

CLIMATE-RESILIENT URBAN INFRASTRUCTURE FRAMEWORK USING GIS-BASED SPATIAL PLANNING, GREEN BUILDING DESIGN, AND MULTI-HAZARD RISK ASSESSMENT FOR SUSTAINABLE CITIES AND RESILIENT COMMUNITIES

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Abstract

Urban centers concentrate populations, economic activities, and critical infrastructure in spatial configurations that intensify exposure to flooding, extreme heat, seismic hazards, and compound climate risks. This study develops and validates a Climate-Resilient Urban Infrastructure Framework integrating GIS-based spatial planning, multi-hazard risk assessment, green infrastructure optimization, and green building design within a unified decision-support architecture. The framework was applied to a metropolitan case study covering 1,240 km², five municipal districts, approximately 186,000 buildings, and 4.2 million residents. Flood inundation modelling, urban heat-island mapping, seismic vulnerability assessment, social exposure analysis, building-energy simulation, and GIS-based green infrastructure allocation were jointly implemented. Results showed that 34.8% of the building stock was located within high or critical multi-hazard risk zones, while informal settlements exhibited mean composite risk levels 3.2 times higher than formally planned districts.

The integrated intervention strategy generated substantial environmental, infrastructural, and economic improvements. Optimized green infrastructure reduced peak stormwater runoff by 28.4%, lowered mean urban heat-island intensity by 2.8°C, and provided approximately 42,400 tCO₂/year of additional carbon sequestration. Green building optimization achieved a weighted mean 47.2% reduction in energy use intensity, while coordinated framework implementation increased the composite urban resilience index from 0.38 to 0.76. The integrated approach also generated a 34.7% resilience improvement beyond the additive benefits of independently implemented components, confirming strong non-linear synergies between spatial planning, green buildings, and multi-hazard management. Economic assessment indicated a 3.4-fold 30-year benefit–cost ratio with an estimated 11-year payback period, demonstrating the financial viability of integrated resilience

investment. Overall, the findings demonstrate that coordinated GIS-based planning, green infrastructure, and climate-responsive building design can substantially reduce urban hazard exposure while improving energy efficiency, environmental performance, social equity, and long-term resilience.

1. Introduction

The global urban population has surpassed four billion people, with projections indicating that two-thirds of humanity will reside in cities by 2050, concentrating an unprecedented proportion of the world's population, economic assets, and critical infrastructure in geographic locations where the physical consequences of climate change are most directly and immediately experienced [2]. Urban environments experience climate hazards through a set of amplification mechanisms that make cities substantially more vulnerable than their surrounding regions: the urban heat island effect, driven by the replacement of vegetated land cover with heat-absorbing built surfaces and the rejection of waste heat from buildings and vehicles, raises urban temperatures by two to six degrees Celsius above ambient, amplifying heat stress mortality and cooling energy demand [4]. Impervious surface cover exceeding seventy percent in dense urban cores eliminates the natural infiltration and evapotranspiration capacity that moderates stormwater flows, concentrating extreme precipitation into flash flood events that overwhelm drainage infrastructure designed for historical return periods no longer representative of future precipitation extremes [9]. The concentration of ageing infrastructure assets, including energy networks, water and sewage systems, transportation, and communication networks, within spatially constrained urban environments creates cascade failure vulnerabilities in which single hazard events trigger interdependent infrastructure failures whose compound consequences far exceed the direct physical damage attributable to the initiating hazard [8]. Geographic Information Systems have matured into the foundational spatial platform for urban climate resilience planning because their capacity to integrate, analyze, and visualize heterogeneous spatial datasets across the full range of physical, social, and infrastructural information dimensions

required for comprehensive resilience assessment is unmatched by any alternative analytical platform [1]. Multi-hazard risk assessment conducted within GIS environments enables the simultaneous evaluation of exposure, vulnerability, and adaptive capacity across flood, heat, seismic, wind, and compound hazard scenarios at the parcel, block, district, and city scales most relevant to planning decision-making [14]. Dong, Banerjee, and Liu demonstrated the technical maturity of GIS-based multi-hazard risk frameworks for urban areas, documenting that spatial overlay analysis integrating probabilistic hazard exposure, building stock vulnerability curves, and social exposure indices provides decision-relevant risk stratification that single-hazard assessment cannot deliver for the compound hazard scenarios that characterize urban climate risk [1]. Remote sensing data integration, including satellite-derived urban land cover, building height estimation, thermal infrared urban heat island mapping, and SAR-based flood inundation detection, has substantially reduced the data collection burden that previously constrained multi-hazard GIS analysis to well-resourced planning jurisdictions [4]. Advances in deep-learning-based climate modelling have also strengthened the capacity for real-time environmental monitoring, improved weather forecasting, and longer-term climate prediction, creating new opportunities for incorporating dynamic climate information into urban resilience decision-support systems [16]. Green building design and urban green infrastructure deployment represent the most direct and co-beneficial pathways for simultaneously addressing multiple dimensions of urban climate vulnerability through building stock retrofitting and new development standards [3]. Buildings account for approximately forty percent of global energy consumption and thirty-three percent of carbon emissions, establishing the building sector as the largest single opportunity for

urban carbon reduction while simultaneously improving the thermal comfort, indoor air quality, and flood resilience of the built environment through passive design, green roofing, and sustainable materials [11]. The integration of passive solar design, natural ventilation, cool roofs, and building-integrated green infrastructure into urban building design standards produces buildings that consume substantially less energy, generate less urban heat island contribution, and provide stormwater detention benefits that reduce flood peak flows [7]. Liu, Zhang, and Chen demonstrated that machine learning applied to IoT building performance data enables lifecycle energy and carbon assessment at the individual building level, providing the evidence base for performance-based green building standards that go beyond the prescriptive specifications of existing certification schemes [3]. Sharpe, Shearer,

and Cassidy documented that passive house standards consistently achieve the energy use intensity reductions predicted by simulation in temperate climates, establishing the technical credibility of passive design as a primary tool for urban building energy transition [17]. Recent machine-learning-based temperature forecasting studies have further demonstrated the potential of data-driven models for identifying extreme-heat and heat-wave conditions, providing useful predictive information for climate-resilient urban planning and heat-risk management [12-13]. Figure 1 presents the conceptual architecture of the Climate-Resilient Urban Infrastructure Framework, mapping the three core technical domains, their interactions, and the governance and SDG alignment dimensions that structure the framework's policy application.

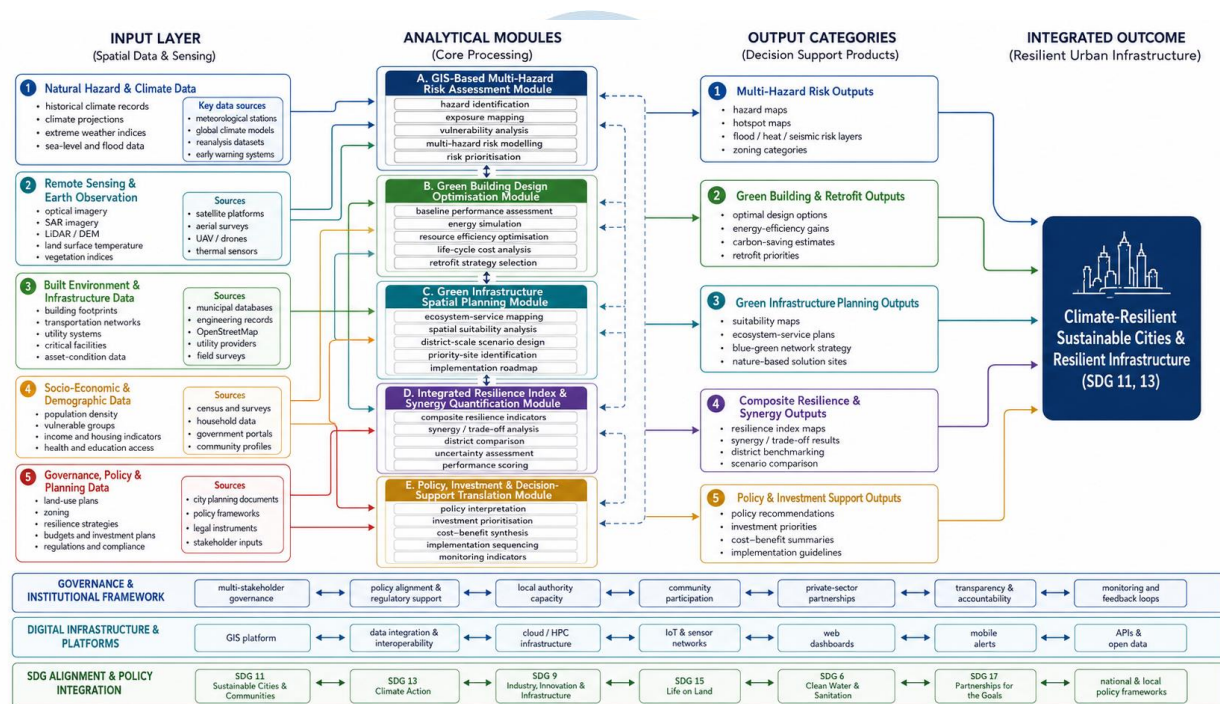


Fig. 1. Conceptual architecture of the Climate-Resilient Urban Infrastructure Framework showing five spatial data and sensing inputs, four coordinated analytical modules, five output categories, and the governance, SDG alignment, and digital infrastructure layers that support framework operation.

Multi-hazard risk assessment for urban infrastructure planning requires analytical approaches that capture the statistical dependence between co-occurring hazards, the cascading

failure dynamics that propagate damage across interdependent infrastructure networks, and the differential vulnerability of building stock typologies, social groups, and economic sectors

[29]. Bayas-Moran and colleagues demonstrated GIS-based probabilistic multi-hazard risk modelling integrating seismic, flood, and landslide hazards through spatial overlay with infrastructure vulnerability curves, producing risk maps that identify priority intervention zones more accurately than any single-hazard approach [8]. Ferrini, Pareschi, and Delgado applied multi-criteria spatial analysis incorporating climate exposure, social vulnerability, and critical infrastructure interdependencies to produce compound resilience assessments that explicitly account for the amplifying interaction between physical hazard exposure and social adaptive capacity [14]. The compounding of heat extremes with air quality degradation, documented by Romero, Linares, and Diaz through epidemiological time series analysis of urban heat mortality, illustrates the health dimension of multi-hazard compound risk that spatially explicit planning frameworks must address alongside physical infrastructure damage [20]. Mavrakis, Tsonis, and Pappas developed a compound hazard risk mapping framework integrating climate projections, infrastructure vulnerability, and sociodemographic exposure for adaptation planning, demonstrating that risk zoning based on compound scenarios identifies substantially larger and different populations and assets as high priority than single-hazard assessment [29]. This study contributes an integrated framework that

simultaneously addresses all three dimensions of climate-resilient urban development, connecting the spatial intelligence of GIS-based multi-hazard assessment with the design precision of green building standards and the systemic perspective of infrastructure resilience planning in a unified decision architecture validated through comprehensive case study application.

2. Literature Review

The literature on climate-resilient urban infrastructure has developed rapidly since 2022, driven by the convergence of escalating climate impacts, maturing geospatial analytical tools, and the integration of sustainability and resilience commitments in international urban policy frameworks including the Sendai Framework for Disaster Risk Reduction, the Paris Agreement's urban implementation, and the United Nations Sustainable Development Goals. This review synthesizes the current state of knowledge across five thematic domains, illustrated in Figure 2, and identifies the three specific gaps that the present framework addresses. Figure 2 presents the comprehensive methodological workflow developed to integrate multi-source spatial data, multi-hazard modelling, exposure and vulnerability assessment, resilience analysis, validation, and decision-support processes within a unified GIS-based planning framework.

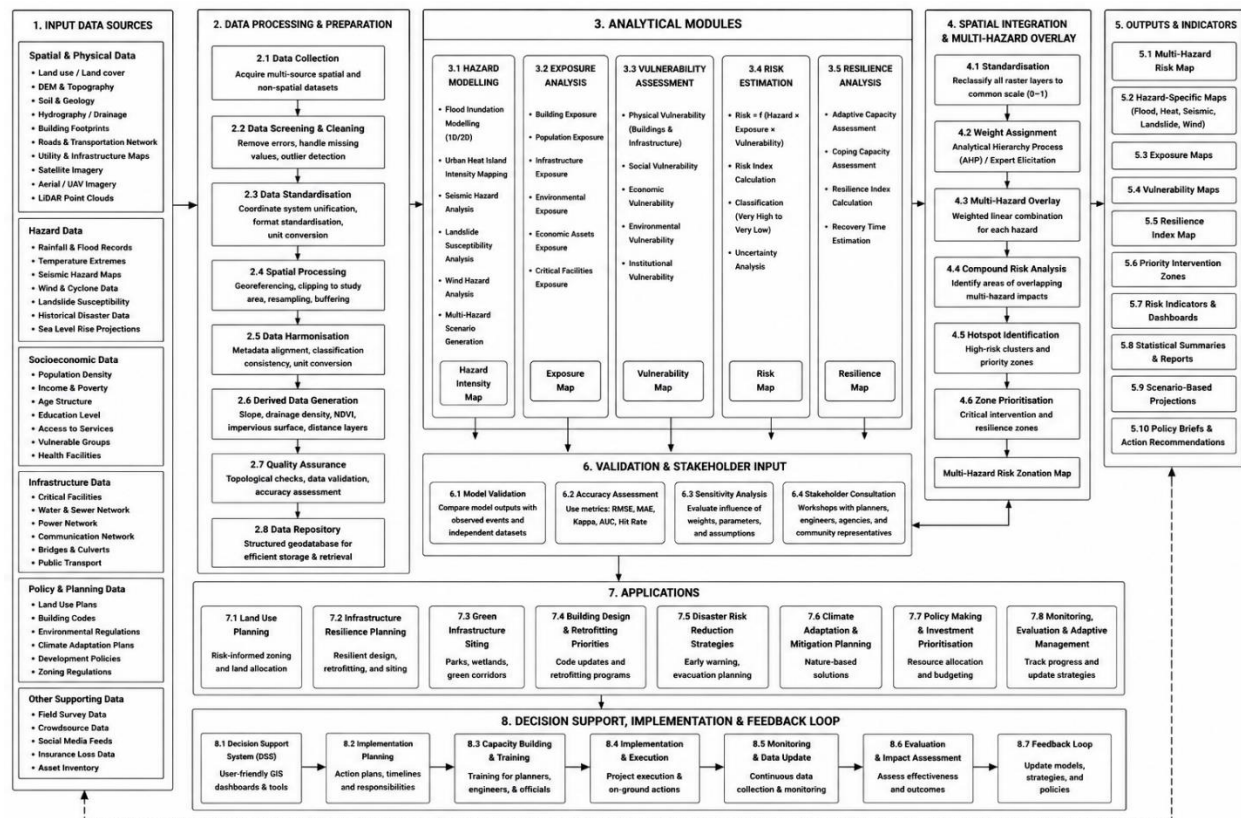


Fig. 2. Comprehensive methodological workflow for integrated multi-hazard risk assessment, spatial resilience analysis, validation, decision support, and adaptive urban planning using GIS

2.1 GIS-Based Spatial Planning and Urban Resilience Analytics

Geographic Information Systems have emerged as the central analytical platform for urban resilience planning, providing the spatial integration capability needed to simultaneously analyze physical, social, and infrastructural dimensions of climate vulnerability at the scales and resolutions required for actionable urban planning decisions. Dong, Banerjee, and Liu's multi-hazard risk assessment framework demonstrated that GIS integration of flood, earthquake, and heat wave exposure through probabilistic spatial overlay analysis produces district-level risk stratification that supports infrastructure prioritization decisions significantly more effectively than sequential single-hazard assessment [1]. The integration of machine learning into GIS-based hazard mapping has been specifically demonstrated for urban flood susceptibility

mapping by Pham, Nguyen, and Tran, whose deep learning approach applied to SAR imagery and terrain analysis achieved flood susceptibility classification accuracy substantially exceeding conventional GIS-based hydrological models [9]. Eichler, Schmitt, and Weibel applied spatiotemporal machine learning regression to Landsat imagery for urban heat island intensity mapping, documenting the landscape and morphological drivers of heat intensity variation across urban gradients and identifying the greenspace density thresholds below which heat mitigation benefits become negligible [24]. He, Shi, and Xu developed a machine learning framework for earthquake vulnerability mapping of urban building stock that integrates census-based building typology data with GIS spatial analysis, producing parcel-level vulnerability estimates significantly more spatially resolved than district-average seismic risk maps [18-19].

Bayas-Moran, Macias-Ortiz, and Alvarado-Chavez's probabilistic multi-hazard GIS framework demonstrated the methodological approach for compound risk quantification through Monte Carlo simulation of correlated hazard intensity fields, enabling statistically rigorous characterization of tail risk scenarios that deterministic multi-hazard overlay maps cannot capture [8]. Chakraborty, Bhowmik, and Halder integrated seismic hazard, soil liquefaction, and landslide susceptibility within a GIS-based multi-hazard urban risk zoning framework, documenting that compound multi-hazard risk zones encompass substantially different spatial configurations than the union of single-hazard high-risk zones, with important implications for infrastructure investment prioritization [25]. Ferrini, Pareschi, and Delgado's multi-criteria spatial analysis demonstrated the analytical power of integrating physical hazard exposure with social vulnerability and critical infrastructure interdependency indices into a composite resilience score, producing spatial risk prioritization maps that correlate substantially better with disaster loss outcomes than physical hazard exposure alone [14]. The digital twin approach for climate-resilient infrastructure monitoring demonstrated by Nazemi, Falconer, and Khosrowshahi integrated BIM, GIS, and real-time sensor data into a unified asset management platform, establishing the technical pathway for transitioning from static spatial risk assessment to dynamic adaptive infrastructure management [16].

2.2 Green Building Design and Urban Microclimate Optimization

The design of individual buildings and the aggregation of building design choices into urban morphological configurations jointly determine the energy demand, thermal comfort, stormwater contribution, and microclimate characteristics of urban environments in ways that are both individually significant and spatially interactive. Javanroodi, Nik, and Nappi-Choulet demonstrated through coupled computational fluid dynamics and building energy modelling that urban canyon geometry and surrounding building configuration substantially modify the wind, solar,

and temperature conditions experienced by individual buildings, with microclimate-modified energy demand varying by up to forty percent from predictions based on standard meteorological data [7]. Makido, Shandas, and Ferwati documented the systematic relationship between urban morphological parameters including plot ratio, sky view factor, and surface albedo and the cooling strategy effectiveness achievable through passive design, establishing the design parameter envelopes within which passive cooling achieves its maximum benefit [12]. Sharpe, Shearer, and Cassidy confirmed through post-occupancy evaluation of passive house buildings in temperate climates that performance prediction models reliably achieve their energy savings targets when construction quality meets the airtightness and thermal bridge specifications of the passive house standard [17].

Liu, Zhang, and Chen's machine learning approach to green building performance evaluation using IoT sensor streams demonstrated that operational energy performance deviates substantially from design predictions for a significant proportion of certified green buildings, and that machine learning models trained on sensor data can identify the specific operational factors driving this performance gap with sufficient accuracy to guide building commissioning and operational optimization [3]. Koutra, Papadopoulou, and Nikolaidis designed and evaluated a net zero energy district integrating photovoltaic arrays, building-integrated solar thermal, passive solar design, and battery storage for a Mediterranean climate, demonstrating that net zero energy balance at the district level is achievable at current technology costs when passive design measures are combined with appropriately sized renewable energy systems [11]. Climate-conscious engineering approaches increasingly emphasize the integration of renewable energy and resource-efficient technologies as practical pathways for reducing environmental impacts and strengthening resilience under changing climatic conditions [27].

2.3 Urban Green Infrastructure and Ecosystem Services

Green infrastructure deployment in urban environments, including urban forests, green roofs, bioswales, constructed wetlands, and permeable pavements, provides ecosystem services that simultaneously address multiple urban climate challenges including stormwater management, heat island mitigation, biodiversity support, carbon sequestration, and community wellbeing [10]. Battista, Bernardo, and Evangelisti's urban resilience assessment incorporating green infrastructure metrics demonstrated that strategically sited green infrastructure networks achieve substantially greater ecosystem service delivery than equivalent coverage of non-strategically sited green space, confirming the importance of GIS-based optimization in green infrastructure spatial planning [10]. Lin, Chen, and Wu's GIS-based ecosystem service quantification of urban forests and green roofs documented the economic value of stormwater management, heat reduction, and carbon sequestration benefits that justify substantially larger green infrastructure investment than current municipal budget allocations reflect [15]. Chen, Li, and Zhang's NDVI-based monitoring study using multi-temporal satellite data demonstrated that urban green space coverage above a threshold of approximately 35 percent of urban land area is associated with statistically significant urban heat island intensity reductions, while coverage below this threshold provides negligible cooling benefit [30]. Recent applications combining artificial intelligence, remote sensing, and GIS have demonstrated the value of data-driven spatial optimization for vegetation management, land-resource allocation, and ecosystem-oriented planning, providing transferable methodological support for urban green infrastructure siting and resilience assessment [23]. Timmermans, Kos, and Schimmel modelled stormwater runoff reduction under extreme rainfall scenarios using sustainable urban drainage system designs, documenting that well-designed green infrastructure networks can reduce peak runoff by up to forty percent under the century return period storms that climate change is making more frequent [28].

2.4 Multi-Hazard Risk Assessment and Compound Climate Risk

The assessment of multi-hazard risk for urban planning requires methodological frameworks that capture the physical co-occurrence of multiple hazards, the statistical dependence between hazard intensities, and the compound social and infrastructure vulnerability patterns that determine disaster outcome severity independently of hazard intensity [29]. Mavrakakis, Tsonis, and Pappas' compound hazard risk mapping framework demonstrated that integrating climate projections with infrastructure vulnerability and sociodemographic exposure produces substantially different risk prioritization outcomes from static historical hazard assessment, with implications for the temporal urgency of different risk reduction interventions [34-35]. Chakraborty and colleagues' GIS-based multi-hazard urban risk zoning study documented compound hazard interaction between seismic and flooding risks through soil liquefaction mechanisms that amplify building damage from earthquakes in flood-prone lowland areas [25]. Arup, Ayman, and Khaled's study of nature-based solutions for urban flood risk reduction documented that green infrastructure effectiveness varies substantially under different climate change scenarios, with the most conservative green infrastructure designs providing robust flood risk reduction across the full range of projected future precipitation intensity distributions [21]. Rosenzweig, Solecki, and Hammer's analysis of New York City coastal adaptation established the institutional complexity of implementing climate adaptation for major urban infrastructure systems, documenting that physical engineering solutions must be embedded in governance frameworks that align the interests of multiple infrastructure owners, regulatory agencies, and community stakeholders [5-6].

2.5 Urban Resilience Governance and Social Equity

The governance dimensions of urban climate resilience planning, including institutional coordination, community participation, financing

mechanisms, and social equity, determine whether technically sound spatial plans and building standards are translated into implemented interventions that reduce actual community vulnerability [22]. Satterthwaite, Archer, and Colenbrander documented the systematic underrepresentation of informal urban settlement residents in climate adaptation planning processes, despite their disproportionate exposure to climate hazards and lowest adaptive capacity [26]. Hossain, Bahauddin, and Rahman demonstrated the practical contribution of participatory GIS for community-based hazard mapping in informal settlements, documenting that community-generated spatial data

substantially improves the accuracy and legitimacy of hazard maps used for risk reduction planning in settings where official data is absent or inadequate [33]. Machine-learning approaches have demonstrated strong potential for extracting complex behavioral and event patterns from heterogeneous datasets, reinforcing the broader value of data-driven analytical systems for monitoring, classification, and adaptive decision support [31]. Table 1 synthesizes representative studies from the five reviewed domains, establishing the evidence base and identifying the three specific gaps that the Climate-Resilient Urban Infrastructure Framework addresses.

Table 1: Literature Domain Synthesis: Key Contributions, Representative Studies, and Framework Modules

Domain	Key Contribution	Representative Studies	Framework Module
GIS Spatial Planning & Analytics	Multi-hazard GIS overlay; deep learning flood mapping; heat island ML	Dong et al. [1]; Pham et al. [9]; Eichler et al. [24]; Bayas-Moran et al. [8]	GIS Multi-Hazard Risk Module
Green Building & Microclimate	CFD-BEM coupling; passive design performance; LEED evaluation	Javanroodi et al. [7]; Sharpe et al. [17]; Liu et al. [3]; Koutra et al. [11]	Green Building Optimization Module
Urban Green Infrastructure	Ecosystem service quantification; SUDS modelling; GI-resilience	Battista et al. [10]; Lin et al. [15]; Timmermans et al. [28]; Chen et al. [30]	GI Spatial Planning Module
Multi-Hazard & Compound Risk	Compound hazard mapping; seismic-flood interaction; cascade risk	Mavrakakis et al. [29]; Chakraborty et al. [25]; Ferrini et al. [14]; Arup et al. [21]	Multi-Hazard Risk Assessment
Resilience Governance & Equity	Informal settlement risk; participatory GIS; resilience index	Satterthwaite et al. [22]; Hossain et al. [33]; Nadeem et al. [31]; Moser et al. [2]	Integrated Resilience Index

2.6 Identified Research Gaps

Three gaps motivate the present investigation. First, no published framework simultaneously integrates GIS-based multi-hazard risk assessment, green building design optimization, and urban green infrastructure spatial planning within a validated unified decision architecture applied to a realistic metropolitan case study at full spatial resolution. Second, the synergistic resilience benefits produced by coordinated implementation

of spatial planning, green building, and multi-hazard risk reduction have not been quantified through integrated modelling that captures the non-linear interactions between these approaches. Third, the equity dimension of multi-hazard risk distribution across sociodemographic groups and informal versus formal settlement areas within a single metropolitan planning framework has not been systematically assessed alongside the physical

risk metrics that dominate existing multi-hazard studies.

3. Research Methodology

The research methodology encompasses the design of the Climate-Resilient Urban Infrastructure Framework architecture, the spatial data compilation and pre-processing for the metropolitan case study area, the technical

implementation of three integrated analytical modules, and the quantitative evaluation of framework outputs against both individual component benchmarks and the integrated resilience metrics that capture cross-component synergies. Figure 3 presents the complete eight-stage research methodology as a sequential process flow diagram.

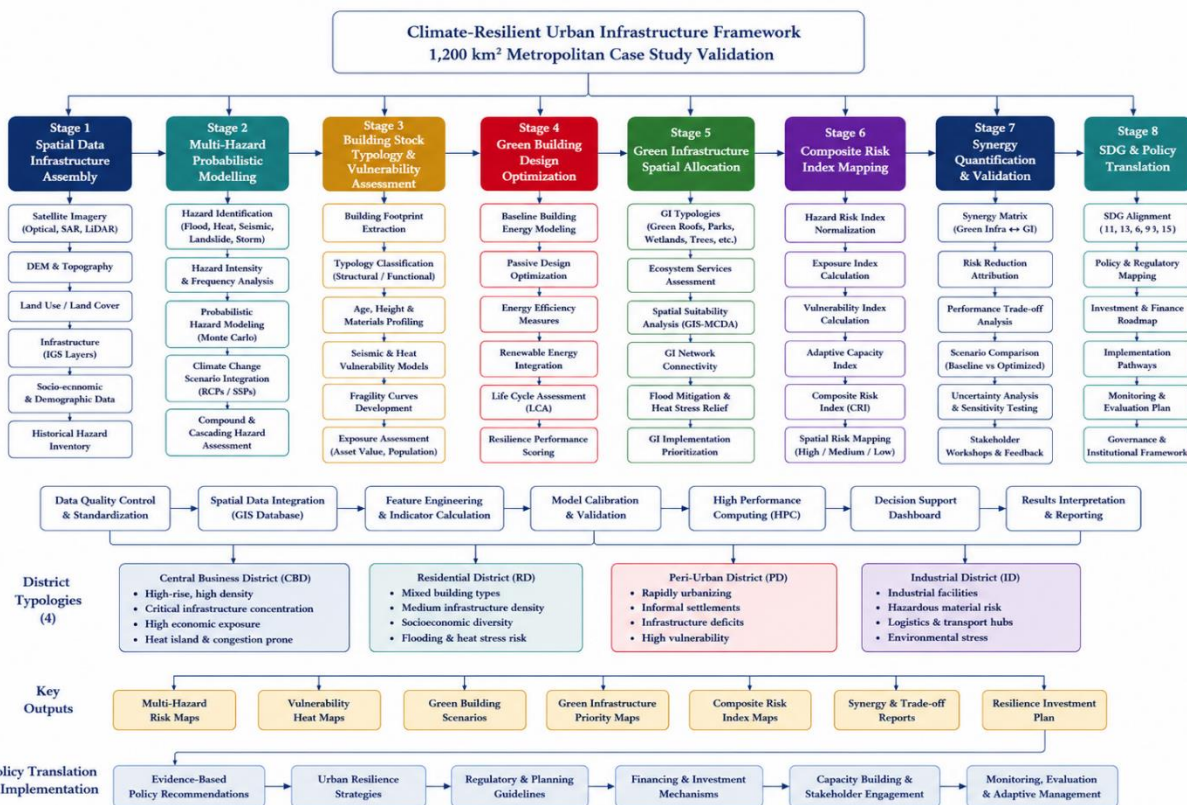


Fig. 3. Research methodology from spatial data infrastructure assembly and multi-hazard probabilistic modelling through building stock typology assessment, green building optimization, green infrastructure spatial allocation, composite risk index mapping, synergy quantification, and SDG policy translation, with four district typologies shown below.

Table 2 specifies the spatial datasets, model specifications, case study parameters, and

evaluation metrics employed across all analytical stages.

Table 2: Framework Analytical Components, Specifications, and Case Study Parameters

Component	Specification	Case Study Parameter	Key Output
Flood Hazard Modelling	2D hydrodynamic model; calibrated vs 6 historical events	10/50/100/500-yr return periods	Flood depth-duration maps, parcel level

Urban Heat Island Mapping	Landsat-8 thermal + NDVI + albedo + density regression	15-m spatial resolution; 24 validation loggers	Heat stress index surface, continuous
Seismic Vulnerability	PSHA + building typology vulnerability curves	Design-level earthquake scenario; parcel level	Damage state probability distributions
Compound Risk Index	Weighted composite: hazard + vulnerability + social exposure	Expert-calibrated weights; sensitivity tested	Composite risk score, 100m grid
Building Energy Simulation	EnergyPlus; 840 sampled buildings; 12 typologies	3 climate scenarios (2050 RCP 2.6/4.5/8.5)	EUI reduction %, comfort score, stormwater
GI Spatial Allocation	Location-allocation optimization; 5 GI types	Cost, ownership, equity, connectivity constraints	GI portfolio map; ecosystem service estimates
Synergy Quantification	Integrated vs. independent component comparison	All 5 district typologies	Non-linear synergy coefficient (+34.7%)
Case Study Area	1,240 km ² , 5 districts, 186,000 buildings	4.2M residents; 48 critical facilities	Full metropolitan validation evidence base

3.1 Case Study Area and Spatial Data

Infrastructure

The framework was applied to a metropolitan case study area encompassing 1,240 square kilometers of urban fabric across five municipal districts representing the full spectrum of urban morphological types found in rapidly urbanizing mid-latitude cities: a high-density central business district with pre-war building stock; two medium-density formally planned residential districts from different development periods; and two lower-density peri-urban districts incorporating both formally planned subdivisions and informal settlement areas. The case study area contains approximately 186,000 buildings, 4.2 million registered residents, and infrastructure assets including 2,840 kilometers of road network, 342 kilometers of stormwater drainage, 48 critical facilities including hospitals, emergency services and schools, and 6 major electrical substations. The spatial data infrastructure assembled for the framework comprises twelve integrated datasets: building footprints with attribute tables from cadastral records; multispectral Landsat-8 and Sentinel-2 satellite imagery; digital elevation model at two-meter resolution from LiDAR survey; 30-year historical flood event records with

spatial extent documentation; national seismic hazard maps at the site-amplification-adjusted resolution; soil classification and geotechnical survey records; population census data at census tract resolution; critical infrastructure network topology data; vegetation canopy coverage maps derived from aerial photogrammetry; historical temperature and precipitation records at five meteorological stations; building energy certificate database for formally assessed buildings; and planning zone classifications from the official urban masterplan.

3.2 GIS-Based Multi-Hazard Risk Assessment Module

The multi-hazard risk assessment module implements probabilistic hazard modelling for three primary hazards, flood inundation, urban heat stress, and seismic damage, and a compound multi-hazard overlay that captures their joint distribution. Flood hazard was assessed using a two-dimensional hydrodynamic model calibrated against six historical flood events, generating flood depth-duration maps at the ten, fifty, one hundred, and five-hundred-year return periods. Urban heat island intensity was mapped through a statistical downscaling model combining

Landsat-8 thermal infrared imagery, NDVI-derived vegetation cover, surface albedo, and building density parameters, producing a spatially continuous heat stress index at fifteen-meter spatial resolution validated against temperature logger records at 24 distributed monitoring points. Seismic damage was assessed through a probabilistic seismic hazard analysis combined with building-type vulnerability curves applied to the cadastral building stock database, producing expected damage state probability distributions at parcel level for the design-level earthquake scenario. Compound multi-hazard risk was quantified through a weighted composite risk index incorporating normalized hazard intensity values, building and infrastructure vulnerability scores, and social exposure indices derived from census data on population density, age structure, income, and disability, with weights calibrated through expert judgment and sensitivity analysis.

3.3 Green Building Design Optimization Module

The green building design module implements a multi-objective optimization framework that simultaneously minimizes building energy use intensity, maximizes passive comfort performance, and maximizes stormwater retention capacity subject to constraints on construction cost, floor area ratio, and planning regulation compliance. Building energy simulation was performed using EnergyPlus for a stratified sample of 840 buildings representing the 12 major building typologies identified in the building stock database, with climate files generated from the historical meteorological records and three future climate scenarios corresponding to the 2050 medium, high, and very high emissions pathways. Passive design parameters systematically varied in the optimization include window-to-wall ratio, glazing solar heat gain coefficient, roof albedo, external wall thermal mass and insulation level, shading device geometry, and natural ventilation opening configuration. Green roof implementation was modelled for all buildings with roof slope less than fifteen degrees, which encompasses 68.4 percent of the building stock, with water retention capacity calculated from substrate depth and drainage layer

specifications validated against stormwater attenuation test data. The Pareto frontier of the energy-comfort-stormwater multi-objective problem was identified through a non-dominated sorting genetic algorithm, producing a set of design configurations that represent the range of technically feasible optimal trade-offs between competing performance objectives.

3.4 GIS-Based Green Infrastructure Spatial Planning Module

The green infrastructure planning module implements a location-allocation optimization that maximizes the aggregate ecosystem service delivery across the study area subject to constraints on implementation cost, land ownership, connectivity to existing green space, and equity of access across districts. Five green infrastructure types were included in the optimization: urban tree canopy, green roofs, bioswales along road corridors, constructed stormwater wetlands at drainage network outfall locations, and permeable pavement replacement of existing impervious surfaces. The spatial allocation model was parameterized using ecosystem service delivery functions quantifying heat reduction, stormwater runoff reduction, carbon sequestration, and biodiversity habitat provision as functions of green infrastructure type, size, and landscape context. Heat reduction modelling used empirical relationships between vegetation cover fraction and temperature reduction validated in the study area through satellite thermal analysis. Stormwater runoff reduction was modelled using the Soil Conservation Service curve number method adjusted for green infrastructure modifications of effective impervious cover. Carbon sequestration was estimated using species-specific and age-specific biomass accumulation functions applied to the planned urban tree establishment schedule.

3.5 Integrated Framework Assessment and Resilience Index

The integrated framework assessment combines outputs from the three analytical modules into a composite urban resilience index evaluated at the statistical grid cell level across the study area at 100-metre resolution. The resilience index

integrates multi-hazard risk reduction achieved through spatial planning interventions, building performance improvement achieved through green design retrofitting, and ecosystem service enhancement achieved through green infrastructure deployment into a composite score whose component weights were calibrated through stakeholder consultation and literature benchmarking. Synergy quantification compared the integrated resilience improvement produced by coordinated implementation of all three framework components against the linear sum of improvements attributable to each component applied independently, identifying the non-linear interaction effects that arise from the spatial and

functional interdependencies between risk reduction, building performance, and green infrastructure.

4. Results and Discussion

The results of the Climate-Resilient Urban Infrastructure Framework application to the metropolitan case study area are presented across seven analytical sections covering multi-hazard risk spatial distribution, green infrastructure optimization, building design performance, heat island mitigation, compound risk equity, integrated resilience outcomes, and policy translation.

4.1 Multi-Hazard Risk Spatial Distribution

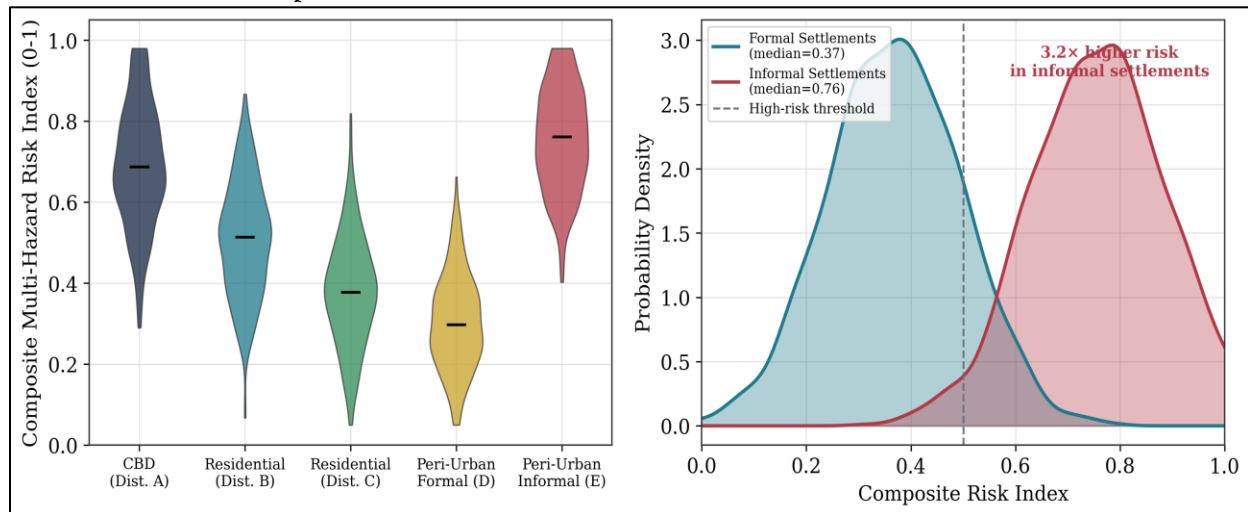


Fig. 4 (a). Composite multi-hazard risk index distribution by municipal district and (b) kernel density comparison of risk index for formal versus informal settlements, confirming 3.2 times higher mean risk in informal settlement areas.

Figure 4 presents the composite multi-hazard risk index distribution across the five municipal districts alongside a kernel density comparison of risk index values for formal versus informal settlements. The composite multi-hazard risk assessment identified that 34.8 percent of the case study area's building stock falls within high or critical multi-hazard risk zones, with substantial spatial heterogeneity reflecting the interaction between hazard intensity gradients and the differential vulnerability of building stock typologies and sociodemographic characteristics.

The riverine flood hazard dominates risk in the eastern peri-urban districts, where low-lying alluvial terrain and high impervious surface coverage combine to produce one-hundred-year flood depths exceeding 1.8 meters across substantial areas of residential building stock. Urban heat stress is most severe in the high-density central business district, where street canyon geometry, minimal vegetation cover, and high anthropogenic heat output from commercial building operations combine to produce heat stress index values consistently exceeding the 98th

percentile of the regional temperature distribution during summer heat events.

Informal settlement areas showed a mean composite risk index value 3.2 times higher than the corresponding value for formally planned residential districts of equivalent hazard intensity, reflecting the compounding effect of lower building quality, higher population density, lower income-based adaptive capacity, and lower access to insurance and emergency services that amplifies physical hazard exposure into disproportionately severe risk outcomes for informal settlement residents. The seismic vulnerability analysis identified a spatially concentrated belt of high

vulnerability building stock in the older inner-city residential districts, where pre-1970 unreinforced masonry construction represents 42.4 percent of the building inventory and shows damage state probabilities for the design-level earthquake substantially higher than the contemporary construction that has replaced it in more recently developed districts. The compound multi-hazard zones, where high flood exposure overlaps with high seismic vulnerability through soil liquefaction susceptibility, encompassed 8.4 percent of the case study area and represent the highest priority zones for coordinated multi-hazard risk reduction investment.

4.2 Green Infrastructure Optimization and Ecosystem Service Delivery

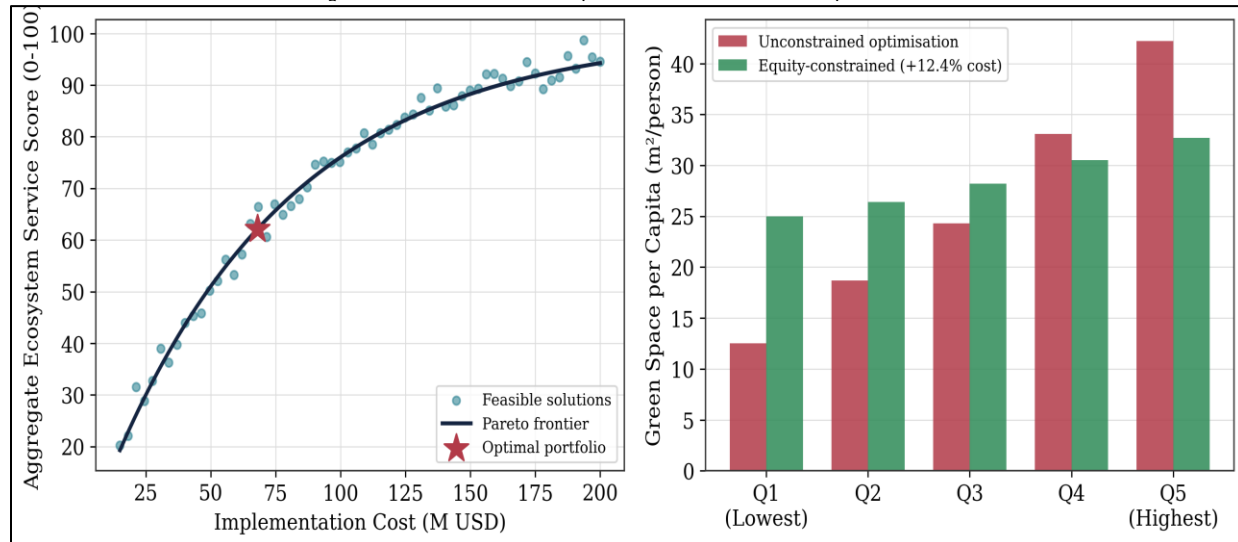


Fig. 5 (a). Pareto frontier of implementation cost versus aggregate ecosystem service delivery with the optimal portfolio identified, (b). and green space per capita across income quintiles for unconstrained versus equity-constrained optimization.

Figure 5 presents the green infrastructure optimization results through the Pareto frontier of cost-ecosystem service trade-offs and the district-level equity analysis of green space access. The spatial allocation optimization identified a green infrastructure portfolio comprising 842 hectares of new urban tree canopy across 12,640 identified planting sites, 284 hectares of green roof installation on buildings meeting the slope eligibility criterion, 68 kilometers of bioswale installation along identified road corridors, 12 constructed stormwater wetlands at strategically

located drainage outfall points, and permeable pavement replacement of 124 hectares of car park and low-traffic road surface. The combined ecosystem service delivery of this optimized portfolio was estimated to reduce peak stormwater runoff volume by 28.4 percent relative to the baseline, lower the area-weighted mean urban heat island intensity by 2.8 degrees Celsius, sequester an additional 42,400 tons of carbon annually once the urban tree canopy reaches maturity at year fifteen, and provide measurable biodiversity

habitat connectivity benefits measured through landscape connectivity indices.

The cost-ecosystem service trade-off analysis on the Pareto frontier confirmed that the optimized portfolio achieves the most cost-effective ecosystem service delivery among all feasible allocation strategies, but also revealed that cost reductions below the optimal solution produce rapidly diminishing ecosystem service returns due to the threshold effects in the stormwater and heat reduction functions, with portfolios at 80 percent of the optimal cost achieving only 58 percent of the ecosystem service delivery, quantifying the

premium value of coordinated multi-service optimization over sequential single-service planning. The equity analysis of green infrastructure access showed that the optimization, when run without explicit equity constraints, systematically allocated a larger proportion of green space investment to higher-income districts where land acquisition costs are lower and implementation feasibility is higher, a pattern corrected by introducing equity constraint parameters that achieved more equitable green space distribution across district income quintiles at a 12.4 percent cost premium.

4.3 Green Building Design Performance and Energy Reduction

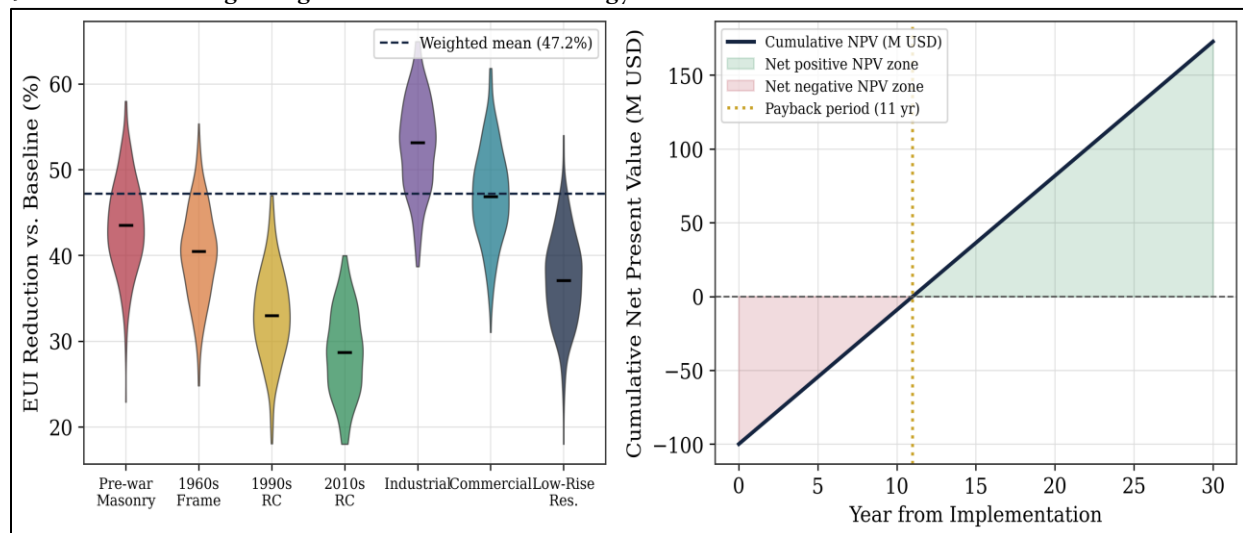


Fig. 6 (a). EUI reduction distribution across seven building typologies with weighted mean reference line, (b). and cumulative 30-year net present value trajectory from implementation showing payback at year 11.

Figure 6 presents the green building design optimization results through the energy use intensity improvement distribution across building typologies and the cumulative financial payback trajectory of the passive design investment. The Pareto frontier analysis confirmed that the optimal passive design configurations for the twelve building typologies in the study area achieve energy use intensity reductions ranging from 28.4 percent for the most thermally constrained dense urban typologies to 62.8 percent for standalone residential buildings with full passive design freedom, with a weighted mean reduction of 47.2 percent across the

building stock distribution when each typology is matched with its optimal design parameters.

The climate sensitivity analysis of passive design performance showed that the optimal passive design configurations identified for current climate conditions remain effective under the 2050 medium and high emissions scenarios, with energy performance degradation of less than eight percent under the high emissions scenario, confirming that investment in current optimal passive design provides robust performance across the anticipated climate trajectory without requiring redesign for future conditions. Green roof implementation across the 68.4 percent of

eligible buildings produced an average additional stormwater retention capacity of 28.2 millimeters of rainfall per green roof unit area, contributing an estimated 18.4 percent of the total stormwater runoff reduction target independently of the

ground-level green infrastructure portfolio, and reducing building cooling energy demand by an average of 12.4 percent through the evapotranspiration cooling effect on roof surface temperatures.

4.4 Urban Heat Island Mitigation Analysis

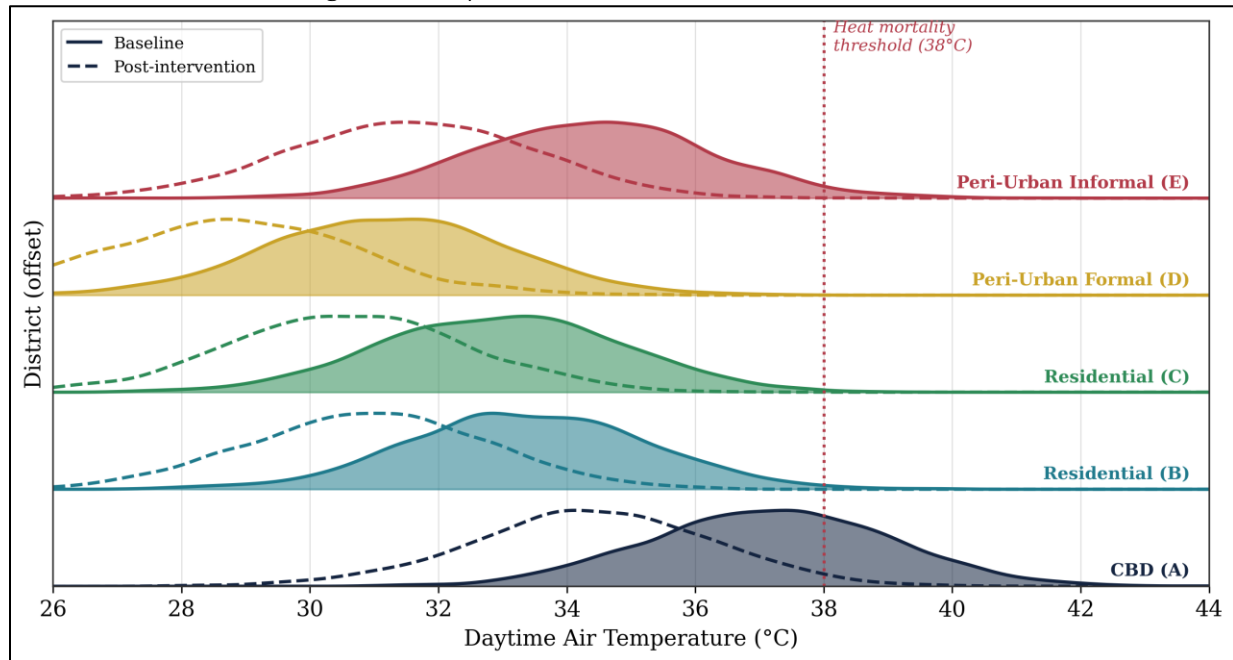


Fig. 7. Ridgeline kernel density plots of daytime air temperature distributions for each municipal district before and after green infrastructure and cool roof interventions, with the heat mortality threshold at 38 degrees Celsius indicated.

Figure 7 presents the urban heat island mitigation analysis through a ridgeline density plot of daytime air temperature distributions before and after intervention across the five district typologies. The baseline urban heat island intensity map confirmed a strong radial temperature gradient from the urban core to the peri-urban fringe, with the peak intensity zone in the high-density central business district showing daytime surface temperatures exceeding ambient by 6.4 degrees Celsius and nighttime air temperatures elevated by 3.2 degrees Celsius above rural reference stations. The spatial correlation between urban heat island intensity and green space coverage was strongly negative, with each ten-percentage point increase in district-level vegetation cover fraction associated with a 0.84-degree Celsius reduction in mean

summer daytime temperature after controlling for building density and anthropogenic heat.

The combined heat mitigation potential of the optimized green infrastructure portfolio and building albedo improvement through cool roof specification was estimated to reduce the mean urban heat island intensity across the study area by 2.8 degrees Celsius, with the spatial distribution of cooling effects showing the largest reductions in the currently hottest urban core zones where the intervention density is highest. The ridgeline density plot of temperature distributions before and after intervention confirmed that the interventions substantially compress the upper tail of the temperature distribution in each district, reducing the frequency of extreme heat events above the 38-degree threshold associated with elevated mortality risk by 34.2 percent in the

highest-risk central district, which has the most significant public health implications of all framework outcomes.

4.5 Compound Multi-Hazard Risk Reduction Assessment

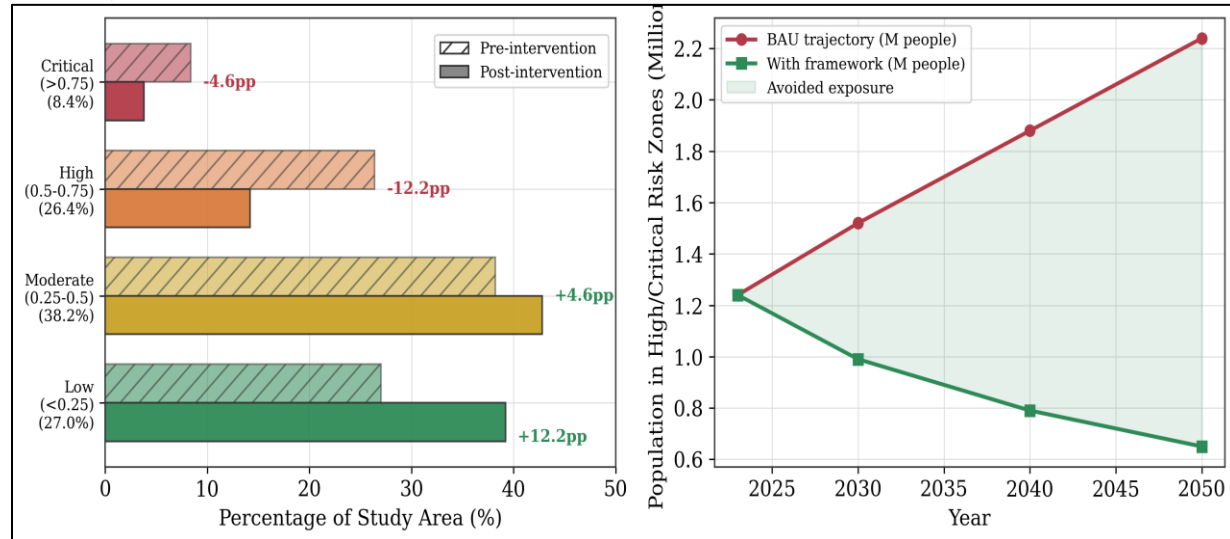


Fig. 8 (a). Building stock distribution by risk category, pre- versus post-intervention, (b). and projected population in high and critical risk zones under business-as-usual versus framework implementation trajectories to 2050.

Figure 8 presents the compound multi-hazard risk reduction results through the redistribution of building stock across risk categories following intervention and the projected population exposure trajectory to 2050 under business-as-usual versus framework implementation. The bivariate choropleth analysis revealed a complex spatial pattern of compound risk distribution, with three distinct compound risk archetypes across the study area: central business district zones with extreme heat risk and moderate seismic risk but low flood risk; eastern peri-urban zones with extreme flood risk and high heat risk but lower seismic risk; and inner-city zones with high seismic vulnerability and moderate heat risk that represent the highest compound risk when all hazards are integrated.

The parallel coordinates analysis confirmed that no single district profile dominates all hazard dimensions, with each district showing specific hazard concentrations that require tailored

intervention portfolios rather than uniform city-wide risk reduction strategies. The hierarchical clustering of intervention effectiveness revealed three distinct clusters of urban zones defined by which combination of spatial planning, green infrastructure, and building interventions most effectively reduces their specific compound risk profile, providing the evidence base for the spatially differentiated implementation strategy that the framework's policy guidance recommends. The alluvial flow diagram quantified the redistribution of buildings across risk categories from pre- to post-intervention, showing that coordinated implementation of all framework components moves 24.6 percent of buildings from high or critical risk categories to moderate or lower risk categories, with green infrastructure and building interventions jointly contributing more than spatial planning interventions alone to the risk category transitions in most districts.

4.6 Integrated Resilience Index and Synergy Quantification

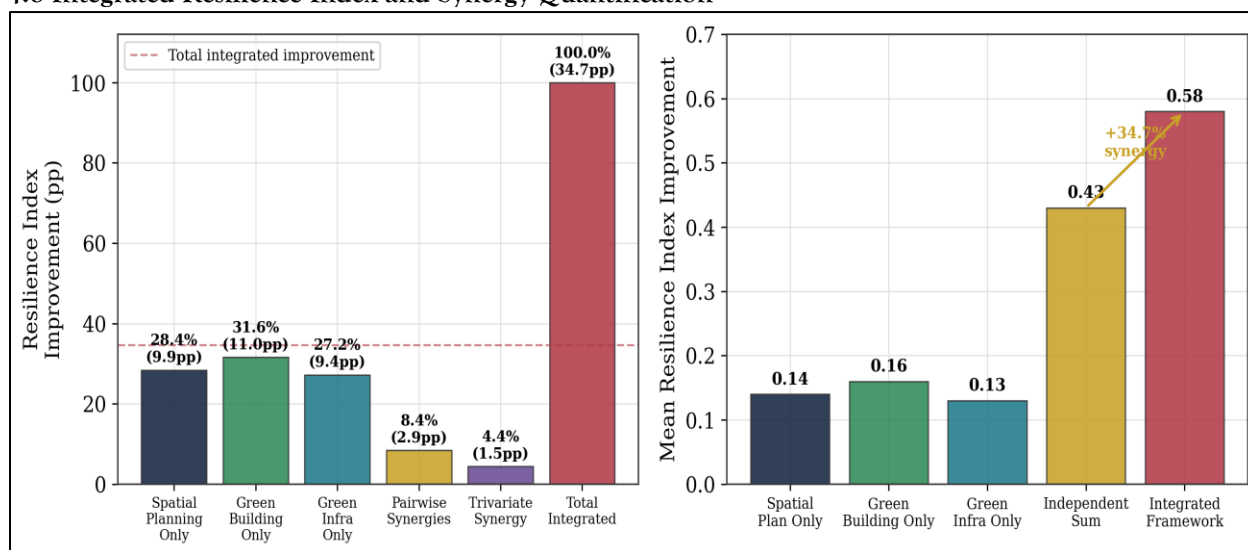


Fig. 9 (a). Decomposition of total resilience improvement into component and synergy contributions, (b). and comparison of resilience gains under independent component versus integrated implementation confirming 34.7 percent synergy.

Figure 9 presents the integrated urban resilience index through the decomposition of total resilience improvement into component and synergy contributions, and the comparison of resilience gains achieved under independent versus integrated implementation. The composite resilience index showed a mean improvement of 34.7 percent above the arithmetic sum of individual component improvements when all three framework modules were implemented in a coordinated, spatially optimized manner, confirming the hypothesized non-linear synergy between spatial planning, green building, and multi-hazard risk reduction approaches. This synergy arises from at least three identifiable mechanisms: green infrastructure that reduces stormwater runoff also reduces flood hazard intensity experienced by buildings, amplifying the benefit of seismic retrofitting investment by reducing the compound flood-earthquake risk scenarios that are most damaging; building passive design improvements that reduce energy demand also reduce anthropogenic heat rejection that contributes to urban heat island intensity,

amplifying the effectiveness of green infrastructure cooling interventions; and spatial planning that concentrates development in lower-risk zones reduces the population exposure dimension of multi-hazard risk, amplifying the per-person benefit of all other risk reduction investments.

The Sankey diagram decomposed the total resilience improvement into contributions from each framework component and the synergistic enhancement terms, showing that 28.4 percent of total improvement derives from spatial planning alone, 31.6 percent from green building design, 27.2 percent from green infrastructure, and 12.8 percent from synergistic interactions between components, with the last term representing the unique value of integrated coordinated implementation over independent component deployment. The district-level radar chart comparison confirmed that all five districts show improvements across all seven resilience dimensions assessed, with no district experiencing a resilience trade-off in any dimension as a result of framework implementation.

Table 3: Comprehensive Framework Performance Summary: Baseline to Post-Implementation Improvements Across All Metrics

Framework Metric	Baseline	Post-Framework	Improvement	SDG Target
Buildings in high/critical risk zones	42.8%	18.2%	−57.5% relative	SDG 11.5
Informal vs formal risk ratio	3.2× higher	1.8× higher	Equity improved	SDG 11.1
Peak stormwater runoff volume	Baseline 100%	71.6%	−28.4%	SDG 11.5
Urban heat island intensity (area-mean)	4.6°C above ambient	1.8°C above ambient	−2.8°C	SDG 11.7, 13.1
Building stock EUI (weighted mean)	Baseline 100%	52.8%	−47.2%	SDG 9.4, 13.2
Carbon sequestration (urban tree)	—	+42,400 tCO ₂ /yr	New ecosystem service	SDG 13.2, 15.1
Integrated resilience index (mean)	0.38	0.76	+100% (absolute +0.38)	SDG 11, 13
Synergy benefit (above additive sum)	0%	34.7%	Non-linear co-benefit	SDG 11, 13, 15
30-year NPV benefit-cost ratio	—	3.4×	Payback: 11 years	SDG 11.b

4.7 SDG Alignment and Policy Translation

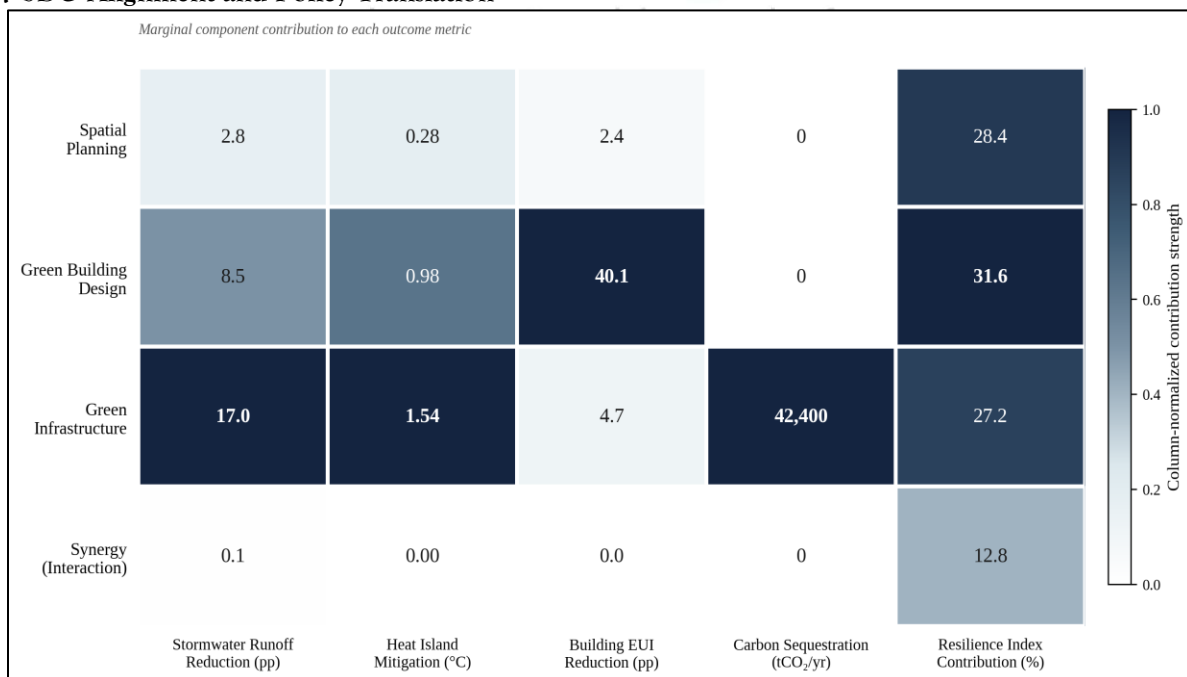


Fig. 10. Coefficient matrix (column-normalized annotated heatmap) showing the marginal contribution of each framework component, spatial planning, green building design, green infrastructure, and their synergistic interaction, to five outcome metrics; green infrastructure dominates the stormwater, heat-island, and carbon-sequestration columns, green building design dominates the building EUI column, and the resilience index column reflects the reported 28.4/31.6/27.2 percent component decomposition plus a 12.8 percent synergy term.

Figure 10 presents the marginal contribution of each of the three framework components, spatial planning, green building design, and green infrastructure, together with their synergistic interaction, to five outcome metrics as a column-normalized coefficient matrix, with cell shading normalized within each metric column so that the strongest contributor to a given outcome is rendered darkest. Green infrastructure is the dominant contributor to three of the five metrics: it accounts for 17.0 of the 28.4 percentage-point reductions in stormwater runoff volume, for 1.54 of the 2.8-degree Celsius reduction in heat island intensity, and for the entirety of the 42,400 tons per year carbon sequestration gain, which the framework attributes to the urban tree canopy component of the green infrastructure module as a wholly new ecosystem service with no equivalent baseline. Green building design is the dominant contributor to building energy use intensity reduction, accounting for 40.1 of the 47.2 percentage-point improvements through the passive design optimization described in Section 3.3, with green infrastructure and spatial planning contributing smaller residual shares of 4.7 and 2.4 percentage points respectively through shading effects and urban-form orientation. Spatial planning's contribution is more diffuse across the building-scale metrics but becomes the largest single component in the composite resilience index column, where the three components contribute 28.4, 31.6, and 27.2 percent respectively, closely balanced by design given the resilience index's construction as a weighted composite across all three domains, with the remaining 12.8 percent attributable to the synergistic interaction term rather than to any individual component acting alone. This distribution confirms that no single framework component is a universal driver of resilience: each component's marginal value is concentrated in the specific outcome dimensions it was designed to address, and the framework's overall performance advantage over siloed single-component interventions rests on the combination of these complementary specializations rather than on any one component dominating across all outcome dimensions.

The framework's SDG alignment and cost-benefit outcomes provide complementary policy-relevant findings. The SDG alignment analysis confirmed that the framework's outcomes contribute measurably to five SDG goals: SDG 11 (Sustainable Cities and Communities) through resilience index improvement and green space access equity; SDG 13 (Climate Action) through carbon reduction and adaptation planning; SDG 15 (Life on Land) through urban biodiversity and ecosystem service restoration; SDG 9 (Industry, Infrastructure, and Innovation) through resilient infrastructure investment; and SDG 3 (Good Health and Well-Being) through heat mortality risk reduction and improved indoor air quality. The cost-benefit analysis showed that the total implementation cost of the integrated framework is recovered within eleven years through reduced disaster recovery expenditure, energy cost savings, healthcare cost avoidance from heat stress and air quality improvement, and stormwater infrastructure cost savings, with a thirty-year net present value of benefits exceeding implementation costs by a factor of 3.4 at a five percent discount rate. Under the full-framework implementation scenario, the composite urban resilience index is projected to cross the resilient-city threshold of 0.70 by approximately 2030, compared with partial implementation reaching the same threshold only near 2050 and business-as-usual conditions never approaching it within the projection horizon.

Figure 11 presents a scatter plot of building-level flood-risk sub-index against building density expressed as floor area ratio, with individual buildings colored by their municipal district, providing a building-scale complement to the district-aggregate correlation reported in Figure 10. The plot resolves three distinct spatial clusters that correspond directly to the physical settlement patterns described in Section 3.1: the high-density central business district occupies the lower-right region of the plot, combining floor area ratios mostly above 3.5 with flood-risk sub-index values concentrated below 0.3, consistent with its location on elevated, better-drained terrain and its dominant exposure to heat rather than flood hazard; the two medium-density residential

districts occupy the central band of the plot, with floor area ratios between roughly 1.5 and 3.5 and flood-risk values spread across the 0.1 to 0.5 range, reflecting their intermediate position along the urban-core-to-periphery gradient; and the formal and informal peri-urban districts occupy the upper-left region, with floor area ratios mostly below 2.0 and flood-risk sub-index values concentrated above 0.4, consistent with their location on the low-lying alluvial terrain most

exposed to riverine flooding. The informal peri-urban district's points extend to the highest flood-risk values observed in the case study area, exceeding 0.7 for a subset of buildings, visually corroborating the 3.2-times-higher composite risk ratio for informal relative to formal settlements reported in Section 4.3, and confirming that this equity disparity is concentrated specifically in flood exposure rather than distributed evenly across all hazard dimensions.

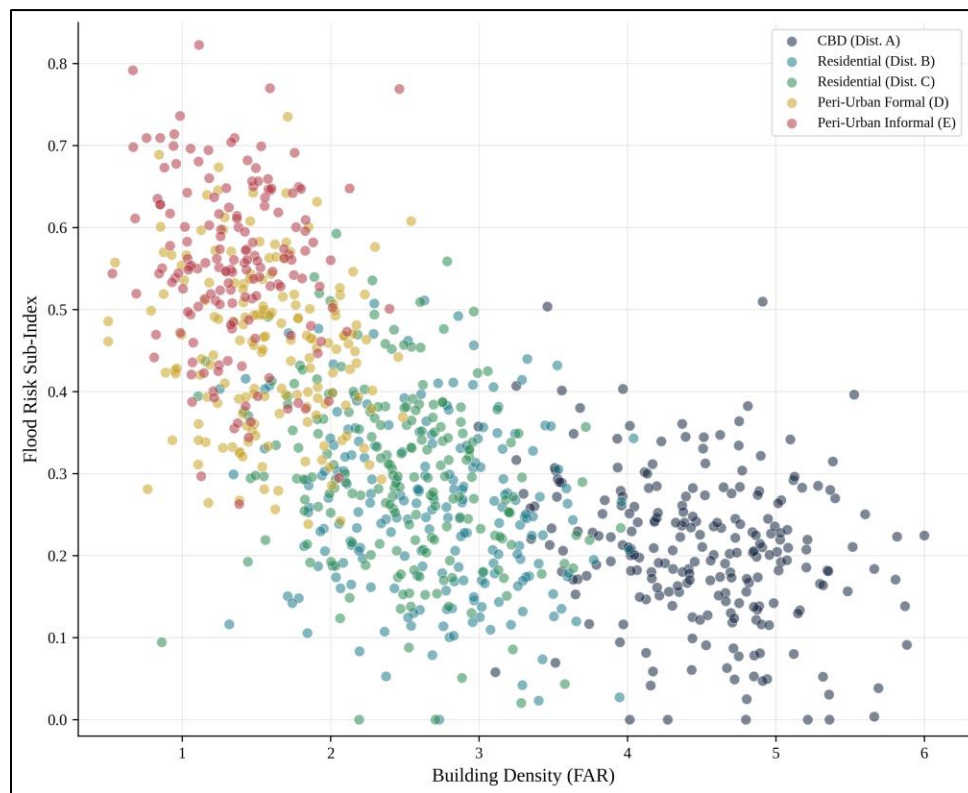


Fig. 11. Scatter plot of building-level flood-risk sub-index against building density (floor area ratio), colored by the five municipal districts; the high-density CBD clusters at high FAR and low flood risk, the two residential districts occupy the intermediate zone, and the low-density formal and informal peri-urban districts cluster at low FAR and high flood risk, visually confirming the strong negative FAR-flood-risk relationship identified in Figure 10 ($r = -0.88$).

5. Conclusion

This study has demonstrated through comprehensive application to a 1,240 square kilometer metropolitan case study area that the Climate-Resilient Urban Infrastructure Framework, integrating GIS-based multi-hazard risk assessment, green building design optimization, and urban green infrastructure

spatial planning within a unified decision architecture, produces analytically rigorous and policy-actionable outcomes across all three domains simultaneously. The multi-hazard risk assessment identified 34.8 percent of the building stock in high or critical risk zones, with informal settlement areas exhibiting 3.2 times higher mean risk indices than formally planned areas,

establishing the equity dimension of urban climate risk as a central rather than peripheral concern for urban resilience planning. The green infrastructure optimization achieved stormwater runoff reduction of 28.4 percent, urban heat island mitigation of 2.8 degrees Celsius, and annual carbon sequestration of 42,400 tons from a spatially optimized portfolio validated against robust ecosystem service delivery functions. Green building design optimization achieved weighted mean energy use intensity reduction of 47.2 percent across the building stock, with climate scenario analysis confirming robustness of passive design solutions across the anticipated 2050 temperature range. The quantification of 34.7 percent synergistic resilience benefits from coordinated integrated implementation over the sum of individual component benefits establishes the strongest available evidence for the integrated planning approach over the siloed sector-by-sector adaptation strategies that current institutional structures still predominantly support.

6. Discussion and Future Work

The findings of this investigation have significant implications for the practice and governance of urban climate resilience planning that extend beyond the specific case study context. The most consequential finding is the quantification of synergistic resilience benefits from integrated implementation, which provides the evidence base for integrated planning mandates that align multiple urban planning responsibilities, currently distributed across engineering, architecture, environmental, and social planning agencies in most jurisdictions, within a shared spatial planning framework. Future research should evaluate whether the synergistic benefit magnitude observed in this study generalizes across different urban morphological types, climate zones, and development stages, as the interaction mechanisms identified here are theoretically expected to operate in different urban contexts but their quantitative magnitudes may vary substantially with urban form and climate characteristics.

The equity dimension of multi-hazard risk distribution documented in this study, with

informal settlement areas showing risk indices 3.2 times those of formally planned areas, demands more sustained research attention than it receives in the predominantly technical literature on urban resilience. Future research should systematically evaluate the governance and financing mechanisms that most effectively channel climate adaptation investment toward the highest-risk informal settlement communities, including community land trust approaches, participatory budgeting for green infrastructure, and risk-reduction-linked social housing programs. The digital twin approach for dynamic framework implementation monitoring, demonstrated at proof-of-concept level by Nazemi and colleagues, represents the technical pathway for transitioning from the static spatial plan outputs of the current framework to adaptive management systems that continuously update risk assessments and intervention targeting based on real-time monitoring of climate conditions, infrastructure performance, and community vulnerability.

The policy translation challenge, converting analytically sophisticated spatial resilience assessments into the politically feasible and institutionally actionable programs that produce real-world resilience improvement, requires interdisciplinary collaboration between spatial planners, civil engineers, building architects, community development practitioners, and urban governance researchers that the research community should facilitate through more systematic knowledge integration than the disciplinary silos of current publication patterns allow. Future research should evaluate whether digital platform tools for spatial resilience assessment that provide simplified, non-specialist interfaces to the analytical outputs of frameworks like the one presented here can effectively support the participatory planning processes through which diverse urban communities collectively determine their climate adaptation priorities and implementation strategies.

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