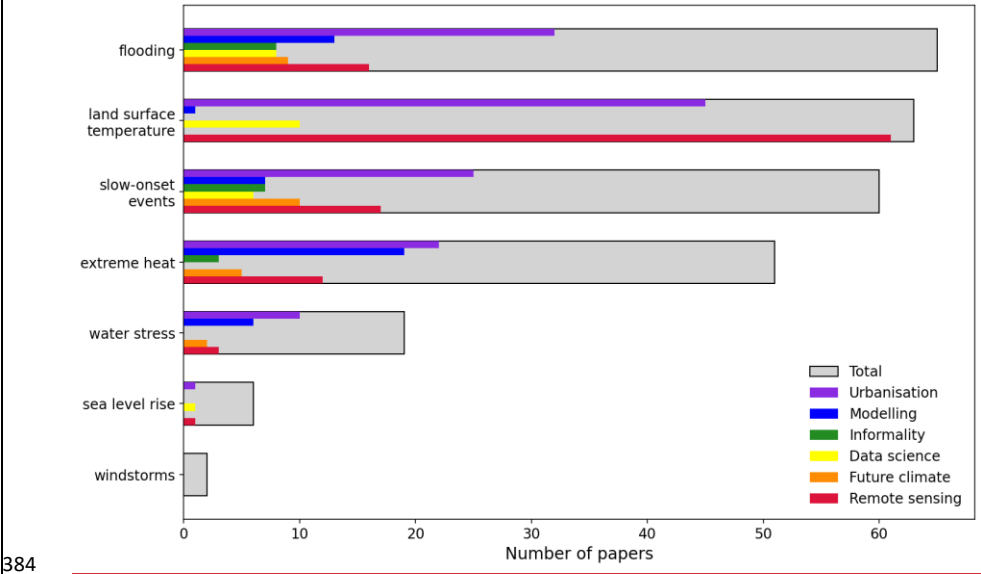


Figure 8. Distribution of reviewed articles across different hazard types. Grey bars show the number of articles for each hazard, while coloured bars indicate the occurrence of methodological/contextual themes (urbanisation, modelling, informality, data science, future climate, and remote sensing). In this figure, ‘LST’ refers to land surface temperature. ‘Modelling’ refers to deterministic climate or hydrological modelling, and ‘Data Science’ refers to artificial intelligence, machine learning, deep learning, etc.

In addition to classifying articles by their dominant climate hazard, we also identified several recurring methodological and contextual themes that characterise how climate risks in African cities are studied. These include urbanisation processes (urban growth and land-use change), deterministic modelling approaches (e.g., urban climate or hydrological models), Earth Observation, and data science techniques such as artificial intelligence and machine learning. We further assessed whether

395 studies explicitly consider future climate projections and whether they address urban informality, a
396 key structural feature influencing exposure and vulnerability in many African cities.

397 Analysing [Figure 8](#) in terms of these conceptual and methodological aspects reveals a host of
398 information:

- 399 • Remote sensing data is used in a minority (10-20%) of studies, except within the land surface
400 temperature (LST) topic, for obvious reasons. A deeper analysis showed that most literature
401 cases made use of Landsat imagery, either to observe patterns of land surface temperature,
402 or to assess historical urban growth.
- 403 • Urbanisation, urban growth or urban dynamics is mentioned in nearly half of the articles, yet
404 nearly all of these have a historical focus, i.e., they consider past urban growth; only 10 (out
405 of 272) articles concern forward-looking urban growth studies.
- 406 • The use of artificial intelligence (AI), machine learning (ML) and similar techniques is limited,
407 while these could offer a way to overcome scaling challenges as well as challenges of access
408 to computational infrastructure for African researchers.
- 409 • Most studies focus on historical or present-day climate periods; relatively few (order 10%)
410 consider future climate projections.
- 411 • Deterministic modelling (urban climate and hydrology) is used to a limited extent only;
412 studies often interpolate climate data from coarse model output fields, thus ignoring the local
413 impact of the urban fabric on its own microclimate (e.g., urban heat island).
- 414 • Considerations of informality remain limited, being mentioned in less than 10% of the
415 selected articles.

3.6 Cross-hazard representation

To complement the dominant-hazard classification, papers were additionally screened for substantive consideration of other hazard categories. Titles and abstracts were examined, with the full text consulted when necessary. Merely incidental references to other hazards were not counted. The recorded dominant and additional labels indicated consideration of more than one thematic category in 30 papers (11%).

A more detailed analysis shows that the cross-hazard nature differs between the themes:

- Slow-onset studies can encompass several distinct hazards within a broader assessment of climatic change and its impacts. For example, research in Pietermaritzburg examines how drought, heatwaves, floods and other climate stressors affect urban livelihoods and coping capacities (Hlahla and Hill, 2018).
- Extreme heat and LST overlap within assessments of urban thermal conditions and vulnerability. In Johannesburg, for example, LST and other environmental indicators are combined with socioeconomic and health variables to assess heat vulnerability (Parker et al., 2025). However, this represents complementary information rather than distinct hazards.
- Flooding and sea-level rise are connected through coastal water levels and drainage conditions. Research in Maputo explicitly examines rainfall–tidal compound flooding and its implications for storm drainage performance (Matos et al., 2023).
- Water stress and flooding can be considered together through both hazard assessment and adaptation measures. Research in Ethiopia assesses urban water availability alongside drought and flood exposure (Abraha et al., 2022). In Beira, rainwater harvesting is examined as a means of reducing demand on municipal water supplies while potentially reducing stormwater flows and urban flooding (Santos et al., 2023).
- Windstorm research can address flooding and storm surge (Williamson et al., 2023).

Some papers explicitly examine distinct hazards within a shared urban context. For example, two studies in Accra and Tamale address flooding and extreme heat and their impacts on healthcare provision and on water and electricity services(Codjoe et al., 2020; Kayaga et al., 2021). Consideration of multiple hazards should be distinguished from analysis of compound or cascading processes. A clear example of compound-hazard analysis is provided by the Maputo study, which examines the combined influence of rainfall and tidal conditions on urban flooding (Matos et al., 2023).

4 Qualitative assessment of the state-of-the-art

The bibliometric analysis presented in Section 3 reveals clear patterns in the thematic focus of the literature on climate risks in African cities. In the following section, we complement this quantitative overview with a qualitative synthesis, with the aim of describing the current state of the art and identifying scientific knowledge gaps. The qualitative analysis consists of (1) a meta-review based on a small number of recent review articles and (2) expert-based thematic reviews organised by hazard type as identified in Figure 8. An exploratory AI-assisted comparison was additionally conducted and is described in Supplementary Material S3; its results were not used as an independent basis for the conclusions of this review.

4.1 Meta-review

A few recent review studies provide important context for understanding recent urban climate research in Africa. These include systematic mapping of adaptation responses (Hunter et al., 2020), bibliometric analyses of research trends (Mhedhbi et al., 2023), thematic assessments of urban thermal change (Li et al., 2022b), emerging multi-risk perspectives (Fekete and Subramanian, 2024), and broader scoping reviews of urban climate risk and governance (Ansah et al., 2024). Together, these review articles describe a rapidly expanding but unevenly developed knowledge base.

462 A consistent finding is the strong growth in publications since the mid-2010s (Mhedhbi et al., 2023).
463 However, research remains geographically concentrated. A limited number of countries – particularly
464 South Africa, Nigeria, Kenya, Egypt and Ghana (also see the findings of Section 2.1) – account for a
465 disproportionate share of studies, while large parts of Central Africa and many secondary cities
466 remain sparsely represented (Hunter et al., 2020; Mhedhbi et al., 2023). Capital cities and
467 economically prominent agglomerations dominate the record.

468 Thematically, heat and flooding receive substantial attention within the urban climate literature,
469 reflecting their relevance for African cities. Flooding is frequently examined through hydrological
470 modelling, exposure assessments and spatial analyses (Hunter et al., 2020). Heat-related research
471 often focuses on land surface temperature and urban heat island characteristics derived from satellite
472 data (Li et al., 2022b). Other hazards, such as wind-storms, coastal flooding and water stress, appear
473 less consistently across the literature. Also, even though calls for integrated multi-hazard perspectives
474 are increasing (Fekete and Subramanian, 2024), most studies still address hazards in isolation.

475 Methodologically, the literature combines Earth Observation, spatial analysis and a range of
476 modelling approaches. While these methods present substantially improved spatial diagnostics in
477 data-scarce environments, high-resolution urban climate modelling and physically detailed
478 representations of urban processes remain limited (Fekete and Subramanian, 2024; Li et al., 2022b).
479 Explicit coupling of hazard, exposure, vulnerability and adaptive capacity is comparatively uncommon
480 (Ansah et al., 2024; Hunter et al., 2020). Although social dimensions (poverty, informality, governance
481 capacity and inequality) are frequently acknowledged, they are less often incorporated into
482 quantitative risk assessments.

483 Forward-looking assessments also remain limited. While some studies employ downscaled climate
484 model outputs, very few integrate future climate scenarios with projected urban growth,
485 demographic change or adaptation pathways (Fekete and Subramanian, 2024; Li et al., 2022b). As a

486 result, the literature provides important diagnostics of present-day patterns but offers fewer insights
487 into long-term urban transformation under climate change.

488 In contrast to the reviews discussed above, the present study takes a hazard-centred perspective and
489 explicitly quantifies the representativeness of the literature. In particular, research coverage is
490 compared with the distribution of African urban populations across climate zones and city-size
491 classes, alongside an assessment of methodological characteristics, including the use of Earth
492 Observation and modelling.

493 4.2 Expert-based thematic reviews

494 In the following subsections, the selected articles – organised by hazard type as occurring in Section
495 3.5.3-5 – were assessed by thematic experts. The length and level of detail of the subsections vary
496 according to the scope and characteristics of the literature identified for each hazard. Rather than
497 providing an exhaustive study-by-study account, the discussion focuses on synthesising the main
498 insights emerging from the reviewed literature for each hazard. Section 4.3 brings these findings
499 together in a synoptic table, providing a concise synthesis across the different hazard themes.

500 4.2.1 Flooding

501 Flooding has always been a critical urban hazard across Africa, but its frequency and severity are
502 rising as climate change reshapes some of its drivers, such as intense rain and high water levels
503 (Abiodun et al., 2017; Douglas, 2017; Muller, 2016; Seidou et al., 2025). A warmer atmosphere
504 potentially carries more moisture (Engel et al., 2017). In many African records, the signal appears not
505 as higher annual totals but as sharper sub-daily bursts and shifts in seasonality (Bulti et al., 2020,
506 2021; Garba and Abdourahmane, 2023; Singirankabo and Iyamuremye, 2022). Several cities in the
507 continent (e.g., Kigali, Rwanda) report steeper intensity-duration-frequency (IDF) relationships and
508 heavier tails (Padji et al., 2024; Tazen et al., 2018). These shifts imply a higher likelihood of short,
509 intense storms (Bibi and Tekesa, 2024). Along the coast, the East African margin shows the fastest

mean-sea-level rise (up to more than 5 mm/year), and its bimodal rainy seasons often coincide with high tides or cyclone driven surges, amplifying backwater effects at outfalls. West Africa faces similar overlaps during monsoons, though with smaller tidal ranges (Brown et al., 2012; Muis et al., 2016; Pajak et al., 2024; Woodworth et al., 2019). As a result, the same storm total can now breach street flooding thresholds that once held (Matos et al., 2023b; Mugume et al., 2023). These climate pressures meet brittle infrastructure (Andreasen et al., 2022; Arinabo, 2022), scarce storage is scarce, and undersized or poorly maintained drains (Lameche et al., 2023). Event analyses show that even small increases in short duration rainfall can flip nuisance ponding into disruptive floods (Bouamrane et al., 2024; Mzava et al., 2020; Nkeki et al., 2022). Community surveys from West, Central, and North Africa's coastal cities confirm the trend with reports of longer rainy seasons, more flash flooding, and widening neighbourhood hotspots (Antwi-Agyei et al., 2023; Attipo et al., 2023; Bouramtane et al., 2021; Shiwomeh et al., 2024).

While these dynamics are universally applicable, they exert a more pronounced effect on numerous African cities, where rapid, often unplanned growth and persistent infrastructure and maintenance gaps amplify storm impacts (Beshir and Song, 2021; Loots et al., 2022). As urban growth expands into floodplains and wetlands, impervious cover spreads and exposure increases. Depression storage in wetlands and natural surfaces that once slowed runoff disappears (Abass, 2020; Dumedah et al., 2021; Ramiaramanana and Teller, 2021). Encroachment into drainage rights-of-way concentrates overland flow at hydraulic constrictions (Neves et al., 2022). Undersized or poorly maintained drainage infrastructure reduces conveyance, so small increases in short duration rainfall add centimetres to water depth and can exceed road closure thresholds (Lameche et al., 2023). In Alexandra, South Africa, along the Jukskei River, increased paving and infill produce sharper, earlier downstream peaks. Events that once ponded now cause street scale inundation (Mawasha and Britz, 2022). Guiding expansion by mapped flow paths and documented bottlenecks helps. With prioritized

534 maintenance and selective upsizing, small targeted upgrades reduce inundation more than uniform
535 area-wide retrofits (Carr et al., 2024; Gumindoga et al., 2024; Nkonu and Antwi, 2024).

536 Across many African cities, urban floods damage homes and disrupt core systems such as road and
537 transit services, water and electricity, and trigger adverse socio-economic impacts on households and
538 businesses (Kayaga et al., 2020; Koroma et al., 2024; Perera et al., 2020). Impacts are most severe
539 where low-lying exposure overlaps with social vulnerability and weak infrastructure (Herslund et al.,
540 2015; Kita, 2017). For instance, In Accra's Odaw basin, brief cloudbursts routinely strand commuters
541 and disrupt local commerce, and the resulting cleanup and lost business hours cascade through
542 household incomes (Abeka et al., 2019; Atakorah et al., 2023). Because a large share of losses stems
543 from functional disruption rather than structural failure, the literature emphasizes multiple
544 operational levers such as pre-storm inlet clearing, fixing bottleneck culverts, and protecting informal
545 right-of-way drains. Timely local warnings also enable asset relocation before peak water. Across
546 cases, such targeted measures shorten flood duration, reduce service interruptions, and curb
547 downstream social and economic losses (Miller et al., 2022; Santos et al., 2023; Tedla et al., 2022;
548 Zehra et al., 2019).

549 Despite how urgent the problem is, Africa's capacity to track and plan for changing flood patterns still
550 lags. Sub-hourly rain gauges, river and tide level loggers, and reliable drainage inventories are sparse
551 or outdated. This scarcity hampers detection of shifts in short-duration extremes and hinders routine
552 non-stationary IDF updates (Boko et al., 2020; Mohamed and El-Raey, 2019; Shikangalah and Mapani,
553 2019). Event-based datasets that link rainfall, inundation extent, and losses in a consistent format are
554 rare (Dufitimana et al., 2025a; Weday et al., 2023). Earth observation (EO) and machine learning tools
555 help overcome challenges accompanied with data scarcity, but their transferability across cities is
556 limited without ground truth and open, maintained asset maps (Ekwueme, 2022; Umer et al., 2022).

557 There is a clear need in Africa for more sustained and comparative studies to trace how a warming
558 climate is reshaping urban floods. These studies should also examine how those shifts interact with

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rapid urban growth and infrastructure constraints (Dos Santos et al., 2017; Schütte and Schulze, 2017). The goal is not just to detect change. It is to turn evidence into practice by supporting adaptive design standards, more reliable warnings, and maintenance and upgrade programs that keep pace with a moving hazard (Abass, 2020; Hassan et al., 2022).

Flooding is a major urban hazard across Africa (Douglas, 2017), with climate change reshaping important hydroclimatic drivers, particularly intense rainfall. Rather than being expressed only through higher annual totals, these changes can involve sharper sub-daily rainfall bursts and shifts in seasonality (Bulti et al., 2021), increasing the likelihood of short, intense storms and making historical intensity–duration–frequency relationships less reliable for design in affected regions (Padji et al., 2024). In coastal settings, heavy rainfall can also coincide with high tides or cyclone-driven surges, amplifying backwater effects at drainage outfalls (Matos et al., 2023). Taken together, these studies indicate that changing rainfall characteristics and, in coastal cities, interactions with marine conditions can alter the magnitude and timing of urban flood hazard.

However, the literature also shows that worsening urban flooding cannot be attributed to changing climate conditions alone. New climate stresses interact with scarce natural storage and undersized or poorly maintained drainage systems (Lameche et al., 2023), while rapid and often unplanned urban growth compounds persistent infrastructure and maintenance gaps (Beshir and Song, 2021). Expansion into floodplains and wetlands simultaneously increases exposure and impervious cover while removing natural surfaces that previously slowed runoff (Andreasen et al., 2023), and encroachment into drainage rights-of-way can further concentrate overland flow at hydraulic constrictions. Urban flood impacts therefore emerge from the interaction between changing rainfall, land-use change and drainage performance, rather than climate exposure alone (Neves et al., 2023).

This interaction between hazard, exposure and vulnerability is also evident in the socioeconomic consequences of flooding. Impacts on households and businesses are most severe where low-lying exposure overlaps with social vulnerability and weak infrastructure (Kita, 2017; Zehra et al., 2019).

Accordingly, the literature considers operational measures alongside physical infrastructure upgrades, including pre-storm inlet clearing, removal of bottlenecks, protection of drainage rights-of-way and timely local warnings (Dumedah et al., 2021). Where mapped flow paths and documented constraints are available, prioritised maintenance and selective upsizing can reduce inundation and service interruptions more effectively than uniform area-wide retrofits (Miller et al., 2022; Tedla et al., 2022). The literature thus links the effectiveness of flood-risk reduction not only to additional infrastructure, but also to how existing drainage systems are maintained, targeted and operated in relation to local exposure and vulnerability. Despite the urgency of these challenges, capacity to track and plan for changing flood patterns still lags in many regions (Boko et al., 2020). Sparse or outdated sub-hourly rain gauges, river and tide-level loggers and drainage inventories hamper both detection of changes in short-duration extremes and routine updating of design assumptions, while consistent event-based datasets linking rainfall, inundation, losses, affected services and intervention performance remain rare. Spaceborne Earth observation and artificial intelligence offer ways to address data scarcity and model-flexibility challenges (Ekwueme, 2022; Weday et al., 2023), but ground validation and open, maintained asset maps remain necessary at city level. Consequently, data limitations affect not only flood characterisation but also the transferability of approaches between cities, reinforcing the need for sustained comparative research to translate changing hazard evidence into adaptive design standards and maintenance and upgrade programmes (Hassan et al., 2022).

4.2.2 Sea level rise

Another consequence of climate change is sea level rise. African coasts are already seeing a higher baseline and more frequent coastal extremes that reshape urban flood risk (Halecki and Bedla, 2025). Notably, compound flooding occurs when intense rainfall coincides with high tide or surge. Less freeboard and higher tailwater at outfalls mean storms that once stayed below street flood thresholds now inundate roads (Mugume et al., 2023). Because these thresholds are highly local,

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decision-relevant mapping must be coupled with fine topography, drainage inventories, and tide stages. This combination identifies first disruption corridors and critical facilities. Risk is highest in embankments, back-beach lagoons and river deltas, where shallow slopes and constricted outlets amplify backwater (Abdrabo et al., 2022). An important example is the Nile Delta, where limited gradients and constrained outfalls mean that even modest sea level rise can flood low-lying corridors and leave the most exposed tracts adjacent to critical urban functions (Kamal et al., 2025).

There are several structural factors that make Africa especially vulnerable. Rapid coastal cities' growth outpaces natural and constructed defences. Risks are compounded by low-lying topography with constricted outlets, maintenance backlogs in drainage systems, concentration of critical services along the shoreline, high social vulnerability and sparse monitoring (Abdrabo et al., 2022; Yankson et al., 2017). Urban expansion also increases the population and assets along the coastal edge. Relative sea level rise is accelerated by land subsidence, which also worsens chronic flooding. Increased exposure and the loss of natural buffers can result from expansion into wetlands, beach areas, and drainage corridors (Noby et al., 2024). Studies propose some management measures including updating zoning and setbacks to new water levels and restoring natural buffers. Drainage upgrades, such as clearing or upsizing outfalls and adding tide or flap gates and pumps, plus compound flood allowances, are also recommended (Halecki and Bedla, 2025; Mugume et al., 2023). Even so, Africa still needs stronger coastal hydro-climatologic data assimilation means, sustained research, dedicated funding, and governance reforms to make these measures standard practice (Yankson et al., 2017).

Another important consequence of climate change is sea-level rise (SLR), which is raising the baseline for coastal flooding and increasing the occurrence of coastal extremes along African coastlines. The resulting hazard is often compound: when intense rainfall coincides with high tides or storm surges, reduced freeboard and higher tailwater levels at drainage outfalls can impede drainage and turn storms that would previously have remained below street-flood thresholds into disruptive inundation. This risk is particularly pronounced in embayments, back-beach lagoons and river deltas.

where shallow slopes and constricted outlets amplify backwater effects, as illustrated by the vulnerability of the Nile Delta (Abdrabo et al., 2022; Kamal et al., 2025). The literature thus presents SLR not simply as gradual coastal inundation, but as an increasing baseline that can amplify existing rainfall, tidal and drainage-related flood processes. Nevertheless, vulnerability is highly location-specific, making locally resolved assessment essential (Halecki and Bedla, 2025). The effects of SLR are further shaped by structural characteristics of African coastal cities. Low-lying topography, constrained drainage outlets, maintenance backlogs and the concentration of critical services along shorelines all increase vulnerability to compound coastal flooding (Yankson et al., 2017). Rapid urban growth is particularly important in the African context (Noby et al., 2024), as the removal of natural buffers and urban growth-related land subsidence can compound relative sea-level rise and extend its effects into beach and wetland areas. Taken together, these studies show that urban vulnerability to SLR is produced by the interaction of rising coastal water levels with urban development, drainage and infrastructure conditions, and the degradation of natural coastal protection. Addressing these interacting risks requires stronger coastal hydro-climatological monitoring and better integration of available data, for which Earth Observation products offer a viable approach in the region. In the shorter term, the literature supports measures such as updating hazard zoning and identifying priority areas for drainage improvement (Halecki and Bedla, 2025). The central research challenge is therefore to translate improved monitoring and modelling of a broadly shared hazard into locally specific assessments.

4.2.3 Water stress

Water stress in Africa in general, and African cities in particular, is rising as climate variability squeezes supply and lifts demand (Angelina et al., 2015; Dos Santos et al., 2017; Muller, 2016). Climate change is driving longer drought periods across Africa (Gumbo and Kapangaziwiri, 2023; Rusca et al., 2023). Long-term droughts and dry spells can depress river flows, shrink reservoir storage, and thin aquifer recharge (Boko et al., 2020b; Foster and Gathu, 2024), making access to

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water less reliable. Even when annual rainfall changes are modest, shifts in timing and longer hot spells raise outage risk (Shikangalah and Mapani, 2019). As utilities fall short, households turn to private boreholes and vendors (Schütte and Schulze, 2017). This shift typically accelerates groundwater drawdown, raises salinity and contamination risks, and pushes higher costs onto poorer areas (Analy and Laftouhi, 2021; Ayanlade, 2024; Safa et al., 2020). Two well documented cases are from Nairobi and Lagos, where shortfalls in piped water supply have pushed households toward private wells and water vendors (Oiro et al., 2020; Shiru et al., 2020). The result is groundwater depletion, risks of salinity and contamination, and higher costs that hit low income areas hardest. Just as in flood and sea level rise catastrophes, rapid and often unplanned urban expansion in Africa is a powerful co-driver of water stress (Congedo and Macchi, 2015; Mohamed et al., 2017). Fast growth lifts demand and reduces recharge. Encroachment on recharge lands and wetlands further weakens natural buffers (Kiflay et al., 2025; Olarinoye et al., 2020). In coastal aquifers, heavy pumping together with rising seas increases the risk of saline intrusion. Therefore, a workable response should combine solutions centred on demand side efficiency with diversified supply (Santos et al., 2023).

Water stress in African cities is a coupled supply–demand problem: climate variability can disrupt freshwater availability while rapid population and urban growth increase demand (Dos Santos et al., 2017). On the supply side, longer droughts and dry spells can reduce river flows, reservoir storage and aquifer recharge (Gumbo and Kapangaziwiri, 2023; Rusca et al., 2023). Even where changes in annual rainfall are modest, shifts in rainfall timing and longer hot spells can increase the risk of supply outages (Ayanlade, 2024). The literature therefore indicates that urban water stress depends not only on the total amount of water available, but also on the timing and reliability of supply relative to growing demand.

On the demand side, population growth and urbanisation are increasing city-wide water requirements, while associated land-cover changes and limitations in service provision influence how severely households experience water shortages (Foster and Gathu, 2024). Where utilities cannot

684 meet demand, households may turn to private boreholes and water vendors, but these responses
685 can accelerate groundwater drawdown, increase salinity and contamination risks, and impose higher
686 costs on poorer areas (Oiro et al., 2020; Shiru et al., 2020). Water stress is therefore also shaped by
687 the capacity of urban water systems to accommodate rising demand: responses to inadequate formal
688 provision can themselves create additional pressures on groundwater resources and uneven
689 socioeconomic burdens.
690 Work on Marrakesh illustrates how these interconnected pressures on water resources and services
691 can generate water stress in contrasting urban contexts (Analy and Laftouhi, 2021). In both cases,
692 urban expansion has increased water demand, while encroachment on recharge areas and wetlands
693 has reduced groundwater recharge. Together, these cases reinforce the central finding that urban
694 water stress emerges from interacting climatic, demographic, land-use and service pressures rather
695 than from water availability or climate variability alone.

696 *4.2.4 Extreme heat*

697 A considerable share of articles in our sample concerns the topic of extreme heat. Among these
698 articles, urbanisation takes an important position: many authors highlight the role of rapid urban
699 growth and associated land cover change in amplifying local heat risk in African cities (Bacha et al.,
700 2024; Dessu et al., 2020; Deton et al., 2025; Galal et al., 2020; Igun et al., 2023b; Mushore et al.,
701 2017a; Zhao et al., 2025). However, most analyses emphasise historical change; future urban growth
702 projections appear less frequently, with fewer articles explicitly integrating scenarios of urban
703 expansion into heat risk analysis (Arsiso et al., 2018a; Avordeh et al., 2021; Brousse et al., 2020b;
704 Cheng et al., 2022; Fahmy et al., 2020; Huang et al., 2024; Marcotullio et al., 2021; Mengistu et al.,
705 2024; Nematchoua et al., 2015; Pereira Marghidan et al., 2023).
706 In the context of urbanisation, informal settlements occupy a special place in relation to heat. Several
707 studies connect informal housing, material characteristics, service deficits, and social vulnerability

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with heightened heat exposure and risk (Baruti et al., 2020; Benjamin-Obe et al., 2023; Egondi et al., 2015; Van De Walle et al., 2021). Urban green space is frequently invoked as a mitigation pathway: trees, parks and broader greening are framed as practical cooling strategies. Yet, relatively few articles quantify the magnitude of cooling benefits. Many mention greening as a recommendation without robust effect sizes or experimental/modelling designs (Frimpong et al., 2022; Mahmoud and Gan, 2018; Morakinyo et al., 2016; Parker et al., 2025; Souverijns et al., 2023).

The number of articles that measure or model impacts of extreme heat is limited compared to general diagnostics. While slow-onset heating trends generate substantial work on vector-borne disease, the direct health effects of extreme heat are treated less consistently, despite projections of much more severe heat to come. Still, there are notable contributions linking heat to health outcomes and vulnerability (Benbrahim et al., 2025; Omonijo, 2017; Souverijns et al., 2022). A smaller subset evaluates energy demand for cooling, sometimes using Cooling Degree Days to estimate or project electricity needs (Ghribi and Dahech, 2023; Mushore et al., 2017b; Wemegah et al., 2025). By contrast, there is little documentation on infrastructure impacts, such as asphalt softening or thermal constraints on power generation and transmission; this appears only sporadically (Gaber et al., 2020; Ngoungue-Langue et al., 2023).

Only a relatively small number of articles perform numerical urban climate modelling with explicit urban physics (e.g., WRF, UrbClim, ENVI-met). Where present, these studies demonstrate the added value of resolving urban form and materials for heat stress (Bounoua et al., 2025; Limona et al., 2019; Obe et al., 2024; Souverijns et al., 2022, 2023; Yahia et al., 2018). More commonly, modelling is limited to downscaling or interpolating coarse GCM/RCM output to city locations, which risks overlooking local-scale effects (Arsiso et al., 2018a; Deton et al., 2025; Marcotullio et al., 2021; Mengistu et al., 2024; Nematchoua et al., 2015; Ngoungue-Langue et al., 2023). Very high-resolution (metre-scale) microclimate studies (e.g., ENVI-met) remain limited, though this area is bound to grow given the emergence of detailed building and vegetation data. At still smaller scales, indoor heat

733 stress and occupational exposure are rarely addressed (Ayanlade et al., 2019; Benbrahim et al., 2025;
734 Mengistu et al., 2024; Mushore et al., 2017b; Wilby et al., 2021).

735 Regarding future climate, only a minority of modelling and risk studies embed explicit future climate
736 projections (time horizons to mid- or late-century) in a way that couples climate scenarios with urban
737 growth or adaptation measures (Arsiso et al., 2018a; Avordeh et al., 2021; Brousse et al., 2020b;
738 Cheng et al., 2022; Deton et al., 2025; Fahmy et al., 2020; Huang et al., 2024; Igun et al., 2023b;
739 Marcotullio et al., 2021; Mengistu et al., 2024; Nematchoua et al., 2015; Pereira Marghidan et al.,
740 2023).

741 On heat stress indicators, authors mention Universal Thermal Climate Index (UTCI), Physiological
742 Equivalent Temperature (PET), Predicted Mean Vote (PMV), Temperature-Humidity Index (THI),
743 Standard Effective Temperature (SET), Wet Bulb Globe Temperature (WBGT), and related metrics;
744 nonetheless, many studies still rely primarily on air temperature as the main indicator (Arsiso et al.,
745 2018a; Avordeh et al., 2021; Ayanlade et al., 2019; Bacha et al., 2024; Balogun and Daramola, 2019;
746 Baruti et al., 2020; Bassett et al., 2020; Benaomar and Outzourhit, 2024; Benbrahim et al., 2025;
747 Boumaraf and Amireche, 2021; Bounoua et al., 2025; Brousse et al., 2020b).

748 Finally, the use of satellite remote sensing in the extreme heat subset is limited relative to the
749 broader UHI literature, which is unsurprising given that much EO work is funnelled into “LST/UHI”
750 diagnostics rather than personal heat exposure (next section). Still, several articles do use EO: Landsat
751 appears frequently, often to delineate land cover/greening trends (Arsiso et al., 2018a; Dessu et al.,
752 2020; Deton et al., 2025; Lachkham et al., 2025; Mahmoud and Gan, 2018; Mushore et al., 2017a).

753 Some also engage Local Climate Zones (LCZ) for urban form classification, occasionally drawing on EO-
754 derived LCZ maps (Benjamin-Obe et al., 2023; Brousse et al., 2020a; Obe et al., 2024; Van De Walle et
755 al., 2021).

756 Observational studies provide evidence of changing historical trends in heatwave characteristics in
757 African cities. In Ghana, for example, heatwaves have become more frequent, especially at night,

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758 while large differences are found between cities (Wemegah et al., 2025). Analysis for Mozambique
759 also finds increases in heatwave frequency and duration across many parts of the country, including
760 urban areas, although the magnitude of these trends depends strongly on how heatwaves are
761 defined, for example using maximum temperature, minimum temperature, or the compound Excess
762 Heat Factor (Pereira Marghidan et al., 2023). Enhanced nighttime heatwaves have also been
763 identified across African urban clusters, pointing towards nighttime conditions as a specific
764 component of urban heat hazard (Igoun et al., 2023). Taken together, these studies provide evidence
765 of changing heatwave characteristics, but the diversity of heatwave definitions complicates
766 comparison between studies and cities.
767 Future urban heat projections constitute another recurring topic in the examined articles. However,
768 while several studies project increasing heat under climate change, only a few include the effect of
769 urban growth, which is projected to be very high in Africa (see the Introduction). Detailed work in
770 Niamey based on the UrbClim-GeoDynamix modelling suite illustrates the value of coupling urban
771 climate modelling with projected urban expansion: future heat stress increases both in intensity and
772 spatial extent as the city grows (Souverijns et al., 2023). This distinction is important because
773 projecting a changing climate over a static representation of the city may overlook this additional
774 influence of urban expansion. Even where future land-cover change is modelled, its feedback on local
775 climate is not always represented. For example, in Lomé and Kara, projected land-cover and
776 vegetation changes are combined with interpolated large-scale temperature and precipitation
777 changes, rather than dynamically coupled to a local climate model (Deton et al., 2025). The literature
778 therefore indicates that future urban heat projections remain limited by the extent to which urban
779 growth and its feedback on local climate are represented.
780 The importance of accounting for urban changes and overall urban morphological characteristics is
781 supported by studies of present-day and historical urban development. Modelling for Kampala
782 demonstrates that urbanisation modifies local climate, interacting with regional atmospheric

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processes (Brousse et al., 2020b). High-resolution simulations in Lagos identify substantial spatial differences in heat stress associated with urban morphology (Obe et al., 2024). At finer scales, measurements in Kampala (Van De Walle et al., 2022) and modelling in Johannesburg (Souverijns et al., 2022) show that these differences lead to strongly varying outdoor heat exposure between neighbourhoods, with particularly high exposure in dense settlements with little vegetation. Microscale measurements in Akure also demonstrate the cooling effect of tree shading on outdoor thermal conditions (Morakinyo et al., 2016). However, a multi-city analysis shows that green space cooling efficiency varies with regional meteorological conditions (Cheng et al., 2022). Overall, the evidence demonstrates that urban form and vegetation substantially modify outdoor heat, but that these effects vary both within and between cities. Research on exposure to extreme heat and its impacts appears more limited. The corpus shows little direct evidence on indoor heat exposure, apart from an article on measurements in low-income communities in Ghana showing that indoor temperature extremes are strongly influenced by housing characteristics (Wilby et al., 2021). Health impacts are also addressed in only part of the examined articles, e.g. one epidemiological study examined the association between temperature and years of life lost in informal settlements in Nairobi (Egondi et al., 2015). Energy impacts receive somewhat more attention: in Sfax, urban heat and thermal discomfort are related to electricity consumption during the hot season (Ghribi and Dahech, 2023), and work in Morocco examines the combined effects of climate variation and urban expansion on building energy demand (Zhao et al., 2025). Overall, the heat hazard itself is more extensively characterised than human exposure and its consequences.

4.2.5 Land surface temperature

Land surfaces absorb shortwave solar radiation and re-emit energy as longwave thermal infrared flux. Land Surface Temperature (LST) is the radiometric “skin” temperature retrieved from this emission by satellite sensors, representing the thermal state of the uppermost surface layer at the time of

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808 overpass. Unlike near-surface air temperature, which is shaped by atmospheric mixing, humidity and
 809 synoptic forcing, LST is governed by surface emissivity, morphology and energy balance. It is therefore
 810 not merely a climatic variable but a spatial expression of how cities are built. Although correlated
 811 with air temperature, LST captures a distinct component of the urban heat system (Li et al., 2022a).
 812 Beyond heat alone, LST indexes broader environmental transformation. In semi-arid basins,
 813 impervious expansion alters runoff dynamics and erosion risk, embedding thermal change within
 814 hydrological restructuring (Mahgoub et al., 2025). Surface warming is thus coupled to shifts in land-
 815 atmosphere and land-water processes. LST operates as an integrative signal of urban environmental
 816 change rather than a standalone metric.

817 In African contexts, where meteorological station networks are sparse and unevenly distributed,
 818 satellite-derived LST has become foundational for diagnosing urban climate dynamics (Arsiso et al.,
 819 2018b; Tarawally et al., 2018). The Landsat thermal archive, spanning four decades, enables
 820 consistent, multi-temporal observation of surface thermal change at neighbourhood scale. This
 821 continuity is critical in rapidly urbanising regions where land transformation often outpaces
 822 institutional monitoring capacity. Urban climate research across Africa converges on a robust
 823 empirical pattern: land-use and land-cover change is the dominant driver of surface warming.
 824 Conversion of vegetated land to impervious surfaces systematically increases LST and intensifies
 825 surface urban heat island (SUHI) patterns (Gyimah, 2023; Koko et al., 2021b, a; Mensah et al., 2020;
 826 Odindi et al., 2022). Reduced evapotranspiration, increased heat storage and artificially reduced
 827 surface albedos amplify heat stress (Mushore et al., 2017a).

828 City-level studies illustrate this structural production of heat. In Addis Ababa, urban expansion has
 829 intensified surface temperatures and reshaped UHI patterns (Arsiso et al., 2018a; Eshetie, 2024;
 830 Moisa and Gemed, 2022). In Bahir Dar, multi-decadal analysis links built-up growth to sustained LST
 831 increases (Melese et al., 2025). Oran exhibits a widening urban-rural thermal gradient over four
 832 decades, with implications for human thermal comfort (Bendib and Boutrid, 2024; Soufiane et al.,

2025). Comparable dynamics are reported in Akure and Osogbo (Oyeniyi et al., 2025), Sekondi-Takoradi (Biney et al., 2024), Kano (Koko et al., 2021b) and Kumasi (Mensah et al., 2020). A continental synthesis confirms that persistent surface “hot-zones” in Africa are overwhelmingly urban (Gyimah, 2023).

Recent research efforts have moved beyond descriptive mapping to identify drivers and spatial differentiation. Urban expansion is consistently identified as a primary instigator of SUHI formation in Ethiopian cities such as Gondar and Adama (Mekonnen et al., 2024b; Melese et al., 2025). In Western Ethiopia, land use and land cover change alters surface temperature and energy fluxes, linking land transformation to modified land-atmosphere exchange (Dibaba, 2023). Across East Africa, SUHI intensity varies with urban form, development trajectory and seasonal dynamics (Garuma, 2023; Li et al., 2021). Heat exposure is therefore spatially uneven and temporally dynamic, reflecting both morphology and climate regime. The Local Climate Zone (LCZ) framework has strengthened this interpretive capacity by classifying urban areas according to surface cover, structure and material properties. LCZ-based analyses improve the attribution of LST variability to specific urban forms and enhance cross-city comparability in data-scarce contexts (Li et al., 2022b; Manyanya et al., 2024; Tarawally et al., 2018). Empirical studies demonstrate measurable LST reductions associated with vegetated and blue-green surfaces (Athukorala and Murayama, 2020). LCZ-informed analysis clarifies how structural urban form mediates these cooling benefits (Li et al., 2022c; Mushore et al., 2019). The spatial distribution of cooling infrastructure is therefore a determinant of thermal inequality. Since the surface heat is unevenly distributed within cities, concentrating in densely built, vegetation-deprived neighbourhoods that often coincide with lower-income populations (Mushore et al., 2017a), LST also reveals the geography of vulnerability. While LST does not directly measure human exposure, it provides high-resolution spatial proxies for heat burden that can be integrated with socio-economic data. It has been demonstrated how remotely sensed thermal patterns can be combined with demographic indicators to assess extreme heat vulnerability (Mushore et al., 2019), and how

incorporating surface characteristics into machine learning models significantly improves urban hazard and vulnerability mapping accuracy (Dufitimana et al., 2025b).

Looking forward, the strategic potential of LST in Africa lies in closing adaptation gaps through systematic, scalable monitoring. First, the Landsat archive provides a consistent baseline against which future expansion trajectories can be evaluated. Historical LST trends can support accountability in urban planning by revealing how land allocation decisions shape thermal risk. Second, integration with machine learning and socio-economic datasets enables anticipatory modelling of heat exposure under alternative urban growth scenarios (Dufitimana et al., 2025b; Mushore et al., 2017a). Third, LCZ-based standardisation supports cross-city comparison and the transfer of mitigation strategies across diverse climatic and governance contexts (Li et al., 2022b; Mushore et al., 2019).

LST research in Africa demonstrates that urban heat in this continent is not an external climatic anomaly. It is a spatial outcome of urbanisation, material choice and infrastructural distribution. Satellite-derived LST makes this production of heat visible, measurable and governable. By linking surface morphology to exposure patterns and social vulnerability, LST provides both a diagnostic lens and a planning instrument. Harnessed strategically, it can help bridge persistent data gaps and reorient climate change adaptation toward spatially explicit, equity-aware urban transformation.

Land Surface Temperature (LST) is the radiometric “skin” temperature retrieved from longwave thermal infrared emission by satellite sensors, representing the thermal state of the uppermost surface layer. Unlike near-surface air temperature, LST is governed by surface emissivity, morphology and energy balance. Although correlated with air temperature, it captures a distinct component of the urban heat system and provides a spatial expression of how the physical characteristics of cities influence surface heating (Li et al., 2022b).

In African contexts, where meteorological station networks are sparse and unevenly distributed, satellite-derived LST has become important for diagnosing urban thermal dynamics. The Landsat archive enables multi-temporal observation of surface thermal change at neighbourhood scale and

allows these changes to be examined alongside urban land-cover transformation (Arsiso et al., 2018; Tarawally et al., 2018). Across the reviewed studies, urbanisation and land-use and land-cover change emerge as important drivers of the spatial distribution of surface heat: built-up and impervious surfaces are associated with higher LST, while vegetation and water generally moderate surface temperatures (Gyimah, 2023; Koko et al., 2021; Odindi et al., 2022). Accordingly, satellite-based studies identify persistent surface hot zones particularly within built-up urban areas (Gyimah, 2023; Melese et al., 2025). Collectively, this evidence links the spatial pattern of surface warming strongly to the transformation and composition of the urban surface.

Research has increasingly moved beyond mapping these patterns towards explaining their spatial differentiation. The Local Climate Zone (LCZ) framework supports this shift by classifying urban areas according to surface cover, structure and material characteristics, allowing LST variability to be related more systematically to different urban forms (Tarawally et al., 2018). Vegetated and blue-green surfaces are generally associated with lower LST, although urban structure mediates the magnitude of this cooling effect (Athukorala and Murayama, 2020; Li et al., 2022c). The literature thus increasingly connects where surface heat occurs with the urban characteristics that help produce or mitigate it.

This spatial differentiation also provides a basis for examining vulnerability. Densely built, vegetation-poor neighbourhoods with elevated surface temperatures can coincide with lower-income populations, creating spatial concentrations of heat vulnerability (Mushore et al., 2017). LST does not directly measure human heat exposure, but its high spatial resolution allows surface thermal conditions to be combined with demographic and socioeconomic indicators. Incorporating remotely sensed surface characteristics into machine-learning approaches can further support urban hazard and vulnerability mapping (Dufitimana et al., 2025; Mushore et al., 2019). LST research therefore increasingly uses spatial patterns of surface heat to identify potentially vulnerable areas, while recognising that LST does not directly measure human heat exposure.

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4.2.6 Slow-onset ~~climate trends~~ events

Climate change impacts are most visible through extreme events with a sudden impact, such as extreme precipitation leading to floods. However, a considerable number of climate change consequences develop on the long term and are only perceived gradually.

One impactful long term climate change impact in Africa is vector borne diseases. Due to climate change, the suitability areas for vectors (i.e., generally mosquitoes in Africa) are expanding, impacting a higher amount of the population. Most studies focus on malaria (Brousse et al., 2019, 2020a; Damte et al., 2023; Diriba et al., 2024; File and Dinka, 2020; Flückiger and Ludwig, 2020; Ibrahim et al., 2022; Kamkuemah et al., 2024; Moha et al., 2020; Morlighem et al., 2022, 2023; Oluwatimilehin et al., 2022) and dengue (Aliaga-Samanez et al., 2024; Kamkuemah et al., 2024; Montgomery et al., 2025; Noureldin and Shaffer, 2019; Osalla et al., 2025), while only one article in the sample focusses on yellow fever (Aliaga-Samanez et al., 2024), and one on zika and chikungunya (Montgomery et al., 2025). Vector suitability maps are constructed using climate modelling, remote sensing, and Local Climate Zone (LCZ) and GIS mapping. Interestingly, most articles denote the link between (future) urbanisation, (future) climate change and higher impacts of vector borne diseases (Rose et al., 2020). Urbanisation and growing urban populations are a distinct problem in Africa, the number of urban dwellers expected to double between 2025 and 2050, from around 700 million to almost 1.5 billion (UN Habitat, 2022). The conversion of natural land to the growing urban extents and densities impacts the local urban climate (i.e., temperature, humidity and rainfall). The interactions between the urban canopy and the atmosphere are investigated using high resolution models (Anande and Park, 2021; Daramola and Balogun, 2019; Zeleke et al., 2023), remote sensing (Frimpong et al., 2022; Ibrahim Mahmoud et al., 2016; Sun et al., 2023; Traore et al., 2025) or ground-based observations (Igun et al., 2023a; Kabano et al., 2022). Downstream impacts focus on various health aspects related to higher temperatures (Adelekan et al., 2015; Codjoe et al., 2020b; Rother, 2020) and a specific focus on unequal impacts within cities, more specifically informal settlements and slums (Corburn et al.,

2022; Damte et al., 2023; Hlahla and Hill, 2018; Nwankwo et al., 2022; Owusu and Nurse-Bray, 2019; Williams et al., 2019).

Apart from impacts on humans, growing urban extents also impact ecosystems and biodiversity. Growing cities (which often occur in uncontrolled ways in Africa) lead to the disappearance of natural ecosystems, habitats and green cover, which are essential urban climate resilience tools (Corburn et al., 2022; Senbore and Oke, 2023; Traore et al., 2025). Several studies track the loss of natural ecosystems via remote sensing tools to monitor environmental quality over time and space (e.g., (Ibrahim Mahmoud et al., 2016; Sun et al., 2023)). Nature-based solutions are proposed to restore biodiversity in cities, while furthermore supporting adaptation to other climate-related consequences (Abraha et al., 2022; Daramola and Balogun, 2019; Igun et al., 2023a).

Increased extreme precipitation events pose direct impacts on populations (Azagoun et al., 2025). However, long-term changes in rainfall patterns and dynamics also create challenges. Changes in precipitation patterns stress agriculture and urban food security (Atiem et al., 2022; Bassirou and Bitondo, 2023), present-day water resource management (Abraha et al., 2022; Bizimana et al., 2024; Mekonnen et al., 2024; Pattanayak et al., 2019), which will increase towards the future (Gamal et al., 2024; Klutse et al., 2024). Even though rainfall trends vary significantly per region and season, it often leads to enhanced irregular water availability and water quality (Gule et al., 2024; Senbore and Oke, 2023) with negative impacts on urban populations (Iradukunda et al., 2023; Mohamed et al., 2024).

Land degradation constitutes an important downstream climate impact of variability in rainfall patterns and extreme precipitation, strengthened by urbanisation. Uncontrolled urban expansion and human pressure hinder effective land management and conservation practices, leading to increased soil erosion rates (Marondedze and Schütt, 2021; Salhi et al., 2023). Apart from the negative consequences for soil quality, they can trigger soil instability, in the form of landslides (Bourenane et al., 2015; Dille et al., 2022; Obda et al., 2022) or coastal erosion (Marzouk et al., 2021).

A general consequence of these slowly evolving climate trends is the long-term socio-economic impact. Infrastructure (Lane Visser and Vanderschuren, 2024), economic assets (De Wit et al., 2023) and human capital (Iradukunda et al., 2023) are at significant risk towards the future.

Climate change impacts are often most visible through sudden extreme events, such as extreme precipitation leading to floods. However, many climate-related consequences develop over longer periods and are perceived only gradually.

One important long-term impact concerns vector-borne diseases. Climate change can expand areas suitable for disease vectors, potentially increasing the population exposed. Most studies focus on malaria (Brousse et al., 2020a; Kamkuemah et al., 2024) and dengue (Osalla et al., 2025), while less research is present on yellow fever (Aliaga-Samanez et al., 2024), zika and chikungunya (Montgomery et al., 2025). Vector suitability is assessed using different methodologies, including climate modelling, remote sensing, Local Climate Zones (LCZs) and GIS mapping. Importantly, the literature increasingly places climatic suitability within a broader urban context: rather than considering climate effects in isolation, multidimensional approaches account jointly for future urbanisation, climate change and their implications for vector-borne disease (Rose et al., 2020).

Rapid urbanisation is an important component of these longer-term changes in African cities, with the urban population expected to approximately double between 2025 and 2050, from around 700 million to almost 1.5 billion (UN-Habitat, 2022). Conversion of natural land as cities expand and densify modifies local temperature, humidity and rainfall. These urban–atmosphere interactions are investigated using high-resolution climate models (Anande and Park, 2021; Zeleke et al., 2023), remote sensing (Frimpong et al., 2022; Traore et al., 2025) or ground-based observations (Kabano et al., 2022), with the advantages and limitations of these methods documented elsewhere (Souverijns et al., 2023). Downstream research addresses health impacts associated with higher temperatures and their different drivers (Codjoe et al., 2020; Rother, 2020), often highlighting unequal impacts within cities. Informal settlements and slums are of particular concern because of limitations in both

981 monitoring and adaptive capacity (Corburn et al., 2022; Damte et al., 2023). Together, these studies
982 show that urbanisation is not only a source of increasing exposure, but also modifies local climatic
983 conditions and the distribution of associated health risks within cities.

984 Urban expansion also affects ecosystems and biodiversity. The loss of natural ecosystems, habitats
985 and green cover as cities grow reduces resources that contribute to urban climate resilience. Nature-
986 based solutions are consequently proposed to restore urban biodiversity while also supporting
987 adaptation to other climate-related impacts (Abraha et al., 2022). This literature therefore connects
988 ecosystem loss and climate adaptation: the same natural systems affected by urban expansion can
989 also contribute to resilience when maintained or restored.

990 Long-term changes in rainfall provide another pathway through which gradual climatic shifts affect
991 urban systems. While extreme precipitation directly affects populations (Azagoun et al., 2025),
992 changing rainfall patterns also place pressure on agriculture and urban food security (Atiem et al.,
993 2022; Bassirou and Bitondo, 2023), and on present-day water-resource management (Abraha et al.,
994 2022), with these pressures expected to increase in the future (Gamal et al., 2024; Klutse et al.,
995 2024). Although rainfall trends vary considerably by region and season, changing rainfall patterns can
996 contribute to increasingly irregular water availability and declining urban water quality (Gule et al.,
997 2024; Senbore and Oke, 2023). The reviewed evidence thus links changing rainfall not only to
998 extreme events, but also to longer-term pressures on food and water systems.

999 Land degradation represents a related downstream impact of rainfall variability and extreme
1000 precipitation, compounded by urbanisation. Uncontrolled urban expansion and human pressure can
1001 hinder effective land management and conservation, contributing to increased soil erosion
1002 (Marondedze and Schütt, 2021; Salhi et al., 2023). Beyond the deterioration of soil quality, these
1003 processes can contribute to soil instability and landslides (Dille et al., 2022; Obda et al., 2022), as well
1004 as coastal erosion (Marzouk et al., 2021). This illustrates how gradual climatic and urban pressures
1005 can accumulate into physical changes in land systems and, ultimately, additional hazards.

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1006 Across these different pathways, a common consequence is the accumulation of long-term
1007 socioeconomic impacts. Infrastructure (Lane-Visser and Vanderschuren, 2024), economic assets (De
1008 Wit et al., 2023), and human capital (Iraddock et al., 2023) are all projected to face increasing risks.
1009 The literature therefore portrays slow-onset events less as a single hazard than as a set of interacting
1010 and cumulative pressures transmitted through urban health, ecosystems, water and food systems,
1011 land and socioeconomic assets.

1012 4.2.7 Wind storms

1013 Winds are a climate-related hazard, affecting not only coastal areas, but also inland areas and cities in
1014 Africa. The southeastern part of Africa is especially vulnerable for high wind speeds, due to the
1015 occurrence of tropical cyclones in the region, not only accounting for high wind speeds, but also
1016 heavy precipitation (Williamson et al., 2023). Wind-driven disasters can cause severe damage to
1017 buildings and essential infrastructure, with particularly high impacts in more vulnerable urban areas
1018 (Kafi et al., 2021). Beyond physical destruction, wind-related disasters can also trigger longer-lasting
1019 and interconnected disruptions to basic services and resources (such as access to key household
1020 needs), which can compound vulnerability and contribute to rising inequality after the event
1021 (Williamson et al., 2023).

1022 Windstorms are a climate-related hazard affecting both coastal and inland areas and cities across
1023 Africa. In southeastern Africa, tropical cyclones can combine high wind speeds with heavy
1024 precipitation (Williamson et al., 2023). High winds can severely damage buildings and essential
1025 infrastructure, with particularly severe impacts in vulnerable urban areas (Kafi et al., 2021). Beyond
1026 direct physical damage, wind-driven disasters can cause longer-lasting disruptions to basic services
1027 and household access to essential resources, thereby compounding existing vulnerability and
1028 inequality (Williamson et al., 2023). The available evidence therefore shows that windstorm impacts
1029 extend beyond immediate physical damage to include wider and potentially longer-lasting disruption
1030 of urban services and livelihoods.

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1031 However, the evidence base remains limited. The studies reviewed here focus mainly on individual
1032 events and observed impacts, while comparisons across cities, future projections, and analyses
1033 linking wind hazards with urban exposure and building vulnerability remain scarce.

1034 4.3 Synthesis of thematic reviews

1035 4.3 Building on the thematic assessment in Section 4.2, Table 2 provides a synoptic overview of
1036 the main findings emerging from the reviewed literature across the different hazard themes. The
1037 table complements the more detailed discussion above by highlighting the principal synthesis for
1038 each theme.

1039 Table 2. Synoptic synthesis of the main findings from the reviewed literature across climate hazard themes.

Theme	Synthesis of the reviewed literature
Flooding	Urban flood hazard emerges from the interaction between changing rainfall characteristics, land-use change and drainage performance, rather than from changing climate conditions alone. Characterisation of changing flood patterns remains constrained by sparse observations (short-duration rainfall and water-level observations), drainage information and consistent event-based datasets.
Sea-level rise	SLR is not only a gradual coastal hazard but an increasing baseline that can amplify existing rainfall-, tidal- and drainage-related flood processes. Its effects are strongly conditioned by local topography, drainage and urban development, making locally resolved assessment important.
Water stress	Urban water stress emerges as a coupled supply-demand problem, in which climatic variability interacts with population growth and land-use change. These

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interactions can place additional pressure on groundwater resources and produce strongly varying conditions between urban contexts.

Extreme heat The literature is strongest in detecting and characterising extreme heat and explaining how urban form and vegetation modify it, with substantial variation within and between cities. Comparison is complicated by inconsistent heatwave definitions, climate projections rarely account fully for urban growth, and evidence on human exposure and associated impacts remains limited.

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Land surface temperature Satellite-derived LST reveals how urbanisation, land cover, vegetation and urban form shape the spatial distribution of surface heat. Combined with demographic and socio-economic information, these patterns can support analysis of heat vulnerability.

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Slow-onset events Slow-onset events lead to a range of gradually developing consequences, including changes in vector suitability, urban climate, ecosystems, food and water systems, and land degradation. Across these areas, the literature highlights the importance of rapid urbanisation in shaping long-term climate impacts.

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Windstorms The available literature is predominantly event-based, showing that windstorms can combine high winds and precipitation and cause both immediate physical damage and longer-lasting disruption. Cross-city comparisons and future projections remain scarce.

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4.4— AI-assisted synthesis

As a final qualitative analysis, we conducted an AI-assisted synthesis to test the robustness of the expert interpretation in Section 4.2. To this end, we used the AI-based tool SciSpace

1044 <https://www.scispace.com>) to identify knowledge gaps mentioned in the 272 selected articles in an
1045 automated manner, activating the 'Research Gaps' and 'Future Research' options within SciSpace's
1046 Library environment.

1047 As this procedure generated more than 50,000 words of output (nearly 100 A4 text editor pages), we
1048 analysed these results using a GPT-5.2 large language model. Specifically, we prompted the model as
1049 follows: "Using the 'Research Gap' and 'Future Research' columns of the uploaded file, identify the
1050 key knowledge gaps regarding climate risk in African cities and generate one paragraph of text for
1051 each." Subsequently, we prompted the model to present the results in a structured (tabular) rather
1052 than in a narrative form. Based on this procedure, the key knowledge gaps presented in Table 2
1053 emerged. Each row synthesises recurring themes across multiple studies.

1054 *Table 2. Key knowledge gaps identified by an AI-assisted procedure, based on the list of 276 selected articles,*
1055 *and using the SciSpace tool's 'Research Gaps' and 'Future Research' options.*

Knowledge gap	Core issue	Consequences	Research needs
Limited high-resolution data	Lack of fine-scale spatial and temporal climate, infrastructure and socio-economic data	Constrains modelling of UHI, flooding and exposure	Enhanced monitoring networks, improved remote sensing, granular datasets
Limited geographic coverage	Overreliance on single-city case studies	Limited generalisability	Multi-city comparative studies, standardised methodologies
Urbanisation-climate interactions	Poor understanding of feedbacks between growth and hazards	Uncertain projections of heat and flood risks	Coupled urban-climate models, morphology-sensitive analyses
Compound and cascading risks	Hazards studied in isolation	Underestimation of systemic vulnerability	Integrated multi-hazard frameworks

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Adaptation effectiveness	Limited empirical evaluation	Uncertain performance of greening/drainage interventions	Performance-based studies (e.g., tree-based cooling)
Informal settlements & vulnerability	Weak integration of social vulnerability	Incomplete risk representation	Interdisciplinary hazard-vulnerability integration
Modelling uncertainty	Coarse projections and simplified growth assumptions	Weak long-term planning support	Explicit uncertainty treatment, improved scenario coupling
Translation to planning	Weak policy uptake	Research-practice gap	Governance studies, decision-support tools
Health impacts	Limited epidemiological evidence	Underestimated public health burden	Exposure-health linkage studies

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A comparison between the AI-assisted and the expert-based reviews (Section 4.2) shows substantial overlap in the knowledge gaps identified. Both approaches point to structural deficiencies in the literature, including the limited availability of high-resolution data, the geographic concentration of case studies in a small number of countries, and the insufficient integration of hazard, exposure and vulnerability dimensions. Similarly, both assessments emphasise the weak coupling of future climate projections with urban growth scenarios, the limited evaluation of adaptation effectiveness, and the underrepresentation of informal settlements and socially vulnerable populations.

At the same time, the AI-assisted synthesis articulates certain aspects more explicitly compared to the expert assessment. In particular, it highlights the overreliance on single case studies, the absence of standardised cross-city comparison, and the limited use of uncertainty-aware modelling

1067 approaches. It also more clearly frames the weak translation of research findings into urban planning
1068 and governance practice as a distinct knowledge gap.
1069 Overall, the qualitative assessment confirms the patterns identified in the bibliometric analysis,
1070 notably the strong focus on flooding and surface temperature and heat studies, and the
1071 comparatively limited attention to other climate hazards affecting African cities.

1072 5 Conclusions

1073 This assessment selected and examined 272 peer-reviewed articles (2015-2025) addressing climate
1074 ~~risk~~ hazard in African cities, combining quantitative mapping, and hazard-based expert review ~~and an~~
1075 ~~AI-assisted synthesis of reported knowledge gaps~~. Together, these approaches reveal a rapidly
1076 expanding but methodologically constrained knowledge base.

1077 The main findings are as follows:

- 1078 1. A fundamental limitation concerns the availability of high-resolution data. Many studies rely on
1079 coarse climate projections or sparse in-situ monitoring networks that are not tailored for urban-
1080 scale processes. Sub-hourly rainfall records, dense temperature observations and modelling, and
1081 fine-scale socio-economic datasets remain scarce across much of the continent. High-resolution
1082 urban climate modelling with explicit representation of urban morphology and materials is also
1083 relatively rare. As a result, urban heat islands, pluvial flooding, compound coastal risks and
1084 exposure patterns are often assessed at spatial and temporal resolutions insufficient to capture
1085 intra-urban variability. This limits the ability to move towards actionable and contextually specific
1086 adaptation planning.
- 1087 2. Earth Observation (EO) has become a central methodological pillar of the field, particularly
1088 through the use of Landsat imagery for land surface temperature and urban growth analysis. In
1089 data-scarce regions, EO provides a consistent and scalable source of information that partly

1090 compensates for limited ground-based monitoring. However, its application remains
 1091 concentrated on surface temperature diagnostics and historical land-cover change. The relative
 1092 share of EO-based studies has remained stable over the past decade. This suggests that, despite
 1093 significant advances in sensor resolution, data availability and processing capacity, its broader
 1094 potential remains underexploited.

1095 3. The geographic distribution of research is highly imbalanced. A small number of countries
 1096 accounts for a disproportionate share of publications. Central Africa in particular remains a blind
 1097 spot. Capital cities dominate the literature, and fast-growing secondary cities are
 1098 underrepresented. This skewed view carries a risk of reinforcing existing disparities in climate
 1099 knowledge and planning capacity.

1100 4. Thematic coverage remains uneven. Flooding and heat-related topics dominate the literature,
 1101 whereas hazards such as sea-level rise, wind-storms and urban water stress receive comparatively
 1102 limited attention. Additional cross-hazard screening shows that substantive consideration of more
 1103 than one hazard occurs, but remains limited and uneven across hazard categories. Explicit
 1104 analysis of interactions between hazards is considerably rarer. Even where hazards are well
 1105 studied, they are frequently analysed in isolation rather than within multi-hazard or cascading
 1106 risk frameworks. Explicit coupling between hazard, exposure, vulnerability and adaptive capacity
 1107 remains uncommon.

1108 5. Social dimensions are insufficiently embedded in quantitative assessments. Informal settlements,
 1109 poverty, governance capacity and inequality are frequently acknowledged but rarely integrated
 1110 systematically into modelling or risk frameworks. Health impacts – particularly those directly
 1111 linked to extreme heat and long-term socio-economic consequences – remain underdeveloped
 1112 relative to projected climate trends.

1113 6. The literature is predominantly retrospective. Most studies assess historical climate variability or
 1114 past urban growth. Only a limited number integrate future climate scenarios with projected

urban expansion or demographic change. As a consequence, while present-day patterns are increasingly well documented, robust assessments of long-term urban transformation under climate change remain scarce.

~~7. Finally, the AI-assisted synthesis highlighted additional structural issues: a systemic overreliance on single-city case studies, limited use of standardised cross-city comparison frameworks, weak treatment of modelling uncertainty, and a persistent gap between scientific findings and their translation into urban planning and governance practice.~~

These findings point to several priorities for future research. First, the strong representation of large cities means that current knowledge is disproportionately shaped by metropolitan contexts. Where local evidence is lacking, smaller and secondary cities may therefore have to rely on hazard information derived from substantially different urban settings, which may not adequately reflect their local conditions and adaptation needs. Greater research attention to small and secondary cities is consequently needed.

Second, the uneven representation of climate zones affects the range of hazard conditions captured by the available evidence. For example, strong representation of dry climates in heat-related research may favour an understanding of heat dominated by high-temperature and dry-heat conditions, whereas humidity becomes an important component of human heat stress in more humid climates. Research in currently underrepresented climate zones is therefore needed to broaden the climatic conditions represented in the evidence base.

Third, the predominance of flooding and heat in the literature should not be interpreted as evidence of their relative importance across African cities. Rather, the observed distribution reflects research attention within the reviewed literature. Greater attention to currently understudied hazards is needed, particularly where their relevance may increase under climate change. Research should also move beyond the predominantly single-hazard perspective by more explicitly considering interactions between hazards where relevant.

1140 Finally, the strong bias towards historical and present-day conditions is particularly important given
1141 the major urban expansion anticipated across Africa. Future cities may differ substantially from
1142 present-day cities in spatial extent, land cover and population distribution. Hazard assessments that
1143 account for future climate change while disregarding future urban growth may therefore provide an
1144 incomplete basis for long-term adaptation decisions. Greater emphasis is needed on studies that
1145 jointly consider future climate and urban development.

1146 Across these priorities, improved high-resolution observations and urban-scale modelling remain
1147 important, while Earth Observation offers a particularly valuable source of consistent and scalable
1148 information in data-scarce regions. However, EO is still used mainly for analysing land surface
1149 temperature and historical land-cover change, while its potential for other applications remains
1150 underexploited. Together, broader geographic and climatic representation, greater attention to
1151 secondary cities and understudied hazards, and stronger integration of future climate and urban
1152 development would provide a more representative evidence base for adaptation and resilience
1153 planning in African cities. ~~Summarising, urban climate research in Africa has grown substantially over~~
1154 ~~the past decade, but it remains constrained by data scarcity, limited high-resolution modelling~~
1155 ~~capacity, geographic imbalance, and insufficient integration of social and forward-looking dimensions.~~
1156 ~~Addressing these gaps will require strengthened monitoring networks and improved urban-scale~~
1157 ~~modelling. In data-scarce regions, Earth Observation offers a particularly valuable source of consistent~~
1158 ~~and scalable information, but its potential remains only partially exploited, especially beyond land~~
1159 ~~surface temperature diagnostics. Broader geographic representation, particularly in Central Africa~~
1160 ~~and secondary cities, is also needed, together with closer integration of hazard, vulnerability and~~
1161 ~~governance perspectives. Such efforts are essential to support evidence-based adaptation and~~
1162 ~~resilience planning in one of the world's most climate-vulnerable urban regions.~~

1163

1164 **Data Availability**
1165 The list of 272 scientific articles used as a basis for the review has been under Supplementary
1166 Material S1.
1167

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