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*Research article*

# Transforming urban growth into resilience pathways: A comparative analysis of hazard vulnerability in Windhoek, Namibia and Accra, Ghana

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**Abstract:** Urban growth in African cities has been rapid and uneven, often intensifying vulnerability to natural and human-induced hazards. This study examines the spatial patterns of urban growth and their implications for hazard vulnerability in two rapidly expanding African capitals: Windhoek, Namibia, and Accra, Ghana. Over the past three decades, both cities have experienced significant transformation, though the scale, form, and spatial distribution of growth differ markedly. The study assesses how urban expansion from 1993 to 2023 has influenced exposure to floods, droughts, fires, and related socio-environmental hazards. Using a mixed-methods approach, the research integrates satellite-based spatial analysis with quantitative assessment and qualitative policy evaluation. Land use dynamics were mapped and complemented by 390 household surveys to capture socio-economic perspectives, while 10 stakeholder interviews and policy analysis examined existing urban resilience frameworks in Namibia and Ghana. Results show that Windhoek exhibits low-density sprawl over underdeveloped land, heightening drought-related vulnerability, whereas Accra displays compact infill growth with increased exposure to floods and fires. Informal settlements remain a key source of vulnerability in both cities. The findings indicate that existing policies emphasize physical risks but insufficiently address underlying socio-economic drivers of exposure. In response, the study proposes a resilience-oriented framework that integrates spatial planning, socio-economic inclusion, and adaptive governance to support sustainable and equitable urban development and transform growth-related vulnerabilities into resilience opportunities across African cities.

**Keywords:** urban resilience; hazard vulnerability; spatial growth; sustainable urban development; African cities

## 1. Introduction

Urban growth is one of the defining global transformations of the twenty-first century, with more than half of the world's population residing in cities and nearly 70% projected to do so by 2050 [1]. While urbanization reflects socio-economic advancement, technological innovation, and expanded access to services, it also generates complex and uneven vulnerabilities. Across much of the Global South, rapid urban expansion has outpaced planning systems, infrastructure provision, and institutional capacity, intensifying exposure to environmental and socio-economic hazards [2–4]. Consequently, the relationship between urban growth and hazard vulnerability has become central to contemporary debates on sustainability, risk, and resilience. In Africa, accelerating urbanization under conditions of limited governance capacity has produced increasingly fragile urban environments highly susceptible to floods, droughts, fires, and related hazards [5,6].

Globally, urban resilience has evolved from a narrow emphasis on post-disaster recovery toward a broader understanding of cities' capacity to absorb shocks, adapt, and reorganize while maintaining essential functions [7,8]. This perspective aligns with Sustainable Development Goal (SDG) 11, particularly Target 11.5, which seeks to reduce disaster-related losses among vulnerable populations. Understanding how urban growth processes shape patterns of hazard exposure is therefore a critical task for both research and policy [9,10].

High-income cities such as Rotterdam and Singapore have increasingly embedded resilience principles through predictive analytics, adaptive infrastructure, and risk-sensitive zoning. In contrast, many low- and middle-income cities experience rapid growth alongside weak institutional frameworks and inadequate infrastructure, resulting in informal settlement expansion and heightened hazard exposure [11]. Africa remains among the fastest-urbanizing regions globally, with its urban population projected to exceed 1.3 billion by 2050 [1,12]. Cities such as Lagos, Nairobi, Accra, and Windhoek exemplify these dynamics, characterized by demographic pressure, divergent spatial growth patterns, and persistent service deficits [1]. Although prior studies recognize links between rapid urbanization and hazard exposure, relatively few examine how specific spatial growth patterns intensify vulnerability or integrate spatial, social, and governance dimensions within a comparative framework [13,14].

Namibia and Ghana illustrate distinct yet interconnected urbanization trajectories. Windhoek has largely expanded through low-density peripheral growth driven by rural–urban migration and economic opportunity, resulting in extensive under-serviced areas and heightened exposure to floods and droughts, particularly within informal settlements that accommodate a substantial share of the city's population [5,6,15,16]. In contrast, Accra's growth has been dominated by high-density and infill development shaped by demographic pressure and geographic constraints, intensifying vulnerability to floods, fires, and sanitation-related hazards despite its relatively compact urban form [17,18]. Weak enforcement of land-use regulations and persistent socio-economic inequalities further compound risk in both cities [5,18,19].

Although both countries have adopted urban policy frameworks—including Namibia's Windhoek Integrated Land Use Plan (WILUP 2017–2032) and Ghana's National Urban Policy—implementation gaps remain, particularly in coordination between national strategies and municipal action [20–22]. Progress toward SDG 11 is uneven, with achievement levels estimated at 68.1% in Namibia and 49.4 percent in Ghana in 2023, underscoring persistent barriers to resilient urban development [23].

Scholarly debate continues over whether urban growth enhances resilience through economic diversification and innovation or exacerbates vulnerability by reinforcing socio-spatial inequality and infrastructure deficits [24,25]. Resilience is therefore not an automatic outcome of development but depends on deliberate spatial planning, effective governance, and inclusive community engagement. Urban form plays a critical role: Compact and polycentric configurations may enhance adaptive capacity, whereas dispersed sprawl often increases exposure and complicates hazard management [26]. However, empirical validation of these relationships within African contexts remains limited, and few longitudinal comparative studies integrate spatial expansion with socio-economic and governance dynamics.

Situated within this gap, the present study examines how urban growth patterns shape vulnerability to hazards in Windhoek and Accra and how these dynamics inform resilience planning consistent with SDG 11 Target 11.5. Both cities exhibit high socio-economic vulnerability and expanding informal settlements, yet existing research rarely links long-term spatial growth trajectories with hazard exposure outcomes. Conceptually, urban growth is treated as both a driver and determinant of hazard vulnerability, mediated by social, economic, and governance contexts. As illustrated in Figure 1, the conceptual framework traces interactions among growth drivers, spatial patterns, hazard exposure, governance responses, and pathways toward resilience or fragility.

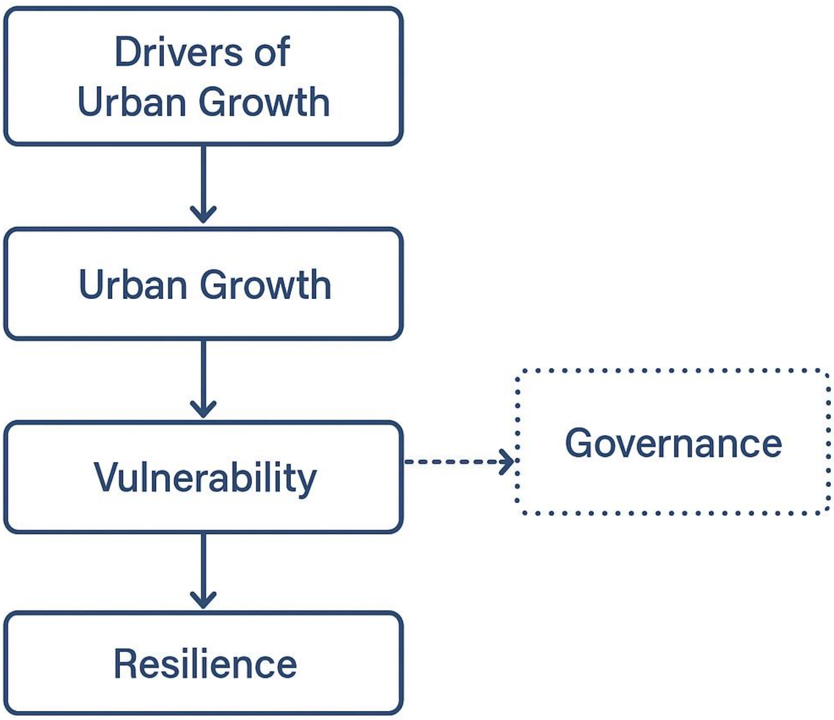



**Figure 1.** Conceptual framework of urban growth, vulnerability and resilience.

Policy frameworks including the Sendai Framework, the Paris Agreement, the New Urban Agenda, and Africa's Agenda 2063 emphasize resilience; however, implementation remains constrained by inadequate data, weak institutional coordination, and insufficient financing [27–31]. Institutional fragmentation at national and municipal levels further undermines effective risk governance in both Namibia and Ghana [32,33]. The contrasting spatial forms of Windhoek and Accra therefore provide a strong empirical basis for assessing how differing urban growth trajectories influence vulnerability. Despite advances in resilience scholarship, comparative African studies remain limited, with most research prioritizing physical expansion over socio-economic and governance dimensions. Longitudinal analyses linking decades of spatial growth to hazard outcomes are particularly scarce, constraining the development of context-sensitive resilience strategies aligned with SDG 11 Target 11.5.

Re-envisioning urban growth as a pathway to resilience rather than vulnerability requires integrating spatial planning, social equity, and adaptive governance. Such integration advances scientific understanding while strengthening planning and policy responses. By situating local urban dynamics within global resilience agendas, this study argues that African urban futures depend on transforming prevailing growth models into resilience-centered development pathways driven by inclusion, innovation, and institutional learning. Against this background, the next section outlines the methodological approach used to analyze long-term urban growth patterns, hazard exposure, vulnerability dynamics, and policy effectiveness in Windhoek and Accra.

## 2. Materials and methods

### *2.1. Study area*

This study focuses on two African capital cities—Windhoek (Namibia) and Accra (Ghana)—representing contrasting urban growth typologies and environmental conditions. Windhoek is located between 22°34′S and 17°05′E in Namibia's central highlands, at approximately 1,650 m above sea level (Figure 2a). It serves as the country's political and economic capital, covering about 645 $km^2$ and surrounded by semi-arid savannah and mountainous terrain. Accra lies between 5°33′N and 0°12′W along the Gulf of Guinea, with elevations ranging from 0–100 m above sea level (Figure 2b). The city occupies an administrative area of approximately 225 $km^2$ within the Greater Accra Metropolitan Area (GAMA) and functions as Ghana's principal commercial and administrative center.

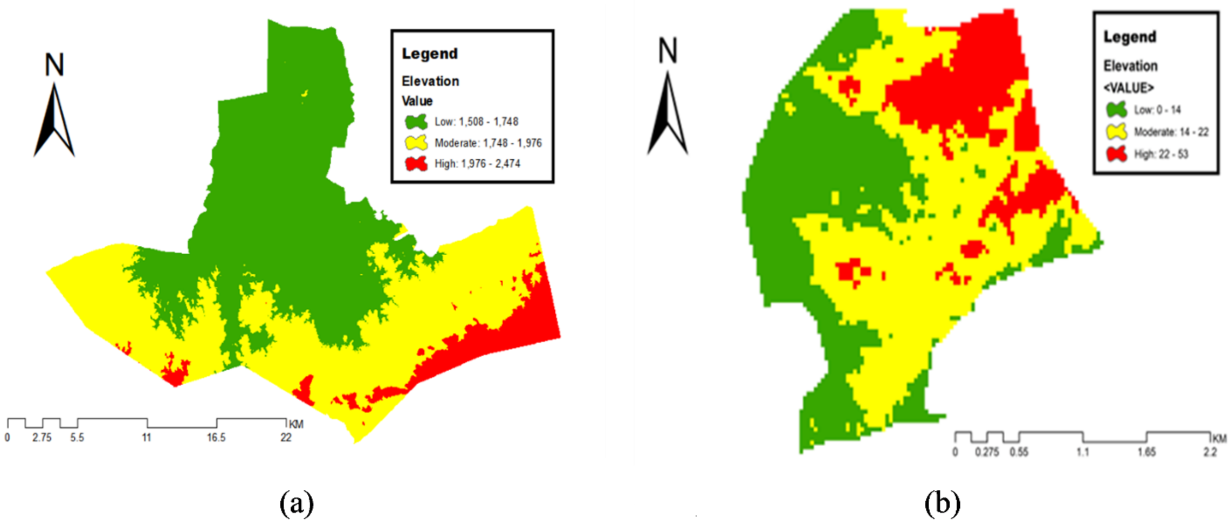



**Figure 2.** (a) Windhoek and (b) Accra's elevation map.

Windhoek's topography is characterized by hilly terrain within the Khomas Highlands, low annual rainfall (~360 mm), and frequent drought conditions [34]. Its population, estimated at approximately 475,000 in 2023, has grown rapidly, resulting in outward low-density expansion and settlement on marginal land. Accra exhibits a humid tropical climate with mean annual rainfall exceeding 780 mm and a much higher population density (~2.5 million in 2023) [35]. Urban growth in Accra is predominantly compact and vertical, shaped by coastal constraints and peri-urban expansion. In both cities, rapid rural–urban migration, informal settlements, and socio-economic inequality strongly influence resilience outcomes.

Hazards in Windhoek are dominated by water scarcity, droughts, and episodic flash floods, whereas Accra is primarily affected by flooding, fire outbreaks, and coastal erosion [36,37]. These risks are exacerbated by informal housing, inadequate drainage infrastructure, and weak urban management. Over the past three decades, hazard intensity in both cities has increased due to climatic variability, land-use conversion, and demographic pressure. Together, these characteristics position Windhoek and Accra as representative cases for examining the relationship between urban growth, vulnerability, and resilience in sub-Saharan Africa (Table 1).

**Table 1.** Comparative characteristics of Windhoek and Accra.

| Feature | Windhoek (Namibia) | Accra (Ghana) |
|---|---|---|
| Coordinates | 22°34′S, 17°05′E | 5°33′N, 0°12′W |
| Elevation | 1,650 m | 0–100 m |
| Area ($km^2$) | 645 | 225 |
| Climate type | Semi-arid (BSh) | Tropical wet-dry (Aw) |
| Estimated population | ~475,000 | ~2,500,000 |
| Main hazards | Droughts, floods | Floods, fires, erosion |
| Growth pattern | Outward low-density sprawl | Compact infill and vertical growth |

Despite marked differences in climate, population scale, spatial morphology, and biophysical setting, the two cities are analytically comparable because they represent dominant African urbanization trajectories: Arid, low-density expansion (Windhoek) and humid, high-density coastal urbanization (Accra). Their contrasts enable comparative learning through harmonized vulnerability indicators, SDG-aligned urban metrics, and standardized settlement-level variables derived from national statistics. This approach ensures methodological comparability while accounting for contextual variation.

*2.2. Analytical framework*

The study adopted a comparative mixed-methods design integrating geospatial, statistical, and qualitative analyses to examine the nexus between urban growth and vulnerability. A three-phase analytical framework was applied: (1) Spatio-temporal analysis of urban expansion, (2) assessment of vulnerability to natural and human-induced hazards, and (3) evaluation of policy and institutional frameworks for urban resilience. This structure enabled triangulation across datasets and perspectives, enhancing analytical robustness [38]. The temporal scope spans 1993–2023, corresponding to major policy reforms and accelerated urban transitions in both cities.

An integrated dataset combining satellite imagery, socio-economic data, hazard records, and policy documents was used. Landsat 5 TM, Landsat 8 OLI/TIRS, and Sentinel-2 MSI imagery (30 m resolution) were obtained from the USGS Earth Explorer for 1993, 2003, 2013, and 2023. Socio-economic data were sourced from the Namibia Statistics Agency (NSA, 2024) and Ghana Statistical Service (GSS, 2024). Hazard data were compiled from the Namibia Disaster Risk Atlas (2020) and the Ghana Flood Hazard Assessment (2022). Policy sources included the Windhoek Urban Structure Plan (2020–2040) and the Accra Metropolitan Development Strategy (2019–2035). All datasets were spatially harmonized to municipal boundaries for Windhoek (~645 $km^2$) and Accra (~225 $km^2$) to ensure consistency in area-of-interest (AOI) delineation.

Land use/land cover (LULC) classification was conducted using a supervised Maximum Likelihood approach in ArcGIS Pro 3.2 and Google Earth Engine. Four classes—built-up areas, vegetation, bare land, and water bodies—were consistently applied across all epochs. Training samples were derived from high-resolution Google Earth imagery and 2023 field verification points. Independent test samples (≥20%) supported accuracy assessment using confusion matrices, overall accuracy, and Kappa coefficients. All classifications achieved accuracies ≥85%, meeting recommended thresholds for urban LULC mapping [39]. Post-classification comparison enabled temporal change detection.

Spatial metrics were computed using FRAGSTATS 4.2, including patch density, edge density, landscape shape index, policy cohesion, and fragmentation metrics to quantify urban morphological change [40]. Urban expansion dynamics were measured using the annual urban expansion rate (AUER), urban density index (UDI), and built-up area extent. SDG 11.3.1 indicators—land consumption rate (LCR) and population growth rate (PGR)—were recalculated using UN-Habitat standard formulas to ensure analytical consistency.

A total of 390 household surveys (195 per city) were administered using a structured quota sampling approach to ensure proportional representation across structured, semi-structured, and unstructured settlements (Table 2). Quotas were equally distributed across settlement types (65 per category per city). Sampling followed Cochran's formula at a 95% confidence level and 5% margin of error. In addition, 10 institutional key informant interviews (five per city) were purposively selected based on institutional relevance and information power. The qualitative component focused on governance interpretation rather than household-level comparison, making the sample fit-for-purpose within comparative urban studies.

**Table 2.** Spatial classification of study communities in Africa.

| African continent | Study communities | Spatial organization |
|---|---|---|
| Namibia | Windhoek: | Expansion: |
| | • Klein Windhoek | • Structured (formal) settlement |
| | • Katutura | • Semi-structured (semi-formal) settlement |
| | • Goreangab | • Unstructured (informal) settlement |
| Ghana | Accra: | Rapid expansion: |
| | • East Legon | • Structured (formal) settlement |
| | • Nima | • Semi-structured (semi-formal) settlement |
| | • Old Fadama | • Unstructured (informal) settlement |

The social vulnerability index (SVI) was constructed from the 390 household surveys using a three-step process: (1) Identification and weighting of vulnerability indicators; (2) multiplication of each weight by response frequency ($x_i \times n_i$); and (3) aggregation of weighted scores to generate a composite vulnerability index (CVI). The study applied the simple additive formula:

$$SVI = \sum (x_i \times n_i) \quad (1)$$

Indicators were grouped under exposure (e.g., flood-prone areas, drought severity, fire incidence), sensitivity (e.g., informal housing, income inequality, dependency ratios), and adaptive capacity (e.g., emergency access, water security, institutional readiness) [41]. Indicators were normalized using min–max scaling and weighted equally, with robustness tested through sensitivity analysis using ±20% weight perturbations and tornado plots. CVI outputs were spatialized using kernel density estimation, and indicator selection was strengthened through the integrated risk linkages (IRL) framework.

Regression analysis and principal component analysis (PCA) were conducted using SPSS 27 and RStudio 4.3.1. Only statistically valid comparisons were reported, with inappropriate city-level p-values excluded. Bootstrapped confidence intervals supported comparison of class-specific change rates. Hazard exposure layers were validated using event-based overlays from historical flood, fire, and drought records, while rank correlation tests assessed consistency between CVI scores and observed hazard densities. Policy documents were analyzed using thematic coding in NVivo 14, with coding reliability enhanced through cross-validation and documented saturation.

Ethical approval was obtained from relevant institutional review boards, and informed consent was secured from all participants. Methodological limitations include the 30 m resolution of historical imagery, boundary inconsistencies, and incomplete hazard records for certain years. These constraints were mitigated through data harmonization, triangulation, and sensitivity testing, as summarized in Figure 3. The next section presents the results, detailing spatio-temporal urban growth patterns, vulnerability profiles, and policy performance across Windhoek and Accra.

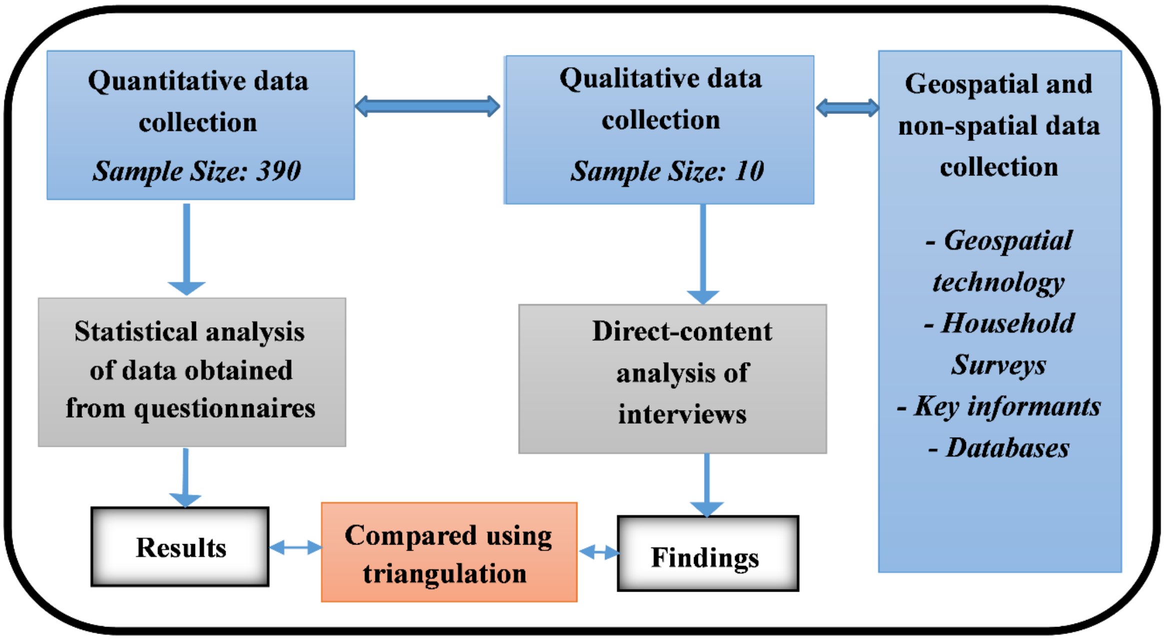



**Figure 3.** Analytical framework linking urban growth, vulnerability, and SDG 11.

## 3. Results

Having instated the analytical framework, this section presents the empirical results on urban growth patterns and vulnerability to hazards in Windhoek and Accra. The results are structured around thematic components derived from the study objectives and integrate spatial, socio-economic, and institutional evidence to reveal interconnections between urban expansion, hazard exposure, and resilience pathways. Quantitative geospatial outputs are synthesized with demographic and governance indicators to demonstrate how land-use transitions and population dynamics shape adaptive capacity. The section begins with spatial growth trends, followed by refined assessments using FRAGSTATS-derived metrics and UN SDG 11.3.1 indicators, establishing the spatial foundation for subsequent vulnerability analysis.

### *3.1. Urban growth trends*

This subsection addresses the first research objective and is guided by the research question: "*What are the current urban growth patterns and their spatial distribution trends over the past 30 years in the study areas?*" Multi-temporal Landsat imagery for 1993, 2003, 2013, and 2023 was classified using a supervised maximum-likelihood algorithm to derive four land use/land cover (LULC) classes: Built-up areas, grassland/vegetation, bare land, and water bodies. Classification reliability was confirmed using confusion matrices, overall accuracy, and Kappa coefficients, ensuring robust temporal comparability. The resulting spatial datasets (Figures 4 and 5) reveal contrasting urbanization trajectories, with Windhoek exhibiting progressive outward expansion along peri-urban margins—particularly the northern and western corridors—while Accra demonstrates dense infill development combined with radial outward growth within the Accra Metropolitan Area (AMA).

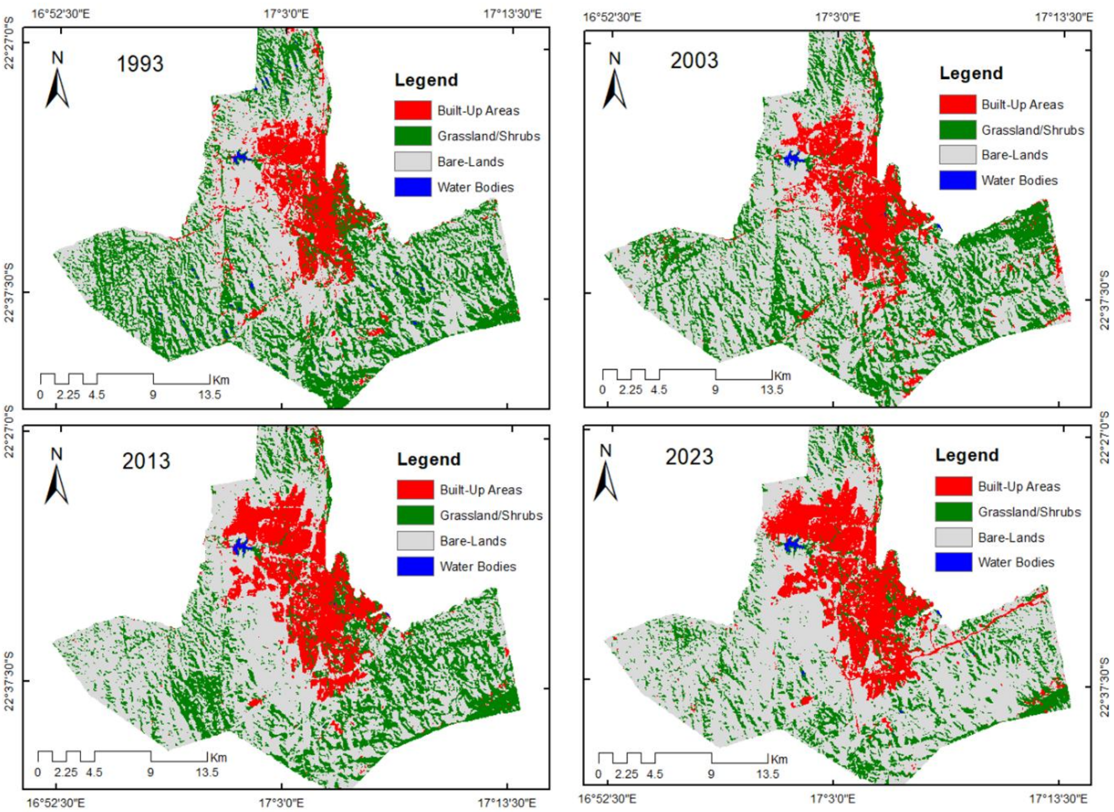



**Figure 4.** Time-series LULC change map of Windhoek 1993–2023.

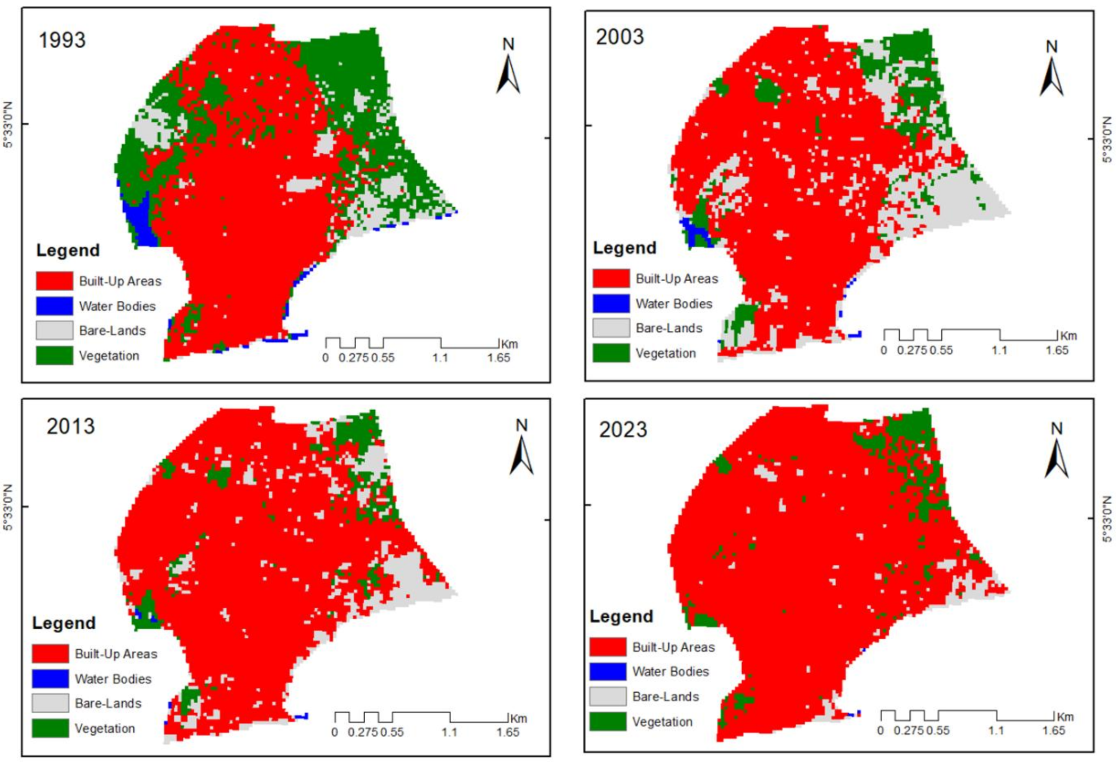



**Figure 5.** Time-series LULC change map of Accra 1993–2023.

These spatial patterns are reinforced by the transition probability matrices (Tables 3 and 4), which quantify land-cover conversions over the 1993–2023 period. In Windhoek, 77.6% of built-up land remained stable, while 13.1% of bare land and 6.8% of grassland transitioned into urban use, reflecting gradual and selective land conversion. Accra retained 97.4% of its built-up areas, with markedly higher conversion rates from grassland (74.7%) and bare land (82.1%) into urban land, signaling intensive and consolidated urban expansion. Land-cover statistics in Table 5 further confirm these trends, with Windhoek's built-up area increasing from 14.2% to 18.2% between 1993 and 2023, while Accra's urban footprint expanded sharply from 66.2% to 88.7% over the same period. The corresponding decline in vegetation, bare land, and water bodies—particularly pronounced in Accra—highlights the intensity of land consumption associated with rapid urbanization.

**Table 3.** Transition probability matrix for Windhoek (pixel in %), 1993–2023.

| | Initial state | Built-up areas | Grassland | Bare-land | Water bodies | Row total | Class total |
|---|---|---|---|---|---|---|---|
| Final state | Built-up areas | 77.644 | 6.781 | 13.071 | 0 | 100 | 100 |
| | Grassland | 4.309 | 41.171 | 3.728 | 68.869 | 100 | 100 |
| | Bare-land | 17.938 | 51.902 | 83.176 | 0.212 | 100 | 100 |
| | Water bodies | 0.108 | 0.145 | 0.025 | 30.919 | 100 | 100 |
| | Class total | 100 | 100 | 100 | 100 | 0 | 0 |
| | Class changes | 22.356 | 58.829 | 16.824 | 69.081 | 0 | 0 |
| | Image difference | 59.242 | −50.755 | 20.518 | −51.715 | 0 | 0 |

**Table 4.** Transition probability matrix for Accra (pixel in %), 1993–2023.

| | Initial state | Built-up areas | Grassland | Bare-land | Water bodies | Row total | Class total |
|---|---|---|---|---|---|---|---|
| Final state | Built-up areas | 97.394 | 74.655 | 82.092 | 60.284 | 100 | 100 |
| | Grassland | 1.068 | 20.155 | 5.071 | 16.312 | 100 | 100 |
| | Bare-land | 1.537 | 5.191 | 12.837 | 20.567 | 100 | 100 |
| | Water bodies | 0 | 0 | 0 | 2.837 | 100 | 100 |
| | Class total | 100 | 100 | 100 | 100 | 0 | 0 |
| | Class changes | 2.606 | 79.845 | 87.163 | 97.163 | 0 | 0 |
| | Image difference | 48.332 | −74.544 | −58.32 | −97.163 | 0 | 0 |

**Table 5.** Urban LULC composition over the past 30 years (pixel in %).

| Land category | Windhoek LULCC | | | Accra LULCC | | |
|---|---|---|---|---|---|---|
| | 1993–2003 | 2003–2013 | 2013–2023 | 1993–2003 | 2003–2013 | 2013–2023 |
| Built-up areas | 14.2 | 15.7 | 18.2 | 66.2 | 79.1 | 88.7 |
| Grassland | 30.1 | 26.5 | 17.1 | 10.6 | 7.3 | 7.1 |
| Bare-land | 55.5 | 57.6 | 64.5 | 22.4 | 13.4 | 4.1 |
| Water bodies | 0.2 | 0.2 | 0.2 | 0.8 | 0.2 | 0.1 |
| Class total | 100 | 100 | 100 | 100 | 100 | 100 |

To refine spatial interpretation beyond areal change, FRAGSTATS-derived landscape metrics and urban growth indicators were applied (Table 6). Edge density, patch density, patch cohesion, and landscape shape index values reveal distinct urban morphologies. Windhoek records higher edge density (42.6 m/ha), patch density (6.8 patches per 100 ha), and landscape shape index (1.87), indicating fragmented, low-density expansion with increasingly irregular urban edges characteristic of outward sprawl facilitated by land availability. By contrast, Accra exhibits substantially higher patch cohesion (94.6%) and a lower landscape shape index (1.34), reflecting a compact and physically connected urban form shaped by infill densification and limited land availability. These spatial metrics corroborate the visual patterns observed in Figure 6 and support the interpretation of structurally different growth processes.

**Table 6.** FRAGSTATS-derived landscape metrics and urban growth indicators (1993–2023).

| Metric (average) | Windhoek | Accra |
|---|---|---|
| Edge density (m/ha) | 42.6 | 27.4 |
| Patch density (patches/100 ha) | 6.8 | 3.1 |
| Patch cohesion index (%) | 82.3 | 94.6 |
| Landscape shape index | 1.87 | 1.34 |
| Annual urban expansion rate (%) | 2.1 | 3.6 |
| Urban density index | 0.42 | 0.78 |
| Land consumption rate ($km^2$/year) | 1.28 | 0.81 |
| Population growth rate (%/year) | 4.53 | 2.87 |
| LCR/PGR (SDG 11.3.1) | 0.28 | 0.24 |

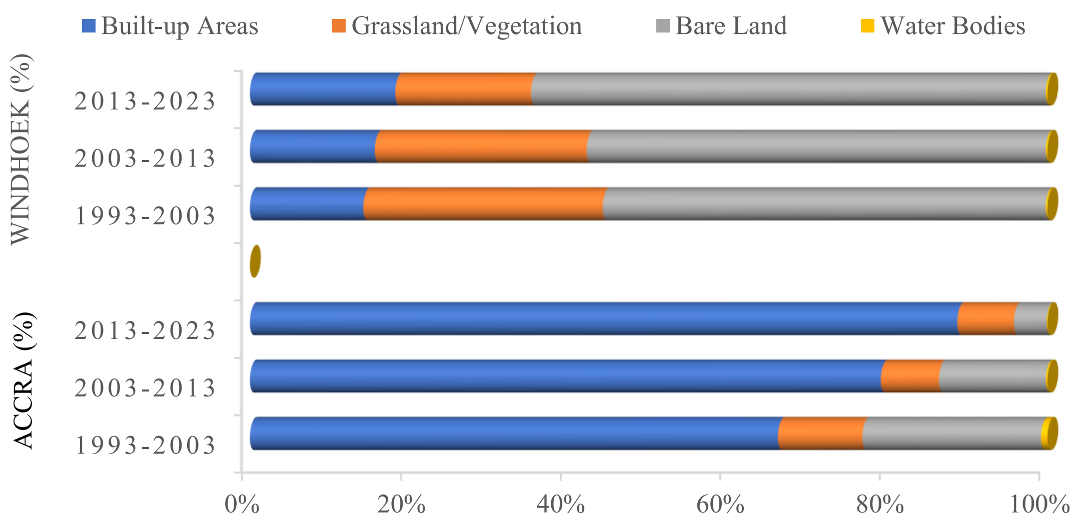



**Figure 6.** Comparative LULC change detection statistics for 30 years.

Urban expansion indicators consistent with UN SDG 11.3.1 further contextualize these spatial patterns. As presented in Table 7, Windhoek's land consumption rate increased modestly from 1.24 $km^2$/year in 1993–2003 to 1.30 $km^2$/year in 2013–2023, while its population growth rate declined from 5.75% to 3.83% per year. This produced an average LCR/PGR ratio of 0.28, indicating that land consumption remained broadly proportional to population growth over the study period. Accra, by contrast, exhibits lower absolute land consumption rates, ranging from 0.48 to 0.93 $km^2$/year, reflecting spatial constraints and reliance on infill development. However, population growth rates remained substantial relative to available land, yielding an average LCR/PGR ratio of 0.24. Although numerically efficient under SDG 11.3.1, this pattern reflects intense land-use pressure within a saturated urban fabric rather than expansive growth.

Population dynamics presented in Table 8 reinforce these findings. Windhoek's population increased from approximately 160,000 in 1993 to 477,000 in 2023, while Accra's population doubled from 1.32 million to 2.66 million over the same period. The correlation between population growth and land consumption is stronger in Windhoek ($R^2 = 0.86$) than in Accra ($R^2 = 0.63$), underscoring the moderating role of planning and governance in shaping urban form. Land conversion statistics in Table 9 show that Windhoek's built-up area expanded from 44.5 $km^2$ to 68.6 $km^2$, reflecting outward, low-density expansion facilitated by extended administrative boundaries and undeveloped peripheral land. Accra's built-up area increased from 24.3 $km^2$ to 34.3 $km^2$, a smaller absolute change occurring within a tightly constrained spatial envelope, confirming that urban growth was achieved primarily through intensive land use rather than spatial expansion.

**Table 7.** Urbanization progress in two African cities (1993–2023) under SDG 11.3.1.

| | Windhoek | | | Accra | | |
|---|---|---|---|---|---|---|
| Years | LCR ($km^2$/yr) | PGR (%/yr) | LCR/PGR | LCR ($km^2$/yr) | PGR (%/yr) | LCR/PGR |
| 1993–2003 | 1.24 | 5.75 | 0.22 | 0.93 | 3.42 | 0.27 |
| 2003–2013 | 1.11 | 3.69 | 0.30 | 0.48 | 2.35 | 0.20 |
| 2013–2023 | 1.30 | 3.83 | 0.34 | 0.52 | 2.12 | 0.25 |
| Average | 1.22 | 4.42 | 0.28 | 0.64 | 2.63 | 0.24 |

**Table 8.** Urban population dynamics over 30 years.

| Years | Windhoek size (N) | Growth rate (%) | Accra size (N) | Growth rate (%) |
|---|---|---|---|---|
| 1993 | 160,000 | 5.26 | 1,324,000 | 3.44 |
| 2003 | 252,000 | 3.28 | 1,777,000 | 2.13 |
| 2013 | 345,000 | 2.99 | 2,195,000 | 2.14 |
| 2023 | 477,000 | 3.47 | 2,660,000 | 2.11 |

**Table 9.** Land conversion for urban use in Windhoek and Accra (1993–2023).

| | Windhoek | | Accra | |
|---|---|---|---|---|
| Years | Built-up area ($km^2$) | Built-up area (%) | Built-up area ($km^2$) | Built-up area (%) |
| 1993–2003 | 44.5 | 24.2 | 24.3 | 10.8 |
| 2003–2013 | 55.6 | 10.2 | 29.1 | 19.5 |
| 2013–2023 | 68.6 | 16.5 | 34.3 | 12.1 |
| Average | 56.2 | 17.0 | 29.2 | 14.1 |

Net land-cover change analysis (Table 10) demonstrates that Windhoek followed a fluctuating but steadily increasing urbanization trajectory, while Accra experienced consistently high-intensity land conversion. Statistical testing confirms that these inter-city differences are significant ($p < 0.05$), indicating structurally distinct growth pathways rather than random variation. Taken together, the integrated interpretation of LULC transitions, FRAGSTATS metrics, and SDG 11.3.1 indicators demonstrate two contrasting urban growth models. Windhoek follows a fragmented, low-density expansion pathway enabled by peripheral land reserves, whereas Accra exhibits compact, highly saturated growth driven by demographic pressure and spatial constraint. While both cities appear relatively efficient in SDG 11.3.1 terms, Accra's compactness reduces ecological buffers and intensifies exposure to urban hazards, whereas Windhoek's sprawl expands exposure through spatial dispersion. These contrasting spatial dynamics establish the empirical foundation for understanding differential vulnerability patterns examined in subsequent sections.

**Table 10.** Net changes in urban land-cover classes over 30 years (pixel in %).

| Land category | Windhoek LULCC | | | Accra LULCC | | |
|---|---|---|---|---|---|---|
| | 1993–2003 | 2003–2013 | 2013–2023 | 1993–2003 | 2003–2013 | 2013–2023 |
| Built-up areas | 24.2 | 10.2 | 16.5 | 10.8 | 19.5 | 12.1 |
| Grassland/vegetation | –13.1 | –11.6 | –35.9 | –62.3 | –31.2 | –1.7 |
| Bare-land | 3.7 | 3.8 | 12.1 | 12.8 | 9.4 | 6.9 |
| Water bodies | –51.9 | 0.5 | 0 | –66.0 | –68.8 | –73.3 |
| Class total | 100 | 100 | 100 | 100 | 100 | 100 |

### *3.2. Hazard vulnerability*

The second objective of this study—to assess the implications of urban growth for vulnerability to natural and human-induced hazards—is addressed in this section. The analysis responds directly to the research question: "*How does the impact of urban growth affect the vulnerability to various types of hazards in the study areas?*" Results are derived from integrated geospatial and empirical evidence, including multi-temporal Landsat imagery (1993–2023), DEM-based terrain analysis, socio-economic indicators, and household survey data (n = 390). Consistent with the methodological framework, findings are structured around land-use change, physical exposure, socio-economic sensitivity, and adaptive capacity, operationalized through the SVI.

Urban growth in Windhoek and Accra shows pronounced spatial expansion with direct implications for hazard exposure (Table 11). Between 1993 and 2023, built-up areas increased by 59.2% in Windhoek and 48.3% in Accra, while grassland/vegetation and water bodies declined sharply—by 50.8% and 51.7% in Windhoek and by 74.5% and 97.2% in Accra, respectively. These shifts reflect extensive conversion of natural surfaces into impervious land cover, intensifying exposure to flooding, heat stress, erosion, and water scarcity. In Accra, the near-complete loss of water bodies indicates sustained encroachment into riparian and lagoon systems, reducing drainage retention capacity and increasing surface runoff. The ecological footprint associated with these LULC transitions therefore reinforces the relationship between rapid urban expansion and escalating hazard vulnerability.

Topographic and geomorphological conditions further shape these exposure patterns. As summarized in Table 12, Windhoek's high elevation (1508–2474 m) and steep slopes (>17%) limit horizontal expansion but heighten susceptibility to drought, erosion, and slope instability, particularly in peri-urban settlements occupying marginal land. In contrast, Accra's very low elevation (0–53 m), gentle slopes (<4%), and predominantly concave terrain promote runoff accumulation and water stagnation, substantially increasing flood susceptibility. These findings confirm the central role of physical landscape characteristics in determining both the type and spatial distribution of hazards across the two cities.

**Table 11.** Ecosystems disturbance within LULC categories (1993–2023).

| Ecological footprint and annual rate of change (1993–2023) | | | |
|---|---|---|---|
| Years | LULC class | Windhoek class status (%) | Accra class status (%) |
| 1993–2003 | Built-up areas | 24.1 | 10.8 |
| | Grassland/vegetation | −13.1 | −62.3 |
| | Bare-land | 3.7 | 28.2 |
| | Water bodies | −51.9 | −66.0 |
| 2003–2013 | Built-up areas | 10.2 | 19.5 |
| | Grassland/vegetation | −11.6 | −31.2 |
| | Bare-land | 4.7 | −40.4 |
| | Water bodies | 0.4 | −68.8 |
| 2013–2023 | Built-up areas | 16.4 | 12.1 |
| | Grassland/vegetation | −35.9 | −1.7 |
| | Bare-land | 12.1 | −69.4 |
| | Water bodies | 0 | −73.3 |
| 1993–2023 | Built-up areas | 59.2 | 48.3 |
| | Grassland/vegetation | −50.8 | −74.5 |
| | Bare-land | 20.5 | −58.3 |
| | Water bodies | −51.7 | −97.2 |

**Table 12.** Geomorphological implications on urban hazard vulnerability classification.

| Digital elevation model for urban landscape | | | |
|---|---|---|---|
| Description class | Standard classification scheme | Windhoek classification scheme | Accra classification scheme |
| Elevation: | | | |
| Low | 0–200 meters | 1508–1748 meters | 0–14 meters |
| Moderate | 200–1000 meters | 1748–1976 meters | 14–22 meters |
| High | Above 1000 meters | 1976–2474 meters | 22–53 meters |
| Slope: | | | |
| Low | 0%–5% | 0%–7.9% | 0%–2.2% |
| Moderate | 5%–15% | 7.9%–17.0% | 2.2%–4.3% |
| High | Above 15% | 17.0%–56.1% | 4.3%–24.0% |
| Aspect: | | | |
| North-East | 315°–135° | −1°–119° | −1°–119° |
| South | 135°–225° | 119°–240° | 119°–238° |
| West | 225°–315° | 240°–360° | 238°–356° |
| Curvature: | | | |
| Concave | −∞ to < −0.01/(−) | <−143 to −5 million | <−27 to −2 million |
| Flat | −0.01 to 0.01/(0) | −5 to 4 million | −2 to 2 million |
| Convex | > 0.01 to ∞/(+) | > 4 to 133 million | > 2 to 62 million |

Temporal hazard trends align closely with observed urban expansion. Table 13 shows that Windhoek is predominantly affected by recurrent droughts and episodic flash floods, whereas Accra experiences higher hazard frequency, dominated by floods, fires, and structural failures. Hazard events increased across successive decades, reflecting rising population exposure, inadequate infrastructure—particularly drainage—and continued settlement encroachment into hazard-prone zones. These trends are especially pronounced in dense informal settlements and low-lying areas.

Socio-economic conditions further amplify vulnerability by shaping household sensitivity and coping capacity. As shown in Table 14, high poverty levels, informal settlement prevalence, unemployment, and unequal access to basic services increase vulnerability in both cities. Windhoek exhibits high youth unemployment (20.6%) and undernourishment (18.0%), indicating structural sensitivity to shocks, while Accra's low access to piped water (41.1%) and compact settlement patterns intensify exposure to flooding, sanitation-related risks, and fire outbreaks.

**Table 13.** Hazard occurrence trends in Windhoek and Accra (1993–2023).

| | Windhoek | | Accra | |
|---|---|---|---|---|
| Period | Dominant hazard events | Approx. frequency | Dominant hazard events | Approx. frequency |
| 1993–2003 | Seasonal droughts; minor flash floods | 4–6 events | Major floods (1995); localized fires | 10–14 events |
| 2003–2013 | 2011 flash floods; multi-year droughts | 7–10 events | 2012 Melcom collapse; severe floods | 15–20 events |
| 2013–2023 | 2017/2021 droughts; 2021 flood | 8–12 events | 2015 floods and fire; 2023 spillage floods | 20–25 events |

**Table 14.** UN-SDG socio-economic indicators for Windhoek and Accra (2023).

| SDG | Socio-economic vulnerability | Windhoek (%) | Accra (%) |
|---|---|---|---|
| 1 | Poverty headcount ratio at $2.15–$3.65 per day | 15.9–28.8 | 20.1–32.8 |
| 2 | Prevalence of undernourishment | 18.0 | 4.1 |
| 3 | Traffic deaths (per 100,000 population) | 34.8 | 25.7 |
| 7 | Population with access to electricity | 56.3 | 85.9 |
| 8 | Youthful unemployment rate | 20.6 | 3.9 |
| 11 | Proportion of urban population living in slums | 41.4 | 33.5 |
| 11 | Access to improved water source, piped (% of urban resident) | 96.9 | 41.1 |
| 16 | Population who feel safe walking alone at night in the city | 41.0 | 60.0 |
| 17 | Government spending on health and education (% of GDP) | 14.0 | 5.9 |

Household-level vulnerability was quantified using the SVI, which integrates demographic, socio-economic, and adaptive capacity indicators (Table 15). Based on weighted survey responses (n = 390), Windhoek recorded a moderate SVI score of 0.46, while Accra recorded a higher score of 0.54 (Table 16), indicating comparatively weaker coping capacity in Accra. These results are consistent with the higher frequency and diversity of hazards observed in Accra. Notably, 82.6% of Windhoek respondents and 80.0% of Accra respondents reported direct experience of hazard impacts (model in Figure 7), underscoring widespread exposure across socio-economic groups.

**Table 15.** SVI indicator dimensions, assigned weights, and descriptions.

| Dimension and category | Weights (x) | Description |
|---|---|---|
| Gender: | | |
| Male/Female | 0.3–0.7 | Female-headed households more sensitive to shocks |
| Age: | | |
| Youth/Adult/Elderly | 0.3–0.7 | Youth and elderly more vulnerable |
| Household size: | | |
| 1–6+ | 0.1–0.7 | Larger households strain resources |
| Housing status: | | |
| Owner/Renter/Public | 0.3–0.7 | Renters have lower adaptive capacity |
| Education: | | |
| None–tertiary | 0.1–0.7 | Low education reduces coping skills |
| Economic activity: | | |
| Employed–retired | 0.1–0.7 | Unemployed/retired more vulnerable |
| Income level: | | |
| High–below poverty | 0.1–0.7 | Low income increases sensitivity |
| Living expenses: | | |
| Food, education, transport | 0.3–0.7 | High expenses reduce resilience |
| Social interaction: | | |
| Years in community | 0.1–0.7 | Low integration increases vulnerability |

**Table 16.** Demographic and socio-economic vulnerabilities.

| | Windhoek | | Accra | |
|---|---|---|---|---|
| Indicators and dimension | N = (x * n) | % = (x * n) | N = (x * n) | % = (x * n) |
| Gender: | | | | |
| Female-headed households more sensitive to shocks | 73.7 | 12.4 | 77.3 | 11.2 |
| Age: | | | | |
| Youth and elderly more vulnerable | 93.7 | 15.8 | 92.3 | 13.4 |
| Household size: | | | | |
| Larger households strain resources | 68.5 | 11.6 | 54.7 | 7.9 |
| Housing status: | | | | |
| Renters have lower adaptive capacity | 67.1 | 11.3 | 85.7 | 12.4 |
| Education: | | | | |
| Low education reduces coping skills | 38.5 | 6.5 | 62.9 | 9.1 |
| Economic activity: | | | | |
| Unemployed/retired more vulnerable | 34.1 | 5.8 | 59.7 | 8.7 |
| Income level: | | | | |
| Low income increases sensitivity | 62.1 | 10.5 | 91.9 | 13.3 |
| Living expenses: | | | | |
| High expenses reduce resilience | 94.2 | 15.9 | 88.9 | 12.9 |
| Social interaction: | | | | |
| Low integration increases vulnerability | 61.1 | 10.3 | 76.1 | 11.0 |
| Total SVI | 593 (0.46) | 46.2 | 689.5 (0.54) | 53.8 |

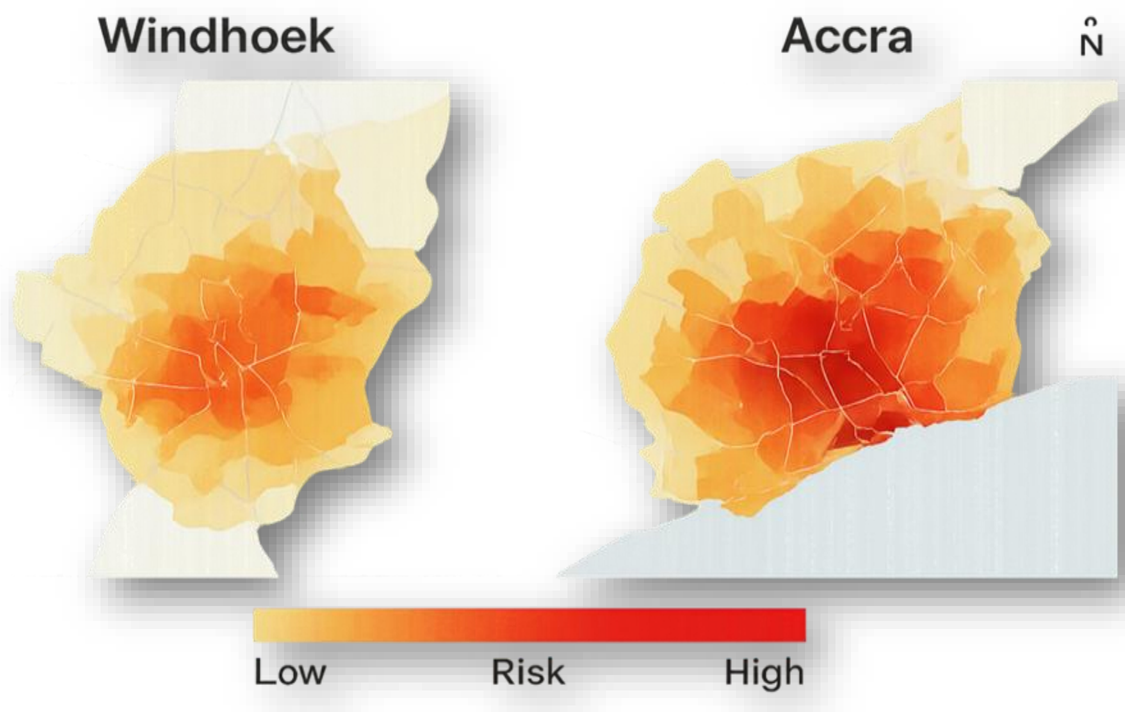


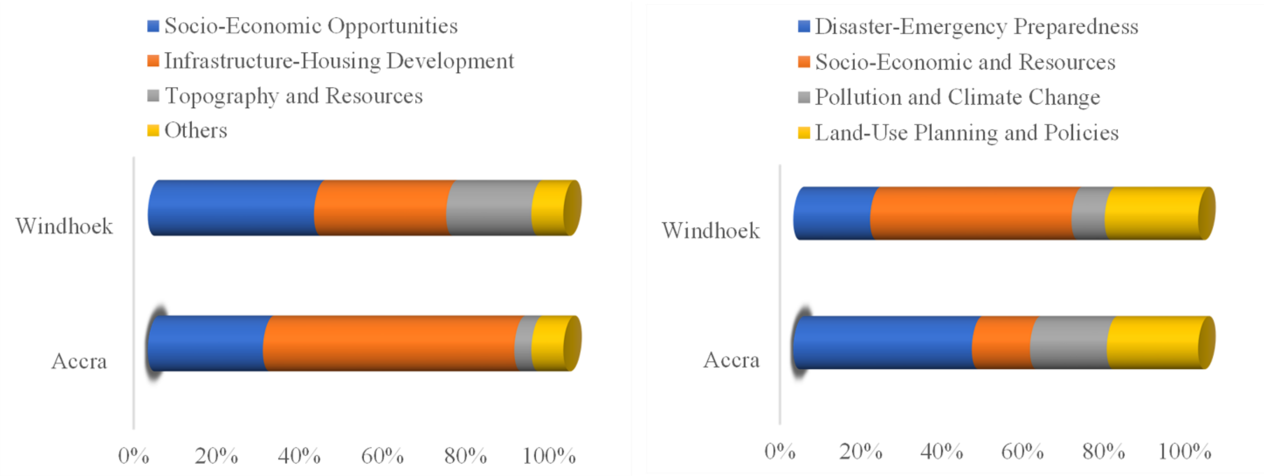

**Figure 7.** Hazards exposure frequencies in Windhoek and Accra.

The SVI results further reveal distinct vulnerability pathways. Windhoek's moderate vulnerability reflects terrain constraints, income inequality, and limited adaptive options, whereas Accra's higher vulnerability is driven by dense settlement patterns, limited water access, and repeated exposure to multiple hazards (Figure 7). These interactions between social conditions and spatial exposure demonstrate how urban growth processes translate into differentiated vulnerability outcomes.

Overall, the integrated geospatial, socio-economic, and index-based analyses show that urban growth has significantly increased hazard vulnerability in both cities, albeit through context-specific mechanisms. Windhoek's vulnerability is shaped primarily by arid topography and elevation-related constraints, while Accra's vulnerability is intensified by low-lying terrain, hydrological modification, and high exposure frequency. These results establish a robust empirical foundation for interrogating why these vulnerability patterns emerge in the subsequent section 3.3.

### *3.3. Underlying drivers*

Having analyzed the rate and patterns of urban growth and their implications for multiple hazard types, this section addresses the research question: "*What are the underlying factors that shape urban growth patterns and vulnerability to hazards in the study areas?*" The results integrate quantitative statistical outputs with lived-experience narratives derived from household surveys and key-informant interviews. Findings are structured around two interrelated dimensions: respondents' socio-economic and institutional drivers and physical–geomorphological drivers, with Figure 8 illustrating the dominant perceived determinants of land-use change and hazard vulnerability across the two cities.




(a) (b)

**Figure 8.** Respondents' drivers of (a) urban growth (LULC) and (b) hazard vulnerability types.

Survey results indicate that socio-economic and infrastructural factors dominate household interpretations of urban growth processes. As shown in Figure 8a, 40.0% of respondents in Windhoek identified socio-economic opportunities—particularly employment access and housing affordability—as the primary driver of urban expansion, whereas 60.5% of respondents in Accra attributed land-use change mainly to infrastructure-led housing development. These perceptions are supported by statistical modelling results, where multivariate regression analysis revealed population density ($\beta = 0.48$, $p < 0.01$) and proximity to major road infrastructure ($\beta = -0.36$, $p < 0.05$) as significant predictors of built-up land expansion across both cities. Principal component analysis further confirms these findings, with the first component (PC1) explaining 42.3% of total variance and loading strongly on population pressure, housing demand, and infrastructure accessibility, indicating that internal socio-economic dynamics are the dominant forces shaping spatial expansion trajectories.

Household assessments of hazard vulnerability (Figure 8b) reveal a differentiated vulnerability profile between the two cities. In Windhoek, 49.7% of respondents identified socio-economic and resource inequalities—particularly water insecurity, high living costs, and inadequate sanitation—as the primary modifiers of hazard risk. In Accra, 44.1% of respondents attributed vulnerability mainly to inadequate emergency disaster services and preparedness, reflecting institutional capacity gaps in flood-prone and densely populated neighborhoods. These perceptions align with regression results linking tenure insecurity ($\beta = 0.41$, $p < 0.01$), household income differentials ($\beta = -0.38$, $p < 0.05$), and limited access to basic services ($\beta = -0.45$, $p < 0.01$) to higher vulnerability scores. Interview narratives reinforce these quantitative patterns, with Windhoek households emphasizing marginalization in peripheral settlements and Accra households describing recurrent flooding, informal drainage adaptations, and reliance on indigenous coping strategies in the absence of formal institutional support.

Although smaller proportions of respondents cited climate change and land-use planning failures as primary drivers, both were consistently recognized as secondary contributors. Driver categorization reveals three interacting classes underpinning observed outcomes: internal drivers (socio-economic, demographic, and infrastructural pressures), external drivers (geomorphological and climatic conditions), and combined drivers reflecting the interaction between human activities and environmental constraints. Overall, urban growth in both cities is predominantly driven by internal socio-economic forces, while hazard vulnerability is amplified by inequality, population pressures, and uneven institutional preparedness.

Demographic dynamics further reinforce these patterns. Population statistics (Table 8) indicate that Windhoek experienced a peak population growth rate of 5.26% (approximately 160,000 persons) during the 1993 period, reflecting rapid post-independence demographic restructuring and outward settlement expansion. Accra's population growth peaked at 3.44% (approximately 1.32 million persons) over the same period, representing a substantially larger absolute increase that intensified densification and infill development. These demographic trajectories contribute to increased exposure in Windhoek's low-lying peripheral settlements and sustained flood sensitivity in Accra's rapidly urbanizing basins. City authority interviews further highlight how historical planning legacies and land governance arrangements continue to shape settlement morphology, reinforcing spatial inequalities and uneven hazard exposure.

To examine the physical constraints interacting with these socio-economic drivers, geomorphological predictors were analyzed alongside land-cover transformation trends. Spatial modelling incorporating elevation, slope, aspect, and curvature (Table 17) reveals that elevation in Windhoek constrains urban expansion, promoting relatively controlled sprawl but increasing exposure to flash flooding in low-lying informal areas. In Accra, higher elevation zones facilitate outward expansion; however, uncontrolled development on low-gradient floodplains intensifies flood exposure. Slope analysis indicates that steeper gradients in Windhoek's periphery contribute to erosion and localized landslide risk, whereas in Accra slope primarily influences runoff velocity and flood intensity during peak rainfall events.

Aspect analysis demonstrates that Windhoek's south- and east-facing slopes support relatively favorable microclimatic conditions for settlement and small-scale agriculture, though prolonged drought conditions persist. In contrast, Accra's aspect conditions contribute to reduced ventilation and poor air circulation in dense settlements, exacerbating environmental discomfort and compounding vulnerability to heat and air-quality-related hazards. Curvature analysis further shows that concave landforms in both cities accumulate runoff, producing waterlogging and drainage failures, particularly in Accra's low-elevation basins and Windhoek's rapidly densifying informal zones.

**Table 17.** Interplay between anthropogenic and geomorphological drivers.

| | Windhoek | | Accra | |
|---|---|---|---|---|
| Predictor | Urban growth effect | Vulnerability effect | Urban growth effect | Vulnerability effect |
| Elevation | + Controlled urban sprawl<br>− Limited expansion | − Flash floods | + Cooler temperatures<br>− Uncontrolled urban sprawl | − Flooding |
| Slope | + Controlled expansion<br>− Surface erosion | − Landslides | + Better drainage<br>− Uncontrolled expansion | − Runoff |
| Aspect | + Favorable micro-climate<br>− Prolonged drought | − Poor air quality | + Supports agriculture<br>− Unfavorable micro-climate | − Ventilation issues |
| Curvature | + Good land use<br>− Waterlogging | − Drainage issues | + Diverse land use<br>− Poor layout | − Drainage issues |

Overall, these results demonstrate that urban growth patterns and vulnerability outcomes are shaped by a strong interaction between internal socio-economic drivers and external geomorphological constraints. Housing expansion, infrastructural development, demographic change, and informal settlement growth interact with terrain characteristics to redistribute hazard exposure spatially. The combined interpretation of territorial and non-territorial data confirms that vulnerability in Windhoek and Accra is not driven by a single factor but emerges from the convergence of socio-economic inequality, institutional capacity, settlement morphology, and environmental conditions over time. The preceding section 3.4 examines how existing policies and institutional strategies respond to these drivers and evaluates their effectiveness in mitigating urban growth-related hazard impacts.

### *3.4. Policy effectiveness*

This section presents empirical results addressing the question: "*How effective existing policies and strategies have been in mitigating the impacts of urban growth on hazards vulnerability in Windhoek and Accra?*" The analysis integrates institutional document review, structured performance evaluation, and respondents' experiential insights, and explicitly compares stated policy objectives with observed urbanization outcomes derived from LULC change patterns, hazard exposure maps, and SVI distributions. Consistent with the methodological framework, policy performance was assessed using pre-intended objectives and post-implementation outcomes across five evaluation criteria—relevance, efficiency, effectiveness, impact, and sustainability (REEIS). The results are summarized quantitatively in Table 18 and synthesized visually in Figure 9.

As shown in Table 18, both cities have adopted a comprehensive suite of policies, plans, programs, and strategies aimed at addressing risks associated with rapid urbanization, climate variability, and hazard exposure. In Windhoek, the National Policy on Climate Change, Fifth National Development Plan (NDP5), Municipal Spatial Development Framework, Disaster Risk Management Policy, and National Housing Policy collectively demonstrate strong policy relevance and strategic alignment with long-term resilience goals. These instruments correspond with observed efforts to regulate urban expansion and promote planned development. However, when compared against observed LULC trends indicating continued peripheral expansion and low-density growth into environmentally sensitive areas, the post-test evaluation reveals implementation gaps, particularly in efficiency and effectiveness. These gaps are reflected in lower weighted scores for infrastructure development (5) and disaster management (6), which correspond spatially with higher SVI values in peripheral and informal settlement zones identified in the results section on vulnerability patterns.

In Accra, the policy framework—including the National Urban Policy Framework, Ghana National Climate Change Policy, Greater Accra Metropolitan Area (GAMA) Sanitation and Water Project, Accra Metropolitan Assembly Development Plan, and NADMO policies—demonstrates comparatively stronger post-implementation performance across multiple criteria (Table 18). Higher weighted scores in urban planning (8), sanitation and water supply (8), disaster management (8), and community engagement (8) align with observed densification trends, improved service coverage in core urban areas, and lower SVI concentrations in zones where sanitation infrastructure and drainage investments have been sustained. These findings suggest a closer correspondence between policy intent and measurable urban and hazard-related outcomes, even though persistent challenges remain in informal settlements and flood-prone low-lying areas.

The weighted comparative assessment in Table 18 quantifies these differences across five thematic areas: urban planning and development, infrastructure development, sanitation and water supply, disaster management, and community engagement. Windhoek attained an overall mean policy effectiveness score of 6.2, while Accra recorded a higher mean score of 7.8. These aggregate scores are visualized in Figure 9, which illustrates the relative distribution of policy performance across the five indicators. The figure shows that Accra outperforms Windhoek in all categories, with the largest performance differentials observed in disaster management, infrastructure provision, and community engagement. These differences are consistent with hazard exposure results, where Accra's stronger disaster preparedness and sanitation investments correspond to relatively lower SVI intensity in serviced areas, despite higher overall exposure to flooding.

**Table 18.** Policy's effectiveness metrics of key areas of comparison summary.

| Indicators | Windhoek's policy metrics | Score | Accra's policy metrics | Score |
|---|---|---|---|---|
| Urban planning and development | *Municipal Spatial Development Framework*<br>Metrics: Structured urban planning is in place, but rapid population growth and informal settlements pose significant challenges. | 7 | *Accra Metropolitan Assembly Development Plan*<br>Metrics: Sustainable urban development efforts have been more effective and organized, despite challenges from rapid urbanization. | 8 |
| Infrastructure development | *National Development Plan*<br>Metrics: Progress in affordable housing exists but is insufficient to meet demand, leading to continued infrastructural strain. | 5 | *National Urban Policy Framework*<br>Metrics: Notable progress in transportation and utilities have been achieved thereby contributing to more sustainable urban growth. | 7 |
| Sanitation and water supply | *National Development Plan 5*<br>Metrics: Mixed success in improving sanitation and water access, with ongoing issues in informal settlements. | 7 | *Greater Accra Metropolitan Area (GAMA) Sanitation and Water Project*<br>Metrics: Significant enhancement in sanitation infrastructure and water supply access, reducing public health risk and environmental pollution. | 8 |
| Disaster management | *Disaster Risk Management Policy*<br>Metrics: Improved disaster response, but resource limitations and logistical challenges hinder full effectiveness. | 6 | *National Disaster Management Organization Policy*<br>Metrics: Strengthened disaster preparedness and response mechanisms, with effective community engagement and risk reduction measures. | 8 |
| Community engagement and public awareness | *National Climate Change Policy*<br>Metrics: Effective urban engagement but limited rural outreach, impacting the widespread adoption of climate-resilient practices. | 6 | *National Urban Policy Framework and NADMO Policy*<br>Metrics: Successful community engagement programs and public awareness campaigns have led to better maintenance of sanitation facilities and increased public involvement in urban management. | 8 |
| Overall Scores: | | (31/5) = 6.2 | | (39/5) = 7.8 |

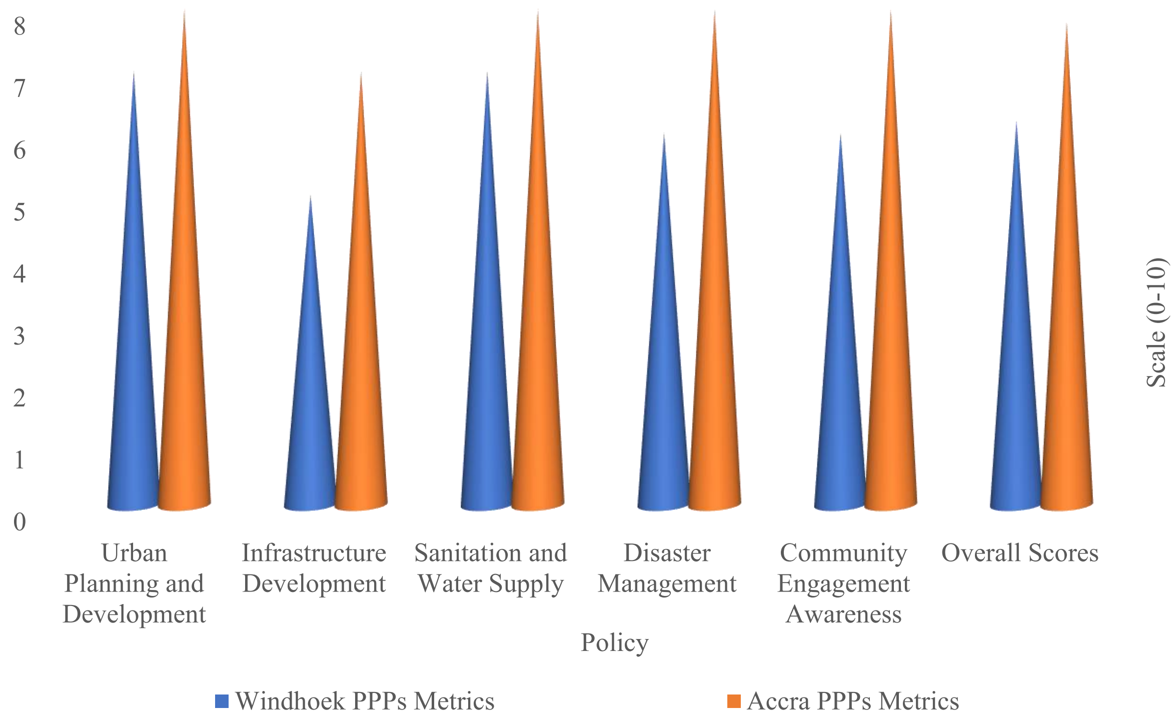



**Figure 9.** Comparative assessment of key performance indicators.

Importantly, the results demonstrate that higher policy effectiveness scores are associated with more favorable hazard mitigation outcomes. In Accra, areas benefiting from sustained infrastructure and sanitation programs show lower composite SVI values and fewer overlaps between high-vulnerability zones and recurrent hazard footprints. In contrast, Windhoek's lower efficiency and effectiveness scores correspond with spatial mismatches between planned development zones and actual urban expansion, resulting in higher vulnerability in rapidly growing peripheral settlements. This alignment between policy performance metrics, LULC trajectories, and SVI patterns strengthens the empirical basis for evaluating institutional effectiveness.

Overall, the findings from Table 18 and Figure 9 indicate that while both cities exhibit measurable progress in addressing the hazards associated with urban growth, Accra's policy framework demonstrates greater consistency between policy objectives and observed outcomes. Windhoek's policies are structurally sound and highly relevant but show slower operationalization, particularly in informal settlement upgrading, resource mobilization, and localized hazard preparedness. These results empirically confirm that policy effectiveness is not determined solely by policy presence, but by the degree to which implementation aligns with evolving urban growth patterns and vulnerability dynamics. The next subsection builds on these findings by synthesizing spatial growth patterns, hazard susceptibility, vulnerability outcomes, and institutional performance to develop an integrated, data-driven framework for sustainable urban development and hazard resilience.

## *3.5. Resilience framework*

Having evaluated the effectiveness of existing policies and strategies, this final results section responds to the question: "*What sustainable urban development framework can effectively mitigate the impact of hazards in cities?*" The framework presented here was empirically derived through the integration of spatial metrics, SVI outputs, hazard overlay analyses, household survey responses, institutional performance scores, and geomorphological suitability assessments generated under the preceding objectives. Figure 10 illustrate the synthesis model emerging from this triangulated evidence base, explicitly linking urban growth trajectories, recurrent hazard exposure pathways, and targeted resilience levers into a structured optimization sequence.

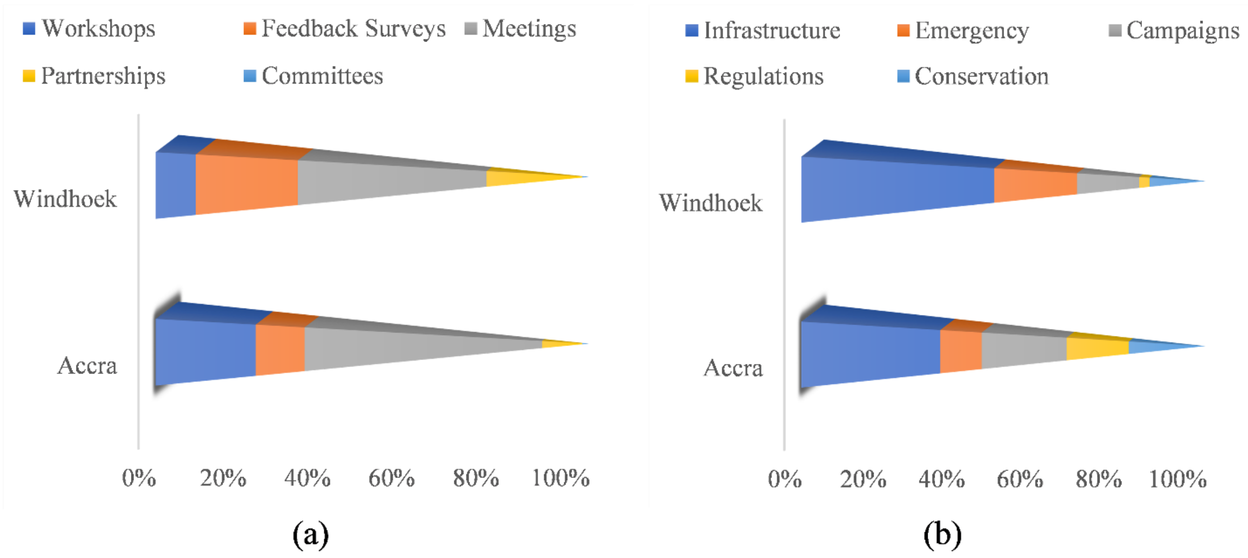



**Figure 10.** Respondents' perspectives on (a) urban resilience and (b) sustainability initiative, integrated with spatial growth and vulnerability clusters.

The empirical derivation of the framework followed three interlinked analytical layers. The first layer—urban growth pressures—was informed by LULC change detection results, spatial growth indicators, demographic trends, and respondent-driven narratives. Across the 1993–2023 period, built-up land expansion rates of approximately 3.2% per annum in Accra and 1.6% per annum in Windhoek, coupled with declining vegetation cover and increasing bare-land conversion, revealed four dominant pressure variables: densification hotspots, peripheral sprawl corridors, infrastructure-deficit zones, and encroachment into hazard-prone land units. Spatial intersection analysis of these variables, illustrated in Figure 10, identified priority intervention zones accounting for approximately 38–42% of newly urbanized areas in Accra and 29–34% in Windhoek, where growth-induced vulnerability scores exceeded the citywide mean SVI by more than one standard deviation.

The second layer—hazard susceptibility patterns—was derived from the multi-dimensional SVI constructed under Objective 2, which integrated exposure, sensitivity, and adaptive capacity indicators related to flooding, drought, fire risk, and socio-economic fragility. The spatial distribution of SVI values revealed distinct vulnerability gradients, with high-to-very-high vulnerability classes (>0.65 on a normalized 0–1 scale) concentrated in low-lying floodplains and informal settlements in Accra, and in peri-urban water-scarce and infrastructure-poor zones in Windhoek. Overlaying these SVI surfaces with urban growth pressure zones revealed three critical risk clusters in each city, collectively accounting for approximately 46% of reported flood incidents in Accra and 41% of drought-related livelihood stress reports in Windhoek, forming the empirical baseline for resilience targeting. These spatial relationships are reflected in the synthesis presented in Figure 10.

The third layer—institutional and policy capacity—was generated from the policy effectiveness scores reported under Objective 4. As previously illustrated in Figure 9, Windhoek demonstrated comparatively higher regulatory coherence and spatial planning alignment (mean score ≈3.7/5), while Accra exhibited stronger performance in project-based hazard mitigation initiatives (mean score ≈3.9/5). However, both cities recorded consistently low scores for community preparedness (≤2.4/5), early warning integration (≤2.2/5), and inter-agency coordination (≤2.5/5). These institutional weaknesses were corroborated by household survey responses, where over 60% of respondents in Accra and 54% in Windhoek reported limited access to hazard information or preparedness training. These low-performing dimensions therefore constitute the operational gaps embedded within the optimization framework.

Synthesizing these three analytical layers resulted in a three-pillar operational resilience framework structured around: risk-sensitive growth management, integrated multi-hazard reduction mechanisms, and adaptive institutional capacity reinforcement. Empirical inputs for the first pillar were derived from geospatial suitability modelling outputs illustrated in Figure 11a, which classified urban land into optimal (approximately 45% of Windhoek's AOI and 32% of Accra's AOI), moderate, and restricted development zones based on slope, hazard exposure, and infrastructure access. For the second pillar, hazard-specific intervention points were extracted directly from SVI maps and respondent-reported vulnerability profiles (Table 18), enabling the spatial prioritization of flood detention basins in Accra's high-density catchments, drought-adaptive land uses in Windhoek's peripheral settlements, and targeted socio-economic support clusters in areas with compounded vulnerability scores. The third pillar operationalized institutional capacity enhancement by sequencing governance improvements around regulatory enforcement, community risk communication, and multi-level coordination platforms, informed by the policy performance gaps identified earlier.

The resulting framework, depicted in Figure 11b, therefore represents a technically grounded, data-driven model that explicitly connects observed growth trends with hazard landscapes and governance capacity, transforming exposure pathways into resilience pathways. It identifies priority spatial zones, operational deficits, and actionable resilience levers, providing an empirically defensible foundation for adaptive urban development planning in both Windhoek and Accra. Implementation implications emerging from the framework indicate differentiated resilience pathways between the two cities. In Windhoek, priority actions focus on informal settlement upgrading, drought-resilient infrastructure provision, and hazard-sensitive development control, while in Accra, resilience pathways emphasize flood–fire mitigation, drainage enhancement, and coastal adaptation. These differentiated strategies demonstrate the framework's flexibility and contextual responsiveness, setting the stage for translating empirical findings into actionable planning interventions. These differentiated responses demonstrate the framework's contextual flexibility and conclude the results section. The next section 4 discusses these findings in relation to existing resilience theory, urban risk literature, and policy implications.

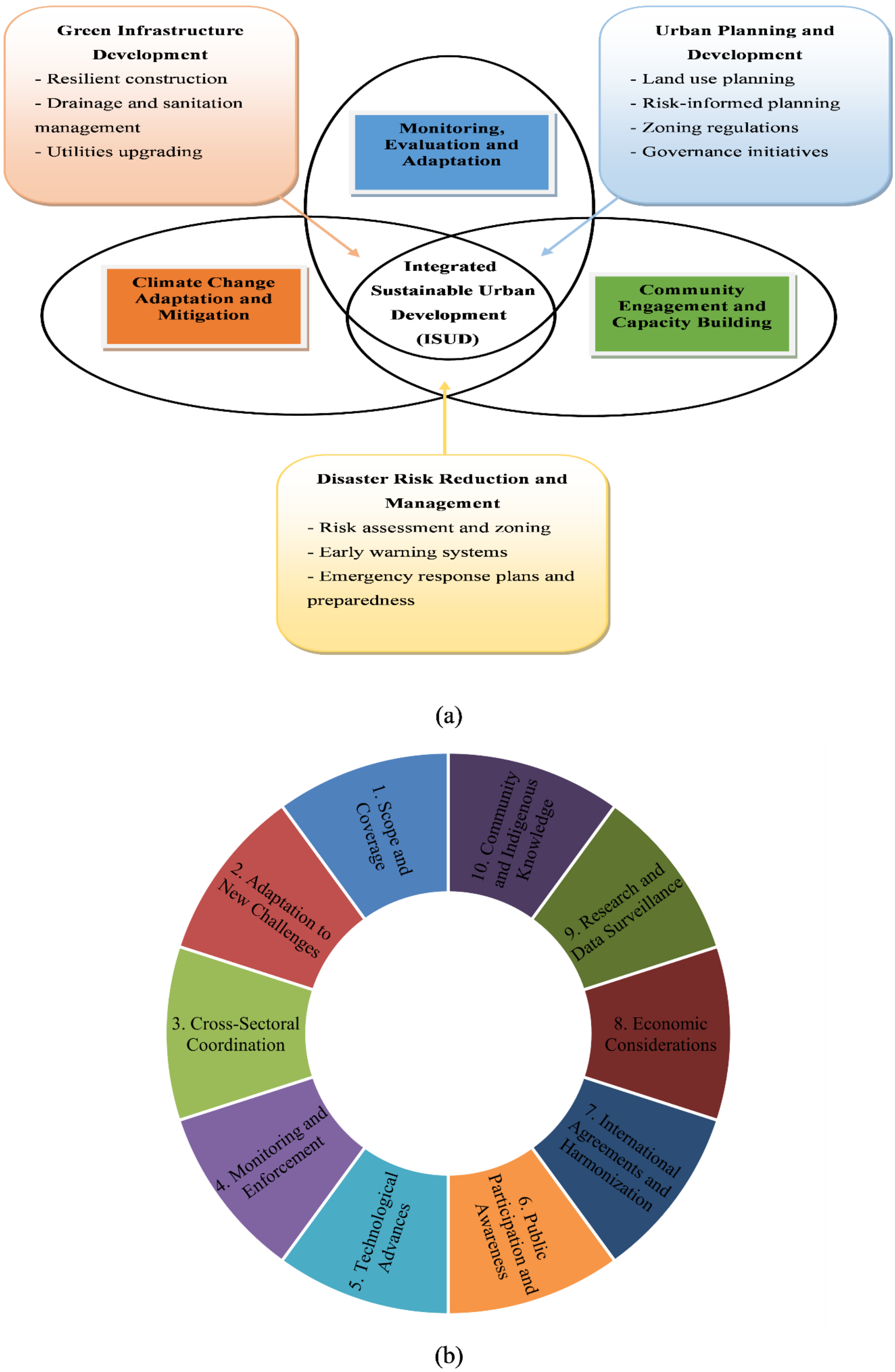



**Figure 11.** (a) Operational resilience framework and (b) action-oriented wheel for integrated sustainable urban development (ISUD).

## 4. Discussion

The findings reveal how urban growth patterns, hazard vulnerability, structural drivers, institutional performance, and resilience capacities interact to shape the developmental trajectories of Windhoek and Accra. Collectively, these results align with urban resilience scholarship, which argues that urbanization impacts cannot be understood solely through physical expansion but must be examined within socio-economic, environmental, and governance systems influencing exposure, sensitivity, and adaptive capacity [42,43]. This discussion integrates the empirical findings from the five objectives with the reviewed literature and the guiding theoretical framework—particularly the Pressure–And–Release (PAR) model, Urban Resilience Theory, and the Sustainable Livelihoods Framework—to interpret results in a wider scholarly and applied context.

The spatial–temporal analysis shows that rapid land-cover conversion across the past three decades has produced distinct yet comparable expansion forms. Windhoek's low-density outward growth reflects peri-urban sprawl, whereas Accra exhibits dense infill linked to demographic pressure. These patterns mirror regional observations in sub-Saharan Africa, where cities with lower population density, such as Windhoek, expand horizontally due to land availability, while high-pressure cities, such as Accra, intensify vertical and infill development [44]. The observed forms reflect expectations of the Urban Ecological Transition Model, which posits that urban morphology evolves with demographic pressure, land scarcity, and economic opportunity [45,46]. Satellite-derived evidence confirms that African cities seldom follow linear trajectories; rather, spatial patterns emerge from overlapping socio-political and economic forces, consistent with findings from Nairobi, Dar es Salaam, and Lagos showing polycentric, fragmented, and weakly regulated growth [47].

The implications for hazard vulnerability are substantial. Expansion in both cities increases exposure to natural and human-induced hazards, though the type and intensity differ. Windhoek's drought vulnerability stems from climatic aridity and socio-economic inequalities, while Accra's recurrent floods and fires relate to high-density settlement, inadequate drainage, and infrastructure deficits. These results reinforce African hazard literature showing that flood risk often reflects weak drainage, informal settlement growth, and insufficient infrastructure [48–50]. The community-level findings closely align with the PAR model, which conceptualizes vulnerability as a progression from root causes to dynamic pressures and unsafe conditions. In both cities, root causes such as poverty and weak institutional enforcement generate pressures including informal settlement expansion and inadequate infrastructure, ultimately producing unsafe conditions—including settlement on floodplains or limited emergency access [46,51]. Accordingly, spatial and socio-economic structures do not merely coexist with hazards but actively shape risk magnitude. Because Accra is larger, denser, wetter, and more hazard-prone than Windhoek, cross-context generalization is conditional rather than universal; however, standardized exposure and vulnerability indicators help maintain methodological equivalence while preserving context.

Hazard sensitivity is also strongly linked to socio-economic conditions including income levels, housing quality, and service access. Informal settlements constitute the physical and socio-economic centers of vulnerability: Windhoek records 41% informal settlement residence and Accra 38%, both areas of heightened exposure. These figures align with studies in Ethiopia, Ghana, Zambia, and Namibia indicating that informal settlements concentrate multi-hazard vulnerability due to their location in risk zones, weak housing, and limited services [23,52]. By linking settlement conditions with resilience outcomes, the study reinforces the Sustainable Livelihoods Framework proposition that social, physical, natural, financial, and human assets shape household capacities to prepare, respond, and recover [53]. The limited asset base in both cities helps explain why hazard impacts persist despite planning interventions.

Underlying drivers—including demographic pressures, economic opportunity, governance weaknesses, and infrastructure inequality—shape both growth and vulnerability. Economic opportunity drives rural–urban migration into Windhoek, stimulating peripheral expansion, while Accra experiences infrastructure-led densification driven by roads, markets, and real estate development. These patterns reflect African urbanization research emphasizing livelihood diversification, land markets, and governance gaps as key forces shaping land transformation [54,55]. The findings extend this literature by showing that drivers influencing growth also intensify vulnerability: Weak enforcement in Accra facilitates floodplain encroachment, while limited mobility in Windhoek reinforces socio-spatial inequality, reducing adaptive capacity. These drivers thus function as components of interdependent systems through which growth and vulnerability evolve concurrently.

Policy evaluation shows that both cities maintain hazard-reduction instruments, but implementation effectiveness varies. Windhoek exhibits moderate institutional coherence and relatively stable emergency systems, yet these remain insufficient to address socio-economic drivers. Accra retains detailed policy frameworks but fragmented enforcement undermines mitigation. These dynamics reflect broader African urban governance literature noting robust policy texts but limited implementation due to fragmentation, resource constraints, political interference, and insufficient engagement [56]. These findings connect with Urban Resilience Theory, which stresses institutional and governance capacities in mediating shocks [57,58]. Policy documents alone are therefore inadequate; resilience emerges from interactions among institutions, communities, and infrastructure.

The resilience assessment indicates that Windhoek performs comparatively better in institutional reliability and land-use compliance, while Accra shows stronger infrastructure but weaker adaptive readiness. These differentiated capacities support the systems-based view of urban resilience as multidimensional, emerging from interactions across physical, social, institutional, and ecological domains [57,59]. The composite readiness index—Windhoek 0.61 and Accra 0.48—confirms structural deficits in different domains, consistent with similar composite studies in Kampala, Kigali, and Johannesburg [60,61]. The radar chart analysis indicates that no single dimension determines resilience; rather, resilience emerges through synergy across institutional performance, infrastructure, community cohesion, and spatial planning.

Objective 5 findings form the empirical basis for a comprehensive sustainable development framework. Identifying institutional gaps, infrastructure weaknesses, community preparedness, and spatial vulnerabilities provides direct entry points for framework design. These align with global frameworks including the Rockefeller Foundation's City Resilience Framework and UN-Habitat's Urban Resilience Profiling Tool, both emphasizing integration of governance, infrastructure, communities, and spatial planning [62]. The comparative approach demonstrates that resilience must be tailored to city-specific growth dynamics, hazard profiles, and institutional structures. Windhoek requires strategies centered on socio-economic inclusion and water security, whereas Accra requires drainage improvement, coastal protection, and enforcement. This differentiation supports contemporary resilience theory calling for context-specific rather than universal strategies [57–61].

Overall, the results highlight the need for integrated planning that transcends sectoral divisions. Urban resilience cannot be separated from spatial planning or socio-economic development; systems must operate in alignment. Evidence from both cities shows that weak coordination between planning and disaster management increases vulnerability, supporting theoretical arguments that resilience is an emergent property of coordinated systems rather than discrete policy actions [58,61]. The findings therefore validate the integration of the Pressure-and-Release model and Urban Resilience Theory within the study's analytical framework.

In synthesizing these results, the study contributes empirical evidence on growth, vulnerability, and resilience from two differentiated yet comparable African cities. It demonstrates the value of mixed methods—particularly spatial analysis, household surveys, institutional assessments, and composite indices—in identifying multi-scale resilience patterns. Moreover, by linking urban growth directly with resilience outcomes, the study extends African urbanization scholarship, which often treats growth and vulnerability separately. The results show that transforming urban growth into resilience pathways is not automatic but requires evidence-based planning supported by functional institutions, responsive governance, and empowered communities.

In conclusion, both Windhoek and Accra face significant challenges in managing growth and reducing vulnerability yet also possess resilience assets that can be strengthened to support sustainable development. The differentiated vulnerabilities and capacities identified provide a foundation for city-specific and regional resilience frameworks. Thus, the next section develops a resilience-oriented sustainable urban development framework grounded in empirical evidence and informed by the theoretical insights discussed above.

Operationalization, however, requires implementation pathways tailored to the differentiated contexts of Windhoek and Accra. To address this, a dedicated implementation strategy is developed specifying actions, responsible institutions, enabling conditions, and monitoring indicators. The purpose is to illustrate how the framework transitions from conceptual relevance to practical applicability. Accordingly, implementation trajectories differ: Windhoek emphasizes informal settlement upgrading, drought-resilient infrastructure, and hazard-sensitive land-use regulation, while Accra prioritizes drainage improvement, coastal adaptation, and community-based early warning systems. These differentiated pathways align with context-specific governance capacities and vulnerability profiles and directly respond to city-specific implementation plan. A detailed action matrix is provided in the following subsection 4.1.

### *4.1. Implementation strategy*

The proposed resilience framework requires locally grounded implementation pathways that respond to three operational pillars across Windhoek and Accra. Under *risk-sensitive growth management*, Windhoek will prioritize hazard-sensitive land-use permitting particularly in informal settlements, led by the City of Windhoek (CoW) and the Ministry of Urban and Rural Development through strengthened development control procedures during the short-to-medium term, monitored through the share of permits integrating hazard criteria and the proportion of settlements with revised land-use zones. In Accra, risk-sensitive growth will focus on enforcing flood-fire sensitive building regulations led by the Accra Metropolitan Assembly, NADMO, and the Department of Town and Country Planning through improved building inspection protocols during the medium term, monitored by the proportion of infrastructure projects applying flood-fire safety standards.

Under *integrated multi-hazard reduction*, Windhoek will pursue drought-adaptive water-supply infrastructure supported by the CoW Water Division and NamWater, implemented through strategic infrastructure upgrading over the medium-to-long term, measured against reduced water deficits and validated drought contingency planning. In Accra, multi-hazard reduction will emphasize improved drainage, stormwater management, and flood-fire detention capacity with the AMA and Hydrological Services Department leading short-to-medium-term drainage/infrastructure rehabilitation, monitored by annual flood-fire reduction and drainage capacity improvements, while coastal resilience and shoreline protection led by the Ministry of Works and Housing, EPA, and NADMO will advance through medium-to-long-term coastal infrastructure actions measured through reduced erosion rates and the number of protected shoreline segments.

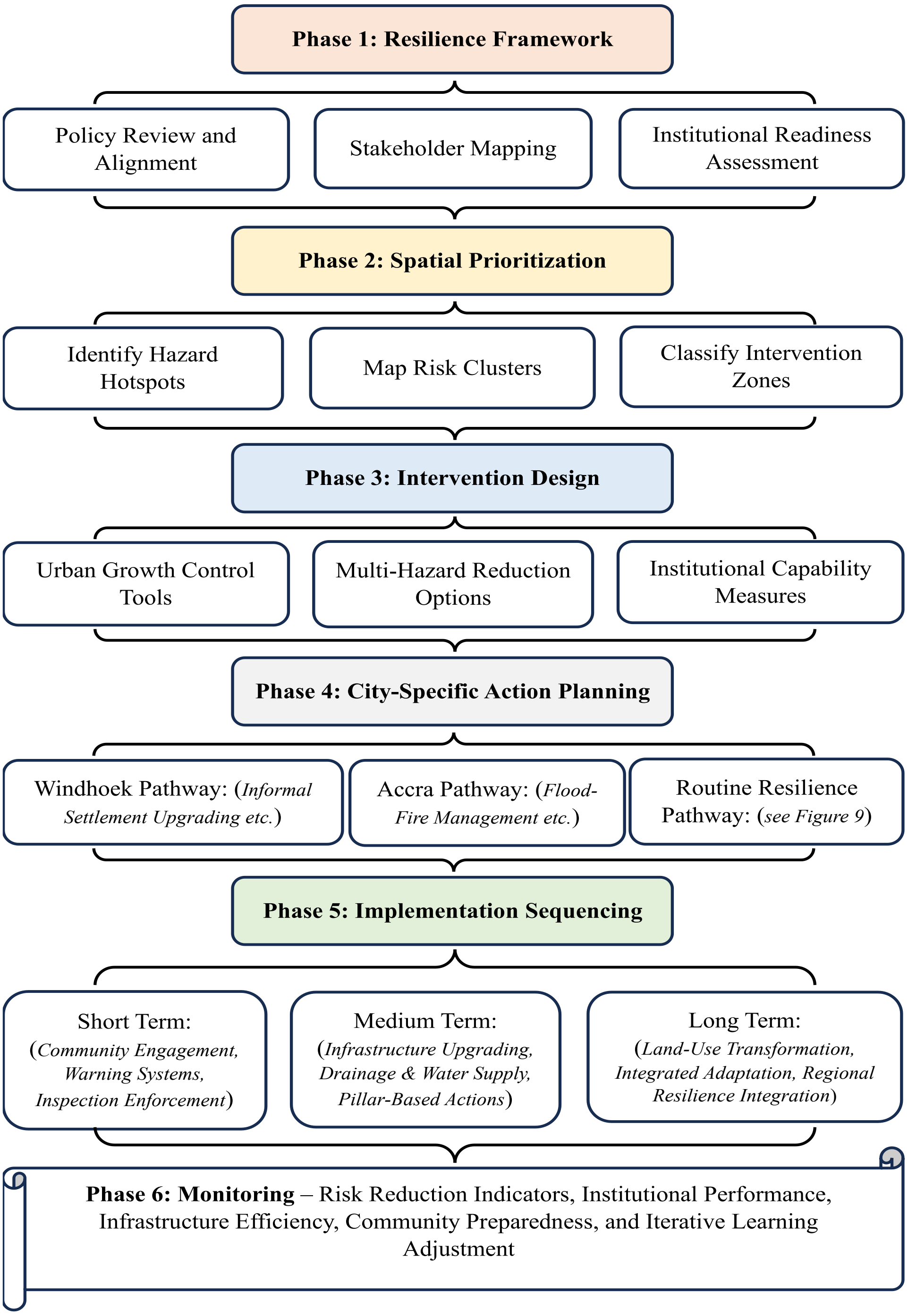



**Figure 12.** Implementation roadmap for resilience operationalization in Windhoek and Accra.

Finally, under *adaptive institutional capacity*, Windhoek will strengthen community risk awareness and early-warning penetration through CoW Disaster Risk Offices and NCRST using community participation platforms in the short term, assessed through preparedness scores and early-warning outreach, whereas Accra will institutionalize multi-agency coordination on flood and drought risk through NADMO, metropolitan assemblies and the EPA via joint inter-agency platforms across the short-to-medium term, monitored by response times, coordination scores, and jointly developed protocols. Operationalization therefore occurs through differentiated pathways across both cities, which are synthesized in Figure 12.

## 5. Conclusion

This study examined how urban growth patterns in Windhoek and Accra shape vulnerability to natural and human-induced hazards and how resilience-oriented development pathways can convert expansion into sustainable outcomes. Using geospatial analysis, socio-economic assessments, and policy reviews, the findings show that although both cities experienced rapid growth during the last three decades, their spatial forms, growth pace, and socio-ecological consequences differ significantly. Windhoek's predominantly horizontal sprawl has intensified exposure to drought, service deficiencies, and socio-spatial segregation, whereas Accra's compact in-fill development has heightened exposure to floods, fire outbreaks, and infrastructure congestion. Integrating evidence from all five research objectives, this chapter synthesizes the major implications for sustainable urban development and resilient African city futures.

Urban growth emerged as a central determinant of hazard vulnerability. Objective 1 showed that Windhoek's outward expansion onto underdeveloped land produces spatial fragmentation and elevates service delivery costs, reinforcing socio-economic and environmental inequalities. Accra's high-density growth instead places stress on drainage, housing, and sanitation systems, exacerbating flood risk. These results support the theoretical position that urban morphology shapes adaptive capacity, consistent with urban political ecology and resilience theory, which emphasize how spatial form interacts with socio-economic systems to create differentiated risk landscapes. Accordingly, urban expansion in both cities functions as a driver of multi-scale vulnerability, demonstrating the need for integrated spatial planning that aligns land use, infrastructure, and hazard mitigation.

Objective 2 demonstrated that vulnerability is multidimensional and rooted in both physical exposure and socio-economic sensitivity. Informal settlements constitute major vulnerability hotspots, with Windhoek recording about 41% and Accra 38% informal settlement prevalence. These settlements face inadequate services, insecure tenure, and weak institutional protection, making them highly sensitive to climate- and human-induced hazards. Vulnerability patterns differ, however, due to governance histories and demographic pressures. Windhoek's vulnerability remains strongly influenced by apartheid spatial legacies, while Accra's is shaped by rapid population growth and infrastructural strain. These findings confirm that vulnerability results from interacting social, economic, and environmental processes rather than hazards alone.

Objective 3 identified drivers of urban growth and vulnerability. Economic opportunity and housing demand largely drive Windhoek's sprawl, while Accra's expansion is propelled by population pressure, commercial development, and infrastructure investment. Environmental feedback—drought in Windhoek and flooding in Accra—reinforces vulnerability, while fragmented land administration and weak enforcement amplify risk in both contexts. Consistent with systems theory, growth becomes either a resilience pathway or a vulnerability trap depending on governance quality, institutional coordination, and socio-economic inclusion. Thus, strengthening proactive governance is essential for transforming growth into resilience.

Objective 4 evaluated policy frameworks and showed that both Namibia and Ghana articulate strong commitments to hazard mitigation, yet implementation remains uneven and reactive. Namibia prioritizes water security, drought management, and land regularization but still faces gaps in socio-economic vulnerability reduction. Ghana emphasizes flood control and decentralized planning but is constrained by institutional fragmentation and limited resources. Although policy frameworks align with the Sendai Framework, the New Urban Agenda, and the Sustainable Development Goals, operationalizing resilience requires stronger interagency coordination, improved data systems, and community-centered planning. Emphasizing sustainable blue cities—water-sensitive governance, flood-resilient infrastructure, and ecological conservation—is therefore central to meeting SDG 11.3, 6.5, and 11.5. Blue development constitutes a critical resilience strategy for both cities.

Objective 5 synthesized evidence into a resilience framework that positions sustainable urban development as both preventive and transformative. The framework shows that resilience emerges from integrating spatial planning, socio-economic inclusion, hazard mitigation, and institutional effectiveness within a unified governance continuum. It highlights adaptive land use, early warning systems, inclusive informal settlement upgrading, climate-resilient infrastructure, and participatory planning. Resilience is thus not merely reactive, but a proactive process that converts growth into an opportunity for environmental sustainability, equity, and economic stability, consistent with resilience theory's emphasis on adaptive and reorganizing capacities.

The synthesis underscores that transforming growth into resilience requires reducing spatial inequalities, strengthening governance capacity, and embedding hazard mitigation within planning processes. Both Windhoek and Accra face rapidly evolving risk profiles that demand forward-looking spatial strategies, improved land management, and stronger implementation of existing frameworks. The findings demonstrate that vulnerability in African cities results from place-specific socio-economic and environmental conditions rather than inevitable outcomes, and that targeted interventions can shift cities toward more resilient trajectories.

For Namibia, policy priorities include integrated water-sensitive planning, drought resilience investments, and socially inclusive land regularization. Accelerating informal settlement upgrading, expanding water infrastructure, and promoting compact, mixed-use development will reduce spatial inequality and strengthen resilience. Policies should emphasize integrated environmental management, risk-sensitive zoning, and cross-sectoral governance to achieve SDG 11.3.1. Strengthening geospatial monitoring systems is essential for evidence-based planning.

For Ghana, policy implications center on comprehensive flood management, improved drainage, and stronger regulatory enforcement. Accra must expand institutional capacities for coordinating city-wide hazard mitigation. Integrated coastal management, waste governance reforms, and capacity building for metropolitan authorities are essential for addressing long-term risks. Enhancing community preparedness, promoting household insurance, and upgrading informal settlements through participatory approaches will advance resilience. Achieving sustainable blue cities requires embedding water-sensitive urban design, stormwater systems, and wetland protection within long-term planning, consistent with SDG 11.5 and 13.1.

Overall, this study shows that urban growth can either deepen hazard vulnerability or function as a resilience driver, depending on governance structures and planning systems. Windhoek and Accra face distinct yet converging challenges that reflect broader urbanization dynamics in sub-Saharan Africa. The findings contribute theoretical value by linking urban morphology, socio-economic vulnerability, and resilience frameworks within a comparative African context, while offering practical guidance for city authorities and planners. Strengthening institutional capacity, integrating hazard mitigation into land-use planning, advancing climate-adaptive infrastructure, and promoting inclusive development constitute essential strategies for building sustainable blue cities and supporting SDG targets related to resilience, water security, and sustainable urbanization.

## Use of AI tools declaration

The authors declare that no Artificial Intelligence (AI) tools were used in the creation, analysis, or writing of this article.

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## Conflict of interest

The authors declare no conflicts of interest in this manuscript. The research was conducted independently, and no financial or personal relationships influenced the outcomes.

## Author contributions

PM: Conceptualization, methodology, software, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, project administration, and funding acquisition. EY: Writing—review and editing, and supervision. All authors have read and agreed to the published version of the manuscript.

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