Geoinformatics advancing resilient urban planning: Risk perception, resilience assessment, and spatial simulation

Wuyang Hong,[1,2] Renzhong Guo,[1,2] Xiaochun Yang,[1,2,*] Xiaoming Li,[1,2] and Weixi Wang[1,2]

[1]School of Architecture and Urban Planning, Shenzhen University, Shenzhen 518000, China

[2]State Key Laboratory of Subtropical Building and Urban Science, Shenzhen University, Shenzhen 518000, China

*Correspondence: yangxc@szu.edu.cn

Received: June 28, 2024; Accepted: November 7, 2024; Published Online: November 29, 2024; https://doi.org/10.59717/j.xinn-geo.2024.100103

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Citation: Hong W., Guo R., Yang X., et al., (2024). Geoinformatics advancing resilient urban planning: Risk perception, resilience assessment, and spatial simulation. The Innovation Geoscience 2(4): 100103.

Under the effect of multiple factors such as climate change, international geopolitical shifts, and resource depletion, uncertainties faced by global cities are continuously exacerbated. As the variety and number of urban risks increase, natural disasters and security incidents occur more frequently. Building resilient cities offers a viable approach to managing these risks. The complex relationship between risk sources and disaster hosts within a city requires comprehensive planning for ideological, material, and organizational preparations. Geographic information technology can mitigate the negative effects of these risks on global cities. Consequently, it is imperative to globally elevate the status of resilient urban planning.

RELATIONSHIP BETWEEN DISASTER RISKS AND URBAN PLANNING FOR GLOBAL CITIES

In recent years, there has been a significant increase in global hazard risks (Figure 1A), posing substantial challenges to human survival and development. Between 2014 and 2023, the world experienced about 3,500 major natural disasters, affecting 191 countries and severely impacting more than 7.3 billion people. Currently, global natural hazards encompass nine main types: floods, storms, biological disasters, earthquakes, geological disasters, other meteorological events, wildfires, volcanoes, and marine disasters, with floods and storms being the most frequent and impactful. Due to its diverse, frequent, and widespread natural disasters, China experiences substantial economic losses. According to data from China's Ministry of Emergency Management, in 2023, 67.6% of the population was affected by natural disasters, resulting in direct economic losses of 345.45 billion RMB. The complexity and severity of disaster risks are high, and the management of such risks remains challenging, which is exacerbated by the intersection of emerging risks and frequent extreme events.

Global cities urgently require transformation and development owing to the growing complexity of impacts and pressures. Enhancing urban resilience is crucial for guiding urban transformation and development.[1-2] Numerous organizations and city governments have explored the development of resilient cities. For example, in 2013, the Rockefeller Foundation launched the Global 100 Resilient Cities Project. In 2015, the United Nations incorporated the 11th goal in the 2030 Sustainable Development Goals, emphasizing urban sustainable development and advocating the creation of inclusive, safe, and resilient cities and human settlements. In 2016, the UN Habitat III Conference highlighted the concept of a "Resilient City" in the New Urban Agenda. At the city level, 104 cities worldwide have formulated resilience plans (Figure 1B), with 52.9% of these plans belonging to coastal cities and 49.0% belonging to cities in developing countries. Examples of the plans include initiatives such as Resilient New Orleans: Action Strategy for Shaping Future Cities, Resilient Kyoto in Japan, and Beijing's Special Plan for Resilient Urban Space (2022–2035). These resilience plans typically address resilience challenges, outline a vision, and propose action plans.[3] However, the overall resilience planning framework has not yet been formulated, and the application of spatial intelligence technology is inadequate.

The lessons learned from urban crises show that planning quality directly affects the severity of risk consequences, with inadequate planning potentially triggering chain reactions. For instance, the 2008 Wenchuan earthquake in China exacerbated losses owing to the inappropriate location of Beichuan's old county town on a fault line of low quality. Similarly, the 2015 explosion at the Tianjin Binhai Chemical Industry Park led to significant economic losses because the storage of hazardous materials was too close to residential areas. In 2021, Canada's heat wave highlighted insufficient urban park accessibility and flexible space allocation, contributing to numerous fires during residents' summer activities. In 2024, widespread flooding in parts of Britain was exacerbated by urban sprawl encroaching upon natural waterways and floodplains, thereby reducing drainage system efficiency. There are some cities that have recognized the importance of resilience planning, such as the Coastal Restoration (LMCR) project of the coastline undertaken by New York's *Research on Climate Resilience in Lower Manhattan*, which has protected six communities in Lower Manhattan and 70% of the coastline. Japan's *Basic Plan for*

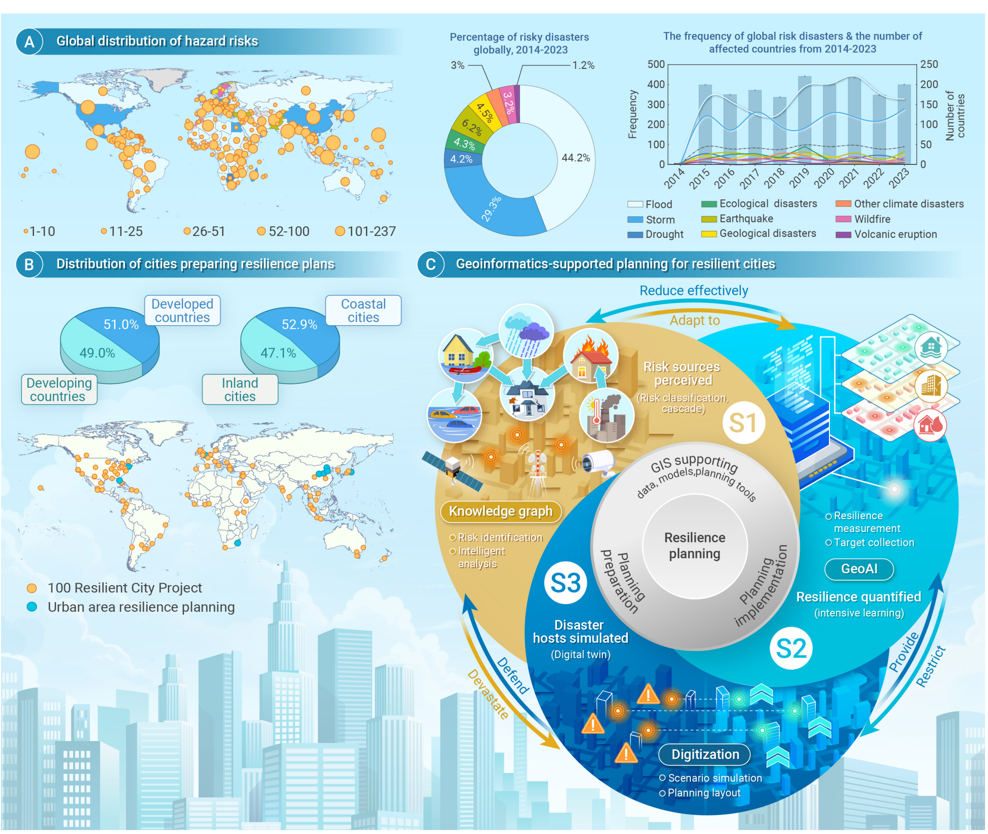

Figure 1. Schematic diagram for Resilient Urban Planning
(A) Global distribution of hazard risks; (B) Distribution of cities preparing resilience plans; (C) Geoinformatics-supported planning for resilient cities

Strengthening the National Land Resilience uses digital technologies, such as the Linear Rainfall Belt Prediction Supercomputer, to forecast rainfall conditions in the county 12 hours in advance and broadcast them to the public through smartphone applications, reducing the impact of heavy rains. The aforementioned recurring issues underscore planning deficiencies. Despite the global increase in resilient city initiatives, clear planning mechanisms and guiding theories are lacking. Thus, it is imperative to implement comprehensive urban planning reforms that address governance at the source with a systematic approach.

SOURCE STRATEGY TO DEAL WITH DISASTER RISKS: RESILIENT URBAN PLANNING

The essence of developing a resilient city is systematically managing potential risk sources and vulnerabilities in urban environments[4] and creating a city capable of not only withstanding external shocks but also quickly recovering and adapting to changes. Resilient urban planning can achieve this objective and requires a problem-oriented and goal-oriented approach. This involves identifying primary risks faced by a city, accurately assessing resilience requirements, and establishing reasonable planning objectives. The aim is to develop a secure, dependable, flexible, and rapidly recovering urban spatial layout suitable for various risk scenarios (Figure 1C).

The planning of resilient cities across different countries and regions must integrate seamlessly with existing spatial planning systems. The planning process should involve integrating various geospatial and historical risk data to assess the types and levels of risks faced by cities and develop resilience plans. Next, the process should entail determining the role and positioning of resilience planning in the overall framework—whether it integrates as a part of comprehensive planning or functions independently as specialized planning. This decision depends on factors such as growth in population, changes in land use, and patterns of resource consumption in local urban settings, weighing economic costs against potential social, economic, and environmental benefits. These benefits encompass direct economic gains, such as reduced post-disaster reconstruction costs, and indirect benefits, such as enhanced resident quality of life and increased investment attractiveness. Finally, targeted management and control measures should address key regional risks while strategically planning buffer zones around disaster-prone areas. This approach aims to establish a scientifically grounded urban spatial layout, facilitating the flow of activities. It involves strengthening city infrastructure like transportation, communication, and energy supply to form a cohesively resilient space while also adjusting urban functional zoning based on risk levels, isolating hazardous materials and flood-prone areas, and improving buildings' seismic and fire safety to bolster disaster resilience.

The successful implementation of resilience planning relies on the dual assurance of technology and policy. Leveraging emerging technologies can significantly enhance the effectiveness of implementing resilience plans.[5] City Information Modeling and digital twinning technologies enable the generation of virtual models for urban infrastructure and buildings. Spatial intelligence technology enhances this by conducting accurate simulations of disaster risks, enabling planners to assess a city's resilience and potential losses under various scenarios. This facilitates the development of comprehensive emergency toolkits for three-dimensional, refined, and dynamic management. Implementing resilience planning involves continuous dynamic adjustment and optimization. Before implementation, it is crucial to assess existing policies and regulations to ensure that they support resilient construction and have legal validity. Timely introduction or modification of standards, specifications, and design guidelines, such as multifunctional land-development policies, will ensure seamless integration of planning and implementation of the plans across the entire city and individual communities. Establishing an urban health check-up framework and resilient city evaluation will ensure ongoing monitoring of urban operations, including traffic flow, environmental quality, and infrastructure conditions. Examples of such urban health check-up frameworks include China's *Regulations for Physical Examination and Evaluation of Cities in National Spatial Planning*, Britain's *Annual Monitoring Report on London Planning*, and the *Annual Report on Urban Conditions* in the United States, which enable quick activation of emergency plans when needed.

GEOINFORMATICS EMPOWERING RESILIENT URBAN PLANNIING

Perceiving S1 risk sources: A comprehensive understanding and detailed representation of complex urban environments are crucial for addressing risk sources during resilience planning. Establishing a spatiotemporal urban disaster knowledge graph that identifies risk sources and provides a scientific foundation and data basis for defining resilience planning objectives is necessary. All cities possess unique spatial characteristics, environmental features, social structures, functional roles, and specific distributions of various risk sources, all of which must be carefully considered when assessing local risk events. Given the interconnected and cascading nature of disasters, broader environmental risks affecting urban safety require special attention. Leveraging GeoAI and other knowledge discovery technologies facilitates the creation of a dynamic digital profile of urban risk characteristics, which involves optimizing digital infrastructure and developing predictive models for short-term risk forecasting and long-term risk evolution. For example, the utilization of high-precision NowcastNet based on deep learning models with physical information fusion, as well as the real-time exploration of disaster-stricken areas using UAVs, can facilitate the accurate early warning and recovery from disasters, enhancing the rationality and effectiveness of planning objectives.

S2 resilience quantification: Quantifying resilience is central when assessing recovery capacity during resilience planning. As a detailed and quantitative indicator for achieving resilience planning goals, recovery capacity relies on the urban disaster knowledge graph and employs a multidimensional, dynamic, spatiotemporal, big-data assessment scheme. For example, the temporal and spatial big data of rainfall, land surface, and water accumulation are fused to describe the dynamic change processes of urban waterlogging. Further, the risk level of urban wildfires is established based on historical images and deep learning technologies, graph neural networks embedded with spatial information are used to predict the trajectory of people flow during public health events, the proxy index is established using the toughness curve method, and key influencing factors under different risks identified using the structural equation model and spatial coping strategies—such as sponge city reconstruction and emergency management measures—are fully considered during resilience planning.

Simulation of S3 disaster hosts: Big-data computing and intelligent analysis are crucial in simulating resilient hosts. Urban resilience planning requires robust computing capabilities to handle vast amounts of urban environmental perception and disaster risk measurement data and simulate and test decision-making frameworks for resilience. Currently, GIS spatial technology platforms are central to urban planning decision support, and technologies such as three-dimensional physical modeling based on buildings and urban spaces can realize risk simulation and visualization. There is a growing need to integrate digital intelligence software platforms to establish a shared information database accurate to specific plots, buildings, and residents, ensuring comprehensive decision-making simulations under interconnected risks. Techniques such as geographically and temporally weighted regression methods using convolutional neural networks and Bayesian belief network-optimized hidden Markov model improve the precision of measurement platforms and enable intelligent multiscenario simulations of decision frameworks. Using methods such as Non-dominated Sorting Genetic Algorithm for multiobjective optimization of urban resilient hosts yields optimal solution sets, supporting resilience planning and optimization with informed decision-making.

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FUNDING AND ACKNOWLEDGMENTS

This research was supported by National Natural Science Foundation of China (NO: 42371427), Strategic Study Project of Chinese Academy of Engineering (NO: 2022-JB-02), Shenzhen University 2035 Program for Excellent Research (NO: 2022B005).

AUTHOR CONTRIBUTIONS

All authors contributed to and approved the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.