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Special Issue Reprint

Spatial Analysis and Spatial Planning for Sustainability in Urban Areas

Edited by
Francesco Zullo and Cristina Montaldi

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Guest Editors

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About the Editors

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Preface

Cities today face unprecedented environmental, social, and economic challenges associated with rapid urbanization, climate change, resource consumption, demographic transformations, and increasing territorial pressures. In this context, the creation of more sustainable, resilient, and liveable urban environments has become a global priority. Addressing these challenges requires interdisciplinary approaches capable of integrating spatial analysis, territorial planning, environmental assessment, and technological innovation. This Reprint brings together contributions that explore theoretical and methodological advances in the field of sustainable urban development, with particular attention to urban resilience, ecosystem services, ecological networks, land-use dynamics, public health, and sustainable mobility. Through international case studies and empirical applications, the authors provide new perspectives for understanding and managing contemporary urban transformations. The motivation behind this Reprint stems from the growing need to better understand the interactions between natural and built environments and to support strategies capable of balancing environmental quality, social well-being, and territorial development. The contributions presented in this volume demonstrate how spatial modelling, geospatial technologies, big data analytics, and simulation tools can support more effective decision-making processes and a more informed management of cities. The topics addressed range from ecological network optimization and ecosystem service assessment to the analysis of urban expansion and its environmental impacts, the design of resilient public spaces, post-disaster reconstruction, mobility, and territorial development policies. Taken together, these contributions highlight the value of integrated approaches for addressing the complexity of contemporary urban contexts and promoting more sustainable and inclusive transformation pathways. This Reprint is intended for researchers, practitioners, and decision makers engaged in the study and management of urban transformations. We hope that the reflections and findings presented in this volume will stimulate further research activities, foster interdisciplinary collaboration, and contribute to the development of innovative solutions for more resilient, inclusive, and sustainable cities.

Francesco Zullo and Cristina Montaldi
Guest Editors

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Review

Integrating Urban Design, Healthy Habits, and Socio-Ecological Networks: A One Health and Well-Being Framework for Sustainable Cities

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Abstract

This article examines the role of urban design in integrating biodiversity preservation with the enhancement of environmental and human health and quality of life in urban and peri-urban areas. Building on three complementary perspectives—urban design, the Healthy Habits framework, and socio-ecological networks—the review seeks to bridge short- to medium-term actions for improving the quality of life with long-term strategies for biodiversity preservation. While partial connections between these domains exist, they remain fragmented, underscoring the need for a holistic and transdisciplinary approach to urban socio-ecological health. The study employs a two-stage methodology, combining a scoping review to map existing evidence with a qualitative thematic review across SCOPUS-indexed research, European and international policy frameworks, and practical applications. The One Health paradigm is used as the principal integrative tool to link urban design, the Healthy Habits framework, and the socio-ecological networks. The topics of European environmental policies, evolutionary pillars, and social cohesion are incorporated to strengthen the interrelations between environmental and societal health and well-being. The findings highlight the importance of a holistic approach, behavioural insights, urban nudges, and participation, which can become key elements in fostering social cohesion, ecological resilience, and overall health. The research concludes that health-oriented urban design must go beyond traditional planning paradigms and tools, adopting adaptive, relational, and transdisciplinary approaches to address the challenges posed by contemporary times.

Keywords: urban and territorial planning; biodiversity and ecosystem services; public health; participatory governance; social cohesion; resilient urban systems

1. Introduction

The Natura 2000 network, throughout Europe, focuses on safeguarding biodiversity by maintaining natural resources (natural and semi-natural habitats, as well as wild flora and fauna) in a state of "satisfactory conservation". There is a growing belief that biodiversity contributes to sustainability [1–3] and must be promoted and maintained, considering economic, social, and cultural needs and regional and local particularities.

The advances in ecology and conservation biology have already shown that the conservationist approach focused on individual threatened species does not yield effective conservation outcomes [4,5]. Conservation instruments, which for most species rely on protected areas, are insufficient to halt biodiversity loss and thus call for conservation initiatives on the broader landscape surrounding protected areas [6]. Therefore, it is necessary to operate within a network vision, in which human activity itself, if well-designed, can help preserve biodiversity. However, the complex interconnections among living beings and their environments must be considered.

Natura 2000, as a network concept, enters a logic of sustainability by recognising that a series of human (traditional agricultural) activities are even indispensable for the protection of biodiversity [7] and that the depopulation and abandonment of areas are anything but beneficial to the conservation of natural and very often semi-natural habitats [8]. Also, the well-being and health of the inhabitants depend on the environmental conditions of the open green spaces and the city [9]. In this interrelation between the quality of biocenoses—groups of interacting organisms living in a particular habitat and forming a self-regulating ecological community—and the quality of life, the Natura 2000 Network takes on particular importance when nature meets inhabited spaces.

All this revolutionises the approach to the management of Natura 2000 Sites and the entire territory, opening the need for exploring new connections between the various disciplines involved in urban planning and design that improve the quality of life and well-being of ecological and social communities. Therefore, it is necessary to radically reconsider the interrelations between the living spaces of plants, animals, and humans, to reconcile the improvement of the biocenoses of a geographical area at the same time as the increase in the quality of life and health of the inhabitants of that same geographical area [10].

The current body of knowledge is examined to demonstrate interrelation intensities among urban planning, the Healthy Habits framework, and socio-ecological networks. The integration of urban design and socio-ecological networks is identified in community gardens and urban green spaces that function simultaneously as ecological nodes, supporting biodiversity and ecosystem services, and as social nodes, enhancing social cohesion and interaction [11,12]. Frameworks such as One Health [13] and the Virtuous Cycle [14] explicitly link urban planning with socio-ecological processes, highlighting participatory planning and justice-oriented processes as critical mechanisms for integration. Design elements of urban form, such as density, accessibility, and walkability, are operationalised in frameworks like the Eight Dimensions (8Ds) [15] and the Walkability Measurement [16], showing context-dependent relations between regional planning and urban design to functions of urban networks in creating healthy and sustainable cities. Research on interactions between urban design and socio-ecological networks reports trade-offs (e.g., compact design may reduce green infrastructure) [13] and highlights synergies (e.g., regenerative approaches align social and ecological objectives) [17].

Socio-ecological networks such as green spaces, parks, and walkable environments are associated with increased physical activity, reduced stress, enhanced mental health, and improved social cohesion [18–20] as indicators of human health and well-being. Subjective perceptions of urban green spaces, such as perceived safety and aesthetic quality, play a key role in whether residents adopt health-promoting behaviours [20]. Also, socioeconomic status and community engagement emerge as moderating factors that affect access to healthy environments and behaviours [21], thus underscoring the necessity for urban planning policies to adopt an inclusive approach [22]. Participatory approaches and community involvement in planning and management [14,19] effectively align socio-ecological structures with health needs.

The influence of urban design features such as walkability, mixed land use, and green infrastructure is linked to human health and Healthy Habits behaviours [18,19], as supported by frameworks such as the Park Network Index [23] and Salutogenic Urban Design [24]. However, some studies on urban form and green infrastructure [13,25] point to adverse or mixed effects in high-density environments, where benefits to human health through walkability and social ties may coexist with reduced access to green spaces and potential isolation.

Examining the interrelations between urban design, the Healthy Habits framework, and socio-ecological networks, the thematic literature review reveals integration of urban design and socio-ecological networks, the impact of socio-ecological networks on human health, and the influence of urban design on human health. Although some of the reviewed frameworks, such as One Health [13], the Eight Dimensions (8Ds) [15], and Salutogenic Urban Design [24], illustrate that the integration of socio-ecological networks and well-planned urban structures reinforces health-promoting behaviours, the holistic interrelation is missing. The current body of knowledge lacks an integrated and systemic understanding of how urban form, socio-ecological networks, and public health outcomes co-evolve and influence one another in shaping social well-being and ecosystem health. This absence of a holistic perspective represents a critical research gap, particularly given the increasing complexity of urban socio-ecological systems. This research gap is evidenced in the prevailing tendency in scholarly and policy discourse to address human health separately from the health of animals, plants, and ecosystems [26]. To address this fragmentation, this review brings together interdisciplinary expertise from urban planning, public health, and urban sociology—disciplines essential for the sustainable management of urban environments, integrating socio-ecological networks and the Healthy Habits principles of its inhabitants. Such integration and holistic understanding are crucial for shaping urban life, which equally supports both human well-being and ecosystem health.

The methodological approach combines a scoping review of scientific bases with a thematic review across urban planning, public health, and sociology disciplines, converging on three complementary perspectives to provide additional knowledge on human well-being, ecosystem health, and sustainability in urban and peri-urban areas. To advance a more holistic understanding of these interrelations, the thematic review is structured around three complementary topics:

- the evolution of European environmental policies influencing urban planning and the design of public green spaces for human and environmental health (urban planning perspective);
- designing healthy cities with the Healthy Habits framework: a One Health model grounded in four evolutionary pillars (public health perspective);
- urban systems and social interaction for healthy cities: the outdoors generating healthy social networks (sociological perspective).

In conclusion, the findings underscore that the effective management of urban green spaces, in conjunction with supportive human behaviours, can significantly enhance public health and increase biodiversity. These outcomes align with the objectives of the main European strategies aimed at fostering sustainable, resilient, and health-promoting urban environments.

2. Methods and Materials

The literature review adopts a two-step methodological approach: (i) an initial scoping review to set the state-of-the-art and identify research gaps in the interrelation of urban design, Healthy Habits, and socio-ecological networks, followed by (ii) a thematic review to deepen the interrelation analysis of these three perspectives within their disciplines

of urban planning, public health, and sociology. This interdisciplinary approach, which combines quantitative and qualitative research, facilitates the identification of key patterns and conceptual overlaps that support an integrated understanding of urban socio-ecological health. By structuring the analysis through three complementary perspectives, the review synthesises insights that are often treated separately.

2.1. The Scoping Review

The scoping review was conducted with the aim of synthesising scientific evidence on how urban design, socio-ecological networks, and the Healthy Habits framework interact to influence human and environmental well-being in urban settings. The review applies a semantic-search approach using Elicit [27], which leverages large-scale language models to identify relevant publications through meaning-based retrieval, rather than keyword matching. Elicit, an AI-based scientific research assistant, indexes academic papers from Semantic Scholar, PubMed, and OpenAlex. The scoping review was conducted in three stages: (i) initial identification, (ii) screening and eligibility, and (iii) refinement, data synthesis, and thematic analysis (Table 1).

Table 1. Methodological approach of the scoping review.

Stages	Process Description	Outputs (n)
Stage 1—Initial identification	Systematic semantic search using Elicit AI	499 retrieved papers
Stage 2—Screening and eligibility	Application of inclusion/exclusion criteria	486 eligible papers
Stage 3—Refinement, data synthesis, and thematic analysis	Ranking the eligible papers by the highest screening scores according to the inclusion criteria	40 studies for data synthesis and analysis

The initial identification was carried out using Elicit by applying the research question: "What are the interactions between urban design, socio-ecological networks, and the Healthy Habits framework in shaping the quality of life for humans and the environment across different urban contexts?" For the requested timeframe of the literature review, from 2010 to 2025, Elicit returned 499 results ranked by semantic proximity.

In the second step, abstracts and metadata of each paper were screened against inclusion and exclusion criteria to confirm the eligibility of 486 papers. Screening criteria of inclusion involve:

- urban setting—study conducted in an urban, suburban, or peri-urban context;
- quality-of-life outcomes—including analysis of both human and/or environmental well-being indicators;
- multi-dimensional scope—investigation of at least two of the three systems—urban design, socio-ecological networks, Healthy Habits related concepts;
- empirical or systemic research—peer-reviewed empirical research, systematic/scoping review, or validated conceptual framework;
- community or spatial scale—intervention or observation at neighbourhood, district, city, or metropolitan level;

Screening criteria of exclusion involve:

- studies conducted in non-urban and rural settings;
- missing evidence base—opinion pieces or editorials;

- missing systemic perspective—missing explicit link between urban design, socio-ecological networks, and health;
- no quality of life or well-being outcomes.

From the initially retrieved papers that met the screening criteria of inclusion and exclusion, 40 studies with the highest screening scores were processed for data extraction and synthesis. For each of the 40 included papers, the Elicit was instructed to extract and tabulate the following dimensions: urban design framework; socio-ecological networks; health-related frameworks; quality of life measures (both human and environmental indicators); urban context; interaction mechanisms; study design (methodology); and key findings. Data were automatically summarised by Elicit and manually verified for coherence and relevance. Further data synthesis and thematic analysis were conducted based on extracted evidence, following PRISMA-ScR guidelines. Patterns were identified across the following interaction types: urban design ↔ socio-ecological networks; socio-ecological networks ↔ healthy habits; and urban design ↔ healthy habits, to set the state-of-the-art and identify research gaps. Results were mapped according to human and environmental quality-of-life outcomes, summarised and discussed in conceptual matrices.

2.2. The Thematic Review

The initial insights provided by the Elicit scoping review were further refined through a qualitative thematic review of three complementary thematic perspectives of urban design, the healthy habits framework, and socio-ecological networks. The thematic review was conducted within urban planning, public health, and sociology disciplines, exploring the interactions between thematic perspectives through the connections between theoretical frameworks and practical applications. The theoretical framework of relevant academic studies was collected from the SCOPUS database, ensuring comprehensive coverage of peer-reviewed research. Additionally, policy documents from the European Commission, the Council of Europe, and the United Nations were reviewed to integrate policy frameworks and strategic directives with scientific evidence.

The theoretical framework is further strengthened through the integration of practical examples, which are explored within a timeframe aligned with the thematic review. The first thematic contribution associates European environmental policies with a holistic vision of urban planning and design, exploring the interactions between different sectoral contents of ecology, urban planning, health, and participation. The evolution of European environmental policies is examined, beginning with the first international and European conferences and policy documents on environmental protection in the 1970s. The second thematic contribution explores how the Healthy Habits (HH) framework, originally developed as a preventive and holistic approach, grounded in the One Health paradigm, with its four evolutionary pillars (physiology, psycho-relational well-being, nutrition, and environment), can inform urban planning and design strategies. The third thematic contribution was achieved by proposing a review of sociological approaches that have sought to understand cities as complex and interconnected systems, partly because of the development of information flows. The space of places has been flanked, or replaced, by the space of economic, cultural, political, and information flows, creating the conditions for the activation of new health connections linked to ecological and natural networks.

This combined research approach (Table 2) supports a more holistic understanding of how the three thematic domains intersect and enhance existing knowledge on urban socio-ecological networks. A comprehensive review highlights the points of contact between actions to improve environmental conditions and to raise the quality of life for healthy cities.

Table 2. The structure of the thematic review on the interactions of urban design, socio-ecological networks, and the healthy habits framework.

Thematic Perspectives of the Thematic Review	Urban Design	Healthy Habits	Socio-Ecological Networks
Disciplines of the three thematic perspectives	Urban planning	Public health	Sociology
Theoretical sources	Relevant academic studies collected from the SCOPUS database		
Policy sources	Review of policy documents from the European Commission, the Council of Europe, and the United Nations		
Thematic review topics	The evolution of European environmental policies influencing urban planning and the design of public green spaces for human and environmental health	Designing healthy cities with Healthy Habits: A One Health model grounded in four evolutionary pillars	Urban systems and social interaction for healthy cities: The outdoors generating healthy social networks
Reviewed European practices	Urban planning and design of public green spaces	Applications of Healthy Habits practices in schools, workplaces, communities	Applications of social and ecological design frameworks

3. The Evolution of European Environmental Policies Influencing Urban Planning and the Design of Public Green Spaces for Human and Environmental Health

Environmental protection is one of the significant global challenges of the twenty-first century and a political priority for the European Union, which considers it an integral part of its sustainable development. Since the 1970s, following the Stockholm Conference on the Human Environment [28], the European Union has progressively evolved its strategies to incorporate the environment into all sectoral policies, thereby influencing urban planning and design and addressing human health.

The Stockholm Declaration of the United Nations Conference on the Human Environment, which was the first world conference to make the environment a major issue, was initiated with a proclamation: 'Man is both creature and moulder of his environment, which gives him physical sustenance and affords him the opportunity for intellectual, moral, social and spiritual growth'. This proclamation embodies two, often conflicting visions of anthropocentrism (human-centred) and ecocentrism (nature-centred), thus paving the way towards a holistic vision of the environment that is reflected in the means of planning and design of urban and peri-urban landscape. The anthropocentric vision considers the environment essential to the extent that it serves humanity, while ecocentrism values nature for its own sake [29]. These two opposed visions of the environment have led to a separatist vision of society and nature in the twentieth century. A more complex understanding, marked in the Stockholm Declaration, recognises the interconnection between humanity and nature as well as the holistic vision of the environment necessary for a fair and sustainable future, in which human well-being is achieved not at the expense of the planet, but in harmony with it.

The fundamental steps in the evolution of European environmental policies are retraced with the aim of identifying opportunities for enhancing the integration of a holistic dimension into the planning and design of public green spaces, focusing on the interdependence of human and environmental health in urban and peri-urban areas. The three phases in the evolution of European environmental policies: (i) distinguishing man from nature: 1970–1987; (ii) integrated vision: 1987–2006; (iii) towards systematic and holistic vision:

from 2007, are reviewed in relation to representative urban planning and design practices (Table 3) and the change in consideration of human and environmental health (Figure 1).

Table 3. Overview of the European environmental policies related to urban planning and design practices of the public green spaces, influencing human and environmental health.

European Environmental Policies	Representative Urban Planning and Design Practices of the Public Green Spaces	Consideration of Human and Environmental Health	Phases of the European Environmental Policies Influencing the Health
1st EAP, 1973–1976 2nd EAP, 1977–1981 Convention on the Conservation of European Wildlife and Natural Habitats, 1979 3rd EAP, 1982–1986	IBA Emscher Park, Ruhr La Vilette, Paris Parc André-Citroën, Paris	Distinction of humanity and nature by seeing environmental protection as a defence of humanity	Distinguishing man from nature 1970–1987
4th EAP, 1987–1992 Natura 2000 Network, 1992 5th EAP, 1993–2000 Council of Europe Landscape Convention, 2000 Strategy for Sustainable Development, 2001, 2006 6th EAP, 2002–2012	Landscape Urbanism Green Urbanism Re-Urbanism New Urbanism Everyday Urbanism	Consideration of both human and environmental health through the concept of sustainable development	Integrated vision 1987–2006
(New) Leipzig Charter on Sustainable European Cities, 2007, 2020 EU Biodiversity Strategy, 2011 Green Infrastructure (GI)—Enhancing Europe's Natural Capital, 2013 7th EAP, 2014–2020 Urban Agenda for the EU, 2016 The European Green Deal, 2019 EU Strategy on Adaptation to Climate Change, 2021 8th EAP, 2022–2030 EU Regulation on nature restoration, 2024	Green Capital of Europe, 2010 European Green Leaf Award, 2015 National Park City network, 2021 Greening City Partnership, 2022	Towards awareness of the interdependence of human and environmental health as a single system	Towards systematic and holistic vision From 2007

(EAP) Environmental Action Programme, (EU) European Union.

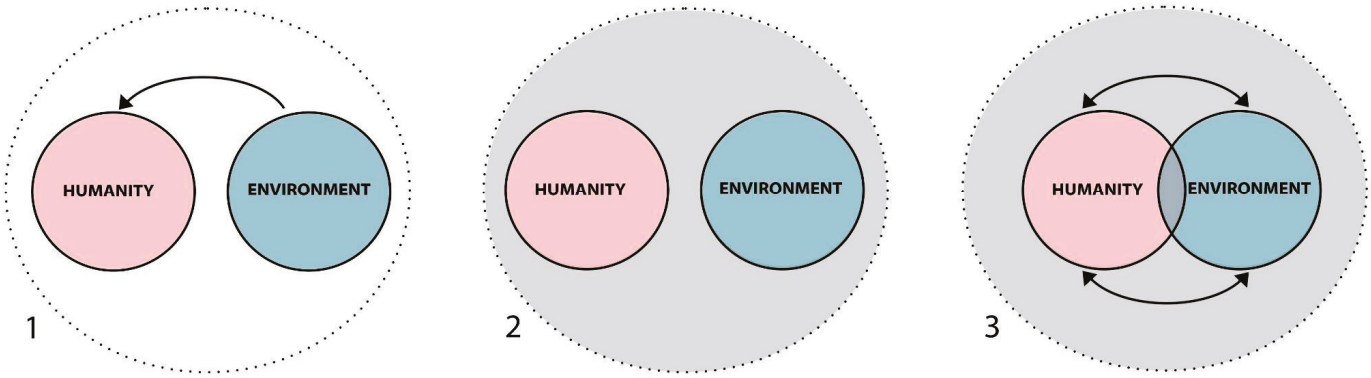


Figure 1. The change in consideration of human and environmental health in the evolution of European environmental policies. First phase (**1**) distinguishes humanity and nature by seeing environmental protection as a defence of humanity. Second phase (**2**) considers both human and environmental health through sustainable development. Third phase (**3**) streams towards awareness of the interdependence of human and environmental health as a single system.

3.1. Distinguishing Man from Nature: 1970–1987 Humanity and Nature as Distinct Entities—Environmental Protection as a Defence of Humanity

The evolution of European environmental policies can be primarily followed through a series of Environmental Action Programmes (EAP) that were inaugurated after the Stockholm Conference [28]. The 1st EAP aimed to improve the setting and quality of life, as well as the surroundings and living conditions of the people. This rationale was sectoral,

focusing on pollution reduction and nature protection, as planned actions aimed to limit the environmental damage caused by urban and industrial development. The Bern Convention further enhanced nature protection, an innovative biodiversity convention adopted in 1979, through the approach of protecting both species and habitats, as well as recognising the intrinsic values of wild flora and fauna [30]. The following EAP-s introduced the preventive approach that required economic and social developments to be undertaken in such a way as to avoid the creation of environmental problems. Even though the first EAP-s demonstrated integrating environmental requirements into many economic and social sectors, the environment was still considered an external entity to humanity.

The evolution of environmental policies in Europe was closely aligned with the establishment of the United Nations Environment Programme, as reflected in the Limits to Growth debate [31]. The international policy documents of the 1970s, such as the UNESCO Convention Concerning the Protection of the World Cultural and Natural Heritage [32], which primarily focused on identifying and listing heritage sites of 'outstanding universal value', demonstrated the perception of humanity and nature as distinct entities. Yet, the UNESCO Man and Biosphere Programme (MAB), established in 1971, aims to provide a scientific basis for enhancing the relationship between people and their environments, thus opening a sustainable development perspective.

The topics opened by the evolution of European environmental policies were reflected in urban planning and design projects for public green spaces in the 1970s and 1980s—especially limiting the environmental damage caused by urban and industrial development, the need for landscape in the transformation of industrial areas, and the development of ecological criteria. This initiation phase coincided with the onset of the post-industrial shift in Europe, characterised by a decline in manufacturing and a corresponding rise in the service sector. From the 1970s, numerous landscape planning and urban development projects referred to the ecological, economic, and cultural renewal of the former industrial region as well as the transformation of former industrial sites into public green spaces, like IBA Emscher Park in the central Ruhr region and projects Parc de La Villette and Parc André-Citroën in Paris. The development of ecological criteria was also followed in urban planning, where the New Urbanism movement [33] promoted urban visions and theoretical models for reconstructing the "European" city, involving the conservation of natural resources and the preservation of environmental health.

The initial phase of European environmental policy evolution reflected a human-centric approach, where the environment was protected based on human needs, without effective integration between social and natural systems. This perception of humanity and nature as distinct entities was manifested in environmental protection as a defence of humanity, limiting the environmental damage caused by urban and industrial development, as well as improving the setting and living conditions as a base for the health and well-being of people. Landscape and urban planning projects and movements from the 1970s introduced social revitalisation and the integration of nature into the urban environment, thus opening a sustainable perspective on development that led to a higher awareness of the integrated vision of environmental and human health in the late 20th century.

3.2. Integrated Vision: 1987–2006 the Environment Becomes Part of Sustainable Development

The Brundtland Report of the World Commission on Environment and Development, entitled Our Common Future, marked a new phase in both international and European environmental policies by adopting the concept of sustainable development. The ability of humanity to make development sustainable means 'to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs' [34], thus paving the way for an integrated vision of economic, social, and environ-

mental policies. The UN Conference on Environment and Development in Rio in 1992, known as the 'Earth Summit', established the concept of sustainable development as a global goal, resulting in the Agenda 21 action programme, the UN Convention on Climate Change, the Convention on Biological Diversity, and the Declaration on the Principles of Forest Management. Further evolution of the sustainability concept was marked by the Kyoto Protocol [35], an international treaty aimed at reducing greenhouse gas emissions, and the Millennium Development Goals, which aligned respect for nature with fundamental values such as freedom, equality, solidarity, tolerance, and shared responsibility, all essential in the twenty-first century.

The 4th EAP laid the foundation for the transition towards 'sustainable development' as a central principle, incorporating environmental protection into all relevant EU policies to integrate with economic growth and job creation in Europe. With the Maastricht Treaty [36], the European Union officially integrated the environment into all sectoral policies, with the objectives of preserving, protecting, and improving the quality of the environment; protecting human health; and ensuring prudent and rational use of natural resources. In this context and by strengthening the EU commitment to the Bern Convention on the Conservation of European Wildlife and Natural Habitats [37], a new approach to environmental protection emerged, based on the coexistence of biodiversity conservation and human activities within the Natura 2000 Network. Two key instruments: (i) the Birds Directive [38], which protects all wild bird species, and (ii) the Habitats Directive [39], together establish the Natura 2000 Network as a European ecological system of protected areas and promote active and participatory land management, reconciling conservation and local development. At the change of the millennia, the scope of policies contributing to environmental protection in Europe, further expanded by, the Council of Europe Landscape Convention [40] that addressed all landscape (outstanding, every-day, and degraded) and the whole of the environment as valuable, and culminated with the EU Strategy for Sustainable Development [41] that affirmed the environment, economy, and society as part of a single system that must ensure equity, quality of life, and ecological protection.

The integrated vision of environmental and human health in European environmental policies at the turn of the millennium was marked by the concept of sustainable development, which promoted economic, social, and environmental sustainability. This was in line with the accelerating post-industrial shift, marked by the growth of science-based industries and the advent of the information age. The landscape and urban planning projects of the time continued the transformation and renewal of former industrial sites through the integration of social revitalisation and nature into the urban environment, like Landschaftspark Duisburg-Nord, Duisburg, and Alter Flugplatz Kalbach, Frankfurt am Main/Bonames, in Germany, and Parc de Bercy, Paris, and Louvre Lens Museum Park, Lens in France. The step towards sustainability was also evident in urban planning and design theories and practices, as Landscape Urbanism emerged as a response to the perceived limitations of traditional urban planning and design approaches [42]. It is a(n) (inter)disciplinary theory that prioritises the landscape as the basic medium of constructing contemporary cities [43,44] and gives a response to urban planning and design challenges—ecological and economic value to sites of stalled development, collaboration across disciplines and communities, and an authentic landscape response of urban identity that arises from the metaphysical side of landscape. The approach of Biophilic cities promotes the integration of nature into urban design and planning [45].

The change of the millennium was characterised by the plurality of urban planning and design theories, approaches, and concepts that influenced the shaping of the urban environment to an extent greater than the individual landscape and urban planning projects. Re-Urbanism is oriented towards constant urbanity; Green Urbanism is focused on eco-

logical sensitivity; New Urbanism is based on a neighbourhood concept and walkability; Post-Urbanism, as a generic hybridity, is concentrated in reinvention and restructuring; Everyday Urbanism promotes vernacular spatiality with a bottom-up approach [46]. These urban planning approaches, varying in intensity, integrate environmental and human needs and are rooted in sustainable development that balances economic prosperity, social equity, and environmental protection.

3.3. Towards Systematic and Holistic Vision: From 2007 Humans and the Environment Belong to a Single System

With the Treaty of Lisbon [47], the European Union has adopted a holistic and interconnected approach to the environment, thus identifying the inextricable link between nature, human well-being, the economy, and society. This represents the definitive overcoming of the sectoral approach of the past: the environment is no longer an isolated area, but a cornerstone of public policies, including in urban, agricultural, and industrial contexts. By adopting the EU Biodiversity Strategy [48], the Commission committed to developing a Green Infrastructure Strategy [49] to enhance Europe's natural capital and give proper value to ecosystem services. The Strategy defines green infrastructure as a tool for providing ecological, economic, and social benefits through natural solutions, which drive towards innovative, sustainable, and inclusive growth.

The UN Conference on Sustainable Development in Rio, in 2012, was framed around the concept of 'green growth' and set in motion the Sustainable Development Goals (SDGs) [50]. The holistic vision of people and environment finds full expression with the adoption of the United Nations 2030 Agenda, whose Sustainable Development Goals have been integrated into EU strategies. A decisive step forward in achieving Sustainable Development Goals, as well as strengthening the EU commitment to the Kyoto Protocol from 1997, is the European Green Deal [51], the EU's strategy to achieve climate neutrality by 2050. The Green Deal extends beyond climate mitigation, encompassing public health, the circular economy, sustainable agriculture, green mobility, biodiversity protection, and social justice, to achieve systemic transformation. The recent EAP-s supports the EU's long-term vision of living well and within the limits of our planet by building upon the European Green Deal. The emphasis on climate action of the European Green Deal and the EU Strategy on Adaptation to Climate Change [52] aligns with the shift in international environmental policies towards addressing climate change [34]. The most recent EU environmental policy is the Nature Restoration Law [53], which further strengthens the integrated approach by introducing the binding environmental restoration obligations for terrestrial and marine ecosystems, including agricultural and urban ones. With these actions, the European Union adopts a systemic vision in which humans are an integral part of ecosystems, and the environment is recognised as a fundamental condition for the future of European society.

The synergy of environmental protection and sustainable development, supported by frameworks such as the UNESCO Man and Biosphere Programme, the Ramsar List of internationally important wetlands, and the UNESCO Global Geoparks Network, is in the twenty-first century further focused on urban areas. The network approach of the UNESCO frameworks is utilised in urban contexts, through the European Commission's Green City Awards, which include two titles: the European Green Capital (EGC) for cities with over 100,000 inhabitants and the European Green Leaf (EGL) for smaller cities with 20,000 inhabitants. These awards for best practices in sustainable urban development [54] recognise local actions towards a transition to a greener future and an improvement in the quality of life and environment. After London became the first National Park City in 2019, the National Park City Foundation [55] was established, aiming to provide a vision and a city-wide community that is acting together to make life better for people, wildlife, and

nature. The initiatives focusing on making cities more sustainable and climate-resilient involve the European partnership Greening Cities under the EU's Urban Agenda, as well as the international partnership Greener Cities, led by the UN Environment Programme (UNEP) and UN-Habitat.

These frameworks, awards, foundations, and partnerships in synergy with environmental protection and urban planning, represent the contemporary network approach to addressing urban environmental challenges and advancing climate-resilient, inclusive, and healthy urban communities. Impacts are achieved through increased citizen participation, enhanced urban biodiversity, and the application of blue and green infrastructure and nature-based solutions. The long-term vision of Europe, which is built upon the European Green Deal, promotes a model in which the environment, economy, and social cohesion are sustainable, equitable, and interdependent. Therefore, Europe aims to accelerate the transition to a climate-neutral and resource-efficient economy, recognising that human well-being and prosperity depend on healthy ecosystems.

3.4. Holistic Vision of the Relationship Between Society and Environmentinterdependence of Environmental and Human/Societal Health

The critical views on dominant growth paradigms, which also include sustainable development and green growth, originate from the Limits to Growth model [56,57]. Made fifty years ago, but still prominent today, Limits to Growth analyses the world economy's environmental relations and the ability of technology to decouple economic growth from ecological collapse [31]. While the Limits to Growth reflected the rise to international prominence of environmental issues in the 1970s with the Stockholm Conference on the Human Environment and the United Nations Environmental Programme, contemporary urban planning opened the ideas of post-growth [31,58] and degrowth [59–62] to address eco-social transition and climate emergency. The alternatives to the growth paradigm are also asked by the planetary boundary framework, introduced in 2009, that aims to define the environmental limits within which humanity can safely operate [63–65]. In the current situation, where the Earth is already well outside the safe operating space for humanity [66], the achievement of global sustainability will largely be determined by cities as drivers of culture, economy, material use, and waste generation [67,68]. The planetary boundaries concept has profoundly changed the vocabulary and representation of global environmental issues by introducing societal boundaries [69], ecological democracy [70], and environmental justice [71]. Strategies to improve both socio-economic and biophysical systems equally, with a focus on sufficiency and equity, have the potential to advance global sustainability and achieve a good life for all within planetary boundaries [72]. Going beyond sustainable development and green growth towards post-growth and degrowth, acknowledge interdependence and mutual creation of healthy environments and healthy societies within planetary boundaries.

A pioneer of critical complexity theory, Edgar Morin [73], stated, 'Humanity cannot be explained without culture, but culture cannot be explained without nature', effectively summarising a holistic vision of the relationship between man and the environment. This perspective transcends classical dualisms, inviting us to view the world through a complex and interrelated lens, where nature and culture continually interact. From the 1972 Stockholm Conference on the Human Environment, which attempted to lay the foundations for a holistic vision in future European environmental policies, it was not until 2015, with the United Nations 2030 Agenda, that this vision materialised. The evolution of European environmental policies shifts from a separatist vision of humanity and nature to a sustainable and holistic perspective. Still, the historical separation between the environment and urban areas continues to influence the way policies are implemented, especially in medium-sized and small cities. Although the relationship between environmental policies and their im-

plementation in urban planning and design practices has evolved in a non-linear manner, the shifting environmental paradigms have influenced the way urban and peri-urban spaces are shaped and developed. Contemporary approaches increasingly emphasise the integration of environmental protection and sustainable development, promoting a holistic vision that links ecological integrity with human health and well-being. In this context, the health synergy of ecological and societal networks, which continuously influence one another and co-evolve with urban environments, is conceptually reinforced and further examined through the One Health framework.

4. Designing Healthy Cities with Healthy Habits: A One Health Model Grounded in Four Evolutionary Pillars

The Healthy Habits (HH) approach represents an evidence-based preventive health framework grounded in the One Health paradigm and structured around four interdependent evolutionary pillars: physiology, psycho-relational well-being, nutrition, and environment. Conceived to monitor and enhance core daily practices as a means to enable effective primary prevention, these four pillars originate from the conceptual foundation of the Healthy Habits (HH) approach. This evidence-based framework has been empirically validated through real-world applications in schools, workplaces, and communities. Rooted in epigenetic and preventive health science [74], the HH model aligns fully with the One Health strategy by integrating biological, social, and ecological determinants of well-being.

The Four Pillars of Human Evolution (Figure 2, Table 4) represent the systemic architecture of the HH framework, where physiology, psycho-relational well-being, nutrition, and environment function as interconnected feedback systems maintaining internal and external balance. The circular composition symbolises the co-evolution between biological, social, and ecological processes that sustain life and health as a dynamic equilibrium.

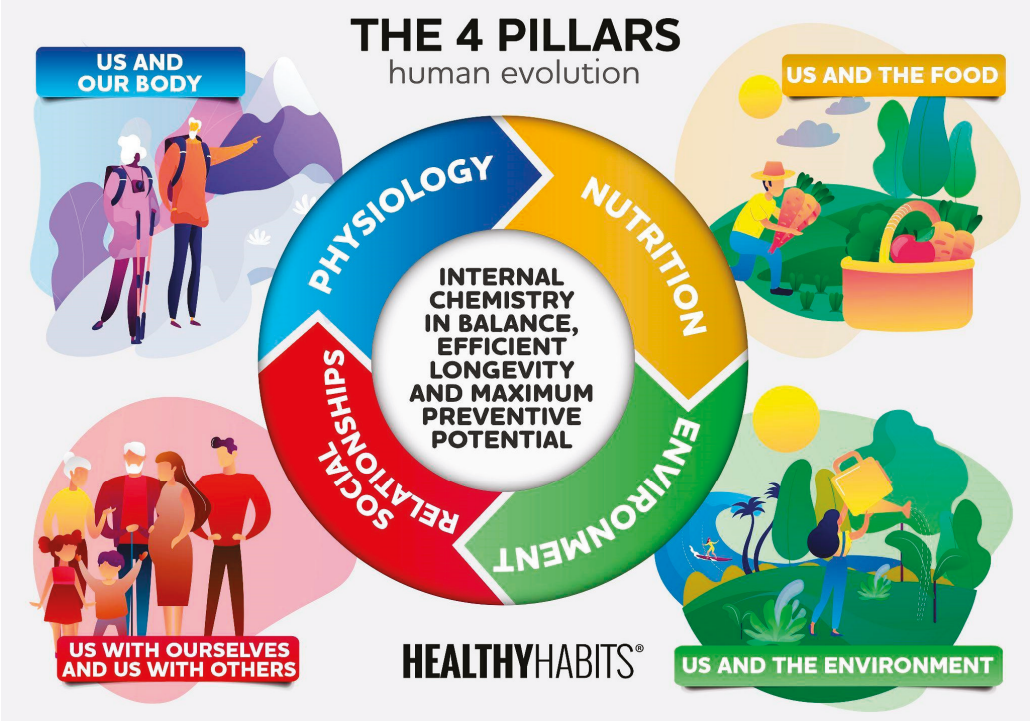


Figure 2. The Four Pillars of Human Evolution representing the Healthy Habits framework.

Table 4. Structural Matrix: "The Four Pillars of Human Evolution".

Pillar	Main Focus	Urban Design Levers	Health Mechanism	Expected Indicator
Physiology	Physical movement, rest, body respect	Walkable pathways, active mobility, sleep-friendly housing	Higher secretion of well-being–related hormones and lower stress hormone levels.	% residents within 300 m of green routes/spaces
Psycho-relational	Emotional and social well-being	Public benches, shaded areas, co-designed community spaces	Oxytocin-mediated social bonding, reduced stress	↓ Loneliness index; ↑ social cohesion score
Nutrition	Food quality and accessibility	Urban gardens, farmers' markets, edible landscapes	Improved gut microbiota, reduced NCD (Non-Communicable Diseases)risk	% households $\leq$ 800 m from fresh-food source
Environment	Natural and built surroundings	Tree canopy, biodiversity corridors, biophilic design	Lower endocrine disruptors, reduced inflammation.	Urban canopy cover %; surface temp Δ °C

↓ = Reducing, ↑ = Increasing.

Each of the evolutionary pillars (Figure 2) can be translated into an operational framework (Table 4), by linking each evolutionary pillar to specific urban-design levers, health mechanisms, and measurable indicators. Establishment of these connections reinforces the empirical foundation of the Healthy Habits approach and illustrates how the four pillars can be practically applied within One Health-oriented urban planning.

Rather than addressing individual behaviour change in isolation, HH promotes the ecological redesign of everyday environments—homes, schools, workplaces, and cities—to foster health across biological, psychological, and social domains [74]. Epigenetic research confirms that lifestyle and environmental factors can modulate gene expression, thereby influencing disease risk, systemic inflammation, and homeostatic balance throughout the life course [74].

'The Line of Life' (Figure 3) as a longitudinal trajectory of human functionality and vitality, shows how everyday habits can progressively influence health outcomes across the life course. The concept visually captures the dynamic balance between positive and negative lifestyle patterns and their cumulative biological, psychological, and social effects. The main environmental and behavioural determinants that shape the upward or downward trajectories in the 'Line of Life' (Table 5) are linked to measurable outcomes in health and well-being, illustrating how positive and negative feedback loops influence human functionality over time. These provide a practical interpretation of how daily habits interact with environmental quality, nutrition, social relations, and physiology to determine long-term public health trends. Together, these relations establish the systemic basis of the HH framework, from which the 'Line of Life' (Figure 3) develops the dynamic dimension of human vitality and its evolution over time.

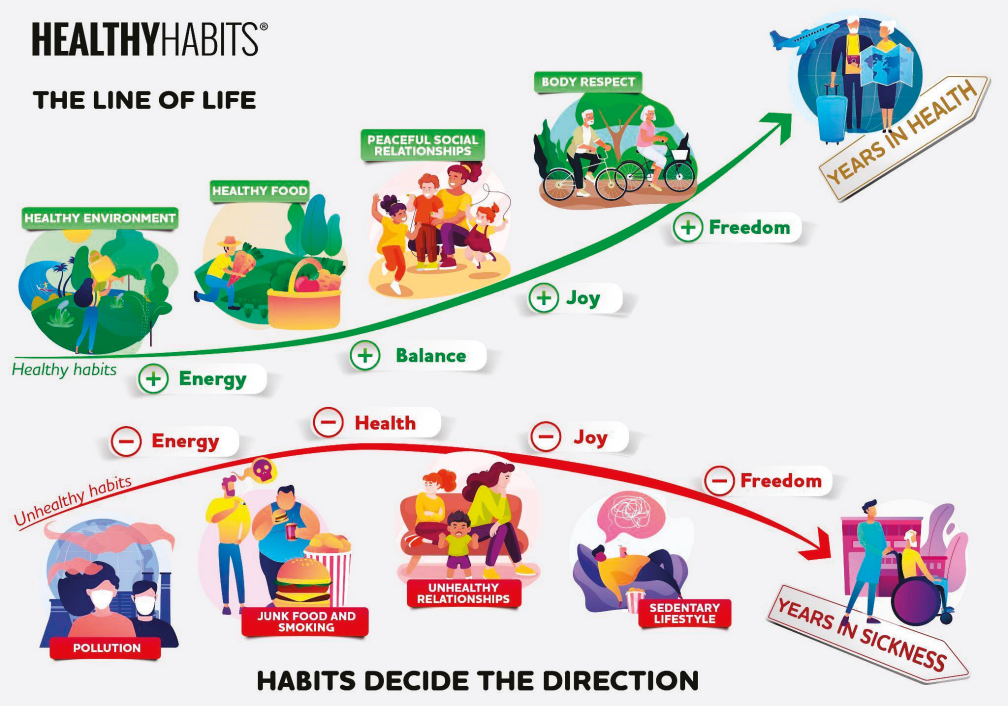


Figure 3. 'The Line of Life' illustrates that the upward curve corresponds to balanced routines that generate energy, joy, and longevity, whereas the downward curve depicts the cumulative effects of unhealthy behaviours such as a sedentary lifestyle, stress, and poor nutrition.

Table 5. Interpretive Matrix: "The Line of Life" Infographic.

Determinant	Healthy Trajectory (Positive Feedback)	Unhealthy Trajectory (Negative Feedback)	Expected Outcome
Environmental quality	Access to clean air, water, and biodiversity-rich spaces	Exposure to pollution and degraded environments	↑ Increasing public health, ↓ Oxidative stress and low-grade inflammation
Nutrition	Fresh, minimally processed food; biodiversity in diet rich in vegetal food.	Processed food, and ultra processed excessive sugar/fat intake	↑ Metabolic balance, ↓ Inflammation, overweight, and obesity.
Social relations	Peaceful, supportive interactions	Isolation, conflict, lack of cohesion	↑ Joy, Eudaimonia, ↓ Loneliness, ↓ Depression
Physiology	Regular movement and respect for body rhythms.	Sedentary behaviour	↑ Functional capacity, ↓ Mortality

↓ = Reducing, ↑ = Increasing.

Collectively, these insights (Figure 3 and Table 5) provide a dynamic interpretation of how the four pillars interact within real contexts, linking daily behaviours to measurable health outcomes. The case study from the Republic of San Marino exemplifies how the HH framework can be effectively implemented at a systemic level through coordinated educational and environmental interventions. A real-world application of the HH model was implemented in all public primary schools in the Republic of San Marino during the 2022–2023 academic year. Coordinated by the national health and education authorities, the programme reached 13 school sites through a structured seven-month intervention. Key components included 40 h of teacher training, experiential activities for children, weekly multimedia content for families, environmental redesign (such as green spaces and movement zones), and co-created school routines.

Initial qualitative assessments—gathered through structured questionnaires and direct observation—revealed notable behavioural shifts: increased outdoor play, better breakfast quality, reduced intake of processed foods, and greater emotional awareness. As emphasised by Dr. Arianna Scarpellini, Principal Primary School, "the most important result was that children themselves became the drivers of change at home" [75].

Quantitative validation came from the 2023 national application of the OKkio alla Salute surveillance system, following WHO-COSI protocols. The results, based on 100% coverage of third-grade students, revealed a decrease in obesity prevalence from 7.7% to 5.3%, and in overall excess weight (including overweight and obesity) from 30.3% to 20.8% compared to the previous cycle [76]. Notably, the WHO Europe COSI Round 6 Report ([77], p. 42) identified San Marino as the only participating country to have registered a statistically significant reduction in childhood obesity among boys between Rounds 5 and 6.

Although causality cannot be formally established due to the lack of a control group, the convergence of programme coverage, absence of other interventions, and alignment with behaviour change theory support interpretation as a "natural experiment" [77,78]. The San Marino case illustrates how system-level health improvements can occur within a short timeframe when environments are designed to align with human biology, emotions, and habit formation.

This experience resonates with major policy frameworks, such as the European Green Deal and the EU Nature Restoration Law, which call for the integration of biodiversity, health promotion, and social equity into urban design. The HH approach—through light, low-cost interventions—provides a practical, evidence-based pathway to advance these goals in both cities and schools.

Further scientific validation of the HH pillars comes from a landmark study conducted by the Harvard T.H. Chan School of Public Health, which built upon two extensive studies spanning multiple decades: the Nurses' Health Study (n = 78,865) and the Health Professionals Follow-up Study (n = 44,354). Researchers identified five key healthy behaviours—non-smoking, normal BMI, regular physical activity, moderate alcohol intake, and a healthy diet—as predictors of longevity. At age 50, women who followed all five behaviours lived 14 years longer, and men 12 years longer, than those who followed none [79–81]. Taken together, these findings reinforce the HH approach as a scientifically grounded, scalable, and policy-relevant framework for embedding health into the daily lives of children, families, and communities.

4.1. The First Pillar: Physiology

Physical activity can be either spontaneous or organised, and is generally categorised into three or four types, each producing distinct but equally beneficial outcomes. These benefits are particularly relevant for promoting the future health of both children and older adults, as they help to support healthy development and active ageing.

Some activities are indicated, for example, to improve muscle trophism, others for cardiovascular health, and still others for flexibility and balance. Facilitating the practice of these activities is possible. Behavioural economics shows us the way through the wise use of various 'gentle nudges'. The Nudge theory [82], which won Richard Thaler the Nobel Prize, demonstrates how much more effective it is to stimulate healthy habits by preparing the context correctly than to try to convince through teachings or prohibitions. Finding equipped parks within walking distance from home, where we can do simple gymnastic exercises or having paths in the green where we can walk safely are two simple but effective interventions to increase the likelihood of practicing physical activity.

Another essential element for our physiology is to create the best conditions for a restful night's sleep at home. A lack of sleep or its poor quality is, in fact, conducive to an increase in chronic silent inflammation [83–85], a significant enemy of human health. Resting in the dark, in silence, and without a substantial presence of disturbing elements (such as alarm clock radios or mobile phones kept charging on the bedside table) facilitates better rest with regenerative capacities and its decisive anti-inflammatory action.

4.2. The Second Pillar: Psycho-Relational Well-Being

The relevance of psycho-relational well-being has become a more recent focus within scientific research; nevertheless, the literature is continually expanding with new studies that underscore its critical role in supporting human health. After all, the importance of relationships and their role within society had already emerged as a common factor even in the famous 'blue zones of the world', the areas where the highest levels of longevity are reached. Feeling accepted, loved, and valued plays a crucial role in maintaining good health. The Harvard Grant Study, initiated in 1938 [86], also confirmed that stable emotional relationships are the primary determinant of human happiness and correlated with healthy longevity.

Designing urban spaces to foster social interaction among older adults can significantly support healthy ageing. Features like benches, tables, and shaded areas enable people to meet, converse, play cards, and engage in light physical activities. When coordinated by trained staff, these spaces encourage consistent participation and strengthen community ties. Structured social engagement has been shown to have numerous health benefits for seniors.

A case is the Frome Medical Practice in England, which adopted an integrated model of enhanced primary care and community support. By combining medical care with social prescribing and community-building initiatives, the programme achieved a 17% reduction in emergency hospital admissions within one year [87]. This highlights the preventive value of socially inclusive urban design, particularly when integrated with coordinated health and community strategies.

Strong social relationships also correlate with lower rates of depression and premature death. As social beings, isolation can be deadly—loneliness is a key predictor of early mortality [88,89]. Keeping older adults connected is a public health imperative. Equally essential to physiological well-being is creating optimal conditions for sleep at home. Poor or insufficient sleep is associated with increased chronic, low-grade inflammation, a driver of many non-communicable diseases and a significant public health concern [84]. Restorative sleep is promoted by limiting nighttime disturbances. Darkness, silence, and avoiding devices like phones or alarm clocks near the bed can all improve sleep quality. In turn, better sleep supports the body's regenerative and anti-inflammatory functions, contributing to long-term health and disease prevention.

4.3. The Third Pillar: Nutrition

Nutrition is a key determinant of health across the life course, with both undernutrition and overnutrition contributing to disease burden. Since the mid-20th century, dietary quality has declined amid the rise of processed and ultra-processed foods, which are high in sugar, salt, and artificial additives. At the same time, access to fresh and diverse foods has become increasingly limited, especially in large metropolitan areas, contributing to reduced dietary biodiversity and weakened gut microbiota—factors closely linked to immune function.

Urban food environments—the physical, social, and economic settings in which people acquire and consume food—are powerful levers for dietary transformation. Municipalities

can take a proactive role by: supporting farmers' markets and km-0 outlets; developing community gardens and edible landscapes; planting fruit trees in public areas; facilitating solidarity-based purchasing groups (e.g., GAS (Solidarity-based Purchasing Groups—from the Italian "Gruppi di Acquisto Solidale"), coops, short supply chains). In addition, dedicated food education zones—such as the "Maestri di Bottega" programme in Italy's Marche region—can combine retail access with nutritional education and biodiversity awareness. These approaches not only improve access to nutritious foods but also empower consumers to value imperfection, recognise the nutritional value of non-standard produce, and reduce food waste.

Finally, nutrition plays a fundamental role in modulating chronic low-grade inflammation, a biological mechanism shared across numerous non-communicable diseases [38]. Promoting food literacy and equitable access to healthy food is a public health priority with long-term impact.

4.4. The Fourth Pillar: The Environment

The physical environment—understood as the ensemble of buildings, their colours, their level of maintenance and care, the layout of streets, and the presence of greenery—can significantly influence our hormonal system and overall well-being. Scientific research shows, for example, that living in cities with abundant green spaces allows our telomeres—segments of DNA that serve as accurate biosensors of cellular ageing—to shorten at a slower rate, which corresponds to slower biological ageing [90].

However, there is growing evidence confirming the importance of greenery for human health. Trees absorb pollutants, filter the air, and provide cooling—three essential functions for public well-being [91]. They also serve as barriers against noise, purify the air by capturing various pollutants, including hazardous fine particulate matter (PM10 and PM2.5), and provide shade, which helps moderate temperatures. This is particularly beneficial for vulnerable populations who are more affected by urban heat islands, where paved surfaces can reach temperatures as high as 40–50 °C, compared to the 20 °C typical of vegetated areas.

The benefits of living in close contact with nature, however, extend far beyond these aspects. Coniferous trees such as pines and firs—as well as ferns, shrubs, and grasses—release volatile organic compounds known as terpenes. These substances have been shown to exert calming effects on the human nervous system by reducing levels of stress hormones such as cortisol. In fact, this mechanism has been formally recognised in some countries as a health intervention under national healthcare systems, through practices like forest therapy [90,92].

Furthermore, the presence of urban greenery has been consistently associated with increased happiness among citizens. A systematic review of over 57 studies conducted between 2013 and 2023 across 21 countries confirmed this association, although with some regional variations—particularly in South American contexts [93].

Living in close contact with nature—or within 300 to 500 metres of green parks—is associated with a reduction in all-cause mortality by approximately 4% to 7%, as demonstrated by a meta-analysis of cohort studies [94]. Notably, a study by James et al. [95] found a 41% lower mortality rate from kidney disease among women residing in areas with the highest levels of green vegetation.

The explanation for this seemingly remarkable phenomenon is multifactorial, involving all four pillars and their dynamic interactions. The presence of green spaces and natural environments encourages people to leave their homes, breathe higher-quality air—which is often difficult to achieve indoors—and spend time exposed to direct sunlight. This exposure is essential for activating some vital biological processes, including the evening production

of melatonin (which supports restful sleep) and the synthesis of vitamin D, a nutrient essential not only for bone health but also as a potent modulator of immune function.

Moreover, green environments naturally promote spontaneous physical activity (physiological pillar). Individuals who engage in regular physical activity are more likely to adopt healthier eating habits (nutritional pillar) [96], cultivate stronger social relationships (psycho-relational pillar) [97], and exhibit a lower incidence of self-harming behaviours such as smoking, alcohol abuse, or drug use (psycho-social pillar) [98].

For these reasons, incorporating natural elements into the built environment—such as homes, schools, workplaces, and public buildings—represents a strategic approach to promoting physical and mental well-being. When thoughtfully implemented, biophilic design principles—including the use of natural materials, colours, and light—have been shown to replicate many of the health benefits associated with direct contact with nature [99]. Similarly, regular exposure to artistic expressions and aesthetically rich environments has been linked to improved emotional regulation, reduced stress, and enhanced overall health and well-being [100].

4.5. Implementation Challenges and Considerations

While the Healthy Habits (HH) approach offers a transdisciplinary framework applicable across scales—from schools to cities—its implementation is shaped by contextual variables such as urban density, cultural norms, socio-economic disparities, and infrastructural capacity. In dense metropolitan areas, opportunities for environmental redesign may be spatially constrained, requiring interventions within micro-environments such as rooftops, courtyards, and mobility corridors. Conversely, in smaller or low-density cities, where access to open space is greater, the primary challenge lies in sustaining social engagement and community participation over time.

Structural inequalities in access to green areas, healthy food, and safe mobility infrastructure persist, particularly in disadvantaged neighbourhoods. Furthermore, the effective integration of health, urban planning, and environmental policy is often hindered by institutional fragmentation and siloed governance. Cultural variability and limited financial resources may also affect the scalability and long-term adoption of HH-based interventions.

Recognising these constraints is essential to ensure both the equity and scientific robustness of the model. Integrating the HH framework into urban planning—through its four evolutionary pillars of physiology, psycho-relational well-being, nutrition, and environment—should therefore be seen not as an academic abstraction but as a strategic investment in preventive public health, capable of reducing the burden of chronic diseases and enhancing the overall quality of life in urban populations.

In this perspective, integrating the Healthy Habits approach into urban planning, grounded in the four evolutionary pillars of physiology, psycho-relational well-being, nutrition, and environment, should not be regarded as a merely academic exercise. Instead, it constitutes a forward-looking investment in public health prevention, with the potential to reduce the burden of chronic diseases and enhance the quality of life in urban populations.

5. Urban Systems and Social Interaction for Healthy Cities: The Outdoors Generating Healthy Social Networks

Over time, various paradigms in urban sociology have focused on the relationship between cities and the environment. In the social sciences, environmental issues have become increasingly important; however, questions related to the relationship between the environment and society are not yet fully incorporated into specific fields of research. The concept of networks is also key to studies of cities and territories and has formed the basis for efforts to model urban systems. This contribution aims to demonstrate that urban

health is not an isolated policy objective, but a systemic property that emerges from the quality of interactions between people, environments, and institutions. In this perspective, the frameworks of Healthy Cities, social capital, and behavioural nudging converge toward a shared goal: the cultivation of preventive, self-regulating, and socially cohesive urban systems. The Healthy Habits (HH) approach provides a connective logic across these frameworks, translating them into operational levers for governance and design.

5.1. Complexity Theories and the Reticular Paradigm Between Social and Biophysical Ecosystems

Systems theory, especially in its sociological evolution proposed by Luhmann [101], together with theoretical and epistemological contributions from diverse fields (mathematics, physics, biology) and authors such as Edgar Morin [73], have shaped the so-called complexity sciences, which in the field of urban and territorial disciplines have inspired Complexity Theories of the City. The central idea of these new approaches is that urban systems are highly complex due to several factors: the multiplicity of actors involved in decision-making; the multidimensional nature of cities (system of economic exchanges, social behaviour, energy flows, etc.); their multi-level nature (from neighbourhood micro-spaces to metropolitan complexes and urban regions). According to this paradigm, cities are systems in constant imbalance due to the flows to which they are permanently subjected, and this approach seeks to identify the modes of self-organisation, the internal processes of the system, capable of generating order and cohesion from the chaos of behaviour. Recent systemic visions, in fact, distance themselves from the idea that it is possible to control the entire framework of variables that govern urban dynamics through external regulation (such as comprehensive planning), in favour of an adaptive-evolutionary vision. We must confidently identify the endogenous factors of self-organisation that urban planning can assist and catalyse through a synergistic interplay of top-down (proposed by institutions) and bottom–up (initiatives arising autonomously in sectors of society) processes, maintaining close contact with the physical and natural sciences [102].

Studies based more specifically on a network conception of urbanism focus on social networks, in which a complex set of actors or spatial units connect, establishing relationships of various kinds. These properties can be studied through specific mathematical formalisms. The reticular paradigm, in general, is an effective tool for understanding many aspects and processes of contemporary societies [103]. Even the concentration in large urban agglomerations must be interpreted as an expansion of networks that connect specific types of places in different regions: the main activities are networked according to their needs, and at the same time, many parts of cities, even "global" ones, live a local life in their own neighbourhoods. However, the use of a network-centred conception of the city leads us to address the broader issue of the relationship between networks themselves.

The contribution we wish to make in this regard is to introduce the importance of including ecological and natural networks in these reflections, both in the dynamics of the development of social relations themselves and in the mutual interaction between the quality of human life and the quality of the environment and biodiversity: social integration and participatory processes are essential for equitable access to green spaces and for maximising their health benefits. The integration of sociological theory—particularly the works of Giddens on structuration and Lefebvre on the production of space—provides interpretive depth to the HH framework. The idea of space as a social construct translates into the co-design of micro-infrastructures that sustain daily routines of movement, rest, and encounter. Similarly, reflexive modernity aligns with the HH emphasis on conscious habit formation, where urban design serves as a behavioural nudge toward self-regulation and collective care. Furthermore, we want to highlight the potential of this interaction between humans and natural outdoor spaces as a generator of social networks for health.

5.2. The City-Environment Co-Evolution to Increase Resilience and Quality of Life

In terms of urban design, the debate on aspects of relationship/interaction has always had two strands: on the one hand, there are virtual relationships, which are increasingly important, especially with the pervasive spread of social media, and on the other, there are physical and sensory relationships. Concerning the latter, our reflection adds an aspect that could prove decisive for a sustainable and desirable future of living: meaningful physical relationships in urban areas are those located not only in traditional places (streets and squares) or connections (airports, stations), but also in contiguous natural spaces that are particularly relevant for the protection of biodiversity. Regarding the integration of design and networks, several studies describe how community gardens and green spaces serve as ecological and social nodes, supporting biodiversity and social cohesion.

Urbanisation processes are interdependent and co-evolve with the environment: social and biophysical systems are both dynamic systems, whose modes of transformation depend not only on principles internal to each of them but also on mutual relationships [104], as already highlighted in the One Health approach. The concepts of 'socio-ecological systems' [105] and 'resilience' [106,107] also point in this direction. Suppose we look at the city as a socio-ecological system. In that case, its spatial dimension cannot be limited to the compact area of the settlement. Still, it must also include less dense spaces, connected by both social and environmental relationships. For this reason, it is necessary to consider certain biophysical indicators (e.g., related to hydrography, geology, or the configuration of ecosystems). The city-environment relationship is multiscale and requires increasing attention not only to the physical form of settlements, but also to how space is used, social practices, and the lifestyles of inhabitants [108]. In many social studies, great importance is attached to the analysis of urban practices, by which we mean all those complexes of human activities centred on the physical dimension of individuals, organised around shared fields of practical meanings [109] (examples of shared urban practices include sports activities in parks, gardening, walking the dog, and using bicycles as a means of transport). For sociologists dealing with theories of shared urban practices within the sphere of everyday life, a point of reference is De Certeau [110], who highlights how individuals can develop creative tactics for using products, which translated into terms of urban space means that 'individuals are not simply consumers of an imposed 'rational' architectural or urban design; they are instead enunciators of their own spatial discourse' ([108], p. 290).

However, it seems interesting to also emphasise the thinking of Georg Simmel, 'the most contemporary of the classics' ([111], p. 11), one of the leading figures of the Chicago School. Simmel's central insight is the universal interaction and interpenetration of all phenomena, the effect of reciprocity or mutual action. Reality is a network of mutually influential relationships between a plurality of elements, and the object of sociology is the forms of mutually influential relationships between people. For Simmel [112], the metropolis is the quintessence of modernity, characterised by a permanent crisis, an age in which change becomes the norm, and where the spirit of the times is embodied, as well as the forms of contemporary life and experience are revealed. In his analysis of experience, the features of the objective world and everyday life correspond to a configuration of the individual personality that is both its product and its prerequisite. And in this cornerstone of Simmelian relativism/relationalism, according to which nothing in life exists without being related to the rest, it is possible to introduce new considerations on the potential and variations of the relationship between man and nature, and on the consequent possibility of experiencing and practising 'healthy networks'. This is the theme on which this article focuses.

5.3. Nudges for Triggering New Urban Practices and Healthy Social Networks

It is necessary to rethink landscapes, green infrastructure frameworks, and connections with Natura 2000 networks, and to listen to communities to identify values and connections, as well as the intensity and types of relationships, to understand where interventions can be effective. It is necessary to define the conditions for coexistence, making the coexistence of anthropogenic and protected natural systems viable and fertile, and making it practicable by building networks and platforms that enable and empower social dynamics and healthy urban practices. Nudges, or gentle pushes, can be a form of urban and communicative action that promotes all of this. A nudge is a communicative act, since it exploits the exact mechanisms as rhetoric, i.e., 'shifting an opinion and pushing towards a behaviour' considering the cognitive, emotional and cultural characteristics of the interlocutor [113]. Moreover, nudging implies 'medium-sized gains for microscopic investments' ([114], p. 397): the former, translated into awareness of risks and/or environmental and health issues of general interest, translate into an impact on the level of collaboration between governments and communities, and on levels of territorial and social sustainability [115] (e.g., the Mexican Women Empowerment/Forest Protection, a poster dissemination via WhatsApp to encourage women's participation in the management of forest protection funds and projects; or the case of Galeria EL in Elbląg, Poland, developed by director Adriana Kotynska, who implemented a natural and organic solution to promote social distancing during the COVID-19 pandemic, namely the creation of a checkerboard effect generated by mowing the lawn). It is in the way we experience cities, islands, and territories, and in the relationship between social and ecological systems, that the challenge of a possible, desirable, and balanced future is played out. Nudges appear to be robust and effective tools in triggering and consolidating sustainable awareness and practices (e.g., community gardens with signage that encourages interaction, apps that reward the use of green spaces, and bench design that encourages conversations). Comparative experiences also reinforce the transferability of Healthy Habits-oriented nudges and social design strategies. In Copenhagen, behavioural insights have informed the redesign of school canteens and active-mobility corridors to promote healthier routines. Barcelona's Superblocks programme integrates environmental nudges by re-prioritising pedestrian space, reducing noise and air pollution while stimulating social exchange. Similarly, in Portland (Oregon), zoning reforms have coupled green infrastructure with social programming to strengthen neighbourhood identity and participation.

The integration of environmental, behavioural, and social cues can generate virtuous feedback across the health and ecological domains. By positioning nudges within a broader ecosystem of social and spatial design, connections can be highlighted between micro-level behavioural interventions and macro-level urban governance. The architects of choices, who develop the nudges, can legitimately influence individuals' behaviour to make their lives safer, longer, healthier and better [82], and therefore institutions, both public and private, should consciously strive to improve the living conditions of citizens through their choices: by encouraging, or "pushing", healthy behaviours; by stimulating urban practices connected to peri-urban ecological networks, and by designing natural and green spaces within cities. The Healthy Habits approach thus acts as a translator between disciplines, showing that material conditions and collective rituals and networks shape everyday behavioural patterns. A healthy city is not the sum of discrete actions, but the outcome of shared habits supported by spatial, institutional, and cultural infrastructures.

6. Discussion

The broader academic literature suggests that explicit connections between biodiversity, social networks, and urban design began gaining significant attention in the mid-2000s,

with foundational work in urban ecology and environmental psychology [116]. The concept of "biophilic cities" [45], blue-green infrastructure, and ecosystem services in urban planning gained prominence around 2008–2012 [117]. This corresponds to the transition from an integrated to a systematic and holistic vision of human well-being and ecosystem health, identified in the evolution of European environmental policies. The integration of biodiversity considerations into urban health research has accelerated, particularly since 2015, coinciding with the UN Sustainable Development Goals [50] and increased recognition of nature-based solutions for urban challenges [118–121]. This rising interest in urban socio-ecological networks and health is further confirmed by data from the Elicit scoping review, which shows an increasing trend in research publications over time (years 2010–2014: 79 publications; 2015–2019: 161; 2020–2024: 209). The most recent period (2020–2024) has the highest number of studies, reflecting a growing academic interest in urban design, socio-ecological networks, and health interrelations.

The scoping review demonstrated the increasing integration of various methods in urban design, including advanced measurement approaches [15,122] and sophisticated assessments of green space quality [20,23]. An increased attention to climate-related factors and environmental justice [12,21,123,124] is reflected in integrated planning for a healthy city. The comprehensive perspective on urban socio-ecological health suggests that synergistic strategies among different approaches can generate significant benefits for the quality of the environment and the quality of life of inhabitants. The evidence examined confirms that physical proximity to natural environments promotes physical activity, reduces the risk of chronic diseases, and improves psychological well-being, while simultaneously creating habitats that support biodiversity. Frameworks such as One Health [13], the Eight Dimensions framework [15], and Salutogenic urban design [24] illustrate that when socio-ecological networks are integrated with well-planned urban structures, healthy habits are reinforced. The One Health paradigm is identified as the principal integrative framework that introduces a holistic approach and reflects the interrelation of human and environmental health with urban design and socio-ecological networks (Figure 4). This holistic vision is outlined in the comprehensive European Green Deal strategy [51] and the United Nations' 2030 Agenda [50]. These instruments promote an urban planning model in which human quality of life is inextricably linked to the health of ecosystems. Despite the progress made, a certain discontinuity persists between political vision and urban planning practice, indicating that the full implementation of the holistic vision still requires further efforts to integrate environmental policies with spatial planning. Therefore, the health-oriented urban design must go beyond traditional planning paradigms and tools, adopting flexible, relational, and transdisciplinary approaches to address the challenges posed by contemporary times.

The scoping review of health outcomes for urban planning and design extends beyond physical activity to include broader well-being measures [12,19,24], social involvement, and community engagement [11,20,117], introducing more nuanced health measures (self-rated health and dietary outcomes, sleep patterns, screen time, loneliness) and health-related quality of life measures [116,125]. The thematic review confirms the Healthy Habits approach as a cross-cutting determinant of public health within the One Health paradigm. It introduces the Healthy Habits approach as a conceptual and operational model for embedding One Health principles into urban design. The Healthy Habits approach introduces an original contribution to urban health theory by integrating behavioural science, evolutionary physiology, and environmental design into a single operational paradigm. It reframes health not as a static condition but as a dynamic equilibrium maintained through continuous interaction among the four evolutionary pillars—physiology, psycho-relational

well-being, nutrition, and environment. While the potential of the HH approach lies in its integrative capacity, its application is not exempt from contradictions and trade-offs.

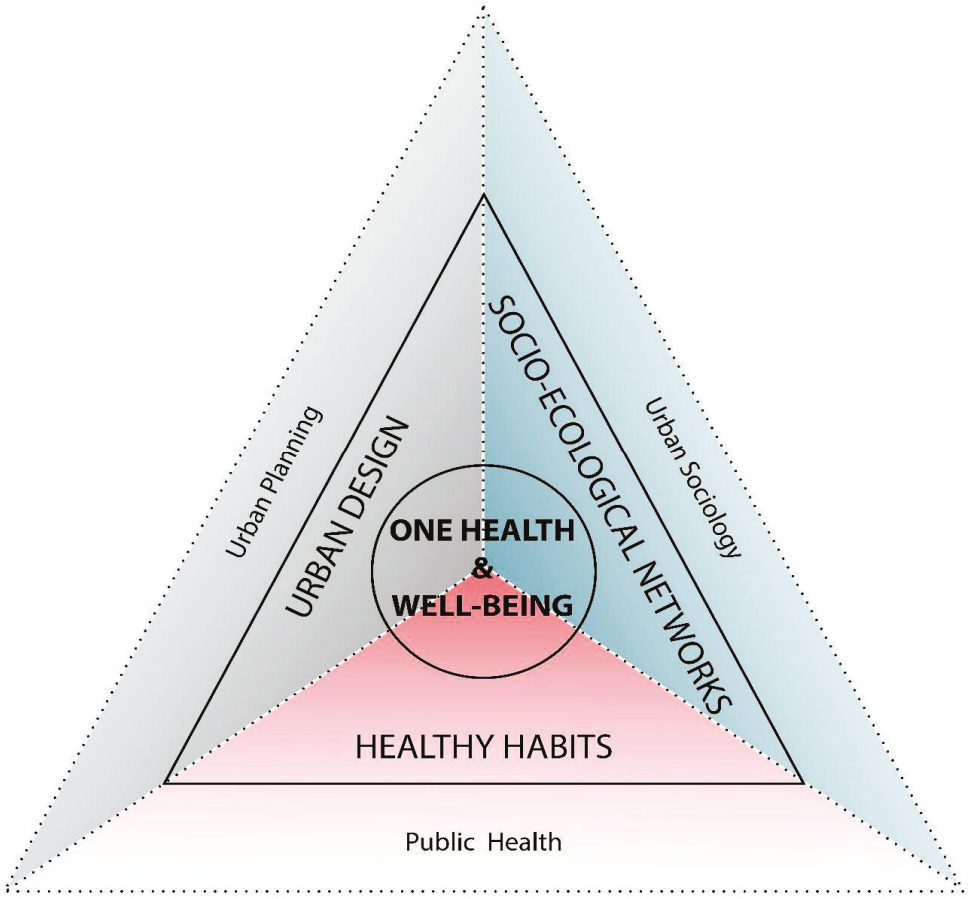


Figure 4. Integration of urban design, Healthy Habits, and socio-ecological networks in the One Health framework for resilient, sustainable, and inclusive cities.

In the thematic review, the application of behavioural insights, particularly nudges, emerges as a cost-effective way to influence lifestyle choices and encourage sustainable practices without resorting to coercion. Urban and communication nudges [82,114] are proposed as the most effective tools for activating and strengthening socio-ecological health networks. Cities become the spaces of flows (economic, cultural, political, and informational) and society becomes a networked system, composed of nodes and relationships. In this sense, interrelationships play a fundamental role: social networks and the urban space of networks influence each other. The inclusion of ecological networks in this co-generation system, along with the use of nudges (urban, green, and digital) to foster healthy behaviours and achieve overall well-being, can contribute to the creation of healthy social networks. Nonetheless, translating these insights into urban planning requires overcoming institutional silos and strengthening collaboration among public health, environmental management, urban design, and public policy sectors. The findings highlight self-organisation, bottom–up initiatives, and the role of open spaces as relational spaces that can become decisive in fostering social cohesion and resilience. The importance of community participation in urban design development fosters healthy social relationships and networks, serving communities and promoting human health, especially when it is intertwined with natural and ecological networks.

In the scoping review, the need for inclusive and accessible urban design is emphasised by setting a greater attention on vulnerable populations, including children and older

adults [12,24,126] and minority populations [11,116]. In general, the research evolved from basic walkability and access measures in the early period to sophisticated, multi-dimensional assessments of urban design impacts on comprehensive health and well-being outcomes, with increasing attention to justice, equity, and climate considerations [21,123,124] in the most recent period. The transformation of urban environments toward healthier and greener standards opens possibilities for inadvertently triggering processes of eco-gentrification, where an improved quality of life leads to rising property values and social displacement. Similarly, resource constraints and administrative inertia can slow the institutional adoption of preventive health paradigms. Recognising these tensions is crucial to avoid an idealised vision of the healthy city and to promote adaptive, context-sensitive policies that balance ambition with equity.

Through this process of exploration and synthesis of different fields of study, the difficulty in establishing a comparison with the current state of the art in urban planning practice has been identified, while simultaneously highlighting the possibility of opening new paths of exploration in the fields of further research. Equity and inclusivity represent critical dimensions in translating the HH approach into practice. Ensuring that vulnerable populations—such as children, the elderly, and low-income residents—benefit from healthy environments requires deliberate policy design. Inclusive participation processes, gender-sensitive data collection, and redistributive resource allocation are key to preventing the concentration of health-promoting infrastructures in privileged areas. By embedding social justice into urban health governance, the HH approach reinforces the ethical and preventive foundations of the healthy city, transforming One Health principles into actionable design and policy strategies that connect human well-being, ecosystem health, and collective resilience.

7. Conclusions

This paper highlights the need to rethink cities as living systems in which human and ecological health are interdependent. With European environmental policies and the One Health approach, the integration of social and ecological networks can guide adaptive, inclusive, and resilient urban design. In this sense, the role of social networks, shared practices, and nudges is analysed, understood as tools to catalyse sustainable urban habits and inclusive governance. The outputs of the literature review suggest that integrating natural systems into urban environments, promoting health-oriented practices, and using behavioural insights can improve public health outcomes, social well-being, and ecological balance.

The results indicate that well-managed urban green spaces, designed with attention to their physical, social, nutritional, and environmental dimensions, can act as catalysts for both improving public health and strengthening biodiversity. Policy frameworks, such as the European Green Deal and the Nature Restoration Law, provide a widely shared strategic foundation. Still, their success depends exclusively on translating these strategies into projects whose impacts can be measured and evaluated.

In this broader perspective, the Healthy Habits (HH) approach offers a novel and operational contribution by translating preventive health principles into a design-oriented paradigm that connects behavioural, ecological, and social dimensions within the One Health framework. By doing so, it redefines the city not only as a space for living but as an ecosystem of health, where everyday habits, social relationships, and environmental design collectively generate resilience and sustainable well-being.

In conclusion, the different arguments supporting the necessary interaction between different approaches could open new avenues of research toward adopting integrated indicators (capable of considering health, ecological quality, and social vitality). Future

research should focus on developing measurable indicators capable of precisely assessing the benefits derived from various combinations of factors that affect short-, medium-, and long-term impacts on human well-being and ecosystem health. In this way, indicators can guide decision-makers in creating urban environments that are not only more liveable for people, but also more supportive of the natural systems on which they depend. Future research should also explore longitudinal and cross-city comparative studies to measure the long-term health and social outcomes of One Health interventions. The integration of digital data (e.g., mobility traces, participatory sensing) with epidemiological indicators could also advance the model's predictive capacity. Such evidence would strengthen the link between experimental design approaches and systemic evaluation frameworks, paving the way for adaptive urban health policies.

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Conflicts of Interest: Author David Mariani is the conceptual developer of the Healthy Habits approach, the owner of the Healthy Habits® trademark, and the director of HHC Srl—Benefit Corporation (Italy), which owns the "Healthy Habits Corporate" trademark. He is also a Corresponding Member of the Accademia dei Georgofili, with a scholarly interest in the scientific discussion and development of the Healthy Habits framework. Author Maurizio Mariani is the director of the non-profit organisation Risteco—La Ville Qui Mange (France) and the managing director of the consulting company Marilac Sàrl (France). His engagement in sustainability and public food policy research is of a scholarly and cultural nature only and not directly or indirectly connected to the specific content of this manuscript. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GAS	Solidarity-based Purchasing Groups (from the Italian "Gruppi di Acquisto Solidale")
EAP	Environmental Action Programmes
EU	European Union
MAB	Man and Biospehere Programme, UNESCO
NBS	Natural based solutions
NCD	Non-Communicable Diseases
UN	United Nations
UNESCO	United Nations Educational, Scientific, and Cultural Organization

References

1. Blicharska, M.; Smithers, R.J.; Mikusiński, G.; Rönnbäck, P.; Harrison, P.A.; Nilsson, M.; Sutherland, W.J. Biodiversity's contributions to sustainable development. *Nat. Sustain.* **2019**, *2*, 1083–1093. [CrossRef]
2. Kowarik, I.; Fischer, L.K.; Kendal, D. Biodiversity Conservation and Sustainable Urban Development. *Sustainability* **2020**, *12*, 4964. [CrossRef]
3. Visseren-Hamakers, I.J.; Razzaque, J.; McElwee, P.; Turnhout, E.; Kelemen, E.; Rusch, G.M.; Fernández-Llamazares, A.; Chan, I.; Lim, M.; Islar, M.; et al. Transformative governance of biodiversity: Insights for sustainable development. *Curr. Opin. Environ. Sustain.* **2021**, *53*, 20–28. [CrossRef]
4. Johnson, C.J.; Ray, J.C. Proactive conservation is essential—But not sufficient: Why biodiversity still needs species-specific protections. *FACETS* **2025**, *10*, 1–15. [CrossRef]
5. Simkins, A.T.; Sutherland, W.J.; Dicks, L.V.; Hilton-Taylor, C.; Grace, M.K.; Butchart, S.H.M.; Senior, R.A.; Petrovan, S.O. Past conservation efforts reveal which actions lead to positive outcomes for species. *PLoS Biol.* **2025**, *23*, e3003051. [CrossRef] [PubMed]
6. Kleijn, D.; Biesmeijer, K.J.; Klaassen, R.H.; Oerlemans, N.; Raemakers, I.; Scheper, J.; Vet, L.E. Integrating biodiversity conservation in wider landscape management: Necessity, implementation and evaluation. In *Advances in Ecological Research*; Academic Press: Cambridge, MA, USA, 2020; Volume 63, pp. 127–159.
7. Agnoletti, M.; Santoro, A. Agricultural heritage systems and agrobiodiversity. *Biodivers. Conserv.* **2022**, *31*, 2231–2241. [CrossRef]
8. Castillo-Rivero, L.; Elbakidze, M.; McCann, P.; Sijtsma, F.J. Depopulation and ecological degradation, two dimensions of marginalization, and peripheralization. Ecosystem integrity as an assessment factor in local revitalization. *Reg. Sci. Policy Pract.* **2023**, *15*, 1625–1647. [CrossRef]
9. Krefis, A.C.; Augustin, M.; Schlünzen, K.H.; Oßenbrügge, J.; Augustin, J. How Does the Urban Environment Affect Health and Well-Being? A Systematic Review. *Urban Sci.* **2018**, *2*, 21. [CrossRef]
10. Cocci Grifoni, R.; D'Onofrio, R.; Sargolini, M. Quality of Life in Urban Landscapes. In *Search of a Decision Support System*; Springer: Cham, Switzerland, 2018.
11. Egerer, M.H.; Fouch, N.; Anderson, E.C.; Clarke, M. Socio-Ecological Connectivity Differs in Magnitude and Direction Across Urban Landscapes. *Sci. Rep.* **2020**, *10*, 1–16. [CrossRef]
12. Enßle, F.; Kabisch, N. Urban green spaces for the social interaction, health and well-being of older people— An integrated view of urban ecosystem services and socio-environmental justice. *Environ. Sci. Policy* **2020**, *109*, 36–44. [CrossRef]
13. Felappi, J.F.; Sommer, J.H.; Falkenberg, T.; Terlau, W.; Kötter, T. Green infrastructure through the lens of "One Health": A systematic review and integrative framework uncovering synergies and trade-offs between mental health and wildlife support in cities. *Sci. Total Environ.* **2020**, *748*, 141589. [CrossRef]
14. Wohldmann, E.L.; Chen, Y.; Schwarz, K.; Day, S.D.; Pouyat, R.V.; Barton, M.; Gonez, M. Building soil by building community: How can an interdisciplinary approach better support community needs and urban resilience? *Front. Sustain. Cities* **2020**, *4*, 941635. [CrossRef]
15. Giles-Corti, B.; Moudon, A.V.; Lowe, M.; Adlakha, D.; Cerin, E.; Boeing, G.; Higgs, C.; Arundel, J.; Liu, S.; Hinckson, E.; et al. Creating Healthy and Sustainable Cities: What Gets Measured, Gets Done. *Lancet Glob. Health* **2022**, *10*, e782–e785. [CrossRef]
16. Rebecchi, A.; Buffoli, M.; Dettori, M.; Appolloni, L.; Azara, A.; Castiglia, P.; D'Alessandro, D.; Capolongo, S. Walkable Environments and Healthy Urban Moves: Urban Context Features Assessment Framework Experienced in Milan. *Sustainability* **2019**, *11*, 2778. [CrossRef]
17. Giusti, M.; Samuelsson, K. The regenerative compatibility: A synergy between healthy ecosystems, environmental attitudes, and restorative experiences. *PLoS ONE* **2020**, *15*, e0227311. [CrossRef]
18. Fathi, S.; Sajadzadeh, H.; Mohammadi Sheshkal, F.; Aram, F.; Pinter, G.; Felde, I.; Mosavi, A. The Role of Urban Morphology Design on Enhancing Physical Activity and Public Health. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2359. [CrossRef]

19. Lafrenz, A.J. Designing Multifunctional Urban Green Spaces: An Inclusive Public Health Framework. *Int. J. Environ. Res. Public Health* **2022**, *19*, 10867. [CrossRef]
20. Chen, S.; Sleipness, O.; Christensen, K.; Yang, B.; Park, K.; Knowles, R.; Yang, Z.; Wang, H. Exploring Associations Between Social Interaction and Urban Park Attributes: Design Guideline for Both Overall and Separate Park Quality Enhancement. *Cities* **2024**, *145*, 104714. [CrossRef]
21. Salgado, M.; Madureira, J.; Mendes, A.; Torres, A.; Teixeira, J.; Oliveira, M. Environmental Determinants of Population Health in Urban Settings. A Systematic Review. *BMC Public Health* **2020**, *20*, 853. [CrossRef] [PubMed]
22. Høyer-Kruse, J.; Schmidt, E.B.; Hansen, A.F.; Pedersen, M.R.L. The interplay between social environment and opportunities for physical activity within the built environment: A scoping review. *BMC Public Health* **2024**, *24*, 2361. [CrossRef] [PubMed]
23. Torabi, N.; Lindsay, J.; Smith, J.; Khor, L.; Sainsbury, O. Widening the lens: Understanding urban parks as a network. *Cities* **2020**, *98*, 102527. [CrossRef]
24. Brunelli, L.; Smith, H.; Woolrych, R. A Salutogenic Urban Design Framework: The Case of UK Local High Streets and Older People. *Health Promot. Int.* **2022**, *37*, daac102. [CrossRef]
25. Hankey, S.; Marshall, J.D. Urban Form, Air Pollution, and Health. *Curr. Environ. Health Rep.* **2017**, *4*, 491–503. [CrossRef]
26. Adams, V.; Behague, D.; Caduff, C.; Löwy, I.; Ortega, F. Re-imagining global health through social medicine. *Glob. Public Health* **2019**, *14*, 1383–1400. [CrossRef]
27. Elicit. 2025. Available online: www.elicit.com (accessed on 1 October 2025).
28. United Nations, Declaration of the United Nations Conference on the Human Environment. 1972. Available online: https://digitallibrary.un.org/record/523249/files/A_CONF.48_14_Rev.1-EN.pdf (accessed on 14 August 2025).
29. Gagnon Thompson, S.C.; Barton, M.A. Ecocentric and anthropocentric attitudes toward the environment. *J. Environ. Psychol.* **1994**, *14*, 149–157. [CrossRef]
30. Díaz, C.L. The Bern Convention: 30 years of nature conservation in Europe. *Rev. Eur. Community Int. Environ. Law* **2010**, *19*, 185–196. [CrossRef]
31. Smith, A.; Ely, A. From limits to growth to post-growth: The international politics of technology in historical perspective. *Sci. Technol. Soc.* **2025**, *30*, 09717218251326833. [CrossRef]
32. UNESCO, Convention Concerning the Protection of the World Cultural and Natural Heritage. 1972. Available online: https://whc.unesco.org/archive/convention-en.pdf (accessed on 14 August 2025).
33. Congress for the New Urbanism, The Charter of the New Urbanism. 2024. Available online: https://www.cnu.org/who-we-are/charter-new-urbanism (accessed on 14 August 2025).
34. United Nations, Report of the World Commission on Environment and Development. 1987. Available online: https://docs.un.org/en/A/42/427 (accessed on 14 August 2025).
35. United Nations, Kyoto Protocol to the United Nations Framework Convention on Climate Change. 1997. Available online: https://unfccc.int/resource/docs/convkp/kpeng.pdf (accessed on 14 August 2025).
36. European Union, Treaty on European Union (92/C 191/01). 1992. Available online: https://eur-lex.europa.eu/eli/treaty/teu/sign/eng (accessed on 14 August 2025).
37. Council of Europe, Convention on the Conservation of European Wildlife and Natural Habitats. 1979. Available online: https://rm.coe.int/1680078aff (accessed on 14 August 2025).
38. 38. European Union, Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the Conser-vation of Wild Birds. Official Journal of the European Union, L 20. 26 January 2010, pp. 7–25. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0147 (accessed on 14 August 2025).
39. European Union, Council Directive 92/43/EEC of 21 May 1992 on the Conservation of Natural Habitats and of Wild Fauna and flora. Official Journal of the European Communities, L 206. 22 July 1992, pp. 7–50. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31992L0043 (accessed on 14 August 2025).
40. Council of Europe, Council of Europe Landscape Convention. 2000. Available online: https://rm.coe.int/16807b6bc7 (accessed on 14 August 2025).
41. European Commission, A Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development. 2001. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52001DC0264 (accessed on 14 August 2025).
42. Balon, N.; Hrdalo, I.; Mrđa, A.; Kamenečki, M.; Tomić Reljić, D.; Pereković, P. Landscape Urbanism—Retrospective on Development, Basic Principles and Application. *Architecture* **2023**, *3*, 739–752. [CrossRef]
43. Waldheim, C. (Ed.) *The Landscape Urbanism Reader*; Princeton Architectural Press: New York, NY, USA, 2006.
44. Waldheim, C. *Landscape as Urbanism—A General Theory*; Princeton Architectural Press: New York, NY, USA, 2016.
45. Beatley, T. *Biophilic Cities: Integrating Nature into Urban Design and Planning*; Island Press: Washington DC, USA, 2010.
46. Olsson, K.; Haas, T. Emergent Urbanism: Structural change and urban planning and design. *J. Urban. Int. Res. Placemaking Urban Sustain.* **2013**, *6*, 95–112. [CrossRef]

47. European Union, Treaty of Lisbon—Amending The Treaty on European Union and The Treaty Establishing The European Community. 2007. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:12007L/TXT (accessed on 14 August 2025).
48. European Union, Our Life Insurance, Our Natural Capital: An EU Biodiversity Strategy to 2020. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0244:FIN:EN:PDF (accessed on 14 August 2025).
49. European Union, Green Infrastructure (GI)—Enhancing Europe's Natural Capital, COM/2013/0249. 2013. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52013DC0249 (accessed on 14 August 2025).
50. United Nations, Transforming our World: The 2030 Agenda for Sustainable Development. United Nations General Assembly Resolution A/RES/70/1. 2015. Available online: https://sdgs.un.org/2030agenda (accessed on 14 August 2025).
51. European Commission, The European Green Deal. 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640 (accessed on 14 August 2025).
52. European Commission, Forging a Climate-Resilient Europe-the New EU Strategy on Adaptation to Climate Change. 2021. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0082 (accessed on 14 August 2025).
53. European Union, Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on Nature Restoration and Amending Regulation (EU) 2022/869. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1991&qid=1722240349976 (accessed on 14 August 2025).
54. Iacomoni, A. Capitali verdi europee. Indirizzi per uno Sviluppo Urbano Sostenibile/European Green Capitals. Best Practices for Sustainable Urban Development. *AGATHÓN* **2019**, *6*, 114–125. Available online: https://iris.uniroma1.it/handle/11573/1341751?mode=simple (accessed on 5 October 2025).
55. National Park City Foundation, National Park City. Available online: https://www.nationalparkcity.org/ (accessed on 14 August 2025).
56. Meadows, D.; Meadows, H.; Jørgen, R.; Behrens, W., III. *The Limits to Growth*; A Report for the Club of Rome's Project on the Predicament of Mankind; Universe Books: New York, NY, USA, 1972.
57. Turner, G.M. A comparison of The Limits to Growth with 30 years of reality. *Glob. Environ. Change* **2008**, *18*, 397–411. Available online: https://www.sciencedirect.com/science/article/abs/pii/S0959378008000435 (accessed on 5 October 2025). [CrossRef]
58. Romero-Martínez, J.M.; Romero-Padilla, Y.; Del Castillo Sánchez, A. Reflections on Post-Growth Planning: Practices of 'Undoing'(De-Urbanisation and Deconstruction) and Methodology for Eco-Social Transition. *Plan. Theory Pract.* **2025**, *26*, 457–472. [CrossRef]
59. Xue, J. Urban planning and degrowth: A missing dialogue. *Local Environ.* **2022**, *27*, 404–422. [CrossRef]
60. Krähmer, K. Degrowth and the city: Multiscalar strategies for the socio-ecological transformation of space and place. *City* **2022**, *26*, 316–345. [CrossRef]
61. De Castro Mazarro, A.; George Kaliaden, R.; Wende, W.; Egermann, M. Beyond urban ecomodernism: How can degrowth-aligned spatial practices enhance urban sustainability transformations. *Urban Stud.* **2023**, *60*, 1304–1315. [CrossRef]
62. Savini, F. Strategic planning for degrowth: What, who, how. *Plan. Theory* **2025**, *24*, 141–162. [CrossRef] [PubMed]
63. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S., III; Lambin, E.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. Planetary boundaries: Exploring the safe operating space for humanity. *Ecol. Soc.* **2009**, *14*, 33. Available online: https://www.jstor.org/stable/26268316?seq=1 (accessed on 5 October 2025). [CrossRef]
64. Mace, G.M.; Reyers, B.; Alkemade, R.; Biggs, R.; Chapin, F.S., III; Cornell, S.E.; Díaz, S.; Jennings, S.; Leadley, P.; Mumby, P.J.; et al. Approaches to defining a planetary boundary for biodiversity. *Glob. Environ. Change* **2014**, *28*, 289–297. [CrossRef]
65. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; De Vries, W.; De Wit, C.A. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, 1259855. [CrossRef] [PubMed]
66. Richardson, K.; Steffen, W.; Lucht, W.; Bendtsen, J.; Cornell, S.E.; Donges, J.F.; Drüke, M.; Fetzer, I.; Bala, G.; Von Bloh, W.; et al. Earth beyond six of nine planetary boundaries. *Sci. Adv.* **2023**, *13*, eadh2458. [CrossRef] [PubMed]
67. Hoornweg, D.; Hosseini, M.; Kennedy, C.; Behdadi, A. An urban approach to planetary boundaries. *Ambio* **2016**, *45*, 567–580. [CrossRef]
68. Algunaibet, I.M.; Pozo, C.; Galán-Martín, Á.; Huijbregts, M.A.J.; Mac Dowell, N.; Guillén-Gosálbez, G. Powering sustainable development within planetary boundaries. *Energy Environ. Sci.* **2019**, *12*, 1890–1900. [CrossRef]
69. Brand, U.; Muraca, B.; Pineault, É.; Sahakian, M.; Schaffartzik, A.; Novy, A.; Streissler, C.; Haberl, H.; Asara, V.; Dietz, K.; et al. From planetary to societal boundaries: An argument for collectively defined self-limitation. *Sustain. Sci. Pract. Policy* **2021**, *17*, 264–291. [CrossRef]
70. Pickering, J.; Persson, Å. Democratising planetary boundaries: Experts, social values and deliberative risk evaluation in Earth system governance. *J. Environ. Policy Plan.* **2020**, *22*, 59–71. [CrossRef]
71. Adelman, S. Planetary boundaries, planetary ethics and climate justice in the Anthropocene. In *Research Handbook on Law, Governance and Planetary Boundaries*; Edward Elgar Publishing: Northampton, MA, USA, 2021; pp. 65–83. Available online: https://www.elgaronline.com/edcollchap/edcoll/9781789902730/9781789902730.00011.xml (accessed on 5 October 2025).

72. O'Neill, D.; Andrew, W.; Fanning, L.; Lamb, W.F.; Steinberger, J.K. A good life for all within planetary boundaries. *Nat. Sustain.* **2018**, *1*, 88–95. [CrossRef]
73. Morin, E. *Method 1: The Nature of Nature*; Raffaello Cortina: Milan, Italy, 2001.
74. Furman, D.; Campisi, J.; Verdin, E.; Carrera-Bastos, P.; Targ, S.; Franceschi, C.; Ferrucci, L.; Gilroy, D.W.; Fasano, A.; Miller, G.; et al. Chronic inflammation in the etiology of disease across the life span. *Nat. Med.* **2019**, *25*, 1822–1832. [CrossRef] [PubMed]
75. San Marino RTV. Intervista alla Dott.ssa Arianna Scarpellini sul Programma Healthy Habits Nelle Scuole Primarie. Radiotelevisione della Re-pubblica di San Marino 2025. Available online: https://www.sanmarinortv.sm/news/attualita-c4/benessere-e-sani-stili-di-vita-a-scuola-presentato-il-modello-san-marino-a273159 (accessed on 13 September 2025).
76. ISS San Marino. Risultati dell'indagine OKkio alla Salute–Repubblica di San Marino. Istituto Sicurezza Sociale 2023. Available online: https://www.gov.sm/pub2/GovSM/dam/jcr:4b84b801-8d09-46d3-ba94-c03c8851fa1d/ReportOKKIO2023_RSM.pdf (accessed on 13 September 2025).
77. World Health Organization (WHO). *WHO European Childhood Obesity Surveillance Initiative (COSI): Report on the Sixth Round of Data Collection, 2022–2024*; WHO European Region: Copenhagen, Denmark, 2025. Available online: https://iris.who.int/server/api/core/bitstreams/8ee17a15-aa52-421e-94d1-892c3cf191e8/content (accessed on 5 October 2025).
78. Craig, P.; Dieppe, P.; Macintyre, S.; Michie, S.; Nazareth, I.; Petticrew, M. Developing and evaluating complex interventions: The new Medical Research Council guidance. *BMJ* **2008**, *337*, a1655. [CrossRef] [PubMed]
79. Li, Y.; Pan, A.; Wang, D.D.; Liu, X.; Dhana, K.; Franco, O.H.; Kaptoge, S.; Di Angelantonio, E.; Stampfer, M.; Willett, W.C.; et al. Impact of healthy lifestyle factors on life expectancies in the US population. *Circulation* **2018**, *138*, 345–355. [CrossRef] [PubMed]
80. Feldscher, K. Healthy Habits Can Lengthen Life. Harvard T.H. Chan School of Public Health News 2018. Available online: https://wwwhsphharvardedu/news/hsph-in-the-news/healthy-habits-can-lengthen-life/ (accessed on 5 October 2025).
81. Li, Y.; Schoufour, J.; Wang, D.D.; Dhana, K.; Pan, A.; Liu, X.; Song, M.; Liu, G.; Shin, H.J.; Sun, Q.; et al. Healthy lifestyle and life expectancy free of cancer, cardiovascular disease, and type 2 diabetes: Prospective cohort study. *BMJ* **2020**, *368*, l6669. [CrossRef]
82. Thaler, R.H.; Sunstein, C.R. *Nudge: Improving Decisions About Health, Wealth, and Happiness*; Yale University Press: New Haven, CT, USA, 2008.
83. Irwin, M.R. Sleep and inflammation: Partners in sickness and in health. *Nat. Rev. Immunol.* **2019**, *19*, 702–715. [CrossRef]
84. Irwin, M.R. Sleep disruption induces activation of inflammation and heightens risk for infectious disease: Role of impairments in thermoregulation and elevated ambient temperature. *Temperature* **2022**, *10*, 198–234. [CrossRef]
85. Mullington, J.M.; Simpson, N.S.; Meier-Ewert, H.K.; Haack, M. Sleep loss and inflammation. *Best Pract. Res. Clin. Endocrinol. Metab.* **2010**, *24*, 775–784. [CrossRef] [PubMed]
86. Vaillant, G.E. *Triumphs of Experience: The men of the Harvard Grant Study*; Harvard University Press: Cambridge, MA, USA, 2012.
87. Abel, J.; Kingston, H.; Scally, A.; Hartnoll, J.; Hannam, G.; Thomson-Moore, A.; Kellehear, A. Reducing emergency hospital admissions: A population health complex intervention of an enhanced model of primary care and compassionate communities. *Br. J. Gen. Pract.* **2018**, *68*, e803–e810. [CrossRef]
88. Rico-Uribe, L.A.; Caballero, F.F.; Martín-María, N.; Cabello, M.; Ayuso-Mateos, J.L.; Miret, M. Association of loneliness with all-cause mortality: A meta-analysis. *PLoS ONE* **2018**, *13*, e0190033. [CrossRef] [PubMed]
89. Holt-Lunstad, J.; Smith, T.B.; Baker, M.; Harris, T.; Stephenson, D. Loneliness and social isolation as risk factors for mortality: A meta-analytic review. *Perspect. Psychol. Sci.* **2015**, *10*, 227–237. [CrossRef]
90. Lin, J.; Epel, E.; Blackburn, E. Telomeres and lifestyle factors: Roles in cellular aging. *Mutat. Res. /Fundam. Mol. Mech. Mutagen.* **2012**, *730*, 85–89. [CrossRef]
91. Singh, A.K.; Kumar, M.; Bauddh, K.; Shukla, S.K. Environmental impacts of air pollution and its abatement by plant species: A comprehensive review. *Environ. Sci. Pollut Res.* **2023**, *30*, 79587–79616. [CrossRef]
92. Li, Q. *Forest bathing: How Trees can Help you Find Health and Happiness*; Viking: Los Angeles, CA, USA, 2018.
93. Syamili, M.S.; Takala, T.; Korrensalo, A.; Tuittila, E.S. Happiness in urban green spaces: A systematic literature review. *Urban For. Urban Green.* **2023**, *86*, 128042. [CrossRef]
94. Rojas-Rueda, D.; Nieuwenhuijsen, M.J.; Gascon, M.; Perez-Leon, D.; Mudu, P. Green spaces and mortality: A systematic review and meta-analysis of cohort studies. *Lancet Planet. Health* **2019**, *3*, e469–e477. [CrossRef]
95. James, P.; Hart, J.E.; Banay, R.F.; Laden, F. Exposure to greenness and mortality in a nationwide prospective cohort study of women. *Environ. Health Perspect.* **2016**, *124*, 1344–1352. [CrossRef]
96. Liutsko, L.; Veraksa, A.; Polikanova, I.; Leonov, S. Type of physical activity, diet, BMI and tobacco/alcohol consumption relationship: How they are associated with our health? *Preprints* **2021**. Available online: https://www.researchgate.net/publication/350554088 (accessed on 14 August 2025).
97. Haslam, C.; Cruwys, T.; Haslam, S.; Jetten, J.; Bentley, S.V. Social identity and health-related behavior: A systematic review and meta-analysis. *Soc. Sci. Med.* **2024**, *338*, 115646. [CrossRef]
98. González, J.L.; Martínez, J.M.; Pérez, M.A. Physical Activity Programmes in the Treatment of Addictions: A Systematic Review. *Appl. Sci.* **2022**, *12*, 9117. [CrossRef]

99. Zhong, W.; Schroeder, T.; Bekkering, J. Biophilic design in architecture and its contributions to health, well-being, and sustainability: A critical review. *Front. Archit. Res.* **2022**, *11*, 114–141. [CrossRef]
100. World Health Organization. *What Is the Evidence on the Role of the Arts in Improving Health and Well-Being? A Scoping Review*; WHO Regional Office for Europe: Copenhagen, Denmark, 2019. Available online: https://www.who.int/europe/publications/i/item/9789289054553 (accessed on 14 August 2025).
101. Luhmann, N. *Soziale Systeme. Grundiß einer Allgemeinen Theorie*; Suhrkamp Verlag: Frankfurt am Main, Germany, 1984.
102. Bertuglia, C.S.; Vaio, F. *Il Fenomeno Urbano e la Complessità*; Bollati Boringhieri: Torino, Italy, 2019.
103. Castells, M. Local and global: Cities in the network society. *Tijdschr. Voor Econ. En Soc. Geogr.* **2002**, *93*, 548–558. [CrossRef]
104. Noorgard, R. A coevolutionary environment sociology. In *The International Handbook of Environmental Sociology*; Redclift, G., Woodgate, G., Eds.; Edward Elgar: Cheltenham, UK, 1997; pp. 158–168.
105. Ostrom, E. A diagnostic approach for going beyond panaceas. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 15181–15187. [CrossRef] [PubMed]
106. Holling, C.S. Resilience and stability of ecological systems. *Annu. Rev. Ecol. Syst.* **1973**, *4*, 1–23. [CrossRef]
107. Cote, M.; Nightingale, A.J. Resilience thinking meets social theory: Situating social change in socio-ecological systems (SES) research. *Prog. Hum. Geogr.* **2012**, *36*, 475–489. [CrossRef]
108. Mela, A. Generi e paradigmi della sociologia urbana contemporanea. In *Le Città Contemporanee. Prospettive Sociologiche*; Ciaffi, D., Crivello, S., Mela, A., Eds.; Carocci Editore: Roma, Italy, 2020; pp. 35–51.
109. Cetina, K.K.; Schatzi, T.R.; von Savigny, E. *The Practice Turn in Contemporary Theory*; Routledge: New York, NY, USA, 2005.
110. De Certeau, M. *L'invention du Quotidien, vol. I, ARTS de Faire*; Gallimard: Paris, France, 1990.
111. Jedlowski, P. Introduzione. In *Le Metropoli e la Vita Dello Spirito*, 6th ed.; Simmel, G., Ed.; Armando: Roma, Italy, 2007.
112. Simmel, G. *Die Großstädte und das Geistesleben*; K.F. Koehler Verlag: Stuttgart, Germany, 1957.
113. Viale, R. *, Macchi, L., (Eds.) Analisi Comportamentale Delle Politiche Pubbliche: Nudge e Interventi Basati Sulle Scienze Cognitive*; Il Mulino: Bologna, Italy, 2021.
114. Bhargava, S.; Loewenstein, G. Behavioral Economics and Public Policy 102: Beyond Nudging. *Am. Econ. Rev.* **2015**, *105*, 396–401. [CrossRef]
115. Polci, V.; Cinella, L. Nudge e comunicazione pubblica per la salute e l'ambiente. Mitigare il rischio e praticare la sostenibilità. *Salut. E Soc.* **2025**, 1–15. [CrossRef]
116. Israel, B.; Schulz, A.; Estrada-Martínez, L.M.; Zenk, S.; Viruell-Fuentes, E.A.; Villarruel, A.; Stokes, C. Engaging Urban Residents in Assessing Neighborhood Environments and Their Implications for Health. *J. Urban Health* **2006**, *83*, 523–539. [CrossRef]
117. Semenza, J.; March, T.L. An Urban Community-Based Intervention to Advance Social Interactions. *Environ. Behav.* **2009**, *41*, 22–42. [CrossRef]
118. Sallis, J.; Cavill, N.; Parker, M.; Thornton, C.; Wilson, A.L.; Cutter, C.L.; Ding, D. Making the Case for Designing Active Cities. 2015. Available online: http://activelivingresearch.org/making-case-designing-active-cities (accessed on 5 October 2025).
119. Kabisch, N.; Korn, H.; Stadler, J.; Bonn, A. *Nature-Based Solutions to Climate Change Adaptation in Urban Areas: Linkages Between Science, Policy and Practice*; Springer: Cham, Switzerland, 2017.
120. Haase, D.; Haase, A.; Wolff, M.; Dushkova, D. *Nature-Based Solutions (NBS) in Cities and Their Interaction with Urban Land, Ecosystems, Built Environment and People: Debating Societal Implications*; MDPI: Basel, Switzerland, 2021.
121. Mahmoud, I.H.; Morello, E.; Lemes de Oliveira, F.; Geneletti, D. (Eds.) *Nature-Based Solutions for Sustainable Urban Planning: Greening Cities, Shaping Cities*; Springer: Cham, Switzerland, 2022.
122. Boeing, G.; Higgs, C.; Liu, S.; Giles-Corti, B.; Sallis, J.F.; Cerin, E.; Lowe, M.; Adlakha, D.; Hinckson, E.; Moudon, A.V.; et al. Using Open Data and Open-Source Software to Develop Spatial Indicators of Urban Design and Transport Features for Achieving Healthy and Sustainable Cities. *Lancet Glob. Health* **2022**, *10*, e907–e918. [CrossRef] [PubMed]
123. Llaguno-Munitxa, M.; Shu, X.; Mistry, B. Multivariate Analysis of the Influence Between Building Design and Energy Performance, Socio-Demographic Metrics, and the Intra-Urban Environment. *J. Phys. Conf. Ser.* **2021**, *2069*, 012056, In Proceedings of the 8th International Building Physics Conference (IBPC 2021), Copenhagen, Denmark, 25–27 August 2021. [CrossRef]
124. Adlakha, D.; John, F. The Future Is Urban: Integrated Planning Policies Can Enable Healthy and Sustainable Cities. *Lancet Glob. Health* **2022**, *10*, e790–e791. [CrossRef]
125. Rajagopalan, S.; Vergara-Martel, A.; Zhong, J.; Khraishah, H.; Kosiborod, M.; Neeland, I.; Dazard, J.E.; Chen, Z.; Munzel, T.; Brook, R.D.; et al. The Urban Environment and Cardiometabolic Health. *Circulation* **2024**, *149*, 1298–1314. [CrossRef]
126. Alidoust, S.; Bosman, C. Planning for an Ageing Population: Links Between Social Health, Neighbourhood Environment and the Elderly. *Aust. Plan.* **2015**, *52*, 177–186. [CrossRef]

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Systematic Review

Sustainable Reconstruction Planning from Natural Disasters (Earthquakes): A Systematic Mapping Study of Machine Learning and Technological Approaches

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Abstract

Natural disasters have various adverse effects on human lives, making it challenging for authorities to manage post-disaster situations with limited resources. Due to the extreme extent of the damage, the huge amount of resources needed to restore life to normality makes such a situation challenging. For this purpose, different methodologies have been proposed to effectively handle these types of situations. All these methodologies consider different aspects of the post-earthquake context, taking into account core parameters such as the time and cost required for reconstruction, as well as the people directly affected by the earthquake. In this paper, we conduct a Systematic Literature Review (SLR) of various state-of-the-art techniques proposed for different phases of post-earthquake situations, specifically for reconstruction planning with sustainability considerations. All these proposed solutions are differentiated on the basis of input data, parameters, and type of solutions (data sciences, civil engineering, socio-economics, and modelling). The time range chosen to filter out relevant studies is between 2000 and 2025. Eventually, we reviewed 55 related articles out of 47,539 analysed from seven different digital libraries. The findings of this SLR reveal that optimization and simulation-based approaches dominate the current research landscape, with a growing trend toward data-driven and AI-assisted reconstruction planning. However, only a few studies focus on integrating socio-economic, environmental, and physical infrastructure aspects, which represents a major research gap. These findings provide insights that can guide future researchers in designing more comprehensive frameworks to improve post-earthquake reconstruction in a sustainable manner by prioritising economic, social, and environmental infrastructures, as well as facilities for affected individuals, thereby utilising available resources more effectively.

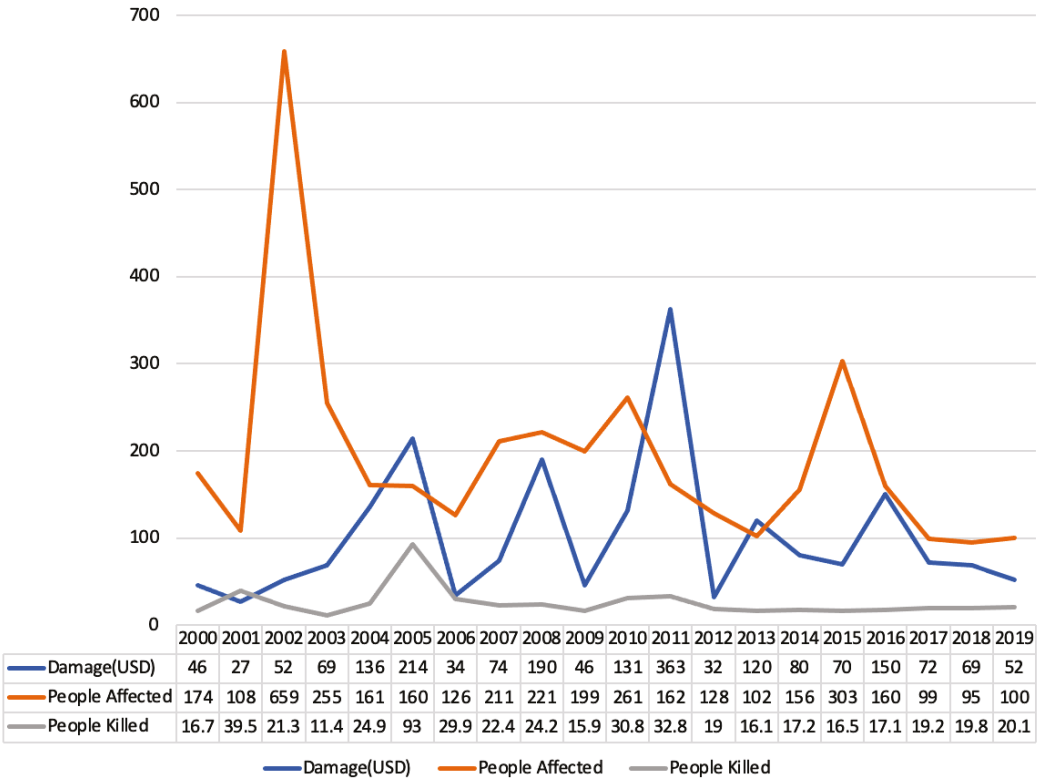
Keywords: decision-support system; natural disaster; social benefits; physical dependencies; city reconstruction planning

1. Introduction

In recent years, numerous natural disasters have been reported, severely affecting various locations all over the world [1]. According to an estimate, the damage cost due to natural disasters was approximately USD 67 billion per year in the last decade [2]. The ratio of economic loss due to these disasters has increased 14 times since 1950 [1]. In addition, these disasters have not only impacted the economy, but, more importantly, thousands of people have also lost their lives. From 1994 to 2003, almost 54,000 people

lost their lives in different kinds of natural disasters. According to a 2003 survey, at least one person out of 25 was affected by natural disasters [3]. The United Nations Office for Disaster Risk Reduction (UNISDR) also presented a report on different types of disasters in the last two decades [4]. UNISDR statistics show that most of these disasters occur in developing countries compared to developed countries. For example, in August 2002, a drought occurred in China, while in December 2004, a tsunami affected millions of people in Indonesia, Sri Lanka, Malaysia, and nearby countries. In October 2010, a massive earthquake occurred in Pakistan, and also in May 2008, the same kind of earthquake occurred in China. Concerningly, these massive natural disasters are happening more frequently in recent years, mainly due to climate change [5].

According to the UNISDR report, among all these disasters, 44% were due to floods, 28% storms, 8% earthquakes, 6% extreme temperatures, 5% landslides, 5% droughts, 3% wildfires, 1% volcanic activities, and <1% mass movements [6]. Subsequently, the economic loss and the loss of human lives are extremely significant, as shown in Figure 1, which shows the global economic and humanitarian impact of natural disasters from the years 2000 to 2019, as by data reported in [7].



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Damage(USD)	46	27	52	69	136	214	34	74	190	46	131	363	32	120	80	70	150	72	69	52
People Affected	174	108	659	255	161	160	126	211	221	199	261	162	128	102	156	303	160	99	95	100
People Killed	16.7	39.5	21.3	11.4	24.9	93	29.9	22.4	24.2	15.9	30.8	32.8	19	16.1	17.2	16.5	17.1	19.2	19.8	20.1

Figure 1. Global statistics on the economic and humanitarian impact of natural disasters between 2000 and 2019 [8].

Recovery of damaged infrastructure in case of a natural disaster is time-consuming and costly due to the requirement of resources such as material, labour force, cost, and time, among others [9]. For example, the disaster caused by Hurricane Katrina in 2005 required five years of recovery and one billion dollars in completion costs [10]. Similarly, in the Hyogoken-Nanbu earthquake in Japan, it took 20 months only to reconstruct the highway [11]. Given the impact that natural disasters cause, authorities must make quick and efficient decisions to overcome disaster situations as soon as possible [12]. Additionally, the extended restoration time can have a significant impact on the local community, both socially and economically. For this purpose, substantial resource management is required,

including budget allocation and time management. Post-disaster recovery plans have been proposed to address these challenges [13].

The post-disaster recovery plan is defined by [14] as a "*complex multidimensional long-term process that involves planning, financing, decision making, and reconstruction*". According to the United Nations Development Program (UNDP), the post-disaster recovery phase is divided into four sub-phases [15]: *relief*, *early recovery*, *recovery*, and *development*. *Relief* gives priority to saving people's lives with the help of search and rescue (SAR) operations [16]; the *early recovery* phase consists of rehabilitation of roads and identification of damage buildings [16]; *recovery* has the goal of restoring basic services and starting reconstruction of buildings including roads by considering social relationship of effected communities [16]; *development* focuses on strengthening the economy and improving quality of life [16].

Public decision-makers, including politicians, public servants, and citizens, frequently face challenges when developing a comprehensive recovery and reconstruction plan. Recovery plans must address all formal and informal requirements of the affected area as quickly as possible [17]. They must also consider the needs of the local community, the vulnerability of buildings, the budget, and the time required to complete the plan. Additionally, decision-makers should ensure that the reconstruction effort enhances the resilience of both physical infrastructure and communities by taking into account stability factors to cope with future disasters.

The post-disaster recovery (PDR) phase encompasses three key components: *goal*, *phase*, and *process* [18]. Each of these components is crucial for the long-term reconstruction of infrastructure. According to the World Bank [19], "Post Disaster Reconstruction begins with a series of decisions that must be made almost immediately. Despite the urgency of these decisions, they have long-term impacts, altering the lives of those affected by disaster for years to come." Moreover, inadequate post-disaster recovery often results in ongoing issues such as vulnerability and instability, a reality observed in many countries that have experienced disasters but failed to implement a proper recovery process [20].

While the PDR stage is critical, it still lacks a comprehensive definition that includes detailed objectives, characteristics, and content [21]. It is also known by other terms, including Post Disaster Recovery [22], Post Disaster Rebuilding [23], and Post Disaster Redevelopment [24]. Although these terminologies differ, no thorough mapping study has yet been conducted to clarify the distinctions between these concepts. Nevertheless, the ultimate aim of all these terms is to restore households, infrastructure, businesses, and government activities to their pre-disaster "normal" levels.

Despite growing research on post-disaster reconstruction, key challenges persist in the literature. Recovery planning remains a complex, multidimensional process, with inconsistent definitions and limited integration of economic, social, and infrastructure factors. Most approaches inadequately address resource constraints, lack real-world validation, and rarely connect reconstruction efforts to sustainability or resilience goals. Additionally, the fragmentation across disciplines limits comprehensive solutions. These gaps motivate our study to systematically map existing approaches those highlight post-disaster reconstruction planning in urban areas, specifically focusing on earthquakes and the application of data science methods. By "data science approaches," we refer to mathematical techniques, including operational research and optimization models, computational models, and advanced solutions such as machine learning.

The mapping study provides an overview of the current state-of-the-art solutions for these issues, detailing the proposed methods and the characteristics of the data science techniques applied to post-disaster reconstruction planning. Through this study, we aim to highlight the limitations of the existing solutions and identify current research gaps that can inform future work [25].

Given the complexity of this problem, we intend to classify the current literature on reconstruction planning techniques after natural disasters more effectively. This paper aims to uncover gaps in the research and summarize improvements across various proposed techniques to better prepare for future natural disasters.

Additionally, our goal in this mapping study is to investigate the research techniques utilized by the majority of scholars and to identify the most active areas of research in this critical field. We have addressed all the defined research questions, which is why we are conducting a systematic mapping study instead of typical secondary analyses.

This paper presents the most recent insights on post-earthquake reconstruction planning, detailing both the advantages and limitations of various proposed techniques. We believe that the findings from this mapping study will be beneficial to researchers and inspire new approaches in this crucial field. Additionally, our study aims to identify research gaps that can guide future investigations and offer innovative directions for ongoing research.

Our main contributions are as follows:

- An analysis of the state of the art that covers methodologies aimed at addressing various types of post-disaster emergencies, published over the past twenty-five years (from 2000 to 2025) across seven different digital libraries.
- A presentation of research trends within the specified time frame.
- An overview of the limitations of the selected primary studies and an identification of open issues that need to be addressed in this research area.

The remainder of the paper proceeds as follows: Section 2 presents the literature review, Section 3 presents the mapping study process, Section 4 presents the results of the systematic mapping study, Section 5 presents the discussion, Section 6 presents a potential research area, Section 7 presents a threat to validity, and Section 8 concludes the paper.

2. Related Work

Research on post-disaster reconstruction planning has gained momentum due to a series of devastating disasters in the past decade. Over time, the focus of research has evolved from merely reporting challenges to identifying key factors and patterns, and more recently, to developing theories and models through theoretical analysis and quantitative methods [1]. The reconstruction process typically involves two main components: rebuilding housing and restoring essential infrastructure such as roads, ports, electricity, railways, and water systems. In many countries, housing is treated as the top priority in post-disaster efforts, as it directly addresses the immediate needs of affected communities and is often the government's primary focus [26].

For our mapping study, we have used seven digital libraries such as IEEE Explorer, Science Direct, MDPI, ACM, Springer, Scopus, and Web of Science. Only limited studies dealt with post-disaster reconstruction planning issues. Some of the approaches from these libraries have been mentioned in this section, but have been detailed in the Appendix A. For example, Mfon et al. [27] proposed a theoretical framework for rapid post-disaster reconstruction that takes into account social, economic, and environmental factors, along with the provision of relief to affected communities. Fan et al. [28] introduced a decision-support model that combines graph convolutional neural networks with deep reinforcement learning to restore road networks in post-disaster contexts. The model is pre-trained on a range of simulated damage scenarios, enabling it to quickly generate near-optimal recovery strategies when an actual disaster occurs. An et al. [29] introduced an algorithm that integrates geographic information system (GIS) data collected through detailed surveys by the Institute of Engineering Mechanics (IEM) and the China Earthquake Administration (CEA) with Synthetic Aperture Radar (SAR) imagery to assess damage after disasters. Similarly,

Doi et al. [30] developed a reconstruction planning method utilising 2D models and 3D renderings, while Mayo et al. [31] conducted a comparative analysis between the Intelligent Master Planning (IMP) approach and Conventional Master Planning (CMP). In addition, several studies have proposed formal modelling techniques aimed at optimising various aspects of the reconstruction process. Similarly, Goujon et al. [32] proposed a multi-criteria decision-making model for post-disaster reconstruction planning, utilising the Myriad tool [33] to prioritise damaged infrastructure and assess reconstruction projects based on population needs. Qiushan et al. [34] developed a post-disaster reconstruction framework focused on rebuilding residential and commercial structures, which was implemented in Dujiangyan central city. This framework emphasises the vital role of various stakeholders, such as markets, local businesses, and social institutions, in driving economic recovery by generating employment opportunities and accelerating reconstruction efforts. However, it builds on conventional methodologies and does not leverage advanced technologies like machine learning to manage post-earthquake scenarios. Moreover, the multicriteria decision making (MCDM) model introduced by Opricovic et al. [35] was designed to support the analysis and modelling of post-disaster reconstruction planning. A core strength of this model lies in its ability to identify the most suitable reconstruction alternative based on predefined input parameters such as time, cost, damage severity, and sustainability.

Based on our analysis of the existing scientific literature, to the best of our knowledge, no comprehensive review, whether in the form of a survey or a systematic mapping study, has been conducted to organise and categorise research focused specifically on post-disaster reconstruction planning [36]. Therefore, our current effort is motivated by the need and opportunity to systematically document, classify, and analyse the body of work published over the past 25 years in this domain.

3. Mapping Study Process

In this section, we describe the process we performed to carry out the systematic mapping study, following the guidelines proposed by [37].

Figure 2 summarises the overall workflow. In the figure, rounded rectangles represent *process* and grey rectangles represent *outcomes* of each process. The general workflow consisted of six steps, namely: *definition of research questions*, *conducting research*, *screening of papers*, *keywords and themes*, and *data extraction and mapping process*. Each process yields a specific outcome, which ultimately creates our mapping study.

In the following, we describe each process of the workflow and the resulting outcomes in detail.

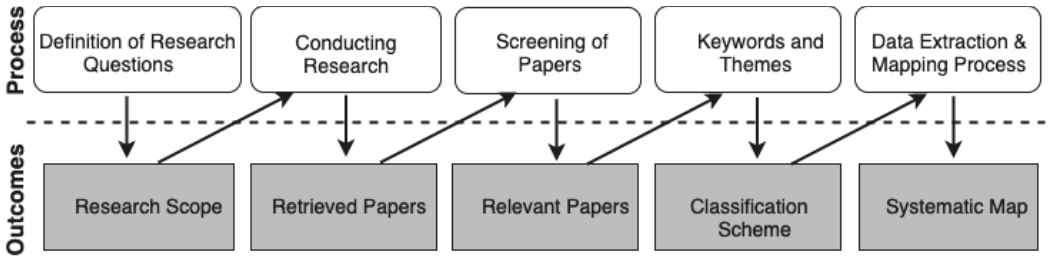


Figure 2. The systematic mapping process.

3.1. Definition of Research Questions

This mapping study aims to provide an overview of the research related to the adoption of AI and ML approaches to post-earthquake reconstruction. This leads us to the following research questions, formulated using the Goal-Question-Metric approach from [37].

The query we have formulated for the Goal-Question-Metric approach is the following:

Analyse the state-of-the-art post-disaster approaches **for the purpose of** infrastructure reconstruction planning **with respect to** the social benefits of affected people, politicians' role and policies, physical dependencies, time and cost for reconstruction, **to what extent** these methodologies including machine learning have been evaluated, latest active research in this domain **from the point of view of** researchers, and practitioners **in the context** of post-disaster reconstruction planning.

The main aim of this mapping study is to determine how post-disaster reconstruction has been managed using models and information technology. According to the goal of our paper, we have defined the following research questions (RQs). In presenting each RQ, we include the aim and rationale of every question we formulated:

- **RQ1:** What kind of problems have been addressed in the post-disaster management research domain?
  Aim: The aim of this RQ is to identify all issues related to post-disaster situations that have been addressed in literature.
  Rationale: In the post-disaster phase, administrators are called to develop reconstruction planning. We aim to understand the extent to which researchers have helped institutions in the reconstruction planning phase.
- **RQ2:** What approaches are used to address post-disaster reconstruction issues?
  Aim: The aim of this RQ is to focus on identifying the kind of proposed approaches e.g., Machine Learning, to handle the post-disaster situation.
  Rationale: On behalf of RQ2 we have clearly defined the criteria about the inclusion of primary studies, anything outside of these criteria will be excluded.
- **RQ3:** Which parameters of post-disaster reconstruction are mainly considered by the literature?
  Aim: Main aim of this question is to identify the key factors (such as required cost, number of affected people, or damage to buildings) mainly considered in the literature.
  Rationale: Through this RQ, we can identify key attributes used in all proposed models, and we can propose a taxonomy based on that.
- **RQ4:** What kind of limitations (i.e., threats to validity and limits) have been observed in the post-disaster reconstruction research domain?
  Aim: The aim of RQ4 is to focus on the limitation and threats to validity in proposed approaches.
  Rationale: Through this RQ, we discuss the threat to the validity of the considered primary study approach, and we can also sketch research gaps and future work.
- **RQ5:** What are the top popular venues and publication trends for the post-disaster management domain?
  Aim: The aim of this RQ is to note down all venues which are publishing articles in the computer science and social science domain related to post-disaster management. Additionally, we aim to highlight the research interest and expertise of researchers in this domain from 2000 to 2025.
  Rationale: Purpose of this RQ is to understand the venues that are publishing most of the primary studies related to the post-disaster management topic. Additionally, the rationale of this RQ is to understand the main research field (e.g., computer science, civil engineering, mathematics) of authors publishing papers in this domain. Therefore, this RQ can be divided into the following sub-RQs:
  - **RQ5.1:** What are the main publishing venues?
  - **RQ5.2:** What are the main research trends from 2000 to 2025?
  - **RQ5.3:** What are the main research fields of authors publishing in this research domain?

- **RQ6:** What are the main research gaps (i.e., open issues) in the research domain?
  Aim: This RQ describes research gaps or grey areas which have not been explored by the literature so far.
  Rationale: The rationale for this RQ is to find directions of unexplored areas for future research.

3.2. Literature Review

We apply the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach for literature identification and review [38]. Figure 3 reports the main PRISMA stages (on the left-most blue vertical columns) and the number of papers involved in each step.

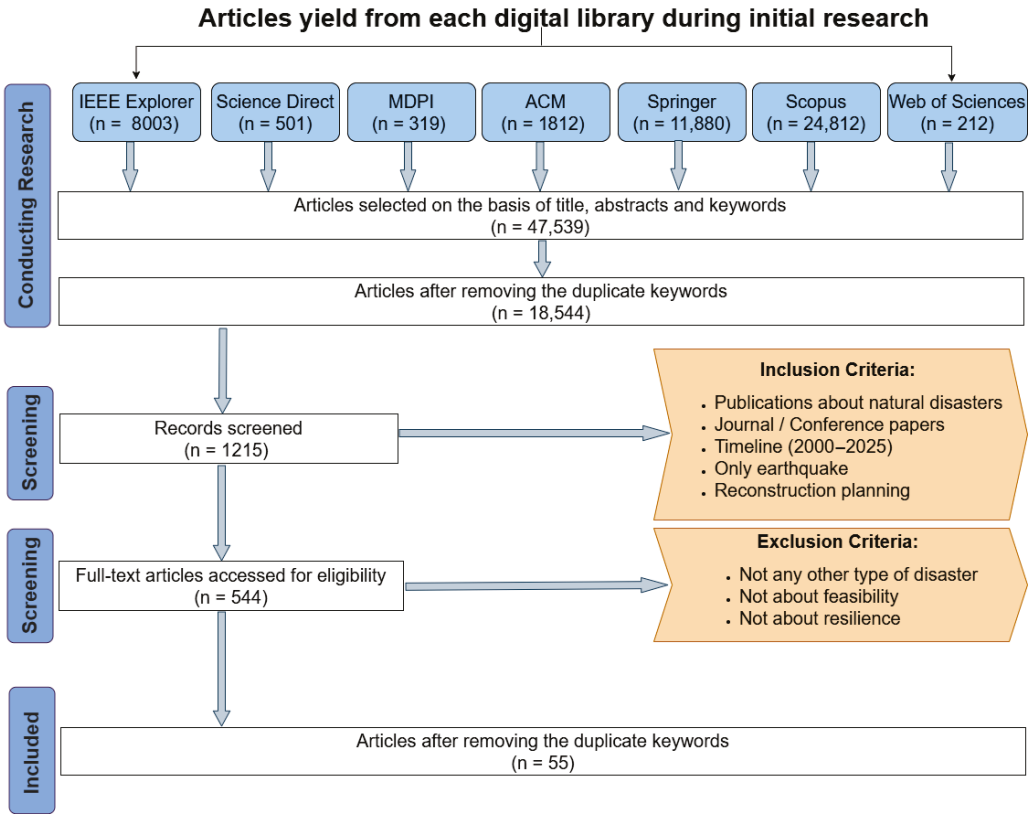


Figure 3. PRISMA flow diagram performed in our study.

The *Conducting Research* phase (see Section 3.2.1) concerns the development of research protocols by identifying the keywords and bibliographic databases to perform the search. The *Screening* phase (see Section 3.2.2) involves defining inclusion and exclusion criteria, as well as the time frame limit, for filtering the main articles. Eventually, the *Included* phase details the main articles selected after applying the screening criteria.

In the following, we detail each phase of the PRISMA workflow. This systematic review follows the PRISMA 2020 guidelines (see Supplementary Material).

3.2.1. Conducting Research

We have used the PICOC (Population, Intervention, Comparison, Outcome, Context) [39] criteria to formulate search strings from research questions.

- **Population:** In this context, population means all those people who are directly affected due to an earthquake or a post-disaster.
- **Intervention:** Intervention is the approach that is used to solve an issue. For example, the technologies or algorithms used to handle a post-earthquake situation.

- **Comparison:** In this study, we compare different approaches from the 'Intervention' step. However, at this level, the alternative strategies are addressed from a qualitative, but not empirical, perspective.
- **Outcome:** Here we focus on factors of importance in the considered methodology like effectiveness, efficiency, or resilience of the reconstruction planning methods, which is quite worthwhile for researchers.
- **Context:** In this study, we consider works coming from both industry and academia.

To find out the most relevant studies that were published over the last 25 years (2000 to 2025), we performed an automatic search from seven selected digital libraries, namely: IEEE Explorer, https://ieeexplore.ieee.org/Xplore/home.jsp, ACM, https://dl.acm.org/, Science Direct, https://www.sciencedirect.com/, Springer Link, https://link.springer.com/, Web of Sciences, https://apps.webofknowledge.com/, Scopus, https://www.scopus.com/, and MDPI, https://www.mdpi.com/. These libraries cover most of the academic literature published. All of these databases have been selected based on the experience reported by [40].

To search for the most relevant studies, we have identified a set of keywords and related synonyms. Next, we have constructed search strings using Boolean operators (i.e., AND and OR). The full query strings are reported in Table 1.

The quasi-gold standard, as explained in the following paragraph, is employed to identify the most relevant primary studies for a specific time frame (2000 to 2025) across conferences and journals [41]. The search string consists of identified keywords that are utilized in all the databases listed in Table 1. Among the selected databases, the IEEE and ACM Digital Libraries have been chosen due to their inclusion of leading international journals and prominent conferences and workshops focusing on data sciences and disaster management. Additionally, we have included ScienceDirect and SpringerLink, as they are comprehensive digital libraries that offer extensive online scientific collections and index-based international journals. The Web of Science (WoS) is also considered, as it is one of the oldest citation indexes for the sciences and contains a collection of scholarly publishing journals, proceedings, and data compilations [42].

To broaden the scope of our research to encompass social and economic perspectives, we ran search string queries in the Scopus digital library. Its developers claim it includes works from 4000 publishers in social science fields and asserts that it is the "largest single abstract and indexing database ever built" [43]. Lastly, we have also taken into account the MDPI digital library, as it is becoming a prominent publisher in this area.

The concept of the *Quasi-Gold Standard* is outlined in [41] and is based on two key criteria: the venue (where) and the time period (when). Using these criteria, we identified relevant publications from the seven specified venues/databases, as summarised in Table 1, through a combination of automated and manual searches. Additionally, the Quasi-Gold Standard (QGS) serves as a valuable tool for assessing search strategies aimed at locating pertinent literature within a defined time frame.

With the assistance of QGS, we compiled a set of studies from related venues, including domain-specific conferences and journals, recognised for the time span from 2000 to 2025. Subsequently, we identified the top publication venues in the fields of computer science and social sciences, as detailed in Table 2.

One significant advantage of using QGS is its ability to efficiently filter relevant studies by focusing solely on the titles and abstracts of the articles. Traditional manual and automated search methods can be time-consuming when it comes to sifting through data and narrowing down publication venues; however, QGS streamlines this process considerably. After identifying relevant studies with QGS, we applied the inclusion and

exclusion criteria outlined in Section 3.2.2. Ultimately, we selected 55 primary studies from the available venues.

Furthermore, we have also applied the backwards snowball technique to avoid missing any relevant primary study published from 2000 onward [44]. The backwards snowballing technique involves reviewing references cited in relevant papers, which increases the likelihood of discovering relevant studies [41]. In this whole process, we follow the guidelines of Wohlin [41].

Table 1. Search strings in databases.

Database	Search String
IEEE Explorer	(“Post disaster” OR “post-disaster” OR “reconstruction planning” OR “earthquake”) AND (“Housing” OR “city” OR “system” OR “building” OR “facilities” OR “road” OR “bridge” OR “infrastructure”) NOT (“Detection” OR “rescue” OR “cyclone” OR “eruption” OR “tsunami” OR “resilience” OR “temporary” OR “feasibility” OR “authentic” OR “war” OR “flood” OR “tornado”))
ACM	(“Post disaster” OR “post-disaster” OR “reconstruction planning” OR “earthquake”) AND (“Housing” OR “city” OR “system” OR “building” OR “facilities” OR “road” OR “bridge” OR “infrastructure”) AND NOT (“Detection” OR “rescue” OR “cyclone” OR “eruption” OR “tsunami” OR “resilience” OR “temporary” OR “feasibility” OR “authentic” OR “war” OR “flood” OR “tornado”))
Science Direct	(“Post disaster” OR “post-disaster” OR “reconstruction planning”) AND(“City” OR “building” OR “road”) AND NOT (“Cyclone” OR “Tsunami”)
Springer Link	(“Post disaster” OR “post-disaster” OR “reconstruction planning”) AND (“Housing” OR “city” OR “system” OR “building” OR “facilities” OR “road” OR “bridge” OR “infrastructure”) AND NOT (“Detection” OR “rescue” OR “cyclone” OR “eruption” OR “Tsunami” OR “resilience” OR “temporary” OR “feasibility” OR “authentic” OR “war” OR “flood” OR “tornado”)
Web of Sciences	(“Post disaster” OR “post-disaster” OR “reconstruction planning”) AND (“Housing” OR “city” OR “system” OR “building” OR “facilities” OR “road” OR “bridge” OR “infrastructure”) AND NOT (“Detection” OR “rescue” OR “cyclone” OR “eruption” OR “Tsunami” OR “resilience” OR “temporary” OR “feasibility” OR “authentic” OR “war” OR “flood” OR “tornado”)
SCOPUS	(“Post disaster” OR “post-disaster” OR “reconstruction planning” OR “earthquake”) AND (“housing” OR “city” OR “system” OR “building” OR “facilities” OR “road” OR “bridge” OR “infrastructure”) AND NOT (“detection” OR “rescue” OR “cyclone” OR “eruption” OR “tsunami” OR “resilience” OR “temporary” OR “feasibility” OR “authentic” OR “war” OR “flood” OR “tornado”)
MDPI	(“Post disaster” OR “post-disaster” OR “reconstruction planning” OR “earthquake”) AND (“Housing” OR “city” OR “system” OR “building” OR “facilities” OR “road” OR “bridge” OR “infrastructure”)

Table 2. Venues investigation during creation of Quasi-Gold standard.

Publication Venue	Subject Area	Type	Databases
ISCRAM	Computer Sciences/Social Sciences	Conf.	IEEE Explorer
CACIE	Computer Sciences/Social Sciences	Journal	Web of Sciences
Disasters	Social Sciences	Journal	ACM
ICT-DM	Computer Sciences/Social Sciences	Conf.	IEEE Explorer
RCIS	Computer Sciences/Social Sciences	Conf.	Springer

Table 2. *Cont.*

Publication Venue	Subject Area	Type	Databases
Journal of Big Data	Computer Sciences	Journal	Springer
Decision Support Systems	Computer Sciences	Journal	ScienceDir.
Advanced Engineering Informatics	Computer Sciences	Journal	ScienceDir.
ICAISC	Computer Sciences	Conf.	Web of Sci.
Expert Systems with Applications	Computer Sciences	Journal	ScienceDir.
Big Data and Society	Computer Sciences/Social Sciences	Journal	IEEE/ACM

3.2.2. Screening of Papers

In this section, we have defined inclusion and exclusion criteria for those studies which are retrieved from automated and manual searches and evaluated by two authors to decide whether these articles should be included based on their title, abstract, and keywords. For inclusion, we have applied the following criteria.

- I1: Studies which are about research methods and results of the considered research domain.
- I2: Studies must have gone under peer-review process and published in leading venues such as journals, conference proceedings, and workshop proceedings.
- I3: Studies about the earthquake.
- I4: Studies that were published from 2000 to 2025.
- I5: Studies written in English.

The studies that fall into at least one of the following exclusion criteria are excluded.

- E1: Studies that are not focused on earthquakes.
- E2: Grey literature like working papers, white and short papers, or presentations that are published in the form of some panel discussion.
- E3: Studies that are just about proposing guidelines, recommendations about disaster situations.
- E4: Secondary studies (such as mapping studies).
- E5: Studies that are not peer-reviewed.
- E6: Studies that are not written in English.
- E7: Duplicate studies which are published in different venues on various stages of their evolution.

We applied inclusion and exclusion criteria to relevant studies identified in digital libraries to determine their eligibility for our research, validating a time span from 2000 to 2025. During the full-text review, we excluded additional articles that did not meet our criteria. For the remaining articles, we employed a snowballing technique, which led us to discover five more relevant studies.

Furthermore, we ensured the reliability of the included studies for our systematic mapping by utilising Fleiss' Kappa [45]. This statistical method assesses the reliability of agreement among a fixed number of raters who classify items based on their nature. The method produces a score in binary form, where 0 indicates poor agreement and 1 indicates full agreement. Throughout this process, we enlisted the help of four independent raters to classify a random sample of 30 studies; 20 of these were already included in our mapping study, while 10 were not. The calculated Fleiss' Kappa result was 0.94, indicating a high level of agreement among the raters.

Additionally, Figure 4 illustrates the percentage of primary studies sourced from seven different digital libraries. According to the distribution, IEEE Explorer contains 38%, Science Direct 17%, MDPI 7%, ACM 19%, Springer 7%, Scopus 6%, and Web of Science 6% of the overall selected primary studies.

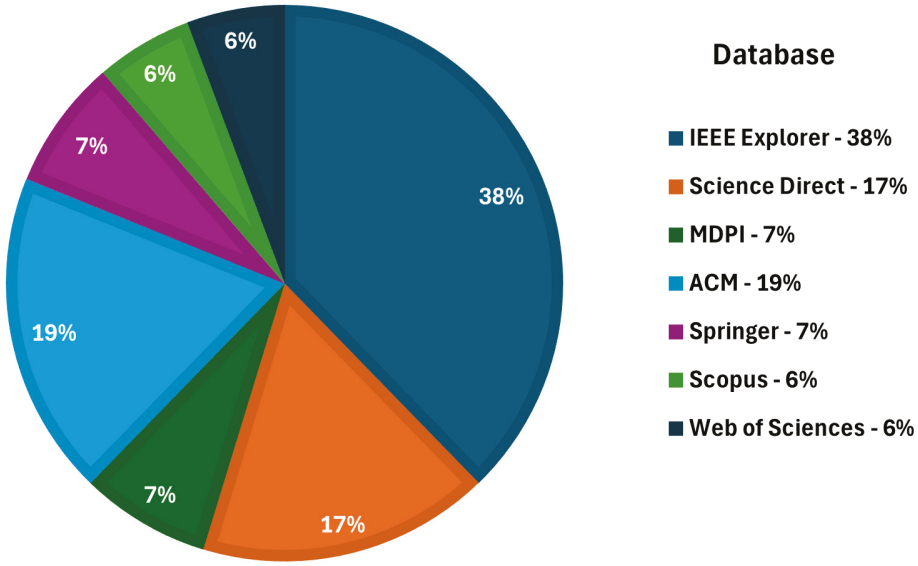


Figure 4. Primary studies percentage in each database.

3.2.3. Keywords and Themes

We have selected 55 articles after a thorough review process and applying inclusion and exclusion criteria following the PRISMA approach.

Figure 5 illustrates the proportion of primary studies sourced from each digital library. The "IEEE Xplore" has the highest number of primary studies, containing 18 articles. In comparison, the "ACM" digital library has 10 articles, while "Science Direct" includes 9 articles. The MDPI digital library has only four articles, and both "Springer Link" and "Web of Science" comprise three articles each. Scopus contributes the least, with only two relevant articles. Additionally, there are a few articles that appear in multiple libraries. For example, there are two common articles between the IEEE and ACM libraries, and Scopus shares three articles with IEEE Xplore.

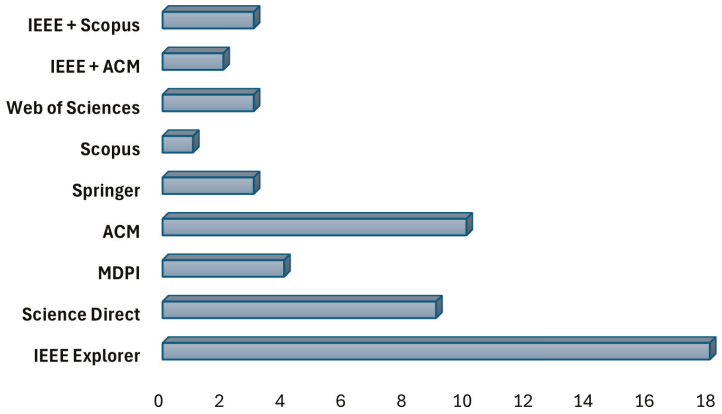


Figure 5. Selected primary studies.

Quality Assessment

After selecting a set of 55 relevant studies, we conducted a quality assessment using the most advanced quality assessment models from [46–49]. Based on the recommendations

provided in these models, we developed a quality assessment checklist, which is presented in Table 3. This checklist includes six different criteria and both subjective and objective questions aimed at verifying the validity of the sources, assessing their suitability, and ensuring they are free from bias.

Table 3. Quality assessment checklist of relevant literature for mapping study.

Criteria	Questions
Producer Authority	• Is the publishing institution/platform reputable (e.g., Progress of Disaster Science)? • Is the author associated with a publishing institute? • Has the author published any other work in this field? • Does the author have expertise in this area (e.g., job title principal software engineer or expert civil engineer)?
Methodology	• Does proposed methodology have a clearly stated aim? • Is the proposed approach supported by authentic references? • Are any limitations of the proposed methodology clearly stated? • Is the proposed work based on specific research questions, and are all questions responded to effectively? • Is the proposed methodology validated by real case studies?
Scope	• Does this work relate to our mapping study domain?
Objectivity	• Is this work balanced in presentation and clearly stated? • Does the problem statement clearly state the objective? • Does this work refer to a particular vendor? • Are the conclusions of this work supported by data?
Novelty	• Does this work introduce a new idea?
Impact	• Check the impact of the considered study with respect to the following criteria. - Number of paper citations - Number of paper backlinks - Number of paper views/read

Using this checklist, we evaluated the quality of the selected literature. By applying specific selection criteria, we effectively excluded all irrelevant studies, which minimised the effort required for the quality assessment activity [50]. These criteria are based on factors such as authority of the producer, methodology, scope, objectivity, novelty, and impact. Additionally, we can utilise the same selection criteria for other research methods, such as surveys, case studies, or experiments, to further assess the quality of studies. For instance, ref. [51] proposed a quality assessment checklist specifically for case studies, which can also be applied to case studies in the formal literature.

3.2.4. Data Extraction and Mapping Process

To extract data from the selected primary studies and address the research questions defined in Section 3.1, we have created Table 4. This table includes key "Data Items" related to the research questions. According to [52], it is beneficial for one researcher to extract the data while another reviews the extraction. Therefore, we employed a two-author approach for the data extraction process. This verification by the authors is a common practice in systematic mapping studies, as noted by [39]. Our defined data extraction strategy ensures that the same criteria are applied consistently across all selected papers, including their classifications.

Analysis and Classification

The extracted information is explained and visually illustrated in Section 3.2.4. During the analysis of the study identification phase, the extracted strategies were categorised based on different search approaches, including the development of the search, evaluation processes, and criteria for inclusion and exclusion. Each of these categories was then assigned themes and sub-themes. The sub-themes were utilised in the inclusion and exclusion process (also known as a priori), which relied on strategies such as resolving disagreements between researchers to minimise bias [53,54]. Finally, the selected papers were counted according to their respective themes and sub-themes.

Data Synthesis

In the data synthesis phase, we extracted and summarized information in a meaningful manner to address the defined research questions (RQs). For this purpose, we employed various techniques for data synthesis based on the guidelines of [55] for systematic literature reviews (SLRs), along with methods for synthesising evidence in software engineering research [56]. These techniques encompass various approaches, including descriptive synthesis, quantitative synthesis, qualitative synthesis, thematic analysis, and meta-analysis. Additionally, we used a descriptive technique, as illustrated in Figure 6, to categorise the publication types (book chapters, conferences, journals, or symposiums) of the selected studies in terms of their venue. Figure 7 provides an overview of the publication ratio of the selected studies over the past two decades (2000 to 2021). Furthermore, we established a classification scheme based on topic-related keywords to effectively respond to certain research questions. These classifications are particularly useful for the mapping process.

Table 4. Data extraction.

Data Item	Value	RQ
Article ID	Integer	
Author Name	Author's name list	
Title of Articles	Name of the article	RQ1
Keyword	Keyword study indexing	RQ1
Publication Year	Calendar year	RQ5
Venue	Publication venue name	RQ5
Reconstruction	Reconstruction of buildings, infrastructure (roads, bridges), economics, education and health	RQ1
Phase	Rescue phase (to evacuate the people)	RQ1
Social Benefits	Social benefits of affected people	RQ3
Planning	Reconstruction planning of buildings	RQ1
Emergency management	Rescue and facilitate people in post-disaster situation	RQ1
Contribution type	whether this article is based on some tool, solution methodology or consist of case study	RQ2
Optimization model	Optimization model is used in proposed study	RQ2
Machine learning	Machine learning algorithm is used in the proposed study	RQ2
Mathematical model	Mathematical model is used in proposed study	RQ2
Characteristic	Which parameters are used in proposed study/algorithm	RQ3
Search Strategy	Guidelines about search strategy that which is followed to select the studies	RQ4
Visualization Type	Which technique is used to visualize the data	RQ3
Classification schemes	How were articles classified	RQ2
Search Type	Manual or automated	RQ4
Open Issues	Limitation of proposed study	RQ4
Domain Expertise	Keywords extracted from the venue description	RQ5

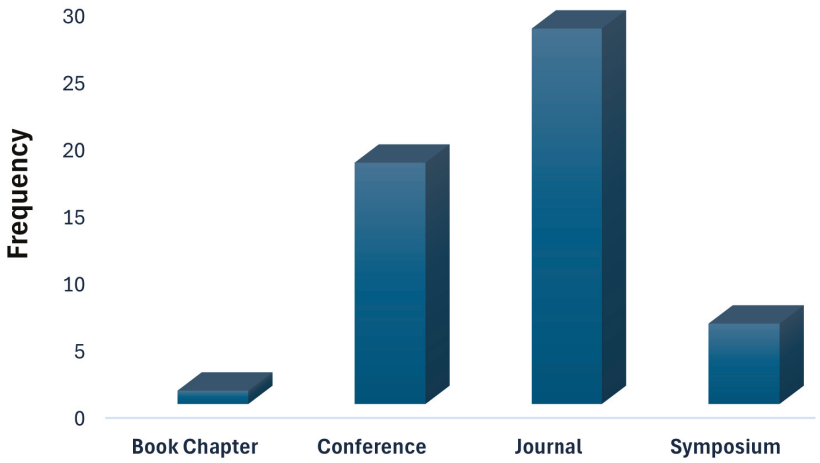


Figure 6. Distribution of selected studies with respect to publication type.

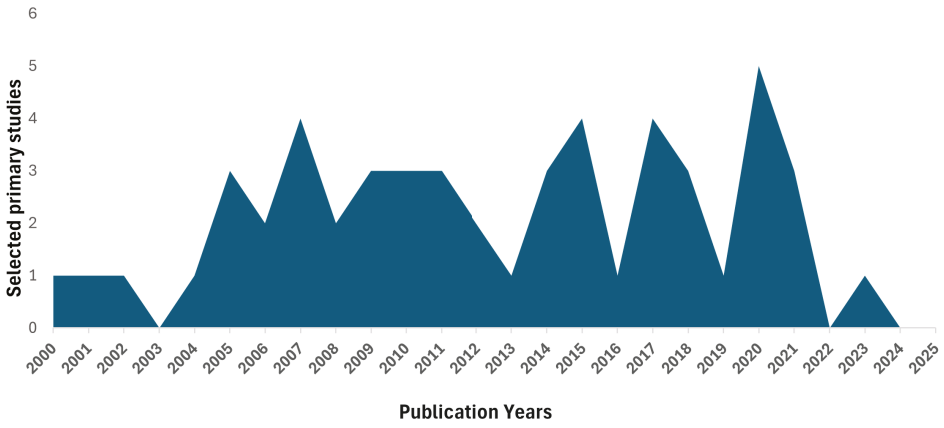


Figure 7. Distribution of selected studies with respect to time span.

4. Systematic Mapping Study Results

We conducted a mapping study in accordance with the guidelines outlined in Section 3 and our research questions. In the initial search, we identified 43 papers based on criteria such as year, country, affiliations, venue, and topic, applying our inclusion criteria. After updating our searches in line with the systematic mapping protocols [37], we discovered 10 additional papers that met the defined inclusion criteria. Ultimately, we finalised a total of 55 primary studies. A brief summary of all the studies considered can be found in Appendix A.

Figure 8 provides a detailed summary of selected primary studies from seven different digital libraries. The chart includes information about the digital libraries where these studies were published, as well as the type of solutions proposed by the authors—whether they pertain to Social & Economics, data sciences, modelling, or civil engineering (as discussed in Section 4.4). The outermost doughnut circle displays the references for the relevant primary studies.

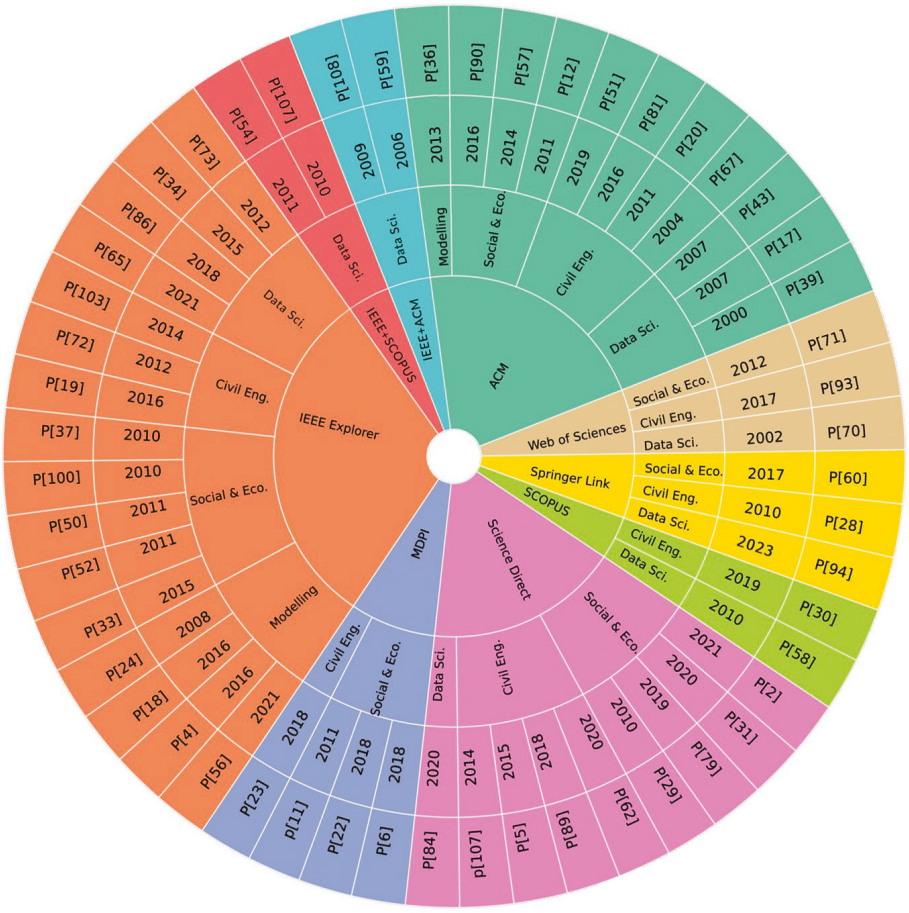


Figure 8. Distribution of publications techniques used for sentiment analysis across years.

4.1. Mapping of Primary Studies According to Publication Type

We have reviewed primary studies published across various platforms, including book chapters (1 study), conference articles (18 studies), journal articles (28 studies), and symposiums (6 studies). The contributions from these studies are illustrated in Figure 6 based on publication type. Journals emerged as the most popular publication platform, accounting for approximately 52.8% of the selected studies related to reconstruction planning in post-disaster situations. In comparison, conference articles comprised 33.9%, symposium contributions made up 11.32%, and book chapters represented the least common type, contributing around 1.88%.

Appendix B provides details on all 55 selected studies, including their publication venues, study types, research topics, the number of studies in each category, and references for the published works. These studies come from 47 different reputable venues. Specifically, there are 28 studies published in 23 different journals, 18 studies from 14 different conferences, and 6 studies from 6 different symposia, which include 1 primary study from a book chapter.

Overall, Figure 6 illustrates that all these forums are of high quality and make significant contributions to our systematic mapping.

4.2. Mapping of Primary Studies According to Publication Years

The distribution of selected studies based on publication years from 2000 to 2025 is illustrated in Figure 7. The X-axis represents the publication years, while the Y-axis indicates the number of selected primary studies.

The results show that researchers began focusing on post-disaster reconstruction planning between 2000 and 2002, utilising technical algorithms. There was little progress in 2003; however, in 2004, significant advancements were made, continuing until 2007. Following this period, there was a slight decline in research output in 2008.

In 2009, the volume of research and publications increased and remained consistent until 2011. Subsequently, a rapid decline in research activity was observed in 2013, 2015, and 2019. However, there was a swift resurgence in research in the following years, except for 2025, within the domain of post-earthquake reconstruction.

4.3. Mapping of Primary Studies According to Research Facet

For the research facet, we have used the classification scheme proposed by [57,58] to categorise primary studies according to the nature or type of research. These classifications are very simple and straightforward, as explained in the following in Table 5.

Table 5. Studies classification according to research type.

Research Type	Number of Studies
Solution Proposal	15
Solution Proposal and evaluation research	17
Solution Proposal and validation research	19
Philosophical papers	1
Opinion and Personal Experience	1

Solution Proposal: These kinds of papers propose a novel solution to the problem without a full-blown validation since these solutions are explained by proof of concept with the help of an example, a sound argument, or by some other means. We have found 15 solution proposals from selected studies.
Evaluation Research: Evaluation research is categorised as empirical research and it is based on research methods to evaluate novel solutions. All studies that are based on formal methods, such as hypothesis testing and performed experiments on real-world case studies, are considered under evaluation research. Our 17 primary studies lie in the 'solution proposal and evaluation research' category.
Validation Research: Validation research provides preliminary empirical evidence of the solution proposal that has been implemented. It is based on very deep and methodologically sound research steps to verify all relevant studies. These research steps include quasi-experiments, prototyping, mathematical analysis, and case studies, which are used to collect evidence as well as for thorough investigations. We have found 18 primary studies in this category of research type.
Philosophical Papers: According to [57], these studies are based on a new conceptual framework or a new way to look at current research. Only one primary study exists in this criteria.
Opinion Papers: These articles just describe the opinion of authors about some research area, like whether it is wrong, good, or needs improvement by using some other methods or techniques. Only one 'opinion paper' exists in our primary studies.
Personal Experience Papers: These studies are based on the author's personal experience from one or more projects. They focus more on *What* the researchers have learned rather than *Why*. These articles mostly come from industry practitioners or researchers who used to work practically on some tool and do not have discussion and methodology sections. In these type of studies, authors mention their experience in the form of a list. Thus, the evidence in these papers is often anecdotal in nature.

We can create more categories beyond the five shown in Table 5, but not all combinations would be worthwhile. For instance, a paper may propose a new technique, include validation, and conclude with a discussion section in which the author shares opinions on the work of other researchers. However, such papers do not fit neatly into defined categories. Due to these limitations, it is impossible to establish more categories [57].

The selected primary studies related to reconstruction planning in natural disasters are listed in Table 5 and have been classified into relevant categories. Almost 28.8% of the papers do not provide comprehensive validation or empirically grounded evidence, relying instead on proof of concepts. These 15 studies were classified as solution proposals. From this data, we can conclude that the relevant studies on reconstruction planning in the context of natural disasters are relatively weak in terms of scientific rigour.

The second type of primary research studies listed in Table 5 is solution proposal and evaluation research, which includes 16 studies. These studies provide high-quality evidence through experiments conducted on real case studies that assess the applicability of innovative solutions.

Validation research studies analyze the potential contribution of selected studies with respect to the experimental setup and mathematical analysis. These kinds of studies are a bit more than solution proposals because some researchers have started working in this domain in the last few years, which is why we have found 18 studies as shown in Table 5.

Currently, only one primary study is categorized under philosophical papers, as there are not many individuals proposing new conceptual frameworks in this domain.

Similarly, there is only one primary study that falls into the opinion and personal experience category.

Additionally, we employed an evaluation classification scheme from [58] to provide a more in-depth classification of selected primary studies into two categories: *real case study* and *limited experiment*, as illustrated in Table 6.

Table 6. Evaluation methods in primary studies.

Evaluation Method	Primary Studies	Total
Real Case Study *(Application of solution on real data as real context)*	PS6, PS9, PS13, PS15, PS23, PS17, PS21, PS10, PS3, PS47, PS32, PS19, PS22, PS36, PS45, PS26, PS18, PS35, PS48, PS30, PS20, PS31, PS33, PS39, PS43, PS5, PS7, PS46, PS52, PS53, PS54, PS55	32
Limited Experiment *(Application of solution unsolicited data on very simple case study)*	PS11, PS14, PS24, PS1, PS25, PS8, PS2, PS50, PS41, PS44, PS49, PS51, PS38, PS29, PS37, PS34, PS42, PS12, PS16, PS4, PS28, PS40, PS27	23

Most of the primary studies employ empirical strategies to support and evaluate their proposed techniques. However, while reviewing the selected studies, we noticed that various papers include sections titled "Case Study" or "Experiment" to validate their proposed solutions. To address this, we have categorised the selected studies into two evaluation methods.

Real Case Study: Just a research method where the researcher explores the proposed solution or topic in depth and validates on a real dataset.

Limited Experiment: Another research method where different variables are used in algorithms to test the hypothesis.

4.4. Mapping of Primary Studies According Post-Disaster Reconstruction Planning Solution Domain Facet

The mapping and classification of primary studies related to post-disaster reconstruction planning (PDRP) solutions begin immediately after data extraction. This process gathers detailed information about current research in post-earthquake reconstruction. It involves two reviewers who work through two distinct steps. In the first step, a systematic mapping is conducted. In the second step, a classification of the solution domain is created, which consists of four categories: social and economic factors, data science, modeling, and civil engineering, as shown in Table 7.

Table 7. PDRP solution facet in primary studies.

PDRP Domain	Res. Topics	Primary Studies	Total Count
Social and Economics	1- Social Sciences, 2- Social and Economic Experts, 3- Management Experts.	PS13, PS46, PS45, PS30, PS39, PS21, PS28, PS15, PS37, PS33, PS27, PS42, PS9, PS35, PS48, PS10, PS44, PS25,PS5	19
Data Sciences	1- Data Sciences, 2- Data Analytics, 3- Intelligent Master Planning, 4- Reinforcement Learning.	PS8, PS17, PS11, PS7, PS12, PS19, PS47, PS22, PS29, PS1, PS50, PS34, PS24, PS52, PS53, PS54	16
Modelling	1- Decision Model, 2- Modelling by Using Software, 3- Computer Aided Design, 4- 3S Planning Technique.	PS31, PS6, PS4, PS38, PS26, PS55	6
Civil Engineering	1- Structural Engineering, 2- Hydraulic Engineering, 3- Transportation infrastructure engineering, 4- Transportation System Engineer.	PS2, PS40, PS16, PS20, PS3, PS49, PS14, PS18, PS23, PS32, PS36, PS41, PS43, PS51	14

4.4.1. Solution and Economics (Social and Eco.)

These multi-disciplinary studies are grounded in economic, social, political, and 542 cultural perspectives [59].

During mapping study, we learned that some researchers have proposed social and economic studies for post-disaster reconstruction planning. The goal of all these types studies is to overcome the post-disaster situation by considering the social and economic factor. However, it is really difficult to handle such circumstances in this way, but despite this, according to Table 7 we have found 19 studies that provide social and economic solutions for post-earthquake reconstruction planning.

4.4.2. Data Sciences

These studies handle post-disaster situations by applying tools and techniques on vast volumes of data to find meaningful information for decision making [60].

In this regard, we have found 15 articles that use algorithmic techniques like genetic algorithms to handle post-earthquake reconstruction planning problems, but the overall percentage of these types of articles is 28.3% from selected studies.

4.4.3. Modelling

To solve a challenging problem, sometimes it is really difficult for researchers to use advanced algorithms or to provide a mathematical solution, and authors use modelling techniques for solution implementation. That is why we have observed during a mapping

study that few authors have proposed simulation solutions but the overall percentage of these kinds of articles is much less, at is 9.4% from selected studies.

4.4.4. Civil Engineering

All these primary studies are based on professional designing and development of the infrastructure or experience papers [61]. The percentage of these kinds of articles is similar to algorithms type solutions, which is 26.4%.

4.5. Classification of Studies According to the Information Learned

According to the results, we have extracted information from different primary studies like solution proposals, empirical studies, evaluation research, philosophical papers, survey papers, and opinion papers. However, during information extraction [62], we have considered key attributes like damage level in the area, required time for reconstruction of properties, cost/budget required to reconstruct properties, and the number of people who got affected by the disaster in the damaged area. Some studies have shown information on abstract level for instance, graphs or graphical representations, which are PS28, PS46, PS33, PS31, PS26, PS1, PS31, PS38, PS4, PS48, PS15, PS39, PS25, PS27, PS44, PS46, PS30, PS21, PS42.

In this mapping we have also found empirical research articles, like PS24, PS50, PS8, PS12, PS22, PS534, PS17, PS43, PS11, PS18, PS7, PS19, PS41, PS47, PS29, PS1, PS50, PS52, PS53, PS54, PS55.

The rest of the primary studies are considered as a general category because every article contains some key attributes. All these articles are mentioned in Appendix A.

4.6. Classification of Studies According to IT Solution and Civil Engineering Field

As we go further in-depth for mapping study analysis, we have analyzed 25 papers based on IT solution and 31 papers suggesting solutions from the civil engineering field from total of 55 studies.

Additionally, the proportion of civil engineering solutions is more than IT because post-earth reconstruction problem is more oriented to the civil engineering field.

4.7. Most Fertile Researchers in Area

On behalf of primary studies, we have analyzed publications trends as well as the number of published articles by each author to check research impacts in this particular area. We have found few active researchers those have published few papers in last 25 years [63] like PS9 [35], PS25 [64], PS46 [9], PS47 [65], PS52 [66], PS53 [67], and PS55 [68]. Although the publication rate of articles increased in 2007, 2015, 2018, and then up to 2025 according to Figure 7. But, based on results and thorough analysis, we came to know that no research group deals with this critical problem by using cutting-edge technologies like machine learning.

5. Discussion

This study systematically mapped the current state of research in post-earthquake reconstruction planning from 2000 to 2025, identifying key themes, methodologies, and technological advancements. The analysis of 55 primary studies across seven digital libraries has revealed several important insights into the evolution of research and its gaps. The findings suggest that while progress has been made toward integrating optimization and decision-support models, there is still a substantial need for comprehensive frameworks that consider sustainability, socio-economic resilience, and real-world validation.

The mapping results show that data driven and AI-based approaches including optimization models, reinforcement learning, and decision frameworks are increasingly

adopted, reflecting a paradigm shift from conventional civil engineering and manual planning techniques to computational and intelligent systems. However, only one study (PS52) [66] applied a reinforcement learning algorithm (DDQN) for reconstruction planning, confirming that the domain is still in its early stage of adopting machine learning for decision-making under uncertainty. This highlights a promising area for further empirical exploration and hybrid modeling.

In addition, the distribution of research types indicates that approximately 29% of the studies are solution proposals lacking empirical validation, suggesting limited methodological maturity. While 32 studies have been validated using real case data, the absence of standardized evaluation frameworks hinders cross-study comparison and reproducibility. This reinforces the need for future work to emphasize experimental validation and benchmark datasets for post-disaster reconstruction scenarios.

The parameters and attributes identified such as time, cost, damage level, sustainability, and political priority demonstrate the interdisciplinary nature of reconstruction planning, where technical, economic, and social dimensions intersect. Yet, most studies treated these parameters in isolation, neglecting their dynamic interdependencies. This fragmentation reduces the applicability of current models to complex, real world settings. A unified approach combining multi-criteria decision analysis (MCDA) with machine learning could address this limitation by optimizing trade offs among competing objectives.

Another key observation concerns the imbalanced distribution of research domains: civil engineering and social-economic studies dominate, while computational and data-science-driven methods remain underrepresented. This suggests that stronger collaboration between engineering and computer science researchers is crucial for advancing intelligent reconstruction planning. Additionally, there is a lack of work incorporating sustainability indicators and community centered design, which are essential to ensure long term resilience and equitable recovery.

6. Potential Research Areas

On the basis of the results of the mapping study, we can say that few people have tried to work but a not fair amount of research has been carried out in this domain. Most of the studies are based on a graphical representation of the damaged area instead of empirical research. That is why we can say that most research efforts are not methodologically sound and some issues remain unexplored. We have found various kinds of potential research directions especially the use of cutting-edge technologies in this critical domain of reconstruction planning in a post-earthquake situation.

Using cutting-edge technologies like machine learning in this area could be very useful because according to the results of the mapping study, we have found only one article PS52 [66] that has used the DDQN reinforcement learning algorithm for reconstruction planning apart from that which no one has used. Creating a reconstruction plan manually is a real challenge for decision makers because it is really hard for them to maintain balance in all formal and informal requirements, including a guarantee to repopulate the damaged area. Secondly, it is compulsory to consider the benefits of affected people that come from optimizing some values, e.g., the vulnerability of buildings, the budget, and time required to accomplish the building plan [69]. Development plans must be implemented according to the new strategies devised to drive future development, including taking into account the sustainability factor.

Furthermore, another aspect that public decision makers do not consider is the societal impact and relative benefits that citizens experience from the implementation of a certain recovery plan [25]. Indeed, the societal impact and benefits are different in every plan, but these are the key features that should be considered in all post-disaster phases.

For the aforementioned complexities, machine learning algorithms are the best solution that can provide a mechanism to public decision-makers, servants, and citizens that can help effectively to define and evaluate rebuilding plans.

Thus, more empirical and detailed research is required to analyze how machine learning algorithms can be used to define reconstruction plans in a post-earthquake situation.

7. Threat to Validity

There are many aspects that need to be considered when assessing systematic mapping study which can potentially limit the validity of the findings but in this section, we have discussed possible validity threats to our systematic mapping study regarding analysis, conduct, design, and clarifications. We have considered threats like bias in the selection of digital libraries, inaccuracy in data extraction, bias in the time frame for primary studies, bias in the definition of search strings, and publication bias.

Bias selection of digital libraries means we might have a distortion in statistical analysis in the selection of all those libraries which contain or do not contain too many related studies. We handled this threat (to at least some extent) by defining comprehensive inclusion and exclusion criteria for post-disaster situation-related studies.

Secondly, *inaccuracy of data extraction* and misclassifications can occur during information extraction which is done by reviewing it in a different ways. To minimize these kinds of discrepancies (to at least some extent) were solved by consensus by all reviewers.

Thirdly *bias in the time frame for primary studies* for this purpose we have considered articles from 2000 to 2025 range to mitigate chances not to miss any recent relevant study.

Fourthly to tackle *bias in search string* we have used all techniques like tabs, quotes, hyphens to exclude words and asterisk wildcard tips (at least some extent) to make a comprehensive string.

Lastly, *publication bias* refers to sometimes positive problems published more as compared to negative and also negative results take a longer time to be published and are usually cited fewer times [55]. To tackle this threat (to at least some extent), we have scanned all related journals and conferences apart from grey literature like reports or Ph.D. theses and unpublished results because all these kinds of things may affect the validity of our results.

Additionally, in this section we have also used classification schemes of [70–72]. According to these schemes, the following types of validity threats have been taken into account, which are descriptive validity, theoretical validity, internal validity, external validity, and conclusion validity. All these have explained the following.

7.1. Descriptive Validity

Descriptive validity is about the accuracy and objectivity of collected information. Usually, threats of descriptive validity exist more in qualitative studies as compared to quantitative studies. For this purpose, we have designed a data collection form to record the data related to post-earthquake situations and also describe the process of data extraction in Table 4 and have reviewed them many times, so as to not miss any related articles. Additionally, this form can be revisited whenever required for primary studies, so this threat is handled very effectively.

7.2. Theoretical Validity

Theoretical validity is about determining collected data on post-earthquake situation fits into what we have require without any bias selection. Because there is always a chance to miss some relevant studies, e.g., ref. [73] did work on two mapping studies on the

same topic and ended up with different articles, we have used PRISMA [74] and backward snowball sampling techniques [75] to handle this threat in Section 3.2.

7.3. Internal Validity

Internal validity is based on two main threats, which are missing relevant studies and bias in paper selection by researchers. By the way, mapping studies consider a wide range of related articles from different databases [76]. So in our mapping study, we have considered the seven most widely used digital libraries to minimize the chance of not missing any relevant study about the post-disaster situation. We believe most of the related primary studies are considered but still, we cannot rule out the possibility that we might have missed some relevant studies during the automatic search in digital libraries. Additionally, we also used quasi-gold standard (Section 3.2) to validate the completeness of automated searches strings which are based on RQs keywords.

Researchers' bias in paper selection might also lead to inaccuracy in data extraction. For this purpose, we have defined data inclusion (DI's) criteria in Table 4 for data extraction, where all researchers were agreed, and if there was any conflict in data extraction, we settled by mutual consensus.

7.4. External Validity

According to [70], external validity of systematic mapping study is about how much findings are generalizable and useful for other population interests. So the major threat is whether considered primary studies are representing the subject area or not. For this purpose, we have followed the standard research process and considered all relevant studies apart from those which were not in English.

Additionally, some primary studies do not provide full information for extraction form. In that case, we have assumed some information on behalf of DIs during data synthesis. Similarly, some approaches did not describe drawbacks.

7.5. Conclusions Validity

Conclusion validity is about up to how much we reached on reasonable conclusion as well as the relationship between selected studies and current research trends in the considered field. To handle the first threat, we have answered all defined RQs on behalf of selected primary studies. Regarding the second threat about data extraction, classification and synthesis were performed as a team. However, still, there is a chance to miss relevant studies because qualitative-based mapping study is really difficult and can be missed in any article.

8. Conclusions

This mapping study has identified the related literature and evaluated with respect to topics, frequency of publications up to 2025, publication venues, and type of disaster.

We believe our mapping study is based on a comprehensive and state-of-the-art overview in post-earthquake reconstruction planning studies, which is quite useful for young researchers and practitioners to get an idea about this challenging field and make a contribution by using cutting-edge technologies.

We have answered all defined research questions (RQs) with the help of analysis and results on behalf of our systematic mapping study.

RQ1: *What kind of problems have been addressed in the post-disaster management research domain?*

According to our primary studies, we have considered only earthquake related studies, which are published in the last 25 years (from 2000 to 2025). After thoroughly studying, we have found 19 types of problems and all these are classified in Table 8.

Table 8. Problems addressed in primary studies.

Problems	Primary Studies
Reconstruction criteria definition	PS1, PS8, PS12, PS15, PS16, PS23, PS30, PS28, PS48
Resources management	PS3, PS14, PS21
Socio-economic policy definition	PS19, PS36, PS39, PS46, PS49
Stakeholders involvement	PS9, PS17, PS20, PS26
Data collection	PS5, PS7, PS27, PS29, PS33, PS35, PS44, PS51, PS53, PS54, PS55
Data visualization	PS4, PS40
Reconstruction planning with social aspects	PS10, PS13, PS34
Resource management	PS3, PS14, PS21
Agent-based reconstruction mechanism	PS37
Cost estimation	PS43
Data modelling	PS24
Decision making	PS25
Index-based reconstruction mechanism	PS45
Master planning	PS11
Metrics definition	PS31
Reconstruction criteria for damage roads	PS47
Reconstruction plan generation	PS52
Sustainable recovery	PS2
Temporary housing	PS22

RQ2: *What approaches are used to address post-disaster reconstruction issues?*

The approaches that we have found in primary studies to solve post-earthquake reconstruction problems are categorized into four types, which are Optimization Model (mathematical model), Decision frameworks (implemented algorithms which can mange resources, cost, time, etc. in post-disaster situation), Machine Learning, Geographical Information System, Visualization model (undirected graph or maps of damage area), and Real experience reports (studies which describe practical implementation of reconstruction plan), as shown in Table 9.

Table 9. Papers grouped based on approach.

Approaches	Primary Studies
Optimization model	PS1, PS24, PS20, PS17, PS12, PS13, PS15, PS21, PS27, PS28, PS29, PS34, PS35, PS39, PS7, PS44, PS46, PS47, PS53, PS54, PS55
Decision frameworks	PS2, PS25, PS9, PS10, PS19, PS18, PS16, PS14, PS26, PS48, PS31, PS50, PS32, PS33,PS51, PS36, PS37, PS38, PS41, PS43, PS45, PS49, PS22, PS30
Machine learning	PS52
Geographical information system	PS5, PS11, PS6
Visualization model	PS4, PS40
Real experience reports	PS3, PS8, PS23, PS42

RQ3: *Which parameters of post-disaster reconstruction are mainly considered by the literature?*

In selected studies, we had the analysis of all those attributes/input parameters that are used in proposed methodologies. We have categorised these parameters into three different tables on behalf of methodologies (algorithmic and mathematical models, visualization models, and real experience reports). Overall, 16 attributes have been noticed, which are time, cost, political priority (PP), damage level (DL), resident numbers (RN),city data (CD), physical dependencies (PD) people opinion (PO), gross domestic production (GDP), sustainability (Sustainbi.), state disaster recovery coordinator (SDRC), 3D, seismic strength (SS), stiffness, historical and cultural (H & C), and environment (Env.). Details of each primary study with respect to parameter/attributes are mentioned in Tables 10–12. Reference *(Ref)* column contains related to paper and in *input parameters* column contain parameters which are mentioned by "x" if it exists in the corresponding paper and blank space vice versa.

RQ4: *What kind of limitations (i.e., threats to validity and limits) have been observed in the post-disaster reconstruction research domain?*

According to the primary studies, our focus is on reconstruction planning of infrastructure in post-earthquake situations. After deep analysis, we have observed three types of limitations in available articles, which are Availability of updated data, Computational resources, and Model efficiency (not validated on real case studies). All primary studies have been categorised with respect to their limitations in Table 13.

Table 10. Algorithmic and mathematical models common parameter table.

Ref	Input Parameters																
PS[Ref]	Time	Cost	PP	DL	RN	CD	PD	PO	GDP	Sustainbi.	SDRC	3D	SS	Stiffness	H&C	Env.	SB
PS1	X	X	X			X			X	X	X						
PS2		X		X		X			X		X						
PS5		X						X									
PS6		X		X	X							X					
PS7		X		X													
PS9			X		X	X							X				
PS10	X	X															
PS11			X	X		X			X								
PS12		X	X		X												
PS13	X		X		X			X									
PS14				X	X	X											
PS15	X	X	X	X		X											
PS16		X	X	X							X						
PS17	X		X			X											
PS18		X		X											X		
PS19				X	X	X											
PS20	X	X	X			X		X									
PS21		X															
PS22				X	X										X		
PS24		X						X									
PS25				X		X					X						
PS26	X	X						X					X				
PS27	X			X		X								X			
PS28		X		X	X										X		
PS29		X	X	X	X					X							
PS30			X		X	X											
PS31	X	X	X	X		X			X			X	X				
PS32	X		X			X					X						
PS33		X		X		X									X		
PS34				X	X	X					X						
PS35	X	X	X			X					X						
PS36		X						X						X			
PS37				X	X			X					X				

Table 10. *Cont.*

Ref	Input Parameters															
PS[Ref]	**Time**	**Cost**	**PP**	**DL**	**RN**	**CD**	**PD**	**PO**	**GDP**	**Sustainbi.**	**SDRC**	**3D**	**SS**	**Stiffness**	**H&C**	**Env.**	**SB**
PS38		X		X					X						X		
PS39		X							X					X			
PS41	X	X								X							
PS43		X	X	X	X						X						
PS44		X	X		X											X	
PS45			X		X	X									X		
PS46		X	X		X						X						
PS47		X	X	X	X		X									X	
PS48			X	X	X	X							X				
PS49		X	X	X	X										X		
PS50		X		X	X				X							X	
PS51		X	X		X								X				
PS52	X	X	X	X	X	X	X										X
PS53	X	X		X			X										
PS54				X			X					X					
PS55							X			X						X	

Table 11. Visualization models common parameter table.

Ref	Input Parameters														
PS[Ref]	**Time**	**Cost**	**PP**	**DL**	**RN**	**CD**	**PD**	**PO**	**GDP**	**Sustainbi**	**SDRC**	**3D**	**SS**	**Stiffness**	**H&C**	**Env.**
PS4	X	X	X			X		X				X				
PS40				X		X										

Table 12. Real experience reports common parameter table.

Ref	Input Parameters															
PS[Ref]	**Time**	**Cost**	**PP**	**DL**	**RN**	**CD**	**PD**	**PO**	**GDP**	**Sustainbi.**	**SDRC**	**3D**	**SS**	**Stiffness**	**H&C**	**Env.**
PS3				X	X	X				X						
PS8	X			X		X										
PS23		X		X							X					
PS42	X			X				X								

Table 13. Papers grouped based on approaches limitations.

Limitations	**Primary Studies**
Availability of updated data	PS4, PS14, PS6, PS18, PS49, PS13, PS30, PS48, PS37, PS23, PS26, PS33, PS8, PS11, PS38, PS45, PS47, PS19, PS39, PS50, PS51, PS53, PS54, PS55
Computational resources	PS1, PS12, PS42, PS34, PS16, PS2, PS29, PS9, PS5, PS46, PS31, PS40, PS35, PS24, PS43, PS20, PS27, PS17, PS32, PS41, PS22, PS44, PS28, PS36, PS52
Model efficiency (not validated on real case studies)	PS3, PS10, PS21, PS7, PS15, PS25

RQ5: *What are the top popular venues and publication trends for the post-disaster management domain?*

During the search of primary studies, we found 11 venues that contain most of the primary studies related to the post-earthquake reconstruction domain. All those venues including research trends and expertise required are explained in the following sub-questions.

- **RQ5.1:** *What are the main publishing venues?*
  In total, we found 46 different venues on behalf of selected primary studies. Among those, only 11 conferences/journals (venues) are the most popular, which contain

more than one primary studies. These popular venues are ISCRAM, CACIE, disasters, ICT-DM, RCIS, Journal of Big Data, decision Support Systems, Advance Engineering Informatics, ICAIS, Expert Systems with Applications, and Big Data and Society as shown in Table 2.

- **RQ5.2:** *What are the main research trends from 2000 to 2025?*
  According to Figure 7, research trends vary from 2000 to 2025. In 2000, only a few people were working and then this ratio goes down in 2003, and then again in 2007 the research trend goes on top and then we can see a slight fall in 2008. Later again, the variation continues in the following years like in 2014, 2017, and 2020 research trends are on top.
  But all these studies have tried to solve the post-earthquake situation by using different techniques.
- **RQ5.3:** *What are the main research fields of authors publishing in this research domain?*
  From primary studies, we came to know that reconstruction planning is related to civil engineering, but during reconstruction, we also need to consider the social aspect of affect communities. For this purpose, the researcher needs expertise in social sciences, data sciences, and technical skills of computer science.

RQ6: *What are the main research gaps (i.e., open issues) in the research domain?*

On behalf of our results, we have observed that not many researchers are working in this research area, especially with respect to cutting-edge technologies (like artificial intelligence and machine learning). In that aspect, we have found numerous directions that can be carried out for research because the empirical research, which has already been done to handle the post-disaster situation, is not sufficient. Most of the proposed solutions in the considered studies are based on visual simulations like undirected graphs instead of empirical solutions.

We can claim that it is a great opportunity for young researchers to explore this unexplored important research fields with respect to cutting edge technologies like artificial intelligence and machine learning.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su172210035/s1, PRISMA 2020 Checklist [77].

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Appendix A

In this index, we have enlisted all considered primary studies.

PS1: Ref. [35] developed a multicriteria model (the application of this model is illustrated with post-earthquake reconstruction problem in central Taiwan including restoration of the "lifeline" system) for analyzing and planning strategies for reducing social and economic cost in the natural disaster area by generating alternatives, establishing criteria, assessment of criteria weight, and application of compromise ranking method (by VIKOR).

First of all, they create alternative reconstruction plans with different scenarios and varying "system Parameters" like s1 = location, s2 = magnitude, s3 = probability s4 = number of reallocated settlements, s5 = land-use types, s6 = development regulation, s7 = fiscal policies, s8 = construction techniques. The first three parameters are determined from seismic data for the considered area and the rest of all are related to regional planning and designing alternatives. Secondly, they establish eight multicriteria (Reconstruction cost, Gross domestic production, Destroyed houses and parameters, Restoration ability, Sustainability, Acceptability by the local public, Government preferences and plans have to be evaluated on the behalf of all these criteria). The relative importance of each criteria in Multicriteria Decision Modeling (MCDM) is expressed by weight using the scaling method without losing any meaning which provides help in modeling decision making. "Equal Importance" weight (wi = 1/n) when there is no information from the decision-maker. Fuzzy logic is used for the linguistic variable (good, fair, and bad) to develop a mathematical model to implement human logic in engineering solutions. All these linguistic variables play an important role in decision-making. The fuzzy multicriteria model can treat all relevant conflicting effects and impacts in their representative units and the development of fuzzy multicriteria model is important because it deals with incomplete information. The Fuzzy multicriteria optimization (FUMCO) method is developed in this paper which has two phases CFU phase(converting fuzzy data into crisp scores) and MCO phase (multicriteria optimization using compromise ranking method). Linguistic variables converted into crispy numbers like low = 0, medium = 0.5 and high = 1 respectively. To avoid conflicts among different criteria, which is very obvious in practical problems that they have used a comparison ranking method known as VIKOR, which is introduced as an applicable technique to implement within MCDM.

PS2: Ref. [78] develop an innovative decision framework by adopting an agent-based approach for short-term redevelopment objectives and also for balancing long term goals by reducing three-dimensional vulnerabilities of communities like social, economic, and environmental ones. For this purpose, they have used residential agents, economic agents, and state disaster recovery agents (SDRC). SDRC's main purpose is to evaluate the recovery plan and prioritize the objective after every simulation through aggregated equations. The proposed approach is composed of five steps: (i) Implementation of an assessment tool to measure the three considered dimensional vulnerabilities; (ii) Modeling of stakeholders objectives, strategies, and behaviors; (iii) Data gathering to extract the information about the damage of the disaster; (iv) Simulation of the impact of the disaster event and of the interaction the stakeholders have during the post-disaster recovery phase; (v) Analysis of the simulation results. The utmost purpose of this research methodology is to provide optimal recovery strategies after disaster and policies at the community level.

PS3: Ref. [79] reviewed disaster management practices in China with an interdisciplinary analysis to check how disaster planning and management can be used efficiently in a top-down government administration system during 2008 Wenchuan Earthquake. Basically two national-level plans were drawn, one is the Overall Plan for Post-Wenchuan Earthquake Recovery and Reconstruction, and the other is the City Town System Plan for Post-Wenchuan Earthquake Recovery and Reconstruction, and the evaluation of plans contents are very helpful for policymakers to build a sustainable infrastructure.

PS4: Ref. [30] proposed a solution for reconstruction after Great East Japan Earthquake (11 March 2011). According to this solution in the start, only 2D drawings of roads and other infrastructure were collected from government offices for the construction plan which was very difficult to make consent with local residents and to start the construction plan. For this purpose, they proposed two policies to accelerate the reconstruction plan (i) Build 3D models for public shapes using CAD (Computer-Aided Design) and private shapes

using CG (Computer Graphics) for better visualization and then they are integrated into the database (ii) Train human resources that can build for 3D models from 2D drawings of roads, river, rail and so on. In order to evaluate the approach, they did joint research with the city planning division of Miyako city. In meanwhile civil engineering related software was also used for 3D modeling like Infrastructure Design Suite (used for planning and visualization), Civil 3D (used for making small objects like sports facilities, parking lots), and ReMake (used for converting photo/laser scanning data into 3D mesh). As a case study in this article, they considered "Kuwagasaki" district of Miyako city. When they used city planning law data of urban planning it was difficult to use because that was in 2D and visually can't be differentiated among different tress e.g "Akinire" and "Yamaboshi" are very rare trees in Japan. For this, they have used JFP a tree generation system (written in eXtensible Plants Modeling Language) to model 3D tree shapes. The author has introduced another efficient way of 3D model of by using reconstruction by using drone came, for realistic and effective 3D models quickly, this method is much faster and efficient as compared to ordinary 3D modeling.

PS5: Ref. [80] have proposed a framework by using 3S (Special data Acquisition, Spatial Data Management, and Special Data Management) and remote sensing (RS provide different resolution remote sensing data before and after the earthquake) techniques for post-disaster reconstruction planning system (PRPSS) after Sichuan Wenchuan earthquake (China) in 2008. Both 3S (geographic information system (GIS), the remote sensing (RS) and the global positioning system (GPS)) and RS (remote sensing) techniques belong to Global Information System (GIS). Overall proposed framework (PRPSS) consisted of three layers Data Source Layer (uses spatial databases technology for the management of disaster areas spatial data), Functional Service Layer (provide primary service function related system construction), and System Application Layer (Set of planning support Analysis, provide effective support for reconstruction planning). PRPSS framework has seven types of databases which contain different kinds of disaster area data like (i) Spatial Metadata Database (describe geographic data sets content, expression, spatial reference and further it is divided into basic information and auxiliary information), (ii) The Basic Geographic Database (caries thematic data and consist of planning area 1:250,000 and 1:50,000 DLG), (iii) DEM Database (contain data which is used for 3D space visualization and 3D spatial analysis), (iv) Remote Sensing Image Database (contain different- resolution remote sensing images such as pre-earthquake and post-earthquake worldview), (v) Geological Disasters Database (contain data related to the earthquake fault zone, landslide) (vi) Social Economy Database (contain data related to the pre-earthquake population of the affected area, GDP and other data) (vii) Planning Results Database (contain plan results related to reconstruction planning). The overall system of PRPSS consisted of four subsystems (i) Spatial Data Management Subsystem (mainly used to manage and maintain databases like DEM database, social economy database), (ii) Disaster Information Extraction Subsystem (Used to extract disaster information using pre-earthquake and post-earthquake remote sensing data) (iii) Planning Support Analysis Subsystem (contain various data analysis tool related to planning business, spatial measurement, spatial data inquiry, map statistical analysis and so on) (iv) 3D Spatial Analysis Subsystem (To plan reconstruction place after analysis by 3D environment).

For the implementation of this system Tsinghua University was responsible for post-disaster reconstruction planning of Aba Tibetan that's why PRPSS constructed rapidly, ESRI's ArcSDE to manage the post-disaster reconstruction planning database. Data was provided free of cost by the State Bureau of Surveying and Mapping, The China Earthquake Administration and Beijing SPOT Company, and others unite. System developed based on component-based GIS technology. 2D GIS functions were developed by ESRI ArcGIS

Engine (ArcGIS Engine 9.3 and ArcSDE 9.3 (Esri, Redlands, CA, USA)) and 3D spatial analysis function developed by Tsinghua TS3DGIS components.

PS6: Ref. [29] say's remote sensing technology is playing an important role in collecting information on social infrastructure which is very important for relief and reconstruction after any disaster. With the increasing availability of remote sensing data, various methods have been developed for damage assessment. In this paper, authors have proposed another enriched algorithm that allows us to combine GIS data (Geographic Information System which is taken by detailed survey results from Institute of Engineering Mechanics (IEM) and China Earthquake Administration (CEA)) and SAR (Synthetic- Aperture Radar) images to estimate damage assessment after any disaster. The method was applied to PALSAR images taken over both areas Wenchuan (China) and Yushu (China) affected by the earthquake in 2008 and 2010 respectively. According to this method, GIS layer is not only applied for scale restriction but also as ancillary (non-video information such as audio data) data of structure vulnerability. As a case study author has considered the city of Dujiangyan, Sichuan, China affected by the earthquake on 12 May 2008. Two images were taken by ALOSPALSAR sensor on 5 February and 22 June 2008, respectively. And ground truth building damage data provided by the Institute of Engineering Mechanics (IEM) and China Earthquake Administration (CEA) based on the detailed survey result in GIS format.

As it is mentioned this research is related to measuring the damage of building with accuracy. For the city of Dujiangyan, GIS polygon (five damage level) of a single building contain structure and occupancy information that is accessible. But in this work, five damage levels are simplified into 3 and sorted all buildings of the study area into three types (Class A, B, and C) by applying our GIS data. By measuring the construction of similar structures building damage is more accurate way to calculate the damage. Each GIS polygon contains several kinds of information like the area of a polygon, the mean structure class of the polygon, and Z1 value of all pixels. Overall in this method GIS data participated in two steps of the whole procedure (i) In SAR intensity changes detection as a scale restriction (ii) Provide ancillary data of structure vulnerability for building damage degree estimation Anyhow still there exist a lot of issues in this methodology like GIS data is not always available; secondly, the method we applied for estimation of building damage is not workable in mountain areas as well as we can't determine moderate damage through this proposed method.

PS7: In this paper [81] have evaluated the restoration situation of a damaged building in the earthquake of 2016 (Kumamoto) in which almost 3000 buildings were completely destroyed, and it was not possible to grasp damage situation information without satellite remote sensing. Furthermore, they have used object-based and pixel-based methods for extracting detail damage of the building and other dwellings as well as to improve the resolution of a satellite image. Generally, a lot of parameters are required for image segmentation and classification by the object-based method but here damage is evaluated by the optical and SAR images observed immediately after the disaster investigated and a lot of damage features of building was investigated by the field surveying. In this paper they have taken Mashiki town as a case study (severe damage in Kumamoto earthquake) for evaluation of proposed methodology, using high-resolution satellite data one year after the earthquake.

PS8: In this paper [82] have discussed the reconstruction approach after the Wenchuan County earthquake in 2008 of Sichuan Province. After three years of post-disaster reconstruction in the disaster area economy, ecology, environment has been fully restored (all this information was collected from the Department of Tourism in Shuimo town). Though achieving such a heavy construction in just three years have shocked the world, on the behalf of this amazing achievement Shami Town in Wecnhuan County was awarded as

"Global Best Example Post-Disaster Reconstruction". From studying and discussing the reconstruction model they found that the town used regional advantages, improved infrastructure, explore tourism resources, changed the economic growth mode, and focused on the protection of historical and cultural. Basically, for the whole construction, they have adopted "Partner Assistance" approach, on the other hand, Shuimo town has traditional culture and historical context which is based on two regions "Chanshou Old Street" and "Qiang city in Shuimo town" as well as it contains natural scenery. In this way tourism industry is the support strength of the national economy. In overall reconstruction, they have adopted the following strategies (i) They have repair old buildings according to their old style, size, and features so they can revive the old style and strengthen the modern technology of resisting the earthquake. (ii) Some buildings which didn't collapse in a disaster such as old houses or shops, left their appearance from outside as it is but inner side structure equipped with modern structure equipment to resist the earthquake up to 9.0 magnitude. (iii) Some buildings did not collapse but their location hampered the design of the city, so they decided to push them down and reconstruct. (iv) Keeping original structure as it is but they brought some other styles of architecture to diversify Qiang Zhai tourism product.

After all state of art post-reconstruction but still, author have few suggestion (i) Secondary disasters caused by an earthquake like debris flow, collapse, landslide have greatly hampered the need to avoid quality reconstruction. (ii) At present, the tourism benefit in shumio town has not shown itself completely. They need to have further refinement about many aspects such as traveling website construction, advertising, the quality of reception etc. (iii) Extend the tourism industrial chain and develop the economy with three-dimensional development direction such as Qiang minority culture, tourism industrial chain.

PS9: Ref. [26] describe the role of key stakeholders in project management during post-disaster reconstruction like project financing and design to start the reconstruction. Additionally, they have identified key challenges during post-disaster reconstruction like policies, construction budget/cost, labour cost, coordination, communication, and political environment. In the end, they have explained 10 critical success factors that must be taken into account during post-disaster reconstruction which are: effective institutional arrangement, coordination and collaboration, supportive laws and regulations, effective information management system, competencies of managers and team members, effective consultation with key stakeholders and target beneficiaries, effective communication mechanism, clearly defined goals and commitments by key stakeholders, effective logistic management and sufficient mobilization and disbursement of a resource.

PS10: In this paper author's [83] have proposed a mechanism for the post-earthquake reconstruction of the building to take care of the environment (like natural environment, social environment, economic and cultural environment) and fulfill basic requirements like reconstruction of sites, the planning system, local culture, building, and environment design, physiological reconstructions and establish a good social and cultural environment to improve peoples quality of life. At last, the authors have validated the approach on Wenchuan earthquake reconstruction planning.

PS11: In this paper [31] did a comparative analysis of Conventional Master Planning (CMP) practices with the Intelligent Master Planning (IMP) approach (By using a case study of a massive earthquake on 8 October 2005 in Azad Jammu and Kashmir leaving more than three millions people homeless). As most developed countries don't have any mechanism to tackle these kinds of massive disasters. So after successful relief operation government has started work of reconstruction and rehabilitation. So master plan project was assigned to the University of Engineering and Technology Lahore, it was a great

challenge because the need of the people was very urgent, and the contemporary planning process was consuming, that's why study required efficient planning groups data collection, and analysis. The new planning approach has been named as "Intelligent Master Planning for Disaster Afflicted Area' and it heavily relied on state-of-the-art remote sensing and GIS technologies, including the use of computer-based data sheets and analytical tools such as MS Excel 2003 ((Microsoft Corporation, Redmond, WA, USA)) and IBM SPSS Statistics 16.0 (IBM Corporation, Armonk, NY, USA) for statistical analysis. They have used 14 different assessment criteria (Time Saving, Effective in disaster afflicted difficult areas, Resource mobilization at the start of a project, Involvement of manpower resources, Maps updating and reproduction, Statistical and analytically choices and opportunities, Spatial data analysis, and thematic maps production, Graphics, and illustrative capabilities, Data transfer-ability, Periodic revision of plan and updating facility, Quick and rational decision-making abilities, Degree of public participation, Spatial and statistical data coverage, Conformity and adaptability with the cutting-edge technologies) on the behalf of all those criteria IMP proved more advantages then CMP. Therefore study propose the adoption of IMP as a modular approach, time-efficient, intelligent, detailed, and disaster sensitive.

PS12: In this paper authors [32] propose a generic decision support model dealing with various sectors (education, housing, and health) that could need after disaster applied through software module to automatically assign a priority value to sets of reconstruction projects in a post-disaster phase. Basically, this article covers damage areas and the priority of reconstruction projects. The objective is to support the decision-makers that are not experts in post-disaster management and that have to take complex decisions related to many parameters: evolution of the disaster effects, population needs in different vital sectors, etc. Multi-Criteria Decision Making process is basically decomposed into Modeling Phase (to construct a decision model that captures the decision-maker preferences) and Exploitation Phase(corresponding to define the priority). They have developed a tool by using Myriad (Multi-Criteria decision tool which contains two sets of criteria weight and interaction and each criteria is evaluated with the value between 0(bad) and 1(good)) which is based on post-disaster methodologies characteristics and consider only high priority sectors like housings, health, education, transportation, energy, water, food, and entertainment. The module first evaluates the relevance of each reconstruction project, and next evaluates the relevance of sets of reconstruction projects taking into account the context and the population needs. It implicitly represents synergies among projects. This approach is implemented in the Destriero project demonstrator to support the prioritization of the reconstruction project after a combination of disasters near Madrid.

PS13: In this paper authors [78] have described that natural disasters affect the built environment's infrastructure and disturb the economic sector's sustainability and welfare. This requires a disaster recovery decision support tool that capitalizes on the redevelopment opportunities to elevate societies to a more-sustainable and less-vulnerable status. As such, this paper presents an agent-based model approach that aims to meet the objectives of stakeholders while decreasing the community's economic vulnerability. Agent behavior considered three assumptions which are Agents are interdependent, Agents follow simple rules, Agents are adaptive. Proposed agent-based model represents the residents of the impacted community, the economic sector, insurance companies, and disaster recovery plans. In addition, the model presents Local Disaster Recovery Management (LDRM), State Disaster Recovery Coordinator (SDRC), and Federal Disaster Recovery Coordinator (FDRC). Accordingly, the proposed model adopts a five-step research methodology: (1) implementing a comprehensive economic vulnerability assessment tool; (2) developing the objective functions and learning algorithms of the associated stakeholders; (3) modeling the different attributes and potential strategies of the various stakeholders; (4) creating

an interdependent agent-based model that simulates the aforementioned information; and (5) interpreting and analyzing the results generated from the developed model. The model is developed and tested on the post-Katrina residential housing and economic-financial recovery in three Mississippi coastal counties. The model proposed an evolving optimal budget distribution that decreased the economic vulnerability and increased the residential and economic recovery. Ultimately, the holistic framework utilized in this study lays down the foundation for a new generation of interdisciplinary managerial decision-making support tools.

PS14: Ref. [84] proposes theoretical model for post-disaster planning using regional and local level plans. The suggested model consists of three phases which are enabling phase, reconstruction planning phase, and reconstruction implementation phase. The main focus of this proposed framework is to make effective management during post-disaster housing reconstruction.

PS15: In this paper [32] proposed a multi-criteria decision model to take a complex decision in a post-disaster situation to reconstruct the damaged area by considering several parameters like damage level in the affected area (number of damaged houses, schools, hospitals, and transportation), the interconnection between damage buildings and to prioritize reconstruction projects. They have validated this model on fictive examples but later they will do it evaluation on real data.

PS16: Ref. [85] describe the overall government reconstruction plan after a massive earthquake in Wenchuan in western China. In this reconstruction strategy's poverty of affected people is the main attribute due to this they have given priority to settle rural areas first to facilitate poor people. According to research although some resources were not used for the poor population because resources were allocated on behalf of damage assessment.

PS17: Ref. [86] have described about community participation in reconstruction planning. According to this approach "where", "why" and "how" users can be involved in the technical design process and decision making where their contribution leads to positive results and outcomes. Ref. [86] have validated this approach on four different post-disaster housing reconstruction projects: one in Colombia, one in El Salvador, and two in Turkey.

PS18: Ref. [34] describes post-disaster housing reconstruction mechanism and policy implementation in Dujiangyan central city. In this model, multiple entities (like market and social institutions) played a vital role in the economic and early completion of buildings reconstruction. But this paper is just elaborating on conventional methods not taking into account cutting-edge technologies to handle the post-disaster situation.

PS19: Ref. [87] describe socio-economic and spatial polarisation framework which is used to recover damaged houses including reconstruction policy which has been defined after Great Hanshin Earthquake in Japan. In this framework, two-tier policy is introduced one is self-help group like people can reconstruct their own houses at market price and the second one is public housing or residential welfare housing directly provided to poor and needy people after reconstruction.

PS20: Ref. [88] present social capital role in post-disaster rehabilitation and reconstruction. According to this model people actively participate and deeply involved in reconstruction programs to make a successful and speedy recovery. Additionally, in this reconstruction model, people have the highest satisfaction rate as well rehabilitation speed. This model is successfully validated in Kobe (Japan) and Gujarat (India) earthquakes.

PS21: Ref. [89] proposed a framework for managing resources during post-disaster situations including stakeholders need, legislation and policy for reconstruction, the capacity of the construction industry to rebuild the buildings, enhance the capacity of a transportation network, and incorporating environmental considerations to reconstruct damaged infrastructure and buildings. According to authors [89] main motivation behind

this framework is the post-Wenchuan earthquake reconstruction process because they have faced a bottleneck to manage resources.

PS22: Ref. [90] proposes a framework for strategic planning to make temporary houses in a post-disaster situation by considering physical, social, economic, and organizational aspects. For analysis of this framework, six case studies have been considered for temporary housing which is Greece in 1986, Turkey and Colombia in 1999, Japan in 1995, Mexico in 1985, and Italy in 1976.

PS23: Ref. [91] describes owner-driven reconstruction approach after 2005 Kashmir and 2013 Awaran earthquakes in Pakistan. This approach is based on private housing and become very successful for safe housing and to complete reconstruction in time. But still, there was a delay in some buildings because of participation of different agencies and took time in decision-making and coordination about the reconstruction process.

PS24: Ref. [92] proposed methodology by using Unmanned Aerial Vehicles (UAV) for 3D modeling of damage or collapsed buildings for reconstruction. In this method, they have used commercial and open-source tools for 3D modeling and computational time is very fast depending upon the number of damaged infrastructure.

PS25: Ref. [64] have used the entropy method for posy-disaster decision making in the proposed framework to define prioritization strategy about damaged bridges or buildings on behalf of available data. They applied the proposed framework to Nisqually earthquake.

PS26: According to [93] post-disaster reconstruction process after 5.12 Wenchuan earthquake was really difficult, complex, and time taking. In their research, they took public opinions during the reconstruction process to consider their social benefits.

PS27: Ref. [94] introduced a framework where they have proposed the use of collaborative photogrammetry to involve disaster-affected people during the planning and reconstruction process. They have validated this approach in sample small data set by a group of citizen-scientists after the 2016 Central Italy earthquake.

PS28: Ref. [95] have proposed an optimization model by using Bean Optimization Algorithm (BOA) based on fuzzy preference relation. According to this model in a post-disaster situation reconstruction of public services will get priority. The proposed model is validated post-earthquake reconstruction in China.

PS29: Ref. [80] proposed framework called post-disaster reconstruction planning supporting system (PRPSS) to reconstruct damaged buildings supporting system by using 3S technique planning for information extraction of the damaged area, assessment of damage cost, reconstruction planning, and so on.

PS30: Ref. [96] proposed an innovative polynomial-time online algorithm for road reconstruction in a post-disaster situation because roads play a vital role to evacuate people and reconstructing damaged buildings. Additionally, they [96] have checked the performance of the proposed algorithm with others on Istanbul road network and show its performance is much superior to others.

PS31: Ref. [97] have proposed reinforcement measures and suggestions during post-disaster reconstruction after the M8.1 earthquake happened near Pokhara, Nepal. They have used finite element software for reconstruction modeling. Additionally, they have considered transmission path of structure, stiffness, consistency of structure, and site selection.

PS32: Ref. [98] proposed a BIM-based post-disaster reconstruction framework called Virtual Permitting Framework (VPF) to improve the quality and to recover damage assets. VPF consisted of five components which are: (i) Buildings inspection and damage assessment (ii) classification of damages into different groups (iii) database of damaged buildings (storage) (iv) reconstruction type with local state regulation (v) virtual permitting

(vi) decision about approval/rejection of construction unit. The proposed framework was successfully validated on the city of Gainesville data set.

PS33: Ref. [99] present a methodical framework for effective management and for reconstruction of buildings in post-disaster situation. Key attributes in the proposed framework are effective management during reconstruction, consideration of affected communities, and involvement of all key stakeholders to take input for the reconstruction plan.

PS34: Ref. [83] present an approach for residential environment planning by considering reconstruction site, planning of the system, maintaining local culture, building design, psychological reconstruction, and keeping intact social and cultural environment for establishing a good quality of life of local residents.

PS35: Ref. [100] present an approach that is based on a collection of information like the design before reconstruction, required stiffness of walls which is increased by using cement, technical regulation for reconstruction are considered.

PS36: Ref. [82] have described the "hematopoietic type" post-disaster reconstruction model which is used in Wenchuan County in Longmen mountain of Sichuan province. In this model, key attributes are infrastructure improvement, education, environment. economic growth, and protection of historical and cultural aspects.

PS37: Ref. [101] present CM-agent model approach is used to solve construction management problem in post-disaster situation. Additionally, this model has the capability to work on "sound and rapid" (without any influence of other stakeholders) construction requirements, can solve public project management problems, and to make ensure the execution of public projects successfully in post-disaster reconstruction.

PS38: The approach proposed by [102] for post-disaster reconstruction in Lueyang county based on analyses of rebuilding houses layout and reconstructing low-cost and affordable houses on a priority basis.

PS39: Ref. [103] present an approach that gives the accurate design of rural housing reconstruction with respect to a lifestyle of residential users. Additionally, housing reconstruction becomes a source of economic revelry including ecological and energy-saving technique for making an economical residence.

PS40: Ref. [30] proposed an approach to speed up reconstruction in at Sanriku coast areas that were affected by Great East Japan Earthquake. They have followed two policies in this model, first one is 3D model to visualize reconstruction plans and the second one is to train the local people that can build 3D models for reconstruction plans by considering all basic entities s like roads, bridges, railways, and buildings.

PS41: Ref. [81] have proposed an approach to reconstruct damaged buildings after one year of 2016 Kumamoto earthquake after gathering information with the help of high-resolution satellite data of Worldview-3. They have used Gray-Level Co-occurrence Matrix (GLCM) for calculation of texture index, and analysis shows there is too much difference with respect to building damage level and recovery situation.

PS42: Ref. [79] reviews post-disaster management strategies for the analysis and management by using a top-down approach after 2008 Wenchuan Earthquake. For this purpose, they have used two different plans which are "Overall Plan for Post-Wenchuan Earthquake Recovery" and "Reconstruction and the City/I-own System Plan for Post-Wenchuan Earthquake Recovery and Reconstruction" by considering different strategies to make reconstruction plan on behalf of available resources and funds.

PS43: Ref. [104] proposed an approach for reconstruction of roads including estimation of repairing cost on behalf of total damage area in a post-disaster situation. In this approach, they also consider bridges, tunnels, and pavements as a part of roads reconstruction. Additionally, they [104] also describe rehabilitation duration for reconstruction with cost.

PS44: Ref. [105] proposed framework for post-earthquake reconstruction which claims proper institutional arrangements can make reconstruction and recovery process fast. They justified their claim with Weizhou Town reconstruction which is consisted of both long-term and short-term reconstruction of a public building with public facilities. Additionally, this approach is a much better top-down approach and rapid reconstruction process.

PS45: Ref. [106] proposed a mechanism for post-disaster reconstruction based on index system to restore the living and to reconstruct damaged buildings and other facilities. They [106] have used the quintile grading method to improve the accuracy of the model by using DIDF method. Validation of this approach is done by empirical analysis of China's 31 provinces.

PS46: Ref. [9] proposed a post-disaster recovery model to define the priority of reconstruction plans of damage projects/facilities on behalf of socioeconomic factors of affected communities with minimum time and cost. They have used AHP (Analytical Hierarchy Process) for decision making, and an optimization model for resource allocation. For evaluation, they have applied this model on counties (called parishes) data. In [9] they didn't consider damage physical dependencies among reconstruction units and their priority to reconstruct but our model explicitly considering.

PS47: Ref. [65] proposed a model for the reconstruction of roads and removing debris in a post-disaster situation. They have used two-stage methodology Steiner Tree Model (to check roads that need to be reconstructed first) and Scheduling Algorithm (Scheduling for restoring roads and crews assignment). For verification, they applied this technique on 1994 Northridge California Earthquake data.

PS48: Ref. [107] proposed an innovative approach for the dynamic evolution of disasters to assess post-damage facilities to help planners for making the right decision on behalf of available information. They have used web-based technologies for collection and analysis of damage territory data. For validation of this approach, they have used Tacloban city data in the Philippines which was affected by Super Typhoon Haiyan in November 2013.

PS49: Ref. [108] present an approach to prioritize damage facilities on behalf of social and economic benefits including resource allocation for reconstruction in a post-disaster situation. They have validated this model with the help of different tools like Federal Emergency Management Agency and GIS.

PS50: Ref. [109] proposed a framework for post-disaster reconstruction called "Building Back Better" which considers five different attributes before starting reconstruction of any damaged unit. Those attributes are financial/economic, social, organizational, and environmental.

PS51: Ref. [110] proposed an approach for reconstruction planning which is consisted of four steps: (i) use agile approach for planning and implementation (ii) specific time for gaining community trust (iii) usage of technologies, expert labor and quality material for hazard-safety housing (iv) capacity building of community until reconstruction work complete. Authors have validated this approach [110] on four different case studies.

PS52: Ref. [66] proposed an approach for post-earthquake reconstruction planning by using DDQN reinforcement learning algorithm. In this approach, they have considered all compulsory attributes like social benefits of affected people, political priority, time, and cost to reconstruct damaged buildings and roads. They have validated the approach by applying it to L'Aquila city which was affected by the earthquake in 2009.

PS53: Ref. [67] proposed an approach in which they presents a robotic crane system using Proximal Policy Optimization (PPO), a reinforcement learning algorithm, to automate construction material transport after earthquakes. Two models are trained—one with obstacle awareness and one without—and tested in simulated tasks. The obstacle-aware

model outperforms the other in safety, efficiency, and path planning. While effective in simulations, further validation in real-world scenarios and comparison with other RL methods are needed.

PS54: Ref. [111] proposed an approach which explores how suburban communities can recover from floods more effectively, focusing on Kogi State, Nigeria. By comparing cases from India and France, it identifies poor land use, weak building codes, and limited planning as major challenges. The authors highlight practical solutions such as elevated housing, better drainage systems, and sustainable land-use practices. They stress that rebuilding after floods should not only restore homes but also improve resilience and sustainability. The paper concludes that integrating disaster risk management and sustainable design can help achieve safer, more resilient communities.

PS55: Ref. [68] proposed study examines how well post-disaster recovery and long-term development were coordinated after the 2008 Wenchuan earthquake in China. Using spatial and statistical analysis, the authors assess changes in the social, economic, and ecological systems from 2009 to 2018. Results show that while recovery has improved overall, progress remains uneven across regions. Some counties advanced quickly, while others lagged behind due to resource and policy differences. The paper introduces a predictive model to forecast recovery effectiveness and guide future reconstruction efforts. It highlights the importance of balanced regional development, sustainable planning, and government support to maintain long-term resilience in disaster-affected areas.

Appendix B

Table A1. Primary studies distribution according to publication resources.

Pub. Venue	Type	Res. Topic	No	Ref
Computer-Aided civil and infrastructure engineering	Journal	Reconstruction Modelling by using Software	1	PS1 [35]
SIGSPATIAL International Conference on Advances in Geographic	Conference	Entropy method	1	PS25 [64]
International Conference on Research Challenges in Information Science	Conference	Reinforcement Learning	1	PS52 [66]
Disasters, Crisis, Hazards, Emergencies and Sustainable Development	Journal	Management Experts	1	PS14 [84]
International Conference on Mechanic Automation and Control Engineering	Conference	Civil Engineer	1	PS35 [100]
International journal of disaster risk reduction	Journal	Data Sciences	1	PS48 [107]
Journal of Infrastructure Systems	Journal	Agent Technology	1	PS2 [78]
International Journal of Disaster Risk Science	Journal	Data Analytics	1	PS3 [79]
International Conference on Network-Based Information Systems (NBiS)	Conference	Computer Aided Design	1	PS4 [30]
IEEE International Geoscience and Remote Sensing Symposium	Symposium	Global Information System	1	PS5 [80]
International Geoscience and Remote Sensing Symposium	Symposium	Geographic Information System	1	PS6 [29]

Table A1. *Cont.*

Pub. Venue	Type	Res. Topic	No	Ref
IEEE International Geo science and Remote Sensing Symposium	Symposium	Pixel-based method	1	PS7 [81]
International Conference on Management Science and Engineering	Conference	Social Sciences	1	PS8 [82]
International Conference on Information Systems for Crisis Response and Management	Conference	Social Sciences Discrete Analysis Social Sciences	3	PS10 [83], PS45 [106], PS34 [83]
International Conference on Advances in Space Technologies	Conference	Intelligent Master Planning	1	PS11 [31]
International Conference on Information and Communication Technologies for Disaster Management	Conference	Myriad Experts	1	PS12 [32]
International Journal of Disaster Risk Reduction	Journal	Data Sciences	1	PS32 [98]
International CIPA Symposium	Symposium	Photogrammetry	1	PS27 [94]
Nepal Engineer's Association Technical Journal	Journal	Social Sciences	1	PS23 [91]
International Conference on Network-Based Information Systems	Conference	Modelling by using software	1	PS40 [30]
IEEE International Geo science and Remote Sensing Symposium	Symposium	Gray-Level Co-occurrence Matrix	1	PS41 [81]
Practical Action Publishing	Book Chapter	Social and Economic Experts	1	PS50 [109]
Applied Mechanics and Materials	Journal	Social Sciences	1	PS26 [93]
Procedia engineering	Journal	Management Experts	1	PS33 [99]
International Conference on Management Science and Engineering	Conference	Data Sciences	1	PS36 [82]
Transportation Research Part B: Methodological	Journal	Transportation Research	1	PS30 [96]
Structures	Journal	Reconstruction Modelling by using Software	1	PS31 [97]
International Journal of Disaster Risk Science	Journal	Social and Economic Experts	1	PS42 [79]
International Journal of Transportation Engineering	Journal	Social and Economic Experts	1	PS43 [104]
Journal of Management in Engineering	Journal	Analytical Hierarchy Process	1	PS46 [9]
Applied Mechanics and Materials	Journal	Social Sciences	1	PS9 [26]
Journal of infrastructure systems	Journal	Agent Technology	1	PS13 [78]
Applied Geography	Journal	Social Sciences	1	PS16 [85]
Habitat international	Journal	Social Sciences, Social and Economic Experts	2	PS17 [86], PS44 [105]
Progress in Disaster Science	Journal	Social and Economic Experts	1	PS18 [34] describes
Housing Studies	Journal	Social and Economic Experts	1	PS19 [87]
International Journal of Mass Emergencies and Disasters	Journal	Social and Economic Experts	1	PS20 [88]
Disasters	Journal	Management experts, Social and Economic Experts	2	PS21 [89], PS22 [90]
Multimedia tools and applications	Journal	Unmanned Aerial Vehicles	1	PS24 [92]
International Conference on Computer Sciences and Convergence Information Technology	Conference	Data Analytics	1	PS38 [102]

Table A1. *Cont.*

Pub. Venue	Type	Res. Topic	No	Ref
International Conference on Electric Technology and Civil Engineering	Conference	Social and Economic Experts	1	PS39 [103]
Operations Research	Journal	Steiner Tree Model and Scheduling Algorithm	1	PS47 [65]
International Conference on Logistics Systems and Intelligent Management	Conference	Agent Technology	1	PS37 [101]
International Journal of Project Management	Journal	Data Sciences	1	PS51 [110]
IEEE Youth conference on information, computing and telecommunications	Conference	Fuzzy Relations	1	PS28 [95]
IEEE International Geo science and Remote Sensing Symposium	Symposium	3S Planning Technique	1	PS29 [80]
International Conference on Information and Communication Technologies for Disaster Management	Conference	Decision Model	1	PS15 [32]
Computing in Civil Engineering 2019: Smart Cities, Sustainability, and Resilience	Conference	Modelling by using software	1	PS49 [108]
Pacific Conference on Earthquake Engineering 2023	Conference	Data Science	1	PS53 [67]
American Journal of Environment 1594 and Climate (AJEC) 2025	Journal	Decision Model	1	PS54 [111]
Land 2025	Journal	Data Science	1	PS55 [68]

References

1. Yi, H.; Yang, J. Research trends of post disaster reconstruction: The past and the future. *Habitat Int.* **2014**, *42*, 21–29. [CrossRef]
2. Guha-Sapir, D.; Vos, F.; Below, R.; Ponserre, S. *Annual Disaster Statistical Review 2011: The Numbers and Trends*; Technical Report; Centre for Research on the Epidemiology of Disasters (CRED), Université Catholique de Louvain: Brussels, Belgium, 2012.
3. Guha-Sapir, D.; Hargitt, D.; Hoyois, P. *Thirty Years of Natural Disasters 1974–2003: The Numbers*; Presses Universitaires de Louvain: Louvain-la-Neuve, Belgium, 2004.
4. United Nations Office for Disaster Risk Reduction (UNISDR); World Meteorological Organization (WMO). *Disaster Risk and Resilience: Thematic Think Piece*; Technical Report; UN System Task Team on the Post-2015 UN Development Agenda: New York, NY, USA, 2012.
5. Berlemann, M.; Steinhardt, M.F. Climate change, natural disasters, and migration—a survey of the empirical evidence. *CESifo Econ. Stud.* **2017**, *63*, 353–385. [CrossRef]
6. Centre for Research on the Epidemiology of Disasters (CRED); United Nations Office for 1320 Disaster Risk Reduction (UNDRR). *Human cost of Disasters: An Overview of the Last 20 Years 2000–2019*; Technical Report; CRED: Brussels, Belgium; UNDRR: Geneva, Switzerland, 2020.
7. Chaudhary, M.T.; Piracha, A. Natural disasters—Origins, impacts, management. *Encyclopedia* **2021**, *1*, 1101–1131. [CrossRef]
8. United Nations Office for Disaster Risk Reduction (UNDRR). The Human Cost of Disasters: An Overview of the Last 20 Years. 2021. Center for Research on the Epidemiology of Disasters Report. Available online: https://www.undrr.org/media/106862 (accessed on 8 November 2025).
9. Ghannad, P.; Lee, Y.C.; Friedland, C.J.; Choi, J.O.; Yang, E. Multiobjective optimization of postdisaster reconstruction processes for ensuring long-term socioeconomic benefits. *J. Manag. Eng.* **2020**, *36*, 04020038. [CrossRef]
10. Petterson, J.S.; Stanley, L.D.; Glazier, E.; Philipp, J. A preliminary assessment of social and economic impacts associated with Hurricane Katrina. *Am. Anthropol.* **2006**, *108*, 643–670. [CrossRef]
11. Chang, S.E.; Nojima, N. Measuring post-disaster transportation system performance: The 1995 Kobe earthquake in comparative perspective. *Transp. Res. Part A Policy Pract.* **2001**, *35*, 475–494. [CrossRef]
12. Shah, A.W.; Wang, K.; Siddique, J.A.; Hussain, J.; Li, W. Explainable machine learning for predicting tensile properties of aluminum alloys in the laser powder bed fusion process. *Mater. Sci. Eng. A* **2025**, *939*, 148482. [CrossRef]

13. Karlaftis, M.G.; Kepaptsoglou, K.L.; Lambropoulos, S. Fund allocation for transportation network recovery following natural disasters. *J. Urban Plan. Dev.* **2007**, *133*, 82–89. [CrossRef]
14. Contreras, D.; Blaschke, T.; Kienberger, S.; Zeil, P. Myths and realities about the recovery of L'Aquila after the earthquake. *Int. J. Disaster Risk Reduct.* **2014**, *8*, 125–142. [CrossRef]
15. United Nations Development Programme (UNDP); Bureau for Crisis Prevention and Recovery (BCPR); Cluster Working Group on Early Recovery (CWGER). *UNDP Policy on Early Recovery*; Policy Report; United Nations Development Programme (UNDP): New York, NY, USA 2008.
16. Alexander, D. From rubble to monument revisited: Modernised perspectives on recovery from disaster. In Proceedings of the Post-Disaster Reconstruction: Meeting Stakeholder Interests, Florence, Italy, 17–19 May 2006 ; Firenze University Press: Florence, Italy, 2006.
17. Mudassir, G. Social-based physical reconstruction planning in case of natural disaster: A machine learning approach. In Proceedings of the Research Challenges in Information Science 14th International Conference, RCIS 2020, Limassol, Cyprus, 23–25 September 2020; Springer: Berlin/Heidelberg, Germany, 2020; pp. 604–612.
18. Lindell, M.K. Recovery and reconstruction after disaster. *Encycl. Nat. Hazards* **2013**, *8*, 12–824.
19. Jha, A.K. *Safer Homes, Stronger Communities: A Handbook for Reconstructing After Natural Disasters*; World Bank Publications: Washington, DC, USA, 2010.
20. El-Masri, S.; Tipple, G. Natural disaster, mitigation and sustainability: The case of developing countries. *Int. Plan. Stud.* **2002**, *7*, 157–175. [CrossRef]
21. Miller, D.S.; Rivera, J.D. *Community Disaster Recovery and Resiliency: Exploring Global Opportunities and Challenges*; CRC Press: Boca Raton, FL, USA, 2010.
22. Nagamatsu, S.; Hayashi, H. Economic recovery scenario planning for a Tokyo inland earthquake. *J. Disaster Res.* **2012**, *7*, 203–214. [CrossRef]
23. Olshansky, R.B.; Johnson, L.A.; Topping, K.C. Rebuilding communities following disaster: Lessons from Kobe and Los Angeles. *Built Environ.* **2006**, *32*, 354–374. [CrossRef]
24. Simunovich, D.V. The quiet of dissolution: Post-disaster redevelopment and status-preserving compensation. *Seton Hall L. Rev.* **2008**, *38*, 331. [CrossRef]
25. Mudassir, G.; Di Marco, A.; Pasquini, L. City Reconstruction Planner with Social Perspective. In Proceedings of the 7th Italian Conference on ICT for SmartCities and Communities, Virtual, 22–24 September 2021.
26. Hidayat, B.; Egbu, C. A literature review of the role of project management in post-disaster reconstruction. In Proceedings of the Procs 26th Annual ARCOM Conference, Leeds, UK, 6–8 September 2010; pp. 1269–1278.
27. Mfon, I.; Olurotimi, O. Post-Disaster Reconstruction: Discussing Strategies and Approaches for Rebuilding and Designing Resilient Communities after Natural or Human- Made Disasters. *Int. J. Res. Publ. Rev.* **2023**, *4*, 945–952.
28. Fan, X.; Zhang, X.; Wang, X.; Yu, X. A Deep Reinforcement Learning Model for Resilient Road Network Recovery Under Earthquake or Flooding Hazards. *J. Infrastruct. Syst.* **2023**, *29*, 04023072. [CrossRef]
29. An, L.; Zhang, J.; Gong, L.; Li, Q. Integration of SAR image and vulnerability data for building damage degree estimation. In Proceedings of the 2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Beijing, China, 10–15 July 2016; pp. 4263–4266. [CrossRef]
30. Doi, A.; Oshida, K.; Takashima, Y.; Sakakibara, K.; Itoh, T. 3D modeling of reconstruction plan at sanriku coast for great east japan earthquake: Visualization of the reconstruction plan for effective information sharing. In Proceedings of the 2016 19th International Conference on Network-Based Information Systems (NBiS), Ostrava, Czech Republic, 7–9 September 2016; IEEE: Piscataway, NJ, USA, 2016; pp. 397–400.
31. Mayo, S.M.; Zaidi, S.S.; Hussain, M. Assessing Potentials of RS and GIS based Intelligent Master Planning Approach against Conventional Master Planning Practices for Disaster Afflicted Difficult Areas: A Case Study of Bagh Town, Azad Jammu and Kashmir. In Proceedings of the 2006 International Conference on Advances in Space Technologies, Islamabad, Pakistan, 2–3 September 2006; pp. 108–112. [CrossRef]
32. Goujon, B.; Labreuche, C. Use of a multi-criteria decision support tool to prioritize reconstruction projects in a post-disaster phase. In Proceedings of the 2015 2nd International Conference on Information and Communication Technologies for Disaster Management (ICT-DM), Rennes, France, 30 November–2 December 2015; pp. 200–206. [CrossRef]
33. Labreuche, C.; Le Huédé, F. MIRIAD: A tool suite for MCDA. In Proceedings of the EUSFLAT Conference, 2005, Barcelona, Spain, 7–9 September 2005; pp. 204–209.
34. Li, Q.; Umaier, K.; Koide, O. Research on post-Wenchuan earthquake recovery and reconstruction implementation: A case study of housing reconstruction of Dujiangyan city. *Prog. Disaster Sci.* **2019**, *4*, 100041. [CrossRef]
35. Opricovic, S.; Tzeng, G.H. Multicriteria Planning of Post-Earthquake Sustainable Reconstruction. *Comput. Civ. Infrastruct. Eng.* **2002**, *17*, 211–220. [CrossRef]

36. Mudassir, G.; Howard, E.E.; Pasquini, L.; Arbib, C.; Clementini, E.; Di Marco, A.; Stilo, G. Toward effective response to natural disasters: A data science approach. *IEEE Access* **2021**, *9*, 167827–167844. [CrossRef]
37. Petersen, K.; Vakkalanka, S.; Kuzniarz, L. Guidelines for conducting systematic mapping studies in software engineering: An update. *Inf. Softw. Technol.* **2015**, *64*, 1–18. [CrossRef]
38. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; The PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Int. J. Surg.* **2010**, *8*, 336–341. [CrossRef] [PubMed]
39. Petticrew, M.; Roberts, H. *Systematic Reviews in the Social Sciences: A Practical Guide*; John Wiley & Sons: Hoboken, NJ, USA, 2008.
40. Kastrati, Z.; Dalipi, F.; Imran, A.S.; Pireva Nuci, K.; Wani, M.A. Sentiment Analysis of Students' Feedback with NLP and Deep Learning: A Systematic Mapping Study. *Appl. Sci.* **2021**, *11*, 3986. [CrossRef]
41. Zhang, H.; Babar, M.A.; Tell, P. Identifying relevant studies in software engineering. *Inf. Softw. Technol.* **2011**, *53*, 625–637. [CrossRef]
42. Birkle, C.; Pendlebury, D.A.; Schnell, J.; Adams, J. Web of Science as a data source for research on scientific and scholarly activity. *Quant. Sci. Stud.* **2020**, *1*, 363–376. [CrossRef]
43. Burnham, J.F. Scopus database: A review. *Biomed. Digit. Libr.* **2006**, *3*, 1. [CrossRef]
44. Wohlin, C. Guidelines for snowballing in systematic literature studies and a replication in software engineering. In Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering, London, UK, 13–14 May 2014; pp. 1–10.
45. Fleiss, J.L.; Levin, B.; Paik, M.C. *Statistical Methods for Rates and Proportions*; John Wiley & Sons: Hoboken, NJ, USA, 2013.
46. Adams, R.J.; Smart, P.; Huff, A.S. Shades of grey: Guidelines for working with the grey literature in systematic reviews for management and organizational studies. *Int. J. Manag. Rev.* **2017**, *19*, 432–454. [CrossRef]
47. Yasin, A.; Hasnain, M.I. On the quality of Grey Literature and Its Use in Information Synthesis During Systematic Literature Reviews. Master's Thesis, Blekinge Institute of Technology, School of Computing, Karlskrona, Sweden, 2012.
48. Kitchenham, B.; Brereton, O.P.; Budgen, D.; Turner, M.; Bailey, J.; Linkman, S. Systematic literature reviews in software engineering–a systematic literature review. *Inf. Softw. Technol.* **2009**, *51*, 7–15. [CrossRef]
49. Tyndall, J. *The AACODS Checklist Is Designed to Enable Evaluation and Critical Appraisal of Grey Literature* ; Flinders University: Adelaide, Australia, 2010.
50. Garousi, V.; Felderer, M.; Mäntylä, M.V. Guidelines for including grey literature and conducting multivocal literature reviews in software engineering. *Inf. Softw. Technol.* **2019**, *106*, 101–121. [CrossRef]
51. Host, M.; Runeson, P. Checklists for software engineering case study research. In Proceedings of the First International Symposium on Empirical Software Engineering and Measurement (ESEM 2007), Madrid, Spain, 20–21 September 2007; IEEE: Piscataway, NJ, USA, 2007; pp. 479–481.
52. Brereton, P.; Kitchenham, B.A.; Budgen, D.; Turner, M.; Khalil, M. Lessons from applying the systematic literature review process within the software engineering domain. *J. Syst. Softw.* **2007**, *80*, 571–583. [CrossRef]
53. Petersen, K.; Ali, N.B. Identifying strategies for study selection in systematic reviews and maps. In Proceedings of the 2011 International Symposium on Empirical Software Engineering and Measurement, Banff, AB, Canada, 22–23 September 2011; IEEE: Piscataway, NJ, USA, 2011; pp. 351–354.
54. Shah, A.W.; Siddique, J.A.; Daraz, U.; Kayani, S.H.; Hussain, J.; Mudassir, G.; Wang, K.; Li, W. Data-driven design of Al–Fe alloys for laser powder bed fusion to enhance recycled aluminum utilization. *J. Alloys Compd.* **2025**, *1039*, 183278. [CrossRef]
55. Kitchenham, B.; Charters, S. *Guidelines for Performing Systematic Literature Reviews in Software Engineering*; Technical Report; Keele University: Keele, UK; University of Durham: Durham, UK, 2007.
56. Cruzes, D.S.; Dybå, T. Synthesizing evidence in software engineering research. In Proceedings of the 2010 ACM-IEEE International Symposium on Empirical Software Engineering and Measurement, Bolzano-Bozen, Italy, 16–17 September 2010; pp. 1–10.
57. Wieringa, R.; Maiden, N.; Mead, N.; Rolland, C. Requirements engineering paper classification and evaluation criteria: A proposal and a discussion. *Requir. Eng.* **2006**, *11*, 102–107. [CrossRef]
58. Durelli, V.H.; Durelli, R.S.; Borges, S.S.; Endo, A.T.; Eler, M.M.; Dias, D.R.; Guimarães, M.P. Machine learning applied to software testing: A systematic mapping study. *IEEE Trans. Reliab.* **2019**, *68*, 1189–1212. [CrossRef]
59. Eichengreen, B. The real exchange rate and economic growth. *Soc. Econ. Stud.* **2007**, *56*, 7–20.
60. Provost, F.; Fawcett, T. Data science and its relationship to big data and data-driven decision making. *Big Data* **2013**, *1*, 51–59. [CrossRef]
61. Reich, Y. Machine learning techniques for civil engineering problems. *Comput.-Aided Civ. Infrastruct. Eng.* **1997**, *12*, 295–310. [CrossRef]
62. Saleem, O.; Latif, S. Information extraction from research papers by data integration and data validation from multiple header extraction sources. In Proceedings of the World Congress on Engineering and Computer Science, San Francisco, CA, USA, 24–26 October 2012; Volume 1, pp. 177–180.

63. Mudassir, G. Reinforcement Learning and Social Based Approach to Post-Disaster Reconstruction Planning. Ph.D. Thesis, Università degli Studi dell'Aquila, L'Aquila, Italy, 2022.
64. Tavakkol, S.; To, H.; Kim, S.H.; Lynett, P.; Shahabi, C. An Entropy-based Framework for Efficient Post-disaster Assessment Based on Crowdsourced Data. In Proceedings of the EM-GIS '16: Second ACM SIGSPATIAL International Workshop on the Use of GIS in Emergency Management, Burlingame, CA, USA, 31 October 2016; Association for Computing Machinery: New York, NY, USA, 2016; pp. 13:1–13:8. [CrossRef]
65. Rodriguez Coca, D.M. Methodology for Planning Reconstruction Activities After a Disaster Considering Interdependencies and Priorities. Ph.D. Thesis, Oklahoma State University, Stillwater, OK, USA, 2020.
66. Mudassir, G.; Di Marco, A. Social-based City Reconstruction Planning in case of natural disasters: A Reinforcement Learning Approach. In Proceedings of the 2021 IEEE 45th Annual Computers, Software, and Applications Conference (COMPSAC), Madrid, Spain, 12–16 July 2021; IEEE: Piscataway, NJ, USA, 2021; pp. 493–503.
67. Xiao, Y.; Yang, T.; Pan, X.; Xie, F.; Chen, Z. A reinforcement learning based construction material supply strategy using robotic crane and computer vision for building reconstruction after an earthquake. In Proceedings of the Canadian Conference—Pacific Conference on Earthquake Engineering 2023, Vancouver, BC, Canada, 25–30 June 2023.
68. Zhao, L.; Zhang, C.; Zhou, X. Post-Disaster Recovery Effectiveness: Assessment and Prediction of Coordinated Development in the Wenchuan Earthquake-Stricken Areas. *Land* **2025**, *14*, 487. [CrossRef]
69. Mudassir, G.; Marco, A.D.; d'Aloisio, G. REPAIR approach for social-based city reconstruction planning in case of natural disasters. *Int. J. Data Sci. Anal.* **2025**, *20*, 7147–7165. [CrossRef]
70. Petersen, K.; Gencel, C. Worldviews, research methods, and their relationship to validity in empirical software engineering research. In Proceedings of the 2013 Joint Conference of the 23rd International Workshop on Software Measurement and the 8th International Conference on Software Process and Product Measurement, Ankara, Turkey, 23–26 October 2013; IEEE: Piscataway, NJ, USA, 2013; pp. 81–89.
71. Campbell, D.T. Experimental and quasi-experimental designs for research on teaching. In *Handbook of Research on Teaching*; Wittrock, M., Ed.; Macmillan: New York, NY, USA, 1963; Volume 5, pp. 171–246.
72. Wohlin, C.; Runeson, P.; Höst, M.; Ohlsson, M.C.; Regnell, B.; Wesslén, A. *Experimentation in Software Engineering*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012.
73. Wohlin, C.; Runeson, P.; Neto, P.A.d.M.S.; Engström, E.; do Carmo Machado, I.; De Almeida, E.S. On the reliability of mapping studies in software engineering. *J. Syst. Softw.* **2013**, *86*, 2594–2610. [CrossRef]
74. Song, M.; Liu, J.; Xia, D.; Yao, H.; Tian, G.; Chen, X.; Liu, Y.; Jiang, Y.; Li, Z. Assessment of intraoperative use of indocyanine green fluorescence imaging on the incidence of anastomotic leakage after rectal cancer surgery: A PRISMA-compliant systematic review and meta-analysis. *Tech. Coloproctology* **2021**, *25*, 49–58. [CrossRef] [PubMed]
75. Jalali, S.; Wohlin, C. Systematic literature studies: Database searches vs. backward snowballing. In Proceedings of the 2012 ACM-IEEE International Symposium on Empirical Software Engineering and Measurement, Lund, Sweden, 19–20 September 2012; IEEE: Piscataway, NJ, USA, 2012; pp. 29–38.
76. Kitchenham, B.A.; Budgen, D.; Brereton, P. *Evidence-Based Software Engineering and Systematic Reviews*; CRC Press: Boca Raton, FL, USA, 2015; Volume 4.
77. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef]
78. Eid, M.S.; El-Adaway, I.H. Decision-making framework for holistic sustainable disaster recovery: Agent-based approach for decreasing vulnerabilities of the associated communities. *J. Infrastruct. Syst.* **2018**, *24*. . [CrossRef]
79. Ge, Y.; Gu, Y.; Deng, W. Evaluating china's national post-disaster plans: The 2008 Wenchuan Earthquake's recovery and reconstruction planning. *Int. J. Disaster Risk Sci.* **2010**, *1*, 17–27.
80. Zhou, W.; Mao, F.; Liu, Z.E.; Li, Q.; Fu, Q. Research and application of planning support system based on 3S technique for post-disaster reconstruction after Wenchuan Earthquake in China. In Proceedings of the 2009 IEEE International Geoscience and Remote Sensing Symposium, Cape Town, South Africa, 12–17 July 2009; Volume 2, pp. II–666–II–669. [CrossRef]
81. Sonobe, M.; Hashiba, H. Characteristics of the Distribution of Textures in the Reconstruction of Damaged Buildings in the Kumamoto Earthquake. In Proceedings of the IGARSS 2018—2018 IEEE International Geoscience and Remote Sensing Symposium, Valencia, Spain, 22–27 July 2018; pp. 7289–7292. [CrossRef]
82. Pan, A.; Hu, L.H.; Qin, J.X. Research on model of post-disaster reconstruction in small towns of Wenchuan, China—A Case of Shuimo Town in Wenchuan County. In Proceedings of the 2012 International Conference on Management Science Engineering 19th Annual Conference Proceedings, Dallas, TX, USA, 20–22 September 2012; pp. 1853–1858. [CrossRef]
83. Li, Z.; Liu, F. Research on residential environment planning and design in the post-earthquake reconstruction. In Proceedings of the International Conference on Information Systems for Crisis Response and Management (ISCRAM), Harbin, China, 25–27 November 2011; pp. 534–537. [CrossRef]

84. Bilau, A.A.; Witt, E.; Lill, I. A framework for managing post-disaster housing reconstruction. *Procedia Econ. Financ.* **2015**, *21*, 313–320. [CrossRef]
85. Dunford, M.; Li, L. Earthquake reconstruction in Wenchuan: Assessing the state overall plan and addressing the 'forgotten phase'. *Appl. Geogr.* **2011**, *31*, 998–1009. [CrossRef]
86. Davidson, C.H.; Johnson, C.; Lizarralde, G.; Dikmen, N.; Sliwinski, A. Truths and myths about community participation in post-disaster housing projects. *Habitat Int.* **2007**, *31*, 100–115. [CrossRef]
87. Hirayama, Y. Collapse and reconstruction: Housing recovery policy in Kobe after the Hanshin Great Earthquake. *Hous. Stud.* **2000**, *15*, 111–128. [CrossRef]
88. Nakagawa, Y.; Shaw, R. Social capital: A missing link to disaster recovery. *Int. J. Mass Emergencies Disasters* **2004**, *22*, 5–34. [CrossRef]
89. Chang, Y.; Wilkinson, S.; Brunsdon, D.; Seville, E.; Potangaroa, R. An integrated approach: Managing resources for post-disaster reconstruction. *Disasters* **2011**, *35*, 739–765. [CrossRef]
90. Johnson, C. Strategic planning for post-disaster temporary housing. *Disasters* **2007**, *31*, 435–458. [CrossRef] [PubMed]
91. Rafi, M.M.; Lodi, S.H.; Bashir, S.; Jamali, A. Pakistan's experience with post-earthquake reconstruction and rehabilitation. *Nepal Eng. Assoc. Tech. J.* **2016**, 116–120.
92. Verykokou, S.; Ioannidis, C.; Athanasiou, G.; Doulamis, N.; Amditis, A. 3D reconstruction of disaster scenes for urban search and rescue. *Multimed. Tools Appl.* **2018**, *77*, 9691–9717. [CrossRef]
93. He, M.; Zhou, B. Reflections on Livelihood Issue in Post-Disaster Reconstruction Planning of Wenchuan Earthquake. *Appl. Mech. Mater.* **2013**, *253–255*, 233–243. [CrossRef]
94. Pezzica, C.; Piemonte, A.; Bleil De Souza, C.; Cutini, V. Photogrammetry as a participatory recovery tool after disasters: A grounded framework for future guidelines. In Proceedings of the 27th International CIPA Symposium, Avila, Spain, 1–5 September 2019.
95. Zhang, X.; Sun, B.; Mei, T.; Wang, R. Post-disaster restoration based on fuzzy preference relation and bean optimization algorithm. In Proceedings of the 2010 IEEE Youth Conference on Information, Computing and Telecommunications, Beijing, China, 28–30 November 2010; IEEE: Piscataway, NJ, USA, 2010; pp. 271–274.
96. Akbari, V.; Shiri, D.; Salman, F.S. An online optimization approach to post-disaster road restoration. *Transp. Res. Part Methodol.* **2021**, *150*, 1–25. [CrossRef]
97. Liu, C.; Fang, D.; Zhao, L. Reflection on earthquake damage of buildings in 2015 Nepal earthquake and seismic measures for post-earthquake reconstruction. *Structures* **2021**, *30*, 647–658. [CrossRef]
98. Messaoudi, M.; Nawari, N.O. BIM-based Virtual Permitting Framework (VPF) for post-disaster recovery and rebuilding in the state of Florida. *Int. J. Disaster Risk Reduct.* **2020**, *42*, 101349. [CrossRef]
99. Bilau, A.A.; Witt, E.; Lill, I. Research methodology for the development of a framework for managing post-disaster housing reconstruction. *Procedia Eng.* **2018**, *212*, 598–605. [CrossRef]
100. Xin, R.; Yu, C.X.; Chen, J.H.; Jiang, L. Discussion on the typical seismic strengthening techniques of masonry building walls after Wenchuan earthquake. In Proceedings of the 2010 International Conference on Mechanic Automation and Control Engineering, Wuhan, China, 26–28 June 2010; IEEE: Piscataway, NJ, USA, 2010; pp. 1126–1129.
101. Yin, Y.-L.; Zhou, J.-E. Research on the application of CM-agent model in public projects of post-disaster reconstruction. In Proceedings of the 2010 International Conference on Logistics Systems and Intelligent Management (ICLSIM), Harbin, China, 9–10 January 2010; IEEE: Piscataway, NJ, USA, 2010; Volume 3, pp. 1756–1760.
102. Feng, L.; Zhongming, M.; Liqi, G. The housing post-disaster reconstruction layout research of Lueyang county after the May 12th earthquake. In Proceedings of the 5th International Conference on Computer Sciences and Convergence Information Technology, Seoul, Republic of Korea, 30 November–2 December 2010; IEEE: Piscataway, NJ, USA, 2010; pp. 794–797.
103. Li, Q.; Meng, H. Thinking of the permanent rural residence's design about the post-Wenchuan's earthquake. In Proceedings of the 2011 International Conference on Electric Technology and Civil Engineering (ICETCE), Lushan, China, 22–24 April 2011; IEEE: Piscataway, NJ, USA, 2011; pp. 1813–1817.
104. Zamanifar, M.; Pooryari, M.; Ahadi, M.R. Estimation of reconstruction cost and traffic functionality relating to roadway transportation lifelines after natural disasters. *Int. J. Transp. Eng.* **2014**, *2*, 67–80.
105. Liu, L.; Lin, Y.; Wang, S. Urban design for post-earthquake reconstruction: A case study of Wenchuan County, China. *Habitat Int.* **2014**, *41*, 290–299. [CrossRef]
106. Cao, W.; Xiao, H. Establishment and application of comprehensive evaluation system for the ability of post-disaster recovery and reconstruction. In Proceedings of the International Conference on Information Systems for Crisis Response and Management (ISCRAM), Harbin, China, 25–27 November 2011; IEEE: Piscataway, NJ, USA, 2011; pp. 403–408.
107. Mejri, O.; Menoni, S.; Matias, K.; Aminoltaheri, N. Crisis information to support spatial planning in post disaster recovery. *Int. J. Disaster Risk Reduct.* **2017**, *22*, 46–61. [CrossRef]

108. Ghannad, P.; Lee, Y.C.; Friedland, C.; Yang, E. Optimizing the socioeconomic benefit of post-disaster strategies by prioritizing reconstruction of damaged facilities. In *Computing in Civil Engineering 2019: Smart Cities, Sustainability, and Resilience*; American Society of Civil Engineers: Reston, VA, USA, 2019; pp. 180–187.
109. Lyons, M.; Schilderman, T.; Boano, C. *Building Back Better: Delivering People-Centered Housing Reconstruction at Scale*; Practical Action: London, UK; London South Bank University: London, UK; International Federation: London, UK, 2010.
110. Vahanvati, M.; Mulligan, M. A new model for effective post-disaster housing reconstruction: Lessons from Gujarat and Bihar in India. *Int. J. Proj. Manag.* **2017**, *35*, 802–817. [CrossRef]
111. Umar, F.; Mohammed, U.A.; Dusserre, G.; Ukwuoma, H.C.; Isa, L.M.; Danladi, A.J. Post-Disaster Housing Reconstruction: Flood Resilience in Suburban Area. *Am. J. Environ. Clim. (AJEC)* **2025**, *4*, 76–83. [CrossRef]

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Research on the Construction and Optimization of Shenzhen's Ecological Network Based on MSPA and Circuit Theory

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Abstract

Under the dual pressures of rapid urbanization and intense human socioeconomic activities, habitat fragmentation and poor landscape connectivity have become critical issues in cities. Constructing ecological networks is essential for maintaining urban ecosystem health and promoting sustainable environmental development. It represents an effective approach to balancing regional economic growth with ecological conservation. This study focused on the Shenzhen Special Economic Zone. Ecological sources were identified using Morphological Spatial Pattern Analysis (MSPA) and landscape connectivity assessment. Circuit theory was applied to extract ecological corridors, ecological pinch points, and ecological barriers. The importance levels of ecological corridors were classified to form an ecological network. The network was optimized by adding ecological sources, stepping stones, and restoring breakpoints. Its structure and functionality were evaluated before and after optimization. The results indicate the following: (1) The core area in Shenzhen City Area covers 426.67 km^2, the largest proportion among landscape types. It exhibits high fragmentation, low connectivity, and a spatial pattern characterized as "dense in the east and west, sparse in the center." (2) Seventeen ecological sources were identified, consisting of 8 key sources, 5 important sources, and 4 general sources, accounting for 17.62% of the total area. Key sources are mainly distributed in forested regions such as Wutong Mountain, Maluan Mountain, Paiya Mountain, and Qiniang Mountain in the southeast. (3) Twenty-six ecological corridors form a woven network, with a total length of 127.44 km. Among these, 13 key corridors are concentrated in the eastern region, while 7 important corridors and 6 general corridors are distributed in the western and central parts. Few corridors exist in the southwest and southeast, leading to ecological flow interruption. (4) The optimized ecological network includes 12 newly added ecological source areas, 20 optimized ecological corridors, 120 ecological pinch points, and 26 ecological barriers. The maximum current value increased from 10.60 to 20.51, indicating significantly enhanced connectivity. The results provide important guidance for green space planning, biodiversity conservation, and ecosystem functionality enhancement in Shenzhen City Area.

Keywords: MSPA; circuit theory; ecological source areas; ecological corridors; ecological networks; Shenzhen City

1. Introduction

In modern urban development, ensuring ecological security and achieving harmony between humans and nature are critical challenges for urban planning. Maintaining healthy, orderly, and balanced regional ecosystems is essential for sustainable urban construction [1]. In Shenzhen City Area, rapid socioeconomic growth and urbanization have eroded ecological patches and intensified landscape fragmentation. Natural habitats are being divided by roads and built-up areas, reducing high-quality habitat space. This severely impedes species dispersal, gene flow, and ecological processes. These changes not only threaten local biodiversity but also weaken the city's capacity to address environmental risks such as floods and heat island effects. The service capacity of natural landscapes has been significantly diminished [2,3]. Intensive land-use changes and construction activities have further degraded the ecological environment. Large areas of forest, grassland, and farmland have been converted to built-up land. Transport infrastructure fragments patches, accelerating habitat isolation [4]. Declining connectivity among landscape patches hinders species migration and contributes to environmental issues including heat islands, floods, smog, and water pollution [5]. Systematically developing ecological networks has become essential for restoring ecological functions and promoting regional coordination in Shenzhen. China's ecological civilization philosophy emphasizes synergistic management of natural elements, proposing the "life community of mountains, waters, forests, farmlands, lakes, and grasslands" concept [6]. This approach integrates ecological conservation into urban and territorial spatial planning. Constructing ecological networks has been widely advocated to reconnect fragmented habitats [7]. Ecological networks help maintain urban ecosystem stability and sustainability. They facilitate energy flow and species migration between patches [8,9], enhance functional connectivity among habitats, and counter the long-term impacts of fragmentation. Ultimately, they serve as a vital pathway toward building a territorial spatial pattern that harmonizes human activities with nature.

Ecological networks serve as a structural skeleton within ecosystems. They are critical for maintaining ecosystem function and structural stability, providing essential conditions for ecological conservation, species dispersal, and reproduction [10]. As global biodiversity loss and ecosystem degradation intensify, ecological networks have become key scientific tools and management approaches. They address urban habitat fragmentation and obstructed species migration [11]. Theoretically, research on ecological networks has deepened the integration of landscape ecology and conservation biology. It has also spurred innovations in research methodologies [12]. Practically, the construction of ecological networks offers a scientific basis for ecological corridor planning and natural resource management. This significantly enhances the safeguarding of ecological security [13]. Globally, studies on ecological networks focus on energy flow, connectivity, soil conservation, cultural services, and sustainable development. These efforts improve habitat quality, promote functional interaction within regional spatial structures, and facilitate ecosystem recovery and health [14–16]. Recent advances emphasize structural optimization, security patterns, spatial planning, and ecological restoration. Such focus is refining ecological network research and providing clear guidance for territorial spatial planning [17–19]. Empirical studies often concentrate on various urban contexts: mountainous, arid, tourism-oriented, coastal, and central cities. These offer multi-level and multi-system practical insights for cities with diverse topographies and functions. Ecological network construction is undertaken at regional, urban, and sub-district scales. Research covers biodiversity, forests, nature reserves, water bodies, green spaces, and wetlands [20]. At macro-regional and urban-agglomeration scales, ecological networks guide ecological restoration and protection [21]. At medium-city scales, they support ecosystem planning strategies [22]. At micro-district scales, they promote sustainable development [23]. In terms of research methodology, the

process of "ecological source identification—resistance surface construction—ecological corridor extraction" is regarded as a new paradigm for ecological network construction [24]. Ecological source identification primarily involves direct identification methods and comprehensive evaluation identification methods, which can identify potential ecological patches but struggle to precisely study the internal structure and spatial morphology of the study area [24]. Barrier surface construction heavily relies on land use type assignment and landscape pattern indices, both of which suffer from limitations such as subjectivity, data dependency, and insufficient spatial heterogeneity [25]. Ecological corridor extraction commonly employs minimum resistance models and graph theory methods [26]. Existing approaches generate only single optimal pathways, neglecting species' multi-path diffusion behavior and failing to reflect the randomness and diversity of migration [27].

Based on the multi-dimensional perspectives and empirical evidence analyzed above, current research on ecological network construction still exhibits several significant limitations: First, there is a lack of comprehensiveness. Although existing studies cover various city types, they rarely include super-large cities with rapid economic growth like Shenzhen. This gap hinders the development of a systematic understanding at the national level. As a core part of Guangdong's "One Core, One Belt, One Area" regional development strategy, Shenzhen faces intense resource and environmental constraints due to extreme urbanization. The city exhibits pronounced habitat fragmentation, insufficient ecological corridors, and an underdeveloped ecological network, leading to declining biodiversity, constrained sustainable development, and disruption of regional ecosystem equilibrium. It stands as a typical example of the ecological challenges confronting super-large cities in China. Second, identification is emphasized over optimization. Most studies focus on static analyses of ecological network structure, paying insufficient attention to active optimization strategies. Systematic design and effectiveness evaluation of measures such as repairing broken corridors, adding stepping-stone patches, and expanding ecological sources are often neglected. As a result, research outcomes are seldom integrated into practical territorial spatial planning. Third, evaluation methods are oversimplified. Assessments predominantly rely on structural indicators such as landscape pattern indices, while functional aspects of ecological networks—such as changes in landscape connectivity and current density—are rarely quantified or compared. This narrow approach limits comprehensive understanding of optimization outcomes. Fourth, approaches are poorly adapted to high-density cities. For super-large cities like Shenzhen, where built-up land predominates and ecological space is highly limited, there is still a lack of refined and operable methodologies for efficiently restoring ecological networks within tightly constrained spaces. Fifth, there are limitations to the methodology. Traditional approaches struggle to account for both the spatial structure of landscapes and the random diffusion processes of ecological flows, failing to adequately simulate the multi-path nature of species migration. This leads to biases in assessing ecological network connectivity. Morphological Spatial Pattern Analysis (MSPA) is a technique capable of decomposing landscapes across multiple scales. It effectively identifies seven key landscape elements—including core areas, bridging zones, and isolated patches—enabling precise extraction of source patches with high ecological value. Building upon the landscape pattern delineation by MSPA, circuit theory is integrated to simulate species' random diffusion processes within the landscape. By analyzing current density, multiple potential migration corridors and critical pinch points are identified, overcoming the limitations of single-path analysis to more accurately reflect ecological functional connectivity.

Based on the various research methodologies and empirical cases discussed earlier, the approach integrating MSPA (Morphological Spatial Pattern Analysis) with circuit theory addresses shortcomings in existing methods for constructing ecological networks and

identifying critical ecological corridors. It overcomes limitations of traditional methods in highly fragmented ecosystems, precisely revealing the key patterns and vulnerable links within Shenzhen's ecological network. This enables multi-scale, comprehensive, and precise assessment of ecological connectivity, facilitating ecological network construction in intensively developed areas. Based on this framework, our study takes Shenzhen City as a research case. We applied Morphological Spatial Pattern Analysis (MSPA) to identify ecological sources and generated an ecological resistance surface. Using circuit theory, we extracted ecological corridors, pinch points, and barriers to construct an ecological network. The network was then optimized by adding ecological sources, corridors, stepping stones, and repairing breakpoints. Finally, the ecological network was evaluated both structurally and functionally before and after optimization. This research aims to offer new insights for spatial planning, ecological network construction, and enhanced ecological conservation functions in other cities.

2. Materials and Methods

2.1. Study Area

Shenzhen is a highly urbanized, super-large special economic zone in southern China's coastal region (22°27′–22°52′ N, 113°46′–114°37′ E) (Figure 1). As one of China's first special economic zones, it is recognized as a national innovative city and a modern marine city. Located on the eastern shore of the Pearl River Estuary, Shenzhen is closely connected to cities such as Hong Kong, Dongguan, and Huizhou, serving as a core area within the Guangdong–Hong Kong–Macao Greater Bay Area. The construction of an ecological network in Shenzhen is not only vital for the city's own sustainable development but also critically important for the health and security of the regional macro-ecosystem. The integrity and connectivity of its ecological system directly influence the ecological security pattern of the entire Pearl River Delta region.

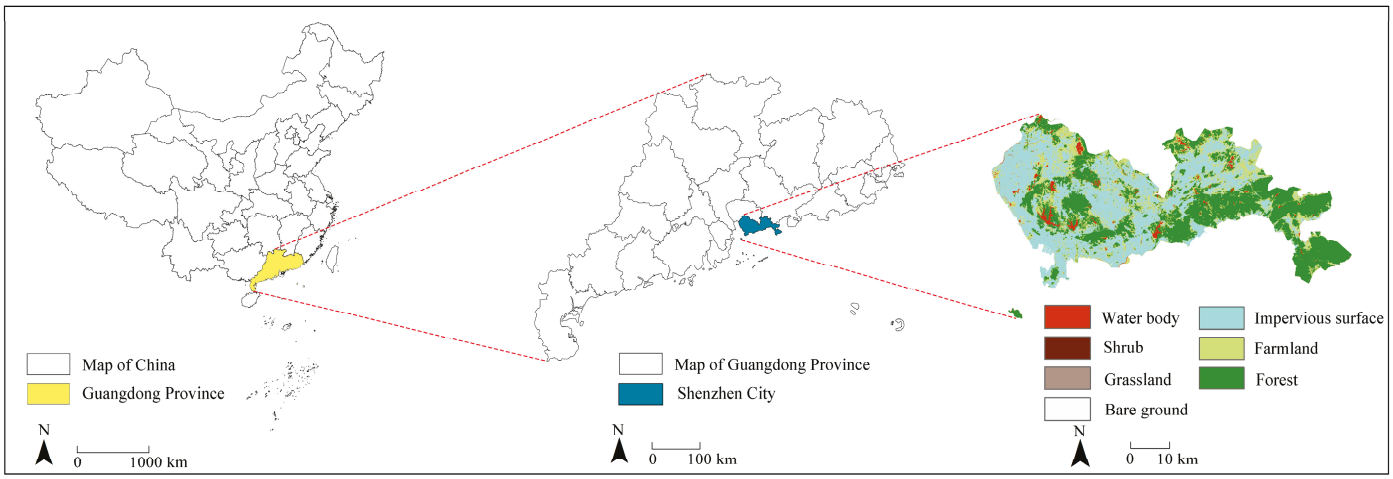


Figure 1. Location and land use types in Shenzhen city.

Shenzhen is endowed with a unique and ecologically significant natural landscape, featuring diverse topography including hills, plains, and coastal wetlands. Within the city, there are 362 rivers with watershed areas exceeding 1 km^2. It is also home to four nature reserves, nine forest parks, and ten wetland parks. The area is rich in biodiversity, hosting dozens of plant and animal species under national key protection. Moreover, Shenzhen serves as a critical node along the East Asian–Australasian Flyway for migratory birds. However, under rapid urbanization, ecological spaces in Shenzhen have been continuously encroached upon, leading to prominent habitat fragmentation. Natural

habitats are dissected by roads and built-up areas, severely hindering species dispersal, genetic exchange, and ecological processes. This not only threatens local biodiversity but also weakens the city's capacity to mitigate environmental risks such as floods and heat island effects. In this context, systematically advancing the construction of an ecological network has become an essential strategy for Shenzhen to restore ecological functions and promote regional coordinated development. By identifying and integrating key ecological patches, and establishing ecological corridors and stepping-stone systems, the ecological network effectively restores landscape connectivity, safeguards animal and plant migration and reproduction, and enhances ecosystem services. On a broader scale, the construction of ecological corridors in Shenzhen will help connect the eastern and western sides of the Pearl River Estuary and link the ecological barriers between Shenzhen, Dongguan, and Huizhou. It plays an irreplaceable strategic role in building a structurally complete and functionally sound ecological security network for the Greater Bay Area. This initiative not only meets urban residents' demand for a high-quality ecological environment but also fulfills vital regional functions such as water conservation, climate regulation, and biodiversity maintenance. Therefore, promoting the development of Shenzhen's ecological network is both a crucial pathway to alleviating conflicts between urban development and ecological conservation, and a core measure supporting high-quality development in the Guangdong–Hong Kong–Macao Greater Bay Area and achieving harmonious coexistence between humans and nature.

2.2. Data Sources

The types and sources of fundamental data used in this study are listed in Table 1. All spatial data were projected to the WGS_1984_UTM_Zone_50N coordinate system. Using ArcGIS 10.2 software, the data underwent preprocessing and geometric correction through radiometric calibration, clipping, and atmospheric correction. All raster data for Shenzhen were standardized to a uniform resolution of 30 m × 30 m, ensuring data quality and compatibility.

Table 1. Data sources.

Data Type	Data Source	Format	Year	Resolution
Administrative division data	Standard Map Service System of the Ministry of Natural Resources of China (http://bzdt.ch.mnr.gov.cn/)	Vector data	2024	-
Land use data	Chinese Academy of Sciences Resource and Environment Science Data Center (https://www.resdc.cn/)	Raster data	2024	30 m
DEM data	Geospatial Data Cloud Website (https://www.gscloud.cn/)		2024	12.5 m
Normalized Difference Vegetation Index (NDVI)	China Qinghai-Tibet Plateau Scientific Data Center (https://data.tpdc.ac.cn/)		2024	30 m
Road data	OpenStreetMap (https://edithistory.peterboswell.net/)	Vector data	2024	-
River data	Geospatial Data Cloud Website (https://www.gscloud.cn/)		2024	-
Soil data	Soil Science Data Center (https://soil.geodata.cn/)	Raster data	2024	30 m

2.3. Methods

Currently, a new research paradigm has been established for the construction and optimization of ecological networks: "identification of ecological sources–construction of resistance surfaces–extraction of ecological corridors–identification of key areas" [28]. Ecological sources function as starting points for the outward diffusion of ecological flows. They are specific habitats crucial for promoting species movement, maintaining biodiversity, and enhancing regional ecological health and resilience [29]. The selection of ecological sources directly affects the overall stability of the ecological network. Most current studies use methods such as direct identification, ecosystem service assessment, and ecological sensitivity evaluation to identify ecological sources [30]. These approaches often directly extract nature reserves or areas of good ecological quality as ecological sources. However, they tend to overlook interactions between different ecosystem services or ecological elements, lacking a certain degree of objectivity [31]. In contrast, the Morphological Spatial Pattern Analysis (MSPA) model is based on graph theory principles. It operates on raster data to classify land cover types. This enables precise differentiation of land and landscape spatial structures. Morphological Spatial Pattern Analysis (MSPA) can identify key ecological habitats that significantly contribute to landscape connectivity within the study area [32,33]. The method offers greater compatibility, effectiveness, and scientific rigor in identifying ecological sources. It also improves the rationality of using the Minimum Cumulative Resistance (MCR) model in constructing ecological networks [34,35]. The ecological resistance surface is the most fundamental component of ecological network construction and serves as the prerequisite for extracting ecological corridors. Previous studies have often assigned resistance values directly based on land use types, followed by modifications using impervious surface indices and nighttime light data [36]. However, such approaches fail to account for spatial heterogeneity within the same land use category, as well as the influences of topography and human activities [37,38]. This study improves the objectivity, rationality, and accuracy of resistance surface setup by integrating multiple factors, including land use type, elevation, hydrographic features, soil conditions, and landscape pattern metrics. Ecological corridors act as bridges for the flow and exchange of organisms and energy between ecological sources. The interconnection of these corridors forms an ecological network, making them core elements of its structure. Currently, the Minimum Cumulative Resistance (MCR) model is the primary method for identifying ecological corridors [39,40]. However, the MCR model only predicts the general direction of movement corridors without delineating specific widths or identifying key nodes, resulting in limited functional attributes [41]. It also struggles to simulate the randomness of species movement and does not support further analysis of corridor width or ecological node identification [42,43]. Circuit theory integrates physical concepts such as current density and resistance values into ecological network construction. It conceptualizes the landscape as an electrical circuit, with the entire study area acting as a conductive surface [44]. Each grid cell is assigned a specific "resistance" to organism movement, and the migration or dispersal processes of species or ecological factors are simulated using randomly walking electrons [45]. Through iterative calculations of current input between corridors and sources, areas where current (representing biological flow) must pass through are identified as ecological "pinch points". These nodes indicate locations with a very high probability of ecological flow and limited alternative pathways [46,47], making them critical for maintaining landscape connectivity. Areas that obstruct current movement between corridors are identified as ecological "barriers" [48]. These zones, which often exhibit high resistance values or contain blocking features, negatively affect corridor formation or maintenance. Their removal or improvement can enhance corridor connectivity and quality. A key advantage of circuit theory is its capacity to evaluate all possible pathways across the landscape. It not only identifies

potential corridors but also locates key ecological nodes critical for certain ecological processes [49]. This provides detailed spatial information that addresses limitations of existing models in representing ecological exchange, thus offering a scientific basis for pinpointing ecological pinch points and barriers [50]. Circuit theory has been widely applied in studies of landscape connectivity, animal migration route identification, and ecological security pattern construction [51,52]. It provides clear guidance for ecosystem restoration and the optimization of ecological networks.

2.3.1. Ecological Source Identification Based on MSPA and Landscape Connectivity Assessment

Ecological sources form the foundation of ecological network construction. They are complexes composed of various natural ecosystems, including forest patches, wetland systems, water bodies, and large green spaces [53]. Dominated by woodlands, water areas, and wetlands, these zones provide habitats, breeding grounds, and migration corridors for species, serving as core carriers for biodiversity conservation [53]. Ecological sources such as forests and wetlands play a key role in carbon sequestration by fixing carbon dioxide through photosynthesis, while also mitigating the urban heat island effect [53]. Furthermore, they regulate the regional water cycle by intercepting precipitation and conserving water resources, functioning as critical starting and regulating points in aquatic ecological processes. As such, ecological sources represent comprehensive and central ecological spaces that integrate multiple ecosystem functions [54]. Morphological Spatial Pattern Analysis (MSPA) is a spatial pattern identification method based on image morphology theory. It uses mathematical morphological operations to segment the spatial structure of raster data, thereby classifying land use and generating landscape ecological patches at the pixel level [21]. This method accounts for the effects of landscape fragmentation, emphasizes structural connectivity, and enhances the objectivity of source area evaluation [29]. Using GuidosToolbox 3.0 software, forest and water bodies with the highest habitat quality were selected as the foreground. The landscape of Shenzhen was classified into seven types: Core, Islet, Loop, Bridge, Edge, Perforation, and Branch. Core areas contribute to enhancing habitat quality stability. Larger core areas exhibit higher connectivity, which facilitates energy transfer and species dispersal [55]. Landscape connectivity regulates the efficiency of material cycling and energy flow, playing a key role in biodiversity conservation [23]. Landscape connectivity indices enable a shift from qualitative research to quantitative management of conservation objectives, transitioning the focus from individual ecological patches to the optimization of entire networks. The quantitative results directly support the goals of ecological control line optimization, ecological corridor construction, and territorial planning, significantly improving the precision and effectiveness of urban ecological governance [36]. Based on this approach, this study identified ecological sources by quantifying ecological patch size and landscape connectivity, thereby supporting the construction and optimization of the ecological network.

In this study, the Morphological Spatial Pattern Analysis (MSPA) model was first applied to extract core area patches larger than 10 km^2 as candidate ecological sources. Subsequently, Conefor Sensinode 2.6 software was used to develop landscape connectivity index (PC) and patch importance index (dPC) models for analyzing connectivity characteristics. These models facilitated the identification of ecological sources and the classification of their importance. The calculation formulas are as follows:

$$PC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i a_j P_{ij}^*}{A_L^2} \quad (1)$$

$$dPC = \frac{PC - PC_{remove}}{PC} \quad (2)$$

In the equation: n represents the total number of ecological patches; a_i and a_j are the areas of patches i and j, respectively; p_{ij}* is the maximum probability of migration between patches i and j; A_L is the total area of all landscape types in Shenzhen; PC is the connectivity index of ecological patches, with higher PC values ($0 \leq PC \leq 1$) indicating higher landscape connectivity; dPC is the patch importance index, indicating the importance of existing ecological patches in maintaining landscape connectivity; PC_{remove} is the landscape connectivity index after removing a specific ecological patch.

2.3.2. Ecological Resistance Surface Construction

During migration and dispersal, species must overcome certain resistance. By assigning resistance values for dispersal from ecological sources to other landscape units, the accessibility and connectivity of these sources can be evaluated [56]. Different landscape types and topographic features result in varying degrees of landscape resistance, which hinders species exchange and energy flow between sources. Frequent human activities also pose significant resistance to the expansion of ecological sources, as increased human presence further impedes species migration [57]. This study integrated factors such as land cover, topographic conditions, and ecological stressors, focusing on 10 types of resistance factors that effectively reflect terrestrial landscape characteristics and human activity intensity (Table 2). An ecological resistance surface was constructed by classifying each resistance factor into five levels, with higher values indicating greater resistance. These factors effectively characterize terrestrial habitat suitability and obstacles to species movement, providing critical support for identifying terrestrial ecosystem-based sources, corridors, pinch points, and barrier areas [58]. The entropy weight method and analytic hierarchy process (AHP) were employed to assign weights to the 10 resistance factors. Building on existing research, 25 domain experts were invited to score each factor based on its importance. Using AHP, a hierarchical indicator structure was constructed, and consistency checks were performed through pairwise comparisons to determine the subjective weights W_i. The original expert evaluation data were then normalized, and an entropy matrix was established for each resistance factor based on entropy calculation formulas to derive objective weights W_j. The entropy weight method offers an objective weighting approach that effectively minimizes errors caused by information overlap and redundancy among resistance factors. In contrast, AHP is straightforward to compute but relatively subjective. Therefore, this study integrated both methods by modifying the AHP results using the entropy weight method, resulting in comprehensive weights W_{ij} (Table 2) that incorporate both expert knowledge and inherent data patterns. Finally, the raster calculation module in ArcGIS 10.2 was used to perform weighted overlay of all resistance factors, generating a comprehensive resistance surface for the study area. The calculation formula is as follows:

$$W_{ij} = \frac{(W_i W_j)^{0.5}}{\sum_{ij=1}^{m} (W_i W_j)^{0.5}} (ij = 1, 2, 3, \ldots, m) \quad (3)$$

In the equation: i and j represent the serial numbers of each resistance factor in Shenzhen City Area; m is the number of experts; W_i represents the subjective weight of the i-th resistance factor calculated through the Analytic Hierarchy Process (AHP); W_j represents the objective weight of the j-th resistance factor calculated through the entropy weight method; W_{ij} represents the final comprehensive weight of the i-th (or j-th) resistance factor.

Table 2. Classification and weight values of ecological resistance factors in Shenzhen.

Resistance Factor	Weight	Resistance Score				
		10	**20**	**30**	**40**	**50**
Elevation	0.0652	[0, 5]	(5, 20]	(20, 35]	(35, 50]	>50
Slope	0.0358	[0, 200]	(200, 400]	(400, 600]	(600, 800]	>800
Normalized Difference Vegetation Index	0.1221	(0.75, 1]	(0.5, 0.75]	(0.25, 0.5]	(0, 0.25]	(0, −0.2]
Distance from the river	0.0407	[0, 350]	(350, 700]	(700, 1050]	(1050, 1400]	>1400
Soil	0.0612	Red soil	Rice soil	Tidal soil	Red soil, Yellow-red soil	Coastal saline soil
Land use	0.1828	Forest	Grassland, Shrubs	Farmland	Bare ground, Water body	Impervious surface
Distance from the railway	0.1104	>2000	(1500, 2000]	(1000, 1500]	(500, 1000]	[0, 500]
Distance to highway	0.0798	>2000	(1500, 2000]	(1000, 1500]	(500, 1000]	[0, 500]
Distance from major city roads	0.0644	[0, 350]	(350, 700]	(700, 1050]	(1050, 1400]	>1400
MSPA landscape type	0.2376	Core	Bridge	Branch, Loop	Edge, Islet	Perforation, Background

2.3.3. Extraction of Corridors, Pinch Points, and Barrier Points Based on Circuit Theory

The introduction of circuit theory into the calculation of biological migration corridors is primarily based on the following three theoretical foundations [44,45]:Firstly, the path randomness in biological migration processes resembles the random walk of electric charges in circuits. Secondly, different landscape types exert varying degrees of resistance to biological movement, analogous to electrical resistors in circuits, enabling the conceptualization of landscape types as resistance units. Thirdly, compared to traditional minimum resistance models, circuit theory more accurately reflects real ecological processes. It allows for the identification of optimal migration corridors and key pinch point areas by calculating paths of energy consumption. Based on these principles, this study applied circuit theory to extract core components in the construction of the ecological network.

(1) Identification of Ecological Corridors

Ecological corridors facilitate cross-regional species exchange and dispersal from core habitats to peripheral areas by reducing migration resistance. They effectively mitigate predation risks and human-induced disturbances during species movement, serving as vital ecological passageways for biological migration [59]. In the process of gene flow, ecological corridors act as transmission media—a function reflecting their deeper value—directly influencing the genetic structure of populations and biodiversity. Simultaneously, they form a restorative network that enhances ecological resilience, strengthening an ecosystem's capacity to resist, recover from, and adapt to disturbances [8]. As key pathways for material cycling, energy flow, and information transfer between ecological sources [41], ecological corridors can be equated to current pathways in circuit theory. Circuit theory, in turn, reflects the relative importance of corridors based on current intensity between sources, thereby predicting species dispersal and migration patterns and identifying movement routes [60]. To better simulate the randomness of biological migration and identify least-cost paths between ecological sources, this study applied the principles of circuit theory. Using the Linkage Mapper tool coupled with ecological sources and a comprehensive resistance surface, ecological corridors were extracted. Their importance was classified through quantification of flow centrality [61].

(2) Identification of Ecological Pinch Points

Ecological pinch points refer to areas where ecological current is concentrated and of high intensity. Species experience lower resistance when moving through these regions, facilitating ecological flows between habitats [62]. In this study, the Pinch Point Mapper 3.0 tool in Linkage Mapper was used to quantify current between sources to identify key pathways and locations for species movement. Areas with high cumulative current values were identified as ecological pinch points [63]. These zones experience frequent ecological processes and have high irreplaceability for species passage, making them critical nodes in constructing ecological security patterns. They play a fundamental role in maintaining landscape connectivity [64].

(3) Identification of Ecological Barriers

Ecological barriers refer to areas that significantly impede species migration between sources, hindering effective connectivity between habitats. Identifying and improving these barriers is crucial for enhancing the connectivity of ecological corridors [65]. Barriers with higher improvement scores indicate that their removal can more effectively reduce resistance to species movement. This study used the moving window method in the Barrier Mapper tool to identify regions with high resistance. Ecological barriers were derived based on current distribution patterns under a relative Least-Cost Path (LCD) improvement score mode, analyzed through resistance thresholds. The improvement in connectivity after barrier removal was characterized by the unit reduction in least-cost distance. Areas with larger improvement values were identified as ecological barriers within the corridors [4].

(4) Current Density Model

In electrical circuits, the movement of charges exhibits random behavior. This randomness resembles the movement of organisms in nature [47]. Therefore, current density can effectively reflect the random walk characteristics of ecological flows and evaluate the state of ecological movement in a study area. Based on circuit theory, ecological sources are treated as current sources and the ecological resistance surface as a resistive surface. Regions with higher resistance hinder the movement of current [66]. In an ecological network, current density refers to the rate at which organisms migrate between ecological patches. Its value depends on the distribution of ecological resistance, the potential difference between ecological sources, and the connectivity of ecological corridors. The calculation formula is as follows:

$$I_{ij} = \frac{|V_i - V_j|}{R_{ij}} \quad (4)$$

$$D_i = \sum_j^N |I_{ij}| \quad (5)$$

In the formula: i and j represent ecological sources; Iij denotes the flow of ecological flow between adjacent ecological sources i and j, measured in amperes (A). A larger value indicates a higher current density passing through this connection point; D_i represents the current density at ecological source i, measured in A/km^2; Vi and Vj represent the electrical potentials of ecological sources i and j, respectively, measured in volts (V); Rij represents the movement resistance between ecological sources i and j, measured in ohms (Ω). A higher resistance value indicates greater movement costs for species.

3. Results

3.1. Identification of Ecological Sources in Shenzhen City Area

3.1.1. Landscape Pattern Analysis of Shenzhen City Area Based on MSPA

Woodland and water bodies in Shenzhen were selected as the foreground. Morphological Spatial Pattern Analysis (MSPA) was applied to analyze their land use types. The resulting

landscape pattern classification is shown in Figure 2 and Table 3. The core areas account for 21.99% of the total study area, representing the largest proportion among all landscape types. These areas exhibit high stability and constitute 60.70% of the foreground area. They are primarily concentrated in the scenic zones, forest parks, and geoparks of mountainous regions such as Wutong Mountain, Maluan Mountain, Paiya Mountain, and Qiniang Mountain in the southeastern part of the city, forming large contiguous patches. In contrast, the northwestern and central regions show sparse distribution of core areas, with high fragmentation and poor connectivity. Islets account for 1.43% of the total area. These small, scattered patches can serve as potential stepping stones in future planning to facilitate the movement of ecological elements. Loop areas, which significantly contribute to ecological flows within the core areas, make up 2.10% of the total area. Bridge areas, representing structural corridors in the landscape ecological security pattern, promote connectivity between ecological patches. However, they cover only 3.37% of the total area, providing limited pathways for energy exchange and material flow. Edge areas act as buffers between woodland and other landscape types and are mainly distributed along the periphery of core areas. These zones exhibit certain marginal characteristics and cover 4.94% of the total area, making them the second most extensive category after core areas. Perforations account for 0.57% of the total area, indicating relatively weak edge effects within the woodland patches of the study area, which lack stability and are susceptible to external disturbances. Branches cover 1.49% of the total area, reflecting moderate overall connectivity within Shenzhen.

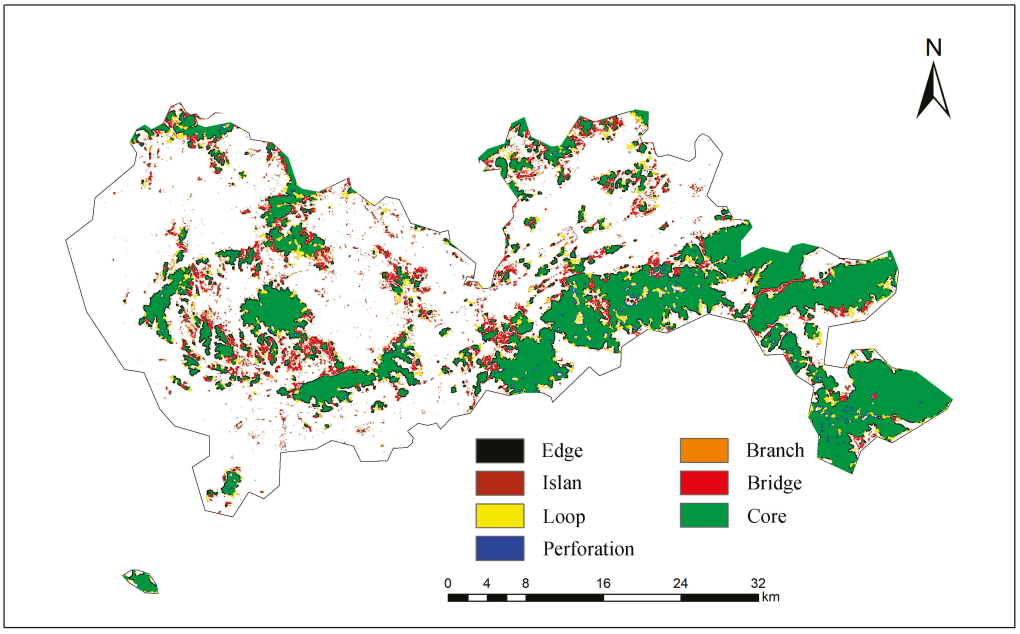


Figure 2. Landscape pattern analysis of Shenzhen based on MSPA.

Table 3. Landscape Types and Proportions in Shenzhen.

Landscape Type	Foreground (Woodland)		
	Area (km^2)	Proportion of Woodland (%)	Proportion of the Study Area (%)
Core	426.69	60.70%	21.99%
Islan	27.68	3.94%	1.43%
Loop	40.85	5.81%	2.10%
Bridge	65.44	9.31%	3.37%
Edge	95.91	13.64%	4.94%
Perforation	11.13	1.58%	0.57%
Branch	28.84	4.10%	1.49%

3.1.2. Identification of Ecological Sources in Shenzhen City Area

In the process of identifying ecological sources, the selection of ecological patch size and aggregation threshold directly influences the rationality of the ecological network structure and its capacity to represent ecological functions [35]. Ecological patch size determines the intensity of ecological functions, species carrying capacity, and regional stability. It supports planning objectives such as maintaining species diversity, ensuring long-term population survival, enhancing ecosystem service supply, and strengthening ecosystem resilience [21]. This study selected ecological patches with core areas larger than 10 km^2 and used an aggregation threshold of 1000 m as criteria for defining ecological sources. A core area of 10 km^2 is considered a critical size that can support continuous species reproduction and life-cycle processes. Research shows that the minimum habitat area required to sustain populations of most medium-to-large mammals and birds ranges between 5–20 km^2. If the patch size threshold is too small, it may include small ecological patches such as community parks, leading to excessive fragmentation of ecological sources, increased management costs, and reduced functional stability. Conversely, an excessively large threshold may overlook key ecological nodes such as small wetland clusters, thereby weakening the integrity of the ecological network. In Shenzhen's delineation of the basic ecological control line, woodlands account for more than 50% of the area. A patch size of 10 km^2 aligns with the typical area of municipal-level nature reserves and forest parks, facilitating the implementation of ecological conservation policies. Thus, setting the threshold at 10 km^2 ensures that ecological sources possess sufficient ecological carrying capacity and internal habitat stability. An aggregation threshold of 1000 m can meet the corridor requirements of most mammals and ensure effective ecological connectivity between aggregated patches. If the aggregation threshold is too small, the number of aggregated patches may increase, but connectivity may decrease. If the threshold is too large, it may lead to over-consolidation of patches, obscuring local ecological heterogeneity. A 1000 m aggregation threshold can integrate dispersed small ecological patches such as woodlands and water bodies in Shenzhen into larger ecological sources, reducing "islandization" effects. This approach maintains the independence of ecological patches while avoiding the loss of ecological functional heterogeneity due to excessive merging [67].

Therefore, to avoid excessive fragmentation in the distribution of extracted ecological sources, this study selected ecological patches with a core area greater than 10 km^2 and a dPC value > 0.1. These patches were aggregated using a 1000 m threshold, resulting in the identification of 17 ecological sources (Figure 3). Spatially, the ecological sources in Shenzhen show a clustered distribution in the eastern region and a scattered pattern in the west. Eastern sources are predominantly located within national geoparks, coastal tourism zones, Guanyin Mountain Park, country parks, reservoirs, and wetland parks. The distribution of ecological sources indicates that the continuous ecological barrier formed by Wutong Mountain, Maluan Mountain, Paiya Mountain, and Qiniang Mountain in Shenzhen serves important functions such as soil and water conservation, water retention, and biodiversity maintenance. Meanwhile, independent mountainous areas including Longyan Mountain, Meilin Mountain, Fenghuang Mountain, Guangming Forest Park, and Ejing Reservoir, along with various nature reserves, play significant roles as essential ecological patches.

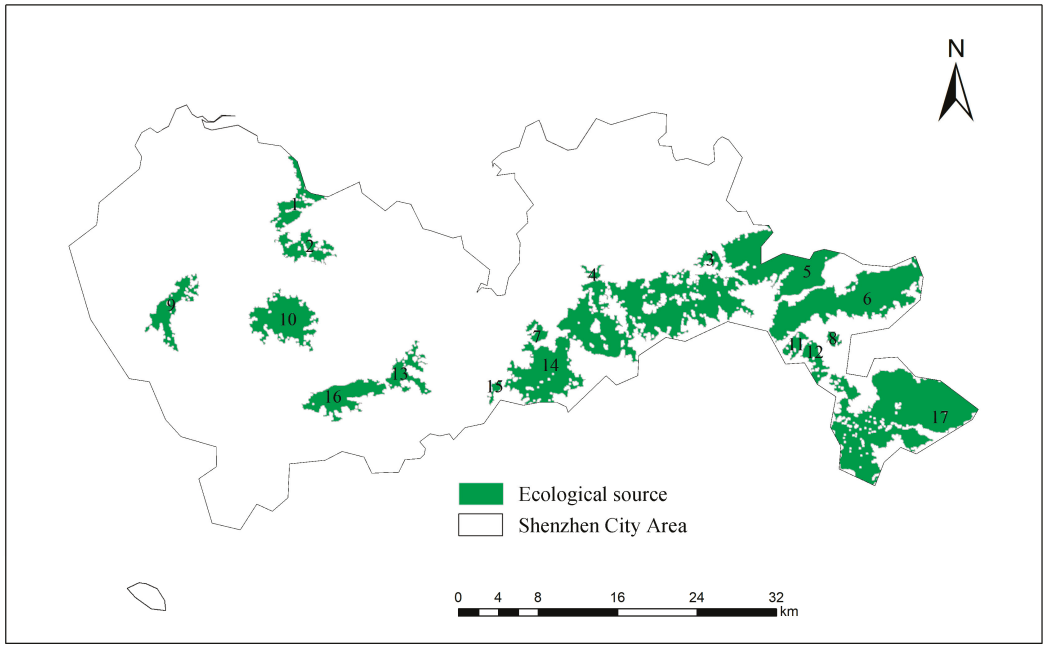


Figure 3. Distribution of ecological sources in Shenzhen.

3.1.3. Classification of the Importance of Ecological Sources in Shenzhen City Area

Shenzhen City contains a total of 17 ecological sources, covering a combined area of 352.50 km^2. Based on the landscape connectivity index (dPC), these ecological sources were classified into three categories: key sources (dPC > 1), important sources (1 > dPC > 0.5), and general sources (0.1 < dPC < 0.5). As shown in Figure 4 and Table 4, key ecological sources are the most numerous, with a total area of 277.48 km^2, accounting for 78.72% of the total ecological source area—significantly larger than the other two types. These are mainly concentrated in the southeastern part of Shenzhen, where ecosystem services are prominent, and human disturbance is relatively low. This region is dominated by large forested areas and includes ecologically significant zones such as wetland parks, country parks, reservoirs, and geoparks. Patch 17 has the highest dPC value of 59.41 and an area of 78.81 km^2. Located south of Hutou Mountain, it contains numerous suitable habitats such as Dapeng Peninsula National Geopark, Fenglang Mountain Park, New Century Seaview Country Park, and Xiangche Reservoir. Patch 14 has the second highest dPC value of 56.24 and the largest area among all patches—102.90 km^2. Situated in the south-central part of Shenzhen, it includes protected areas such as Maluan Country Park, Chi'ao Reservoir, Sanzhoutian Forest Park, and Wutong Mountain Forest Park. Patch 6 has a dPC value of 41.98 and is primarily located around Ling'ao Reservoir and surrounding mountains. Patch 5, with a dPC value of 36.15, is located in Longgang District and encompasses resource-rich areas including Luowuwei Reservoir and Jingxin Reservoir. Patch 7 is situated in Pingshan District and contains protected areas such as Songzikeng Forest Park. Patches 11 and 12 are located in Longgang District and include Guanyin Mountain Park, Ecological Garden, Maque Mountain, and adjacent mountain ranges. Patch 3, located in Pingshan District, contains protected areas such as Chi'ao Reservoir. There are 5 important ecological sources, with dPC values between 0.5 and 1. These are mainly distributed in the western and southwestern parts of Shenzhen and are relatively small in area. The 4 general ecological sources all have dPC values between 0.1 and 0.5. Most are located in the western and northwestern fringes of the city, with large intervals between them, contributing minimally to the overall connectivity of Shenzhen.

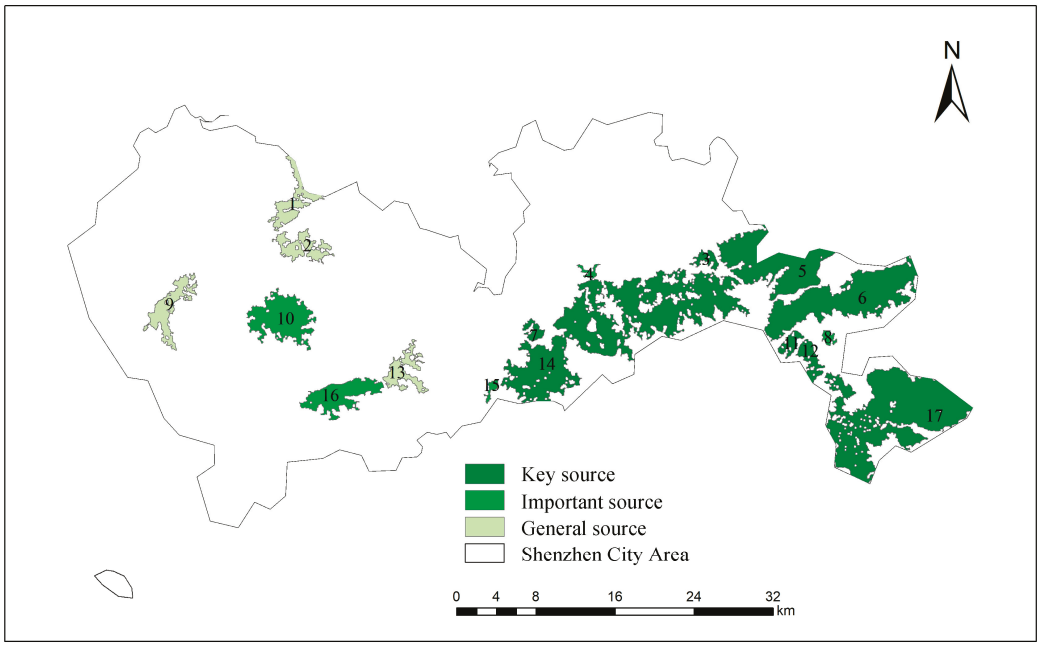


Figure 4. Distribution of the importance of ecological sources in Shenzhen.

Table 4. Classification of the importance of ecological sources in Shenzhen.

Importance Level of Ecological Source Areas	Quantity	Percentage of Total Ecological Source Areas (%)	Area (km^2)	Proportion of Total Ecological Source Area (%)	Connectivity Index (dPC)
Key source	8	47.06%	277.48 km^2	78.72%	dPC > 1
Important source	5	29.41%	39.59 km^2	11.23%	1 > dPC > 0.5
General source	4	23.53%	35.43 km^2	10.05%	dPC < 0.5

3.2. Extraction of Ecological Corridors in Shenzhen City Area

3.2.1. Construction of Ecological Resistance Surface in Shenzhen City Area

The ecological resistance surface serves as the basis for calculating species dispersal paths under resistance constraints. Different natural ecological backgrounds and human activities exert varying degrees of influence on the flow of materials, energy, and information. In this study, based on various resistance evaluation factors and their weights, ten resistance factor layers were established in ArcGIS 10.2, including elevation, slope, vegetation, distance to rivers, soil type, land use, distance to railways, distance to highways, distance to major urban roads, and landscape type. Using the Raster Calculator, weighted summation was performed on these resistance factors to generate an ecological resistance surface (Figure 5) that aligns with the unique ecological characteristics of the study area. In Shenzhen, the ecological resistance values range from 16.18 to 78.37, showing significant regional variation. High resistance values are observed in the northwest, southwest, northeast, and central regions. These areas are predominantly urban built-up land, located near city centers and transportation routes, with frequent human activities and high disturbance levels. They exhibit fragmented and scattered patterns, resulting in severe ecological fragmentation, which hinders species migration and material flow, leading to poor regional connectivity. In contrast, low resistance values are found in the eastern and southeastern parts of Shenzhen. These regions feature higher elevations, steeper slopes, and are primarily covered by woodlands. With minimal human impact and favorable habitat conditions, they demonstrate high connectivity and low resistance to species movement.

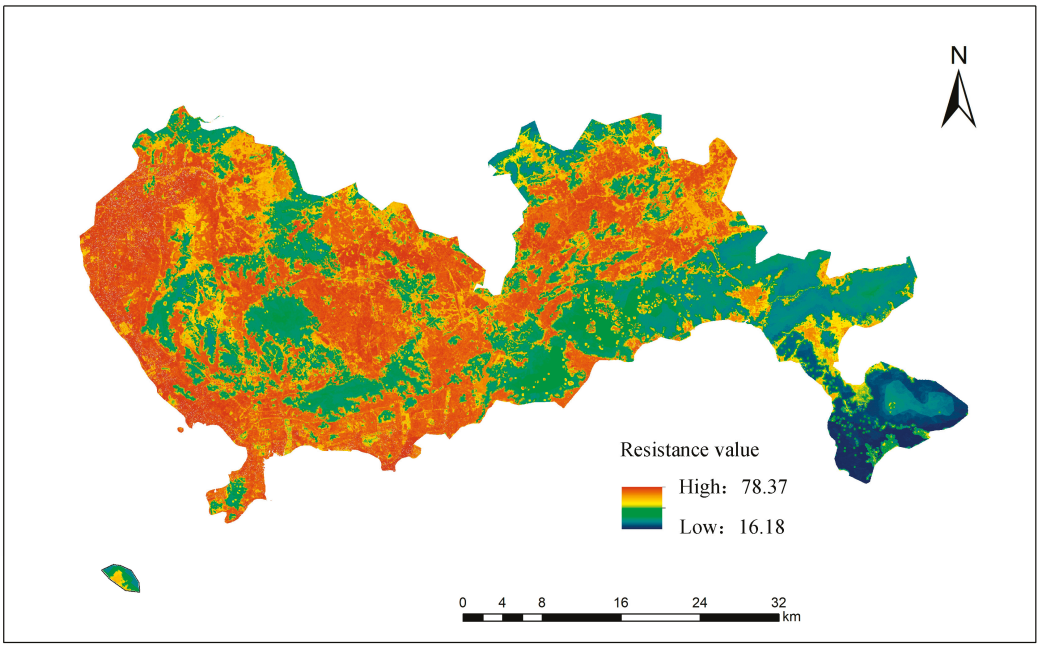


Figure 5. Ecological resistance surface in Shenzhen.

3.2.2. Extraction of Ecological Corridors in Shenzhen City Area

Based on circuit theory, ecological sources and the ecological resistance surface were input into the Linkage Mapper tool, identifying a total of 26 ecological corridors forming an interconnected network with a total length of 127.44 km. Corridors shorter than 5 km account for 69.23% of the total, indicating relatively poor overall connectivity and high landscape fragmentation (Figure 6). In general, short-distance corridors are mainly located in the southeastern part of the study area, connecting large and densely distributed ecological sources. Long-distance corridors link ecological sources in the western and eastern regions of Shenzhen, while also connecting scattered and isolated sources in the west, thereby enhancing landscape connectivity in these areas. The current intensity values of the corridors range from 2.35 to 8.29. Using the quantile method, the corridors were classified into key corridors, important corridors, and general corridors, numbering 13, 7, and 6, respectively, with total lengths of 18.24 km, 41.94 km, and 67.26 km. The longest corridor, measuring 28.26 km, is classified as a general corridor. It bypasses areas with extremely high resistance but still carries a risk of biological flow interruption. Spatially, the southeastern part of Shenzhen exhibits a high density of corridors, predominantly key corridors, with fewer and shorter important and general corridors distributed sporadically. In contrast, the northwestern region has sparse but longer corridors, mostly general ones, which effectively connect western and central ecological sources. These provide favorable conditions for biological movement and migration, partially compensating for the lack of ecological sources in Shenzhen. This pattern suggests that constructing stepping stones in areas with poor ecological connectivity can effectively shorten inter-patch distances and facilitate ecological flows. Additionally, some long-span corridors integrate diverse landscape types, traverse urban built-up areas, and are primarily established along roadsides. Therefore, urban planning should emphasize the development of roadside landscapes to avoid corridor disruption due to inadequate reservation and restoration, thereby enhancing the continuity and stability of ecological corridors.

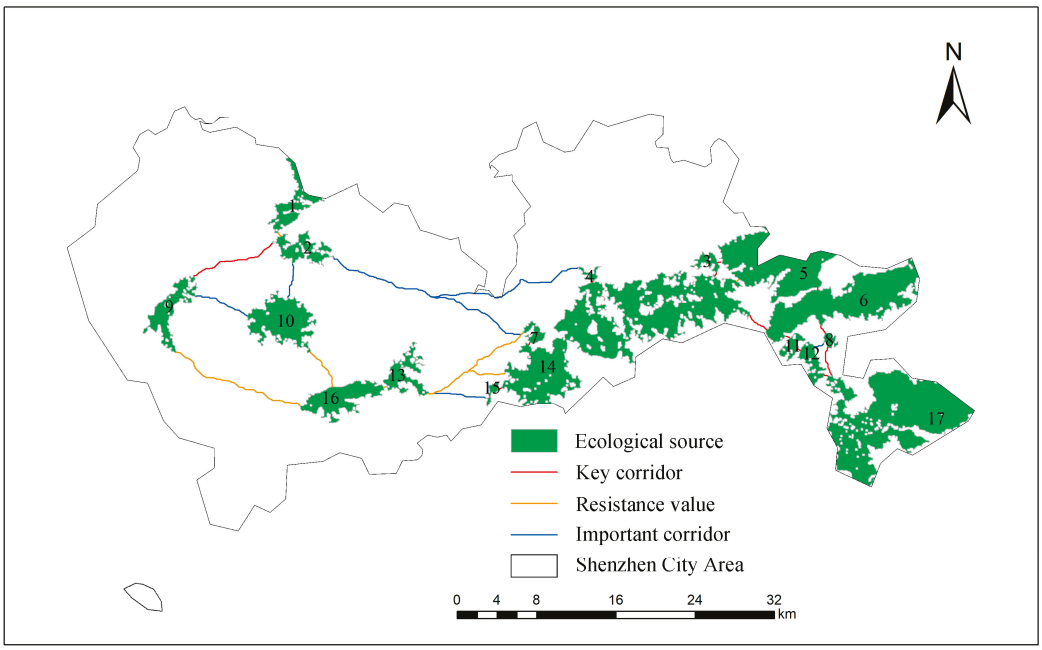


Figure 6. Classification and distribution of ecological corridors in Shenzhen.

3.3. Identification of Ecological Pinch Points in Shenzhen City Area

Based on circuit theory, ecological pinch points were identified as areas within ecological corridors with high current density. A higher current density value indicates a greater number of electrons (representing species) passing through per unit area, implying a stronger flow and greater importance in maintaining connectivity between patches. Regions with high current density are critical for biological movement. Given that the width of ecological corridors has limited influence on pinch points, and considering the actual conditions in Shenzhen, a weighted cost distance of 1000 m was set as the corridor width to extract areas with the highest current values as ecological pinch points. Using the Linkage Mapper tool, a total of 120 ecological pinch points with the highest cumulative current values were identified (Figure 7), covering a total area of 41.64 km^2. The largest pinch point spans 7.4 km^2, while the smallest is 0.06 km^2. These pinch points are all located within ecological corridors, mostly exhibiting linear distributions. In terms of land cover, the pinch points are predominantly composed of forest land, grassland, and water bodies. At the same time, construction land is often found surrounding these pinch points, indicating that while they serve to maintain landscape connectivity, they are also under threat from human activities. Ecological pinch points tend to occur where ecological corridors connect to ecological sources or in intermediate segments of the corridors. If these areas become fragmented, the functionality of the entire ecosystem may be disrupted or impaired.

3.4. Identification of Ecological Barriers in Shenzhen City Area

Areas with high cumulative current recovery values are identified as ecological barriers. Using the Barrier Mapper tool, 26 ecological barriers were identified (Figure 7), covering a total area of 27.87 km^2. The largest barrier, located in the eastern part of Shenzhen, has an area of 4.6 km^2. In terms of land cover composition, the ecological barriers are predominantly farmland and urban built-up land. Approximately 50% of the barriers have an area of less than 1 km^2, yet they account for only 0.96% of the total barrier area. These smaller barriers are mainly scattered in a dotted pattern across western Shenzhen and can be relatively easily restored. Their remediation would significantly enhance regional landscape connectivity. Barriers larger than 1 km^2 mostly exhibit patchy or linear distributions and are concentrated in the central and eastern regions—dispersed in the central area

and densely clustered in the east. Most ecological barriers are located at the edges of or in gaps between ecological sources. Some barriers overlap with ecological pinch points, threatening the integrity and stability of the ecological base and limiting the expansion of ecological corridors. These areas require priority restoration.

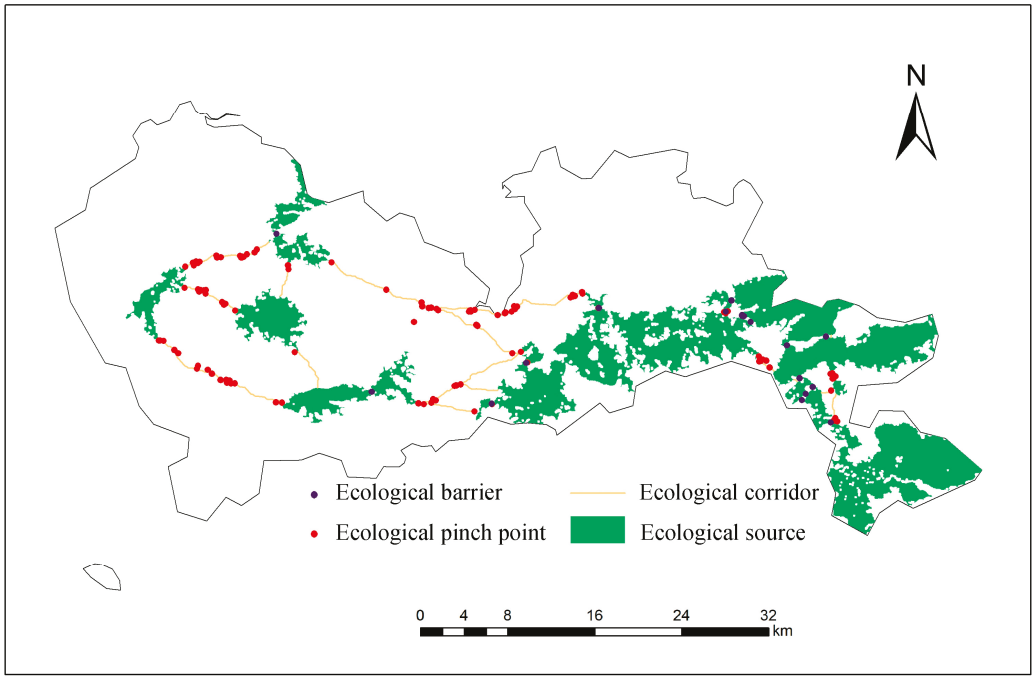


Figure 7. Distribution of ecological pinch points and ecological barriers in Shenzhen.

3.5. Optimization and Evaluation of the Ecological Network in Shenzhen City Area

3.5.1. Network Structure Optimization by Adding Ecological Sources and Stepping Stones

The ecological network in Shenzhen is primarily distributed in the southeastern and western regions, while the northwest, northeast, central, and southwestern areas lack sufficient ecological connectivity (Figure 6). Overall, the network exhibits an uneven spatial distribution. To improve the structure of the ecological network, it is necessary to add ecological sources and corridors in these underrepresented regions to enhance connectivity. Based on the existing ecological network of Shenzhen and in reference to the Shenzhen Territorial Spatial Master Plan (2021–2035), 12 new ecological sources were added according to the spatial distribution of core area patches (Figure 2). These include Luotian Forest Park, Dapingzhang Forest Park, Xili Lake Greenway, Shiyan Wetland Park, Nanshan Park, Changlingpi Reservoir, Pinghu Ecological Park, Sanlian Country Park, Qinglinjing Forest Park, Pingshan Huangzhu Reservoir, Songzikeng Forest Park, and Yanziling Park. Using circuit theory, 20 new ecological corridors were planned (Figure 8) to connect the newly added ecological sources with the existing ones. In subsequent urban planning, emphasis should be placed on the development of these new ecological sources and corridors to improve landscape connectivity. This will facilitate the flow of ecological processes from well-connected regions into areas lacking ecological networks, promote cyclical ecological flows across Shenzhen, and enhance the stability of ecosystems and biodiversity throughout the city.

The stability of ecological corridors is affected by external activities and internal conditions. Longer corridors are more vulnerable to external disturbances, reducing their stability. Connectivity between western and central parts, as well as central and northern parts of the Shenzhen City Area, is relatively low. Ecological resistance is high, and ecological sources are distant. Breaks have occurred in some ecological corridors, making the

construction of stepping stones urgent. To address issues such as excessively long corridors, dead-end routes, and high migration volumes at corridor intersections, 18 stepping stones were added at ecological corridor connections (Figure 8 and Table 5). This helps enhance the success of species dispersal and migration. Furthermore, animal movement is affected by urban roads during migration. Ecological breakpoints occur where ecological corridors and road networks intersect. These areas impact local biological flow, hinder migration processes, and reduce migration survival rates. This study integrated transportation networks and identified 16 ecological breakpoints (Figure 8). Urban road planning should consider establishing passages for species migration or avoiding migration routes. Examples include building elevated bridges to preserve original green pathways and creating green underground passages for wildlife. These measures can restore ecological breakpoints and minimize the impact of urban roads on the ecological network.

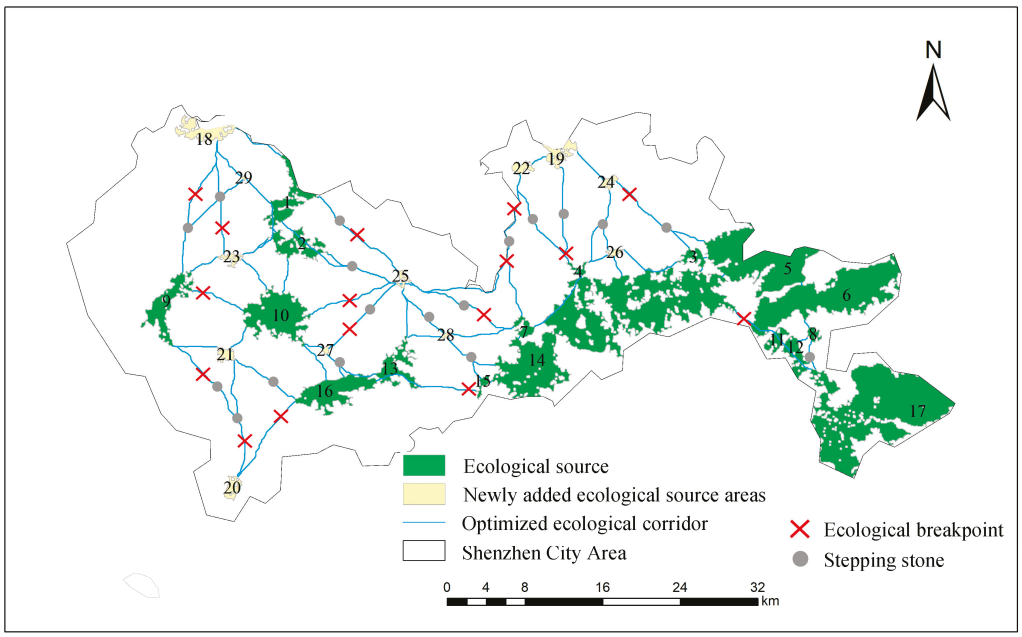


Figure 8. Shenzhen Ecological Network Optimization.

Table 5. Comparison of Shenzhen's Ecological Network Before and After Optimization.

Category	Optimized State	Quantity	Area (km^2)	Length (km)	Current Density (A)
Ecological sources	Before optimization	17	352.50	-	-
	After optimization	29	415.98	-	-
Ecological corridor	Before optimization	26	-	127.44	-
	After optimization	46	-	358.73	-
Ecological pinch point	Before optimization	0	0	-	-
	After optimization	120	41.64	-	-
Ecological barrier	Before optimization	0	0	-	-
	After optimization	26	27.87	-	-
Ecological network current density	Before optimization	-	-	-	10.60
	After optimization	-	-	-	20.50

3.5.2. Functional Evaluation of the Ecological Network Based on Circuit Theory

As shown in Figure 8, before optimization, the ecological flow from surrounding ecological sources to high-density urban areas was limited. It was mainly concentrated in Luohu District and Dapeng New District. The ecological flow between source 6 and source 11 was strong. These two ecological sources are close to each other, facilitating easier dispersal. Ecological sources between source 2 and source 4 were relatively scattered.

Sources 10, 16, 13, and 15 acted as important stepping stones, exhibiting strong ecological flow. Overall, the distribution of ecological flow was uneven before optimization. The limited flow reaching high-density urban areas restricted the service scope and capacity of ecological sources. After optimization, the maximum current value increased from 10.60 to 20.50 (Figures 9 and 10 and Table 5), showing a significant improvement in current density. Ecological flows from surrounding sources spread along the optimized network. More flow now passes through central urban areas like Guangming, Nanshan, Longhua, and Longgang Districts. This demonstrates that the optimized ecological network successfully channels ecological flow into central urban areas of Shenzhen. It promotes biological movement and is highly significant for improving urban habitat quality.

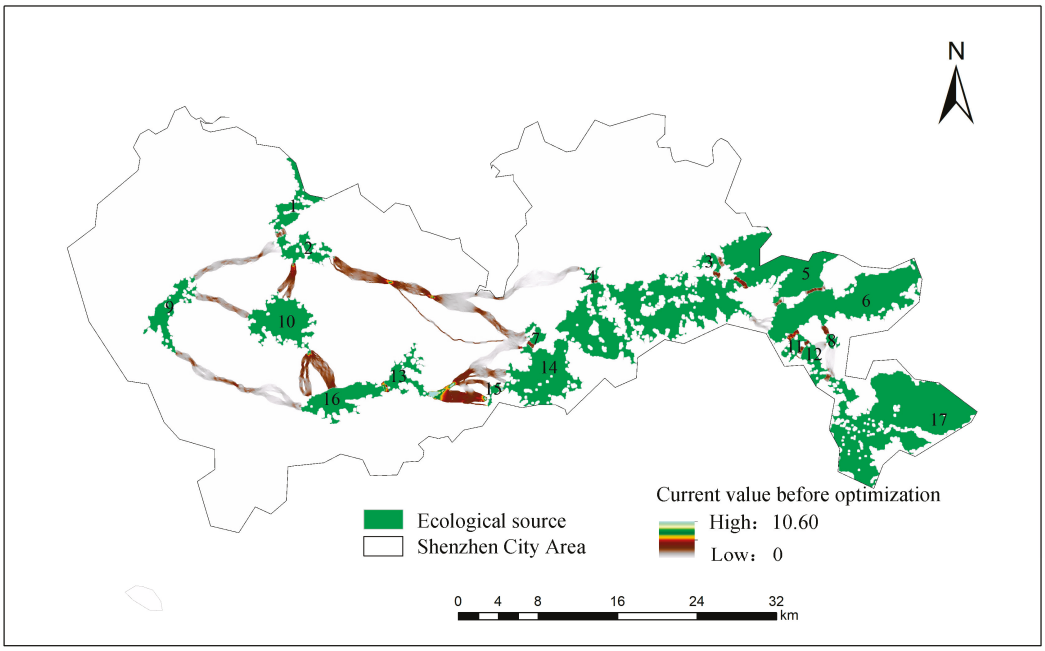


Figure 9. Current distribution diagram of Shenzhen's ecological network prior to optimization.

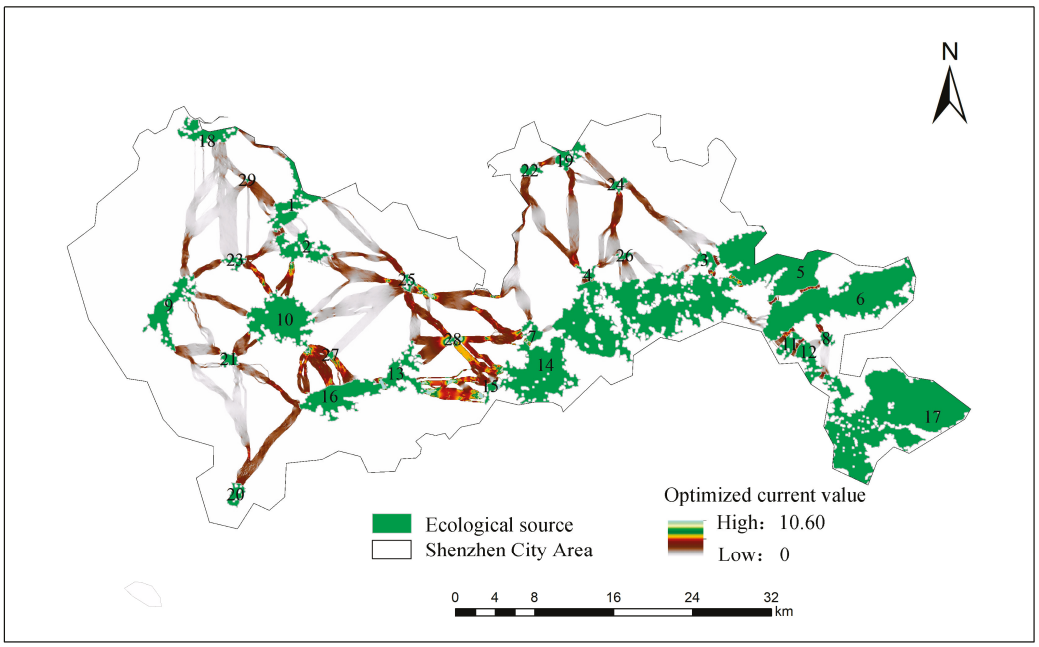


Figure 10. Current distribution map of Shenzhen's ecological network after optimization.

4. Discussion

The construction of ecological networks not only maintains regional natural ecological processes and protects the integrity and connectivity of landscape structure, but also secures the supply of ecosystem services required for regional socio-economic development. This study utilized Morphological Spatial Pattern Analysis (MSPA) to identify ecological sources and constructed a resistance surface by integrating natural and social factors. Ecological corridors, ecological pinch points, and ecological barriers were extracted using circuit theory to establish the ecological network. Overall, the landscape integrity and connectivity in the Shenzhen City Area are relatively low. Functions such as water conservation and soil retention are not prominent. Issues include uneven spatial distribution of ecological sources and localized fragmentation. In particular, densely distributed roads and urban built-up areas within ecological sources fragment natural landscapes. This disrupts gene exchange between populations, hinders the normal flow of materials and energy within the ecosystem, and affects its stability and ecological service functions. It is recommended to continue implementing natural forest protection projects and farmland-to-forest conversion programs in the transition zones between urban built-up areas and forestlands in northeastern, central, northwestern, and southwestern parts of the Shenzhen City Area. Efforts should focus on integrating dispersed ecological sources in western and central regions. Ecological restoration projects should be prioritized in areas with numerous barriers to enhance the integrity of natural ecological units.

Compared to previous studies [54,55], this research incorporates Morphological Spatial Pattern Analysis (MSPA) into source identification. Unlike conventional methods that extract ecological sources based on habitat quality or ecosystem service functions using the InVEST model [55], Morphological Spatial Pattern Analysis (MSPA) places greater emphasis on structural connectivity. It comprehensively considers landscape structural integrity and connectivity by identifying seven landscape types with connective importance [56], and is less affected by spatial scale. The analytical mechanism and identification process of Morphological Spatial Pattern Analysis (MSPA) complement those of the InVEST model, significantly improving the accuracy of source identification [57]. Furthermore, considering that ecological sources primarily serve as terrestrial animal habitats, this study placed particular emphasis on patch size and land use type during source identification. Compared to other ecological source extraction methods [58], this approach demonstrates better generalizability for constructing ecological networks across different regions. Additionally, during the construction of the resistance surface and extraction of corridors, multiple factors were comprehensively considered in line with the characteristics of Shenzhen City Area, including land use type, human activity intensity, and natural environmental features. Ecological corridors were extracted using random walk theory, which effectively simulates the complexity and randomness of species migration paths. This method fully accounts for corridor redundancy, more accurately reflects corridor width and importance levels, thereby enhancing the scientific rigor and precision of the study. Moreover, connectivity analysis based on circuit theory forms a critical component of ecological network construction. It enables the identification of spatially explicit elements such as ecological corridors, pinch points, and barriers through current values, independent of corridor width constraints. This approach breaks the homogenization limitations inherent in least-cost path methods for ecological corridors, providing more specific basis for ecological restoration and planning while effectively reducing subjectivity in functional zoning of ecological security patterns.

Although this study has achieved certain innovations and breakthroughs, some shortcomings remain that require further refinement in future research. The optimization strategy proposed in this study is primarily based on the necessity and feasibility of ecological principles, emphasizing the enhancement of ecological functions, and has not yet

incorporated an explicit cost–benefit assessment system. While the current strategy implicitly accounts for migration costs between land types through resistance surfaces, it fails to quantify economic inputs such as land acquisition, vegetation restoration, and engineering implementation associated with establishing new source areas or corridors. It also neglects the complexity of management coordination. To address this, future research should build upon the existing optimized framework by integrating socioeconomic data—including land prices, development intensity, and ecological conservation redlines—to construct a dual-dimensional "ecological benefits–implementation costs" evaluation model. This will assess the feasibility of ecological network optimization and facilitate the substantive implementation of optimization strategies. Specific measures include: At the ecological objective level, quantifying the ecological functional value of the ecological network based on species migration requirements, landscape connectivity indices, and ecosystem service values; At the economic objective level, generate high-resolution land price grids using real estate transaction data. Combine spatial land price interpolation models, construction land simulation, and building density to construct a composite resistance surface of land prices and development pressure. Assign differentiated resistance weights to areas of high economic value and high development intensity, while introducing development pressure threshold constraints. Employing a multi-objective particle swarm optimization algorithm under spatial constraints, we derive a Pareto optimal solution set to balance the linear relationship between ecological network planning and development costs. Finally, through scenario simulation analysis examining the impact of varying policy intensities on optimization outcomes, this study identifies the sensitivity ranges of key variables. It provides planners with dynamic decision support that balances ecological security patterns, land use efficiency, and socioeconomic benefits. This approach advances ecological network planning toward the coordinated development of a multidimensional, integrated "ecological–economic–social" system, ensuring both the scientific rigor of planning proposals and the feasibility of their implementation. By incorporating economic feasibility analysis, this study's optimization scheme evolves from a purely ecological feasibility framework into a decision-support tool that integrates scientific rigor, economic viability, and operational feasibility. This transformation not only enhances the implementation prospects of planning schemes but, more importantly, establishes a scientific framework capable of seeking a dynamic equilibrium between ecological conservation and urban development.

Moreover, this study focused solely on the static identification and optimization potential of the current ecological network in Shenzhen City Area, without investigating its spatiotemporal evolution. This limits the ability to identify degradation trends, such as the shrinkage of ecological sources, fragmentation of corridors, or disappearance of pinch points. Static analysis also fails to reveal the cumulative impacts of rapid urban expansion on the ecological network, weakening the capacity to anticipate future pressures. Future studies should incorporate multi-temporal remote sensing data to analyze the evolutionary trajectory and driving mechanisms of the ecological network. This would support a shift from "current-state optimization" to "dynamic adaptive planning," enhancing the resilience and long-term sustainability of the ecological network. This study constructs an ecological network using Morphological Spatial Pattern Analysis (MSPA) and circuit theory. It simulates terrestrial species migration influenced by landscape patterns and land use. The optimization targets species that depend on connected woodland habitats. While water bodies and woodlands were included as ecological sources, the study does not create separate networks for aquatic species or migratory birds. Future research could integrate river connectivity models and bird migration routes. This would support the development of a multi-species ecological network. Furthermore, this study focuses on the construction and optimization of ecological networks. Future research should build upon this foundation

to explore implementation-oriented phased development pathways for ecological networks and establish an adaptive management framework centered on "monitoring–evaluation–adjustment." It is essential to assess the optimized ecological networks from both economic and feasibility perspectives, thoroughly examining the practicality of their implementation. This represents a critical task for advancing the implementation of ecological networks and achieving sustainable urban development.

5. Conclusions

This study takes Shenzhen City Area, a special economic zone, as its research area. It applies Morphological Spatial Pattern Analysis (MSPA) and circuit theory to analyze landscape patterns and identify ecological sources. The importance levels of these sources were classified using landscape connectivity indices. Based on the constructed ecological resistance surface, ecological corridors were extracted, and their importance levels were defined. Ecological pinch points and barriers were also identified to construct the ecological network. The network was optimized by adding ecological sources, ecological corridors, stepping stones, and rehabilitating ecological breakpoints. Finally, the pre- and post-optimization ecological networks were evaluated from both structural and functional perspectives. The effectiveness of the optimization was verified by comparing current density values. This study aims to provide new perspectives and insights for urban planning, regional development, and ecological balance in Shenzhen City Area. The results indicate the following: (1) The land use types in Shenzhen City Area comprise seven landscape patterns: core, islet, perforation, edge, loop, bridge, and branch. The core area, with a total area of 426.69 km^2, is the largest among all types. It exhibits high fragmentation and poor connectivity, primarily distributed in the southeastern forested regions, showing a pattern of "dense in the east and west, sparse in the center." The edge area ranks second in size, serving as a buffer zone with high susceptibility to external disturbances. The bridge area covers 65.44 km^2, accounting for 9.31% of the foreground landscape. It functions as a potential structural corridor in the ecological network, facilitating connectivity. (2) A total of 17 ecological sources were identified based on ecological patch area screening, predominantly forested. These sources form an ecological barrier in the southeastern region, with a spatial distribution characterized by concentrated contiguous patches in the east and scattered patches in the west, resulting in an incomplete ecological network system. The northeastern, southwestern, northwestern, and parts of the central areas lack green spaces for wildlife habitats and activities. Future efforts should focus on adding stepping stones to improve ecological conditions. Based on landscape connectivity index analysis, the ecological sources were classified into 8 key sources, 5 important sources, and 4 general sources. Key sources occupy the largest area, provide significant ecosystem services, and experience minimal human disturbance. They include various large urban parks and protected natural areas. (3) The ecological resistance values in Shenzhen City Area range from 16.18 to 78.37, showing significant regional variation. Areas with high resistance are primarily characterized by urban built-up land, located in city centers and along transportation routes, where species migration and material flow are hindered. Using circuit theory, 26 ecological corridors were identified, forming an interconnected network. The western and eastern regions exhibit a transition from long and sparse to short and dense corridors. The eastern distribution is relatively stable, while connectivity is poor in the northeastern and northwestern regions, urgently requiring the construction of ecological corridors. Based on quantile classification, the corridors were categorized into 13 key corridors, 7 important corridors, and 6 general corridors. (4) A total of 120 ecological pinch points and 26 ecological barriers were identified in Shenzhen City Area. The pinch points cover a total area of 46 km^2, all located within ecological corridors, mostly

exhibiting linear distributions. Their land cover is predominantly forest, grassland, and water bodies. The ecological barriers cover a total area of 27.87 km^2, mainly consisting of farmland and urban built-up land, typically appearing as patches or linear strips. They are mostly situated at the edges or gaps between ecological sources. The optimization plan added 12 new ecological sources and planned 20 new ecological corridors. Eighteen stepping stones were incorporated at corridor junctions, and 16 ecological breakpoints were identified. Using circuit theory, a functional comparison between the pre- and post-optimization ecological networks showed the maximum current value increased from 10.60 to 20.50, indicating a significant improvement in current density. This demonstrates that the optimized network effectively channels ecological flows from sources into central urban areas, promoting biological movement. The ecological significance of this research is mainly reflected in four aspects: First, it contributes to biodiversity conservation and ecological corridor restoration. The newly added ecological source areas and ecological corridors provide stepping stones for species, repair ecological flow pathways, enhance the continuity of ecological patches, reduce migration risks, and provide a structural foundation for regional species exchange. Second, it helps improve ecosystem services and enhance nature's provisioning capacity. By optimizing the spatial configuration of ecological sources and corridors, the supply capacity of the urban natural environment is strengthened, indirectly improving ecosystem services such as water retention, soil conservation, and air purification, thereby increasing the resilience of the urban ecosystem. Third, it supports the construction of an ecological security pattern to mitigate ecological risks. The construction of the resistance surface helps identify hotspots where ecological flows are obstructed, providing a basis for defining "ecological redlines" in urban planning. The multi-level ecological structure of core–buffer–edge provides an ecological safety net for Shenzhen City Area to cope with uncertain climate challenges. Fourth, it guides sustainable urban development by balancing ecological protection and economic growth. The optimization of the ecological network not only restores the natural–social system but also upgrades the social system, providing green infrastructure for the city and delivering ecological benefits to residents.

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References

1. Shi, X.H.; Liang, K.Y. Construction of Ecological Security Pattern Based on Ecological Supply-Demand and Land Change: A Case Study of Jiangyin City, Jiangsu Province. *Res. Soil Water Conserv.* **2025**, *32*, 423–434.
2. Zhou, X.Y.; Di Lire, T.; Hou, M.L.; He, Y.; Ding, X. Assessing Land Carbon Metabolism in Hubei Section of Three Gorges Reservoir Area Based on Ecological Network. *Chin. J. Appl. Ecol.* **2025**, *36*, 2150–2158.
3. Ma, Z.Y.; Zhu, M.J.; Luan, B. Construction of Ecological Network in Guangdong-Hong Kong-Macao Greater Bay Area Based on ESV and Circuit Theory. *Ecol. Sci.* **2025**, *44*, 8–18. [CrossRef]

4. Liu, X.Q.; Huang, B. Construction of Urban Ecological Security Pattern Based on Multi-Source Data: A Case Study of Shenzhen. *Ecol. Sci.* **2025**, *44*, 241–253. (In Chinese)
5. Sallustio, L.; De Toni, A.; Strollo, A.; Di Febbraro, M.; Gissi, E.; Casella, L.; Geneletti, D.; Munafò, M.; Vizzarri, M.; Marchetti, M. Assessing habitat quality in relation to the spatial distribution of protected areas in Italy. *J. Environ. Manag.* **2017**, *201*, 129–137. [CrossRef]
6. Fu, W.X.; Gao, C.; Ren, G.Y.; Liu, D.-F. Construction of Composite Blue-Green Ecological Network in Wuhan Based on Complex Network Theory. *Chin. J. Appl. Ecol.* **2025**, *36*, 2139–2149.
7. Skokanová, H.; Netopil, P.; Havlíček, M.; Šarapatka, B. The role of traditional agricultural landscape structures in changes to green infrastructure connectivity. *Agric. Ecosyst. Environ.* **2020**, *302*, 107071. [CrossRef]
8. Feng, Y.L.; He, M.; Li, B.; Lei, J.; Ai, L. Construction and Optimization of Urban Ecological Network in Chongqing Main Urban Area. *Ecol. Environ. Sci.* **2025**, *34*, 699–709.
9. Liu, C.; Zhang, S.Q.; Huang, Y.Z.; Li, Y. Ecological Network Construction in Yunnan Province from the Perspective of Major Function-Oriented Zones. *J. Soil Water Conserv.* **2025**, *39*, 172–181+190. (In Chinese)
10. Kamusoko, C.; Gamba, J. Simulating urban growth using a random forest-cellular automata (RF-CA) model. *ISPRS Int. J. Geo-Inf.* **2015**, *4*, 447–470. [CrossRef]
11. Wang, X.Y.; Feng, Q.Y.; Wang, C.X.; Yan, Y. Construction of Ecological Security Pattern in Guangdong-Hong Kong-Macao Greater Bay Area Based on Ecological Adaptation Theory. *Acta Ecol. Sin.* **2025**, *45*, 5769–5782. (In Chinese)
12. Kowe, P.; Mutanga, O.; Dube, T. Advancements in the remote sensing of landscape pattern of urban green spaces and vegetation fragmentation. *Int. J. Remote Sens.* **2021**, *42*, 3797–3832. [CrossRef]
13. Ren, Y.J.; Lu, Y.H.; Jiang, W.; Li, T. Ecological Protection and Restoration Strategies of Territorial Space in Xianyang City Based on Ecological Network. *Sci. Surv. Mapp.* **2025**, *50*, 48–63.
14. Li, J.J.; Gu, Y.Y.; Xing, Z. Construction of "Biological Migration-Regional Cooling" Composite Functional Ecological Network in Wuhan Metropolitan Area. *Landsc. Archit.* **2025**, *32*, 96–104. [CrossRef]
15. Simpkins, C.E.; Dennis, T.E.; Etherington, T.R. Assessing the performance of common landscape connectivity metrics using a virtual ecologist approach. *Ecol. Model.* **2018**, *367*, 13–23. [CrossRef]
16. Wang, Z.L.; Qiao, J.J.; Liu, H.L.; Wang, G.; Feng, Y. Spatiotemporal Evolution and Optimization Strategies of Ecological Security Patterns in the Middle Reaches of the Yellow River of China. *Trans. Chin. Soc. Agric. Eng.* **2024**, *40*, 231–239.
17. De Montis, A.; Ganciu, A.; Cabras, M.; Bardi, A.; Mulas, M. Comparative Ecological Network Analysis: An Application to Italy. *Land Use Policy* **2019**, *81*, 714–724. [CrossRef]
18. Men, D.; Pan, J. Ecological Network Identification and Connectivity Robustness Evaluation in the Yellow River Basin under a Multi-Scenario Simulation. *Ecol. Modell.* **2023**, *482*, 110384. [CrossRef]
19. Rinaldo, A.; Gatto, M. River networks as ecological corridors: A coherent ecohydrological perspective. *Adv. Water Resour.* **2018**, *112*, 27–58. [CrossRef]
20. Zeng, W.; He, Z.; Bai, W.; He, L.; Chen, X.; Chen, J. Identification of Ecological Security Patterns of Alpine Wetland Grasslands Based on Landscape Ecological Risks: A Study in Zoigê County. *Sci. Total Environ.* **2024**, *928*, 172302. [CrossRef]
21. Peng, J.; Yang, Y.; Liu, Y.; Hu, Y.; Du, Y.; Meersmans, J.; Qiu, S. Linking Ecosystem Services and Circuit Theory to Identify Ecological Security Patterns. *Sci. Total Environ.* **2018**, *644*, 781–790. [CrossRef]
22. Chen, X.; Kang, B.; Li, M.; Du, Z.; Zhang, L.; Li, H. Identification of Priority Areas for Territorial Ecological Conservation and Restoration Based on Ecological Networks: A Case Study of Tianjin City, China. *Ecol. Indic.* **2023**, *146*, 109809. [CrossRef]
23. Bombrun, M.; Dash, J.P.; Pont, D.; Watt, M.S.; Pearse, G.D.; Dungey, H.S. Forest-Scale Phenotyping: Productivity Characterisation Through Machine Learning. *Front. Plant Sci.* **2020**, *11*, 99. [CrossRef]
24. Li, C.; Su, K.; Liang, X.; Jiang, X.; Wang, J.; You, Y.; Wang, L.; Chang, S.; Wei, C.; Zhang, Y.; et al. Identification of Priority Areas to Provide Insights for Ecological Protection Planning: A Case Study in Hechi, China. *Ecol. Indic.* **2023**, *154*, 110738. [CrossRef]
25. Song, S.; Gong, Y.; Yu, Y. Integrating Pattern, Process, and Function in Urban Landscape Ecological Network Planning: A Case Study of Harbin Central City. *Ecol. Indic.* **2024**, *159*, 111671. [CrossRef]
26. Rosales, F.O.; Fath, B.; Llerena, G. Quantifying a Virtual Water Metabolic Network of the Metropolitan District of Quito, Ecuador Using Ecological Network Methods. *J. Ind. Ecol.* **2023**, *27*, 1304–1318. [CrossRef]
27. Liu, W.; Xu, H.; Zhang, X.; Jiang, W. Green Infrastructure Network Identification at a Regional Scale: The Case of Nanjing Metropolitan Area, China. *Forests* **2022**, *13*, 735. [CrossRef]
28. Huo, J.; Shi, Z.; Zhu, W.; Li, T.; Xue, H.; Chen, X.; Yan, Y.; Ma, R. Construction and Optimization of an Ecological Network in Zhengzhou Metropolitan Area, China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 8066. [CrossRef]
29. Zhao, Y.; Xia, J.; Xu, Z.; Zou, L.; Qiao, Y.; Li, P. Impact of Urban Expansion on Rain Island Effect in Jinan City, North China. *Remote Sens.* **2021**, *13*, 2989. [CrossRef]
30. Vlková, K.; Zýka, V.; Papp, C.-R.; Romportl, D. An Ecological Network for Large Carnivores as a Key Tool for Protecting Landscape Connectivity in the Carpathians. *J. Maps* **2023**, *20*, 2290858. [CrossRef]

31. Wang, F.; Gao, H.; Liu, J.; Fu, T.; Qi, F.; Gao, Y.; Zhao, L. Study on the Characteristics of Ecological Network and Critical Areas of Ecological Restoration in Hebei-Tianjin Coastal Wetlands. *Wetlands* **2024**, *44*, 24. [CrossRef]
32. Johnston, S.; Good, R. The Benefits of Restored Linear Vegetation Corridors for Biodiversity Conservation: A Case Study. *Australas. Plant Conserv. J. Aust. Netw. Plant Conserv.* **2016**, *24*, 22–24. [CrossRef]
33. Yang, H.Y.; Xiu, C.; Li, L.L.; Ye, Y.H.; Chen, Y.L. Construction of Ecological-Urban Network Pattern for Ecological Synergy in Bay-Area Urban Agglomeration: A Case Study of Guangdong-Hong Kong-Macao Greater Bay Area. *Acta Ecol. Sin.* **2024**, *44*, 11049–11064. (In Chinese)
34. Modica, G.; Praticò, S.; Laudari, L.; Ledda, A.; Di, F.S. Implementation of multispecies ecological networks at the regional scale: Analysis and multi-temporal assessment. *J. Environ. Manag.* **2021**, *289*, 112494. [CrossRef]
35. Liu, M.; Wang, Q.; Liang, G.; Liu, M.; Hu, X.; Lin, S.; Wu, Z. Construction of an Ecological Security Pattern Based on the PLUS and MSPA Models: A Case Study of the Fuzhou Metropolitan Area. *Sustainability* **2025**, *17*, 5830. [CrossRef]
36. Song, Y.; Li, M.; Duo, L.; Chen, N.; Lu, J.; Yang, W. Multi-Scenario Simulation and Assessment of Ecological Security Patterns: A Case Study of Poyang Lake Eco-Economic Zone. *Sustainability* **2025**, *17*, 4017. [CrossRef]
37. Guo, S.; Zhang, Q.T.; Cui, Y. Spatiotemporal Evolution and Optimization of Ecological Network in Rapidly Urbanizing Area of Nanning. *Chin. Landsc. Archit.* **2025**, *41*, 125–131. (In Chinese)
38. Cao, W.J.; Yang, Q.K.; Jia, G.X.; Bai, H.; Guo, Z.; Wang, Z.; Wang, L.; Wen, L. Construction and optimization of ecological network based on ecological vulnerability in Ulanqab, Inner Mongolia, China. *Chin. J. Appl. Ecol.* **2025**, *36*, 376–382.
39. Pan, Y.; Yang, T.; Gong, J. Identification of Ecological Restoration Areas Based on "Ecological Quality-Ecological Network" Framework: A Case Study of Wuhan. *China Land Sci.* **2024**, *38*, 129–142. (In Chinese)
40. Zou, C.; Tang, X.; Tan, Q.; Feng, H.; Guo, H.; Mei, J. Constructing Ecological Networks for Mountainous Urban Areas Based on Morphological Spatial Pattern Analysis and Minimum Cumulative Resistance Models: A Case Study of Yongtai County. *Sustainability* **2024**, *16*, 5559. [CrossRef]
41. Fábos, J.G. Green way plann in gin the United States: Its origins and recent case studies. *Landsc. Urban Plan.* **2004**, *68*, 321–334. [CrossRef]
42. Ford, A.T.; Sunter, E.J.; Fauvelle, C.; Bradshaw, J.L.; Ford, B.; Hutchen, J.; Phillipow, N.; Teichman, K.J. Effective corridor width: Linking the spatial ecology of wildlife with land use policy. *Eur. J. Wildl. Res.* **2020**, *66*, 69. [CrossRef]
43. Díaz, S.; Settele, J.; Brondízio, E.S.; Ngo, H.T.; Agard, J.; Arneth, A.; Balvanera, P.; Brauman, K.A.; Butchart, S.H.; Chan, K.M.; et al. Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* **2019**, *366*, eaax3100. [CrossRef]
44. Klar, N.; Herrmann, M.; Henning-Hahn, M.; Pott-Dörfer, B.; Hofer, H.; Kramer-Schadt, S. Between ecological theory and planning practice: (Re-) Connecting forest patches for the wildcat in Lower Saxony, Germany. *Landsc. Urban Plan.* **2012**, *105*, 376–384. [CrossRef]
45. Zhang, L.; Lin, X.H.; Ge, S.; Zhao, P.; Zhang, M.; Li, Y. Formation Mechanism and Evolution Characteristics of Cultivated Land Carbon Flow Ecological Network in Hubei Province Under "Dual Carbon" Goals. *Acta Ecol. Sin.* **2025**, *45*, 1599–1612. (In Chinese)
46. Zhang, L.X.; Chai, B.; Zhang, Y.; He, W.; Tan, X. Comparative Study of Ecological Networks Based on Gravity Model and Circuit Theory: A Case Study of Jining City. *Acta Ecol. Sin.* **2025**, *45*, 1684–1696. (In Chinese)
47. Huang, J.; Huang, Y.Z. Regional Ecological Network Construction in Wenshan Prefecture Based on InVEST-MSPA. *Environ. Monit. Manag. Technol.* **2024**, *36*, 41–46. (In Chinese)
48. Lian, H.G.; Liu, C.F.; Ni, B.W.; Qu, Z. Ecological Network Construction and Optimization of Protected Area System in Arid Northwest China: A Case Study of Hexi Corridor. *Chin. J. Appl. Ecol.* **2025**, *36*, 259–270.
49. Fortin, M.-J.; Dale, M.R.T.; Brimacombe, C. Network ecology in dynamic landscapes. *Proc. R. Soc. B* **2021**, *288*, 20201889. [CrossRef]
50. Opdam, P.; Steingröver, E.; van Rooij, S. Ecological networks: A spatial concept for multi-actor planning of sustainable landscapes. *Landsc. Urban Plan.* **2006**, *75*, 322–332. [CrossRef]
51. Zhou, Y.; Liu, M.Y.; Wang, L.N.; Yu, J.; Luo, Q. Ecological Restoration Strategy of Territorial Space Based on Comparative Optimization of Ecological Network. *Chin. Landsc. Archit.* **2024**, *40*, 43–49. (In Chinese)
52. Liu, C.F.; Ni, B.W.; Lian, H.G.; He, Y. Resilience Evolution and Enhancement Strategy of Ecological Network in Arid Inland River Basin: A Case Study of Shiyang River Basin. *J. Nat. Resour.* **2024**, *39*, 2087–2101. (In Chinese)
53. She, Y.C.; Chen, C.L.; Mao, S.Z.; Tan, J. Construction and Optimization of Ecological Network in Core Area of Changsha-Zhuzhou-Xiangtan Based on MSPA-Linkage Mapper. *For. Grassl. Resour. Res.* **2024**, *4*, 60–69. (In Chinese)
54. Keeley, A.T.H.; Beier, P.; Gagnon, J.W. Estimating landscape resistance from habitat suitability: Effects of data source and non-linearities. *Landsc. Ecol.* **2016**, *31*, 2151–2162. [CrossRef]
55. Terrado, M.; Sabater, S.; Chaplin-Kramer, B.; Mandle, L.; Ziv, G.; Acuña, V. Model development for the assessment of terrestrial and aquatic habitat quality in conservation planning. *Sci. Total Environ.* **2016**, *540*, 63–70. [CrossRef]

56. Yan, Y.; Chen, X.M.; Xie, Y.W.; Zeng, Z.; Wang, Z.; Xue, X.; Tan, D.; Li, X. Construction of Composite Green Space Ecological Network Under Multi-Objective Orientation: A Case Study of Central Urban Area of Quanzhou. *J. Ecol. Rural Environ.* **2025**, *41*, 308–322. (In Chinese)
57. Pan, Z.H.; Zhou, Y.; Yao, J.; Ning, S.; Luo, Y.; Wang, M. Optimization of Urban Thermal Environment Ecological Network Based on Morphological Spatial Pattern Analysis and Minimum Cumulative Resistance Model. *J. Zhejiang AF Univ.* **2024**, *41*, 1085–1093. (In Chinese)
58. Yang, G.R.; Jiang, G.G.; Zhou, J. Construction and Optimization of Landscape Ecological Pattern in Jialing River Basin Based on ESV-ERI-MCR Evaluation. *Bull. Soil Water Conserv.* **2024**, *44*, 124–135. (In Chinese)
59. Zhang, F.Q.; Wei, X.J.; Xie, M.R.; Zhong, S.; Chen, W.; Xia, Y. Nested Analysis of Ecological Network in Nanchang City Based on Comprehensive Identification of Multi-Scale Ecological Sources. *Res. Soil Water Conserv.* **2024**, *31*, 408–418. (In Chinese)
60. Pili, S.; Serra, P.; Salvati, L. Landscape and the city: Agro-forest systems, land fragmentation and the ecological network in Rome, Italy. *Urban For. Urban Green.* **2019**, *41*, 230–237. [CrossRef]
61. Cunha, N.S.; Magalhaes, M.R. Methodology for mapping the national ecological network to mainland Portugal: Aplanning tool towards a green infrastructure. *Ecol. Indic.* **2019**, *104*, 802–818. [CrossRef]
62. Harvey, E.; Gounand, I.; Ward, C.L.; Altermatt, F. Bridging ecology and conservation: From ecological networks to ecosystem function. *J. Appl. Ecol.* **2017**, *54*, 371–379. [CrossRef]
63. Hernandez, A.; Miranda, M.; Arellano, E.C. Landscape dynamics and their effect on the functional connectivity of a Mediterranean landscape in Chile. *Ecol. Indic.* **2015**, *48*, 198–206. [CrossRef]
64. Yang, W.Y.; Xu, Z.H.; Ye, H.Y.; Li, T. Impact of Road Infrastructure on Ecological Network in Guangdong-Hong Kong-Macao Greater Bay Area. *Chin. J. Appl. Ecol.* **2024**, *35*, 1653–1660.
65. Shen, Z.; Yin, H.W.; Kong, F.H.; Su, J.; Sun, H.; Li, J. Construction and Optimization of Egret Habitat Network in Nanjing Based on Habitat Clustering Analysis and Landscape Corridor Simulation. *Acta Ecol. Sin.* **2024**, *44*, 3303–3316. (In Chinese)
66. Xu, J.; Wang, D.R. Construction and Optimization of Ecological Network in Lanzhou-Xining Urban Agglomeration Based on Adaptive Cycle. *Arid Zone Res.* **2024**, *41*, 856–864.
67. Wang, Z.Y.; Gao, Y.; Li, F.; Cheng, C. Research Progress on Urban Ecological Space Under Territorial Spatial Planning. *Chin. Landsc. Archit.* **2024**, *40*, 22–28. (In Chinese)

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Linking Land Uses and Ecosystem Services Through a Bipartite Spatial Network: A Framework for Urban CO_2 Mitigation

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Abstract

Urban CO_2 mitigation strategies typically aim at particular zones or sectors but do not account for spatial interdependencies among different components within the city. Understanding how land uses emit within and across districts can reveal systemic leverage points for climate-resilient urban planning. This study applies a bipartite spatial network approach using high-resolution Urban Atlas land-use data and a hierarchical spatial framework for emissions and sequestration estimation. The approach links urban land uses to their emissions profiles, offering a structural view of how different areas interconnect within urban carbon dynamics, moving beyond fragmented emission accounting. Using the Reggio Calabria Functional Urban Area in Italy as a case study, the analysis identifies influential areas and emission-intensive land uses. Subsequently, using centrality metrics highlights the spatial units with strong connections to emission-dense land uses, marking them as points of intervention. Results show that although 53% of districts act as net carbon sinks, their sequestration capacity is outweighed by the intensity of a smaller group of emitter districts. Among these, five central districts (IDs 94, 82, 107, 108, and 72) emit over 500 million kg CO_2 per year, making them leverage points for systemic mitigation. The integration of bipartite spatial network and multiscale territorial analysis provides a replicable, data-driven framework for urban CO_2 mitigation. Ultimately, the study demonstrates that mapping emissions through spatial interdependencies enables planners to target interventions where localized action yields the greatest network-wide climate impact.

Keywords: bipartite spatial network analysis; urban ecosystem services; urban CO_2 mitigation; land use; Urban Atlas

1. Introduction

Urban areas are at the heart of the climate emergency, accounting for a large proportion of the global CO_2 emissions [1–3]. Cities consume a huge amount of energy and resources due to their economic growth and population growth drivers, which make them both contributors to and potential solutions for climate change [4–6]. This duality puts cities at the forefront of global ambitious climate policy; global and European agendas, like the EU's Green Deal and Fit for 55, Cohesion policy, and others place-based systemic responses to the challenge of decarbonization and spatial equity [7–10].

Yet, efficient urban CO_2 reduction continues to face methodological and empirical barriers, especially in bridging the emission data to applicable spatial planning solutions [11–13]. A common limitation in urban mitigation planning is to address emissions

in individual sectors or areas without consideration of the complex spatial interdependencies that drive emission patterns in the urban area [1]. Land-use types like residential zones and transport infrastructure do not operate in silos; their effects extend across multiple districts [14,15]. Failing to consider these linkages limits urban planners from being able to target the factors that influence emissions, or to intervene at their most effective locations [16].

Over the past decade, there have been several studies that examined urban CO_2 emissions through sectoral, land use, and spatial econometric approaches [16–20]. Most studies rely upon top-down inventories or activity-based energy models, which are robust from an aggregate level but do not provide spatial specificity for urban planning needs [21,22]. Existing work has employed geospatial modeling and remote sensing data to downscale emissions to local spatial scales [23–25]. However, these typically treat land uses as independent emission sources, overlooking the functional and relational drivers among spatial units that jointly shape dynamic emission patterns [26].

To complement emission reduction strategies, recent efforts have incorporated the ecosystem services perspective, particularly focusing on regulating services as a key component of nature-based solutions for mitigating urban environmental pressures such as climate change [3,17,18]. Among these regulating services is CO_2 sequestration. It is one of the important indicators to monitor environmental performance [19]. It measures the process of sequestering carbon from the air and accumulating it in ecosystem carbon pools, representing net carbon uptake over a given period of time [20,21]. Examining the balance between CO_2 sequestration and emissions reveals the spatial dynamics of carbon sources and sinks in urban environments, highlighting current environmental conditions and potential for mitigation [22,23].

Consequently, there is a need for an analytical framework that integrates these spatial interdependencies within urban areas while remaining compatible with existing land-use data. This research addresses that gap by proposing a network-based spatial analysis that models the urban CO_2 landscape as a system of interlinked functional relationships between spatial units and land uses [24].

Unlike conventional emission mapping that addresses each spatial unit in individual isolation, the bipartite spatial network formally captures relational dependencies between land-use functions and urban districts. This allows one to identify structurally significant areas whose mitigation would generate network-wide benefits, thus broadening the analytical horizon of urban carbon accounting.

The article uses a bipartite spatial network analysis interconnecting adopted spatial units of the urban CO_2 landscape: eco-districts as spatial planning and decision-making units, and land-use types as functional elements influencing emissions. By modeling emissions as a network of relationships between these two node types, weighted by emission intensity, the study identifies which eco-districts are most influenced by high-emission land uses and which land uses contribute the most to CO_2 emissions. These spatial units can then be explored in detail at the eco-community and eco-cell levels, as more granular spatial units to locate where targeted interventions could most effectively reduce emissions.

This study is part of larger research activities aiming to develop spatially explicit, data-driven methodologies towards integrating urban ecosystem services into urban planning. Here, the focus is on evaluating CO_2 emissions by using a bipartite spatial network analysis to examine the structural dependencies between land use and urban CO_2 emissions. The approach links eco-districts to specific land-use categories according to the proportional share of their emissions contribution and applies centrality measures to identify areas with the highest systemic influence potential.

Figure 1 outlines the full methodological workflow of the overall research project, covering data collection, CO_2 calculation, spatial modeling with the spatial Durbin model (SDM), and scenario interpretation. Within this broader framework, the present paper specifically develops a spatial network analysis to capture inter-district ecological interactions.

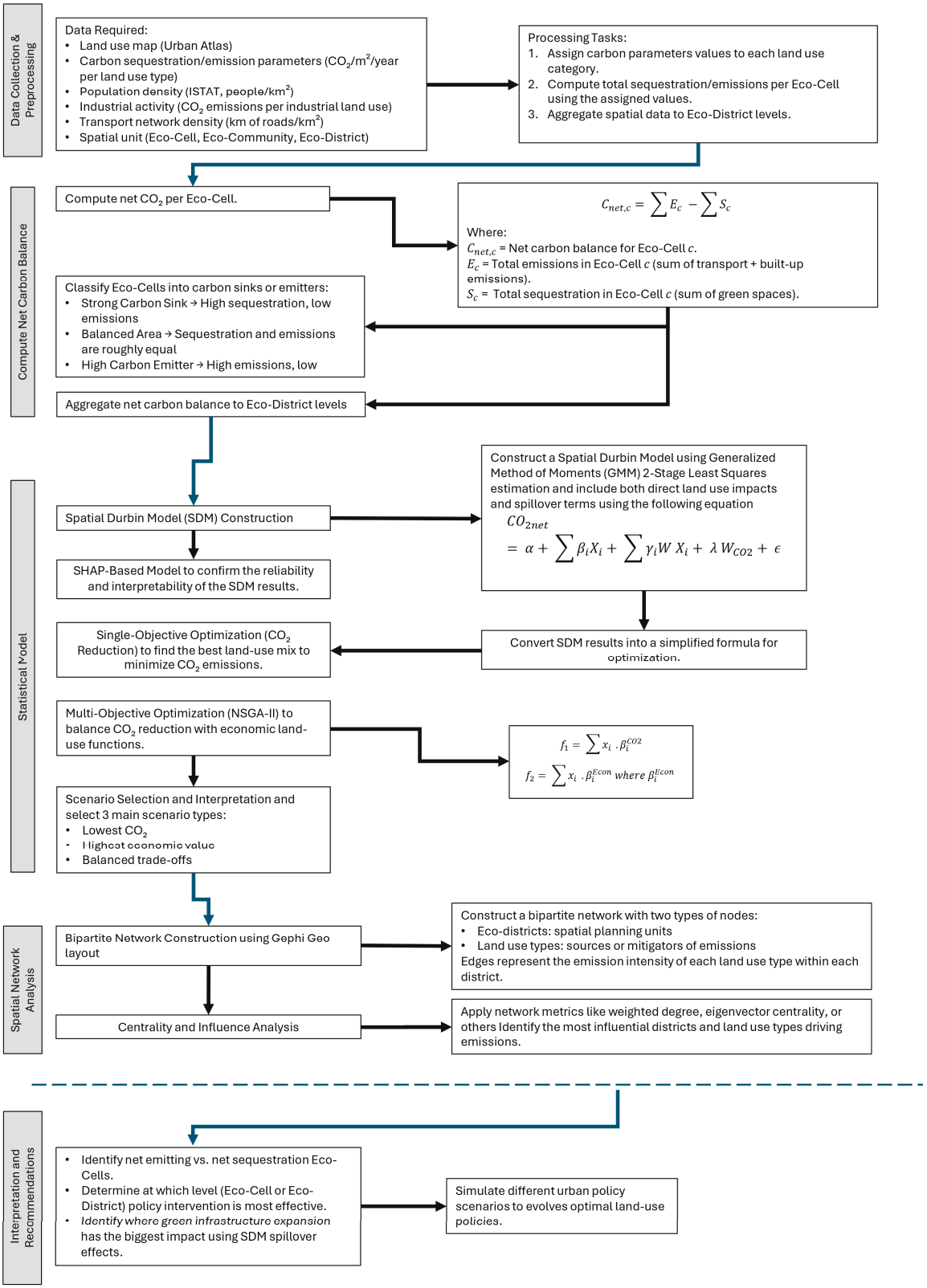


Figure 1. Workflow diagram of the research project methodology for modeling urban CO_2 emissions and spatial dynamics.

This study is guided by the following research question: How can a bipartite spatial network linking eco-districts and land-use categories be used to reveal structurally influential districts and pinpoint priority locations for targeted CO_2-mitigation in an urban area?

The bipartite spatial network model aims to address three analytical questions: (i) which eco-districts are structurally central to the urban CO_2 emission system, (ii) which land-use types most influence those districts, and (iii) how these interdependencies can inform spatial prioritization for mitigation. Within this framework, the network metrics are interpreted as follows: weighted degree reflects how strongly a district is connected to its neighbors through adjacency-based relationships; degree centrality indicates how embedded it is within the network of bordering districts; and eigenvector centrality captures its overall influence through connections with other key districts. Together, these indicators act as proxies for prioritizing interventions, translating network-derived insights into spatial planning actions.

To answer the main research question, the study concentrates on three primary objectives:

1. Create a bipartite spatial network connecting eco-districts and land-use types, weighting edges based on land-use-specific CO_2 emissions derived from Urban Atlas data and parameters identified in the literature.
2. Identify influential eco-districts and top-emitting land uses using centrality metrics to identify interdependencies that create emissions patterns.
3. Suggest intervention hotspots and recommend spatial actions.

We hypothesize that urban CO_2 emissions are not necessarily evenly distributed across space, nor are they merely a consequence of land-use intensity. Instead, spatial structure, connectivity, and functional roles within the built environment will influence in which locations the emissions will be concentrated and how mitigation resources need to be allocated.

The paper is organized as follows: Section 2 provides the background literature and theoretical foundations in spatial network analysis (SNA) and urban ecosystem services; Section 3 outlines methodology, data sources, network construction, and analytical approaches; Section 4 outlines results from the network; Section 5 provides the discussion with particular focus on planning implications; and Section 6 contains a conclusion and potential avenues for further research.

2. Literature Review

Recent scholarship highlights the role of ecosystem services, particularly regulating services, as the basis for nature-based solutions (NbS) to mitigate urban environmental pressures such as climate change [3,17]. Within this perspective, CO_2 sequestration has become as a key indicator of urban environmental performance, representing the net carbon uptake of ecosystems over time [18]. Several studies have highlighted that balancing CO_2 sequestration and emissions provides valuable insight into the spatial configuration of urban carbon sources and sinks, supporting the design of mitigation and adaptation strategies [21,22].

Urban mitigation strategies have further evolved through technological innovation, policy reforms, and the integration of NbS [25–27]. Research on the built environment underscores the importance of green and energy-efficient buildings, which account for nearly 40% of global energy-related CO_2 emissions [28]. Parallel studies in urban mobility highlight that enhancing public and active transport, supported by smart technologies, can significantly reduce urban emissions [29,30].

Yet, these approaches often remain sector-specific, and their application might be challenging, for example, in narrowing the gap between systemic understanding and local action and pointing out where land-use changes or design changes would have the most effect [31,32].

In response to this challenge, scholars increasingly investigate how emissions are structured by spatial interdependencies within cities [1,33,34]. Research is now working to uncover the spatial logic of emission sources, offering results that could underpin more targeted, place-specific mitigation responses, although such results still need to be better integrated into planning practice. This has led to an increasing recognition of the need for integrated approaches across sectors and spatial scales [35–38]. This would offer a foundation for addressing complex emission patterns. It also highlights the need for planning strategies that link high-level sustainability goals with operational, spatially specific interventions.

A study analyzing urban density and carbon emission performance in spatial terms identified a dynamic interaction between urban density and carbon performance with implications that increased density will result in more effective utilization of land as well as reduced emissions [39]. Similarly, research into the spatial patterns of the intensity of CO_2 emissions in urban areas highlighted the important role of road network length in shaping emission patterns [40].

Moreover, spatiotemporal analysis based on satellite imagery-based methods estimated the CO_2 emissions of cars, revealing different emission hotspots and time patterns [41]. Additionally, studies based on machine learning methods have revealed causal relationships between city form and car CO_2 emissions, pointing to the role of destination accessibility and street connectivity in determining emission rates [42].

Furthermore, land-use changes and urbanization have been identified as being significant sources of CO_2 emissions. An empirical study on land urbanization in China demonstrated that land-use intensity and structure change have direct effects on urban carbon emissions [43]. In addition, research on carbon metabolism in Beijing's urban zones emphasized how land-use changes from natural to artificial land components induced high emissions, while other land-use changes facilitated carbon sequestration [44].

Additionally, a study using a spatial Durbin model examined inter-city technology patent transfers in China, showing that technological progress in one city can impact carbon emissions in nearby areas [45]. Also, research on the coupling evolution of urbanization and carbon emissions in the Yangtze River Economic Belt found that urbanization levels and per capita emissions have strong spatial dependence and integration [46].

A growing body of research highlights the importance of nested spatial structures in promoting urban sustainability, in which planning entities at varying scales work to address both systemic broader effects and local interventions [47,48]. Studies also emphasize the value of spatial redundancy, diversity, and multi-scalar frameworks for boosting urban adaptive capacity [32].

This research uses a multiscale territorial strategy based on a hierarchical spatial framework inspired by the Sino-Singapore Tianjin Eco-City project [49]. The framework divides the study area into three spatial units: eco-cell (400 $\times$ 400 m), eco-community (800 $\times$ 800 m), and eco-districts (1600 $\times$ 1600 m). The eco-district serves as the main unit in our analysis, acting as a strategic planning tool to integrate different parts of the city for a systemic study of emissions patterns, land-use functions, and ecosystem services.

Although analysis is focused on the district scale in order to establish city-wide strategies, these lower units are necessary to illustrate how our findings can be scaled down for future, more localized action (see Figure 2). They provide a conceptual framework for identifying specific sites for micro-level interventions, such as tree planting or the introduction of pocket parks, should a more detailed analysis be required at some future point.

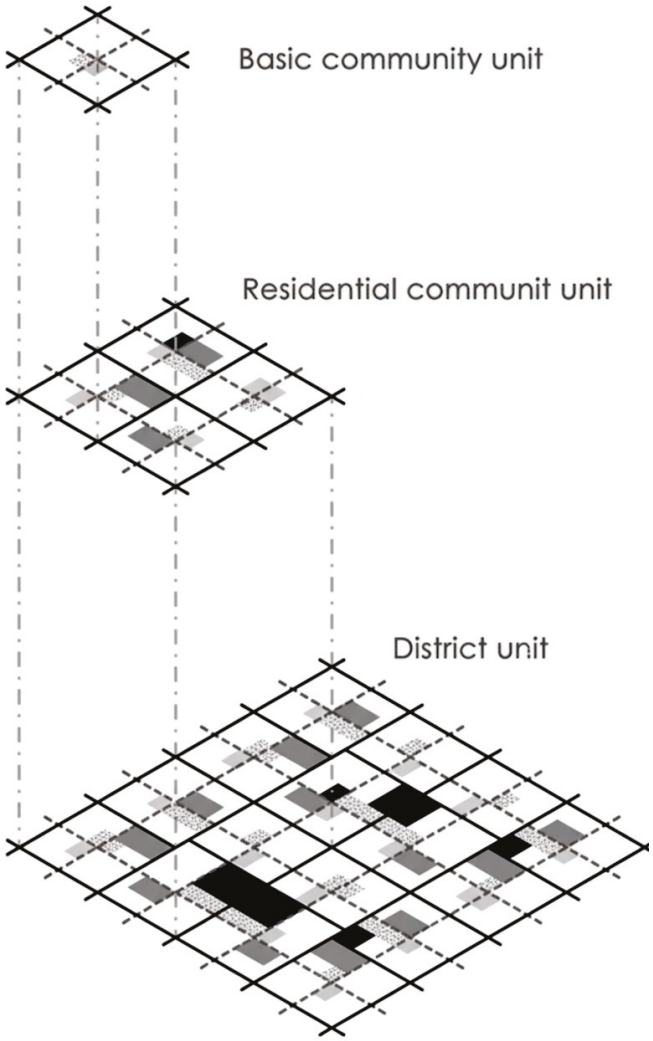


Figure 2. Hierarchical spatial framework for urban analysis.

The spatial structure identifies eco-districts as the unit of analysis at the primary scale. Eco-districts consist of various eco-cells, allowing for the investigation of aggregate land use and spillover impacts among contiguous areas.

Eco-District: District Unit

The eco-district is defined as 1600 m × 1600 m. This macro-scale analysis focuses on cumulative impacts and regional dynamics, such as overall carbon sequestration capacity. At the district level, we integrate findings to address large-scale challenges and opportunities.

Eco-Community: Residential community Unit

The eco-community is at this intermediate scale, where the exploration of the relations between pressures and impacts will be possible. This level specifies the areas where collective action can be used to increase the ecosystem services to the maximum.

Eco-Cell: Basic community unit

The eco-cell is a 400 m × 400 m square area. This scale is appropriate for examining localized dynamics and assessing how small-scale land use and ecological processes interact.

Eco-community and eco-cell are included within this framework to demonstrate how our findings can be scaled down. They represent an opportunity for a more granular assessment of localized dynamics for future work.

This multiscale approach reflects an increasing recognition in planning the literature of the need to connect regional or city-wide environmental strategies with operational planning tools

at the neighborhood or block level. It enables both a reading of broader emission trends and a capacity to implement spatially precise changes that respond to local dynamics.

To apply this framework, consistent land-use-based methods are required for estimating emissions and identifying priority areas. A growing body of research has taken this route, estimating CO_2 emissions for various land uses within the same year to allow for detailed spatial analysis and targeted mitigation.

For instance, a study by Shi et al. analyzed CO_2 emissions across different land uses in Shanghai's development zones [50]. Their findings indicated significant interactions between land-use mixing and CO_2 emissions, and the necessity of considering spatial configurations in emission reduction efforts [50]. Chuai et al. used terrestrial ecosystem modeling and auxiliary data to spatially simulate carbon emissions by land-use type, showing the functional impact of land-based patterns [51]. Similarly, Li et al. explored the connection between land-use diversity and emissions, identifying a correlation between urban land mixing and CO_2 outputs [52]. Morelli et al. conducted a spatiotemporal cluster analysis of greenhouse gas emissions in European NUTS-2 regions between 1990 and 2022, highlighting the spatial heterogeneity of emissions across sectors and land-use categories [53]. Baur et al., studying 52 European cities, found that urban sprawl and low-density development were associated with higher per capita emissions, while compact and fragmented dense urban forms performed more efficiently in terms of emissions [54].

Together, these studies reinforce the relevance of land-use-based CO_2 accounting and support the use of spatially explicit planning tools to advance data-driven, adaptive mitigation strategies. Yet, despite the fact that these approaches provide an understanding of emissions in detail, they do not necessarily look at how the various components of a city interact with one another.

While land-use-based emissions provide spatial understanding, it does not reveal how different locations interact within the urban area. To address this, this study uses a bipartite spatial network to analyze the relationship between eco-districts and land-use types based on CO_2 emissions. spatial network analysis (SNA) offers a suitable tool for examining complex relationships in urban systems [24]. This spatial network captures territorial units (eco-districts), on one side, and functional categories (land uses) on the other side, with edges connecting them based on their CO_2 emission contributions.

In this network, centrality metrics are used to measure a node's structural influence. High-centrality eco-districts are those strongly connected to land-use types that significantly contribute to urban CO_2 emissions. This means interventions in these districts can create widespread positive effects through the network's interdependencies and spatial spillovers. This approach moves the focus from static emission hotspots to dynamic influencers, offering a more strategic way to target place-specific mitigation efforts while prioritizing network position over specific locations.

A key takeaway of this approach is its potential to guide ecological compensation strategies in urban development, which involves redistributing or improving ecosystem services in areas lacking them by utilizing the capacity of areas with surplus provision [32].

This study applies these concepts in the Reggio Calabria FUA, Italy. The methodology section will illustrate how this framework identifies and links areas with surplus and deficit carbon performance.

3. Methodology

The study is conducted in the Reggio Calabria FUA, an urban area dealing with notable spatial and environmental issues. The choice of this urban setting offers an opportunity to test spatially targeted mitigation strategies in a context where emissions and ecosystem

service potentials vary across the area. Figure 3 shows the land-use map of Reggio Calabria FUA, retrieved from the Urban Atlas dataset [55].

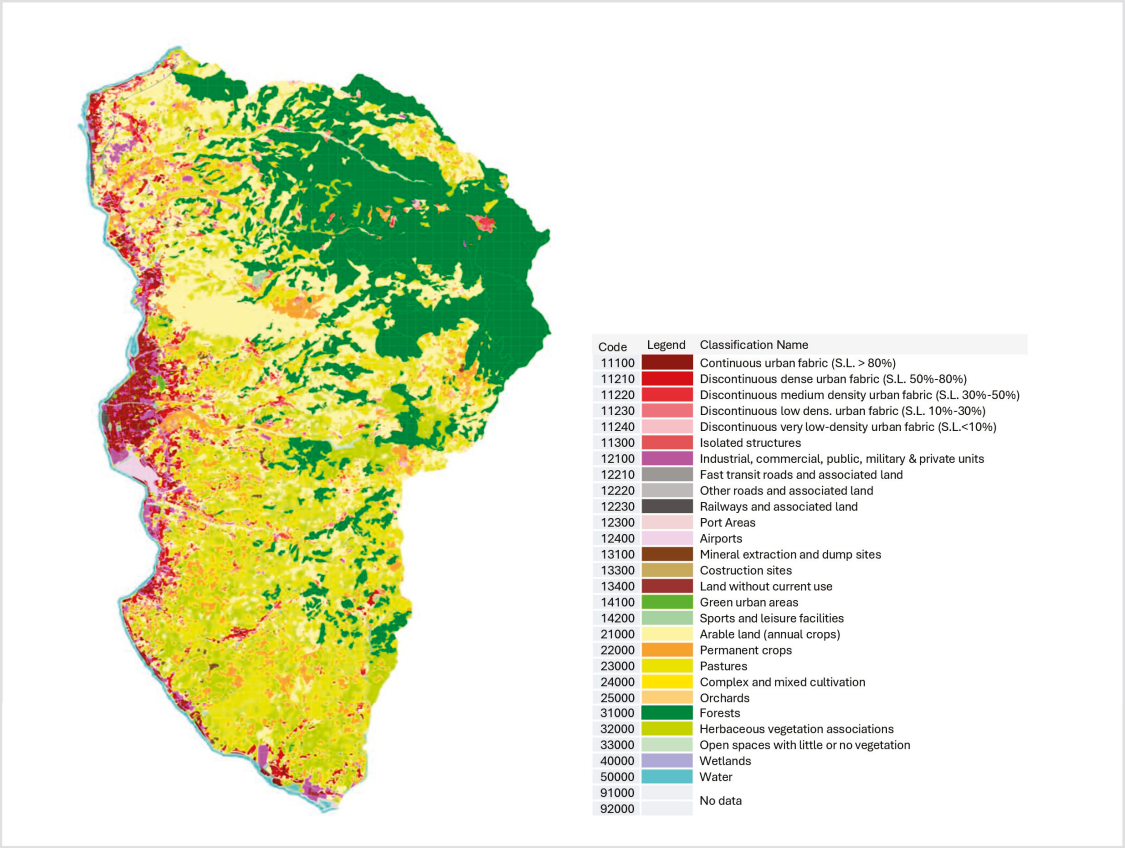


Figure 3. Land-use map of Reggio Calabria FUA, derived from the Urban Atlas dataset [55].

Urban Atlas, developed by the Copernicus Land Monitoring Service, offers standardized and detailed land-use classifications for European Functional Urban Areas. Although not a legal substitute for official zoning regulations, it generates a consistent spatial dataset to support uniform land-use analysis among different urban contexts. Urban Atlas data are used in this study as a proxy for land-use zoning because of its consistent classification and spatial resolution, and thus is particularly well-suited for comparative and analytical research. However, its minimum mapping unit (MMU) of 0.25 ha (2500 m^2) for urban classes and 1 ha (10,000 m^2) for rural classes is less than ideal for the functional analysis of urban ecosystem services. To address this gap, this study uses a hierarchical system of spatial units. This framework divides the territory into 232 eco-districts (1600 m $\times$ 1600 m).

The study primarily considers CO_2 emissions, but it is also necessary to consider CO_2 sequestration. This provides a clearer picture of the carbon footprint of the area. It allows for an understanding of how much carbon various land types can absorb, which indicates how the area can offset emissions.

Carbon metrics are utilized to estimate how much carbon can be absorbed and how much CO_2 is emitted for various land uses. This is based on values from the literature and national databases (Table 1). These parameters provide the average annual rates of absorption or emission for each land-use type, kilograms of CO_2 per square meter per year ($kgCO_2/m^2/year$). These rates were based on standardized coefficients from national datasets and the prior literature. Although this may overlook localized behavioral variations, it ensures methodological consistency and reproducibility across all spatial units.

Table 1. Land-use categories and CO_2 emission/sequestration coefficients.

Code	Classification Name	Parameter	Source
11100	Continuous urban fabric (S.L. > 80%)	37.5 kg $CO_2/m^2/yr \times 100\%$	[56]
11210	Discontinuous dense urban fabric (S.L. 50–80%)	37.5 kg $CO_2/m^2/yr \times 65\%$	
11220	Discontinuous medium density urban fabric (S.L. 30–50%)	37.5 kg $CO_2/m^2/yr \times 40\%$	
11230	Discontinuous low dens. Urban fabric (S.L. 10–30%)	37.5 kg $CO_2/m^2/yr \times 20\%$	
11240	Discontinuous very low-density urban fabric (S.L. < 10%)	37.5 kg $CO_2/m^2/yr \times 5\%$	
11300	Isolated structures	37.5 kg $CO_2/m^2/yr \times 1\%$	
12100	Industrial, commercial, public, military, and private units	62.8 kg $CO_2/m^2/yr$	
12210	Fast transit roads and associated land	Regional road transport CO_2 emissions downscaled to Reggio Calabria FUA, distributed per capita, then allocated to roads based on area.	
12220	Other roads and associated land		
12230	Railways and associated land	50 kg$CO_2/m^2/yr$	[57]
12300	Port Areas	Villa San Giovanni port emissions ~ 10,640 tCO_2/yr Reggio Calabria port emissions ~ 950 tCO_2/yr	[58]
12400	Airports	72,104 tCO_2/yr	Author's calculations based on data retrieved from the airport's official website (flight schedules and destinations), Flightradar24 (air traffic monitoring), and emission factors by destination/travel distance.
13100	Mineral extraction and dump sites	Landfills: 0.88–2.08 kg $CO_2/m^2/yr$	There are no active mining activities in Reggio Calabria [59,60]; therefore, the parameter applies only to landfills [61].
13300	Construction sites	9.31 kg CO_2/m^2	[62]
13400	Land without current use	0	
14100	Green urban areas	-1.06 kg $CO_2/m^2/yr$	[63]
14200	Sports and leisure facilities	75.9 kg $CO_2/m^2/yr$	[56]
21000	Arable land (annual crops)	-0.1 to -0.3 kg $CO_2/m^2/yr$	[64]
22000	Permanent crops	-0.22 to -2.17 kg CO_2 m^2 yr^1	[65,66]
23000	Pastures	-0.2 to -0.7 kg $CO_2/m^2/yr$	[64]
24000	Complex and mixed cultivation	-0.15 to -0.5 kg $CO_2/m^2/year$	
25000	Orchards	There are no Orchards in Reggio Calabria FUA	
31000	Forests	-1.36 kg $CO_2/m^2/yr$	[67–69]
32000	Herbaceous vegetation associations	-0.22 to -2.17 kg CO_2 m^2/yr	[70]
33000	Open spaces with little or no vegetation	0	
40000	Wetlands	There are no wetlands in Reggio Calabria FUA.	
50000	Water	Beaches: -0.007 kg $CO_2/m^2/year$	[71]
		Small lakes and ponds: -0.52 kg $CO_2/m^2/year$	[72]
		Rivers: -0.65 kg $CO_2/m^2/year$	[73]
91000	No data	0	
92000	No data	0	

To apply this framework, the Reggio Calabria FUA was divided into 232 Eco-Districts (see Figure 4). This primary unit of analysis is a 1600 m × 1600 m grid, which allows for a macro-scale focus on cumulative impacts and regional carbon dynamics, such as overall carbon sequestration capacity. While the analysis is centered on the district level to establish city-wide strategies, the smaller units—the eco-cell and eco-community—are included within this framework to provide a conceptual basis for demonstrating how findings can be scaled down for future, more localized interventions.

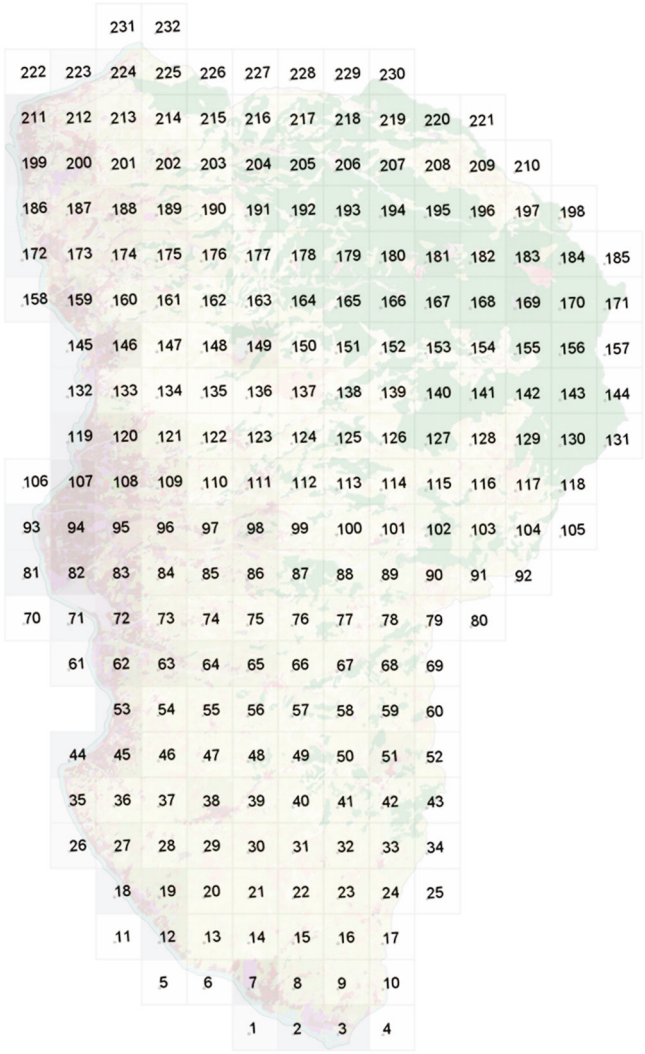


Figure 4. Map of eco-districts and their ID numbers in Reggio Calabria FUA.

Network Construction and Visualization

After calculating the CO_2 emissions for each eco-district, each land-use category, and for each land-use type within every eco-district, the resulting dataset was cleaned to remove all records with zero values to ensure analytical consistency. The processed data were then structured in two separate tables corresponding to the nodes and edges of the network.

The node table contained the following attributes: ID, sum (total CO_2 emissions), latitude, longitude, and type (distinguishing between eco-districts and land-use categories). The edge table included three columns: Source (eco-district ID), Target (land-use category), and Value (CO_2 emissions generated by that land-use type within the corresponding eco-district).

These two datasets were imported into Gephi (version 0.10.1), an open-source network analysis and visualization software, where they were integrated to form a bipartite spatial network linking eco-districts (spatial units) with land-use categories (functional units). Each connection (edge) in the network has a numerical value showing how much CO_2 is produced by that land-use type within a specific district.

A geo-layout was then generated in Gephi to spatialize the network, enabling each district node to be positioned according to its real-world geographic coordinates.

In this structure:

- There are two types of nodes:

- Eco-districts;
- Land-use categories.

- Nodes are weighted according to the total emissions of each eco-district or land-use category.
- Edges indicate the emissions contribution of each land-use type within an eco-district.
- The weights of the edges are determined by calculating the total CO_2 emissions generated by a land-use type in a specific district.

The final network was then exported and overlaid with the eco-district map of the Reggio Calabria FUA, to enable the spatial interpretation of emission relationships within the urban fabric.

To accurately analyze inter-district connectivity and ensure that the centrality metrics reflected relationships only among the eco-districts, the bipartite network was projected onto a single-mode network containing only the eco-district nodes, excluding the land-use categories. In this network, districts are connected when they share a common border, allowing the analysis of spatial relationships and adjacency effects influencing emission patterns.

Three centrality measures were computed to quantify the structural properties of the projected network:

- Degree centrality, representing the number of neighboring districts directly connected through shared borders;
- Weighted degree, expressing the total strength of adjacency-based connections for each district, reflecting the magnitude of emission linkages with its neighbors;
- Eigenvector centrality, measuring the overall influence of a district within the network, considering both its direct connections and the importance of its connected neighbors.

In this study, centrality metrics act as a proxy for prioritization, where higher values signal spatial units that are more connected within the urban system, suggesting that targeting these areas could have a bigger impact on reducing CO_2.

The next section will outline how this framework is applied to create specific scenarios for the Reggio Calabria FUA.

4. Results

The overall carbon dynamics of the Reggio Calabria FUA reveal an uneven distribution and a structurally imbalanced CO_2 profile. Table 2 presents a summary of the net CO_2 balance across all eco-districts within the Reggio Calabria FUA. The total CO_2 emissions produced by land-use activities across the study area are estimated at approximately 2.22 billion kilograms of CO_2 per year. On the other hand, the ecosystem-based sequestration capacity of the urban area, driven by green areas, is estimated at around -369 million kg of CO_2 per year (see Figures 5 and 6 for emissions and sequestration visualization in Reggio Calabria FUA). The total of these estimates reveals a net CO_2 balance of about 1.85 billion kilograms, emphasizing the substantial disparity between emissions and sequestration.

Table 2. Summary of net CO_2 balance for Reggio Calabria FUA.

Total CO_2 Emissions (million kg)	2222.49
Total CO_2 Sequestration (million kg)	−368.96
Net Emissions (million kg)	1853.53
Number of Eco-Districts	232
Number of Net Emitter Eco-Districts	109
Number of Net Sequestering Eco-Districts	123

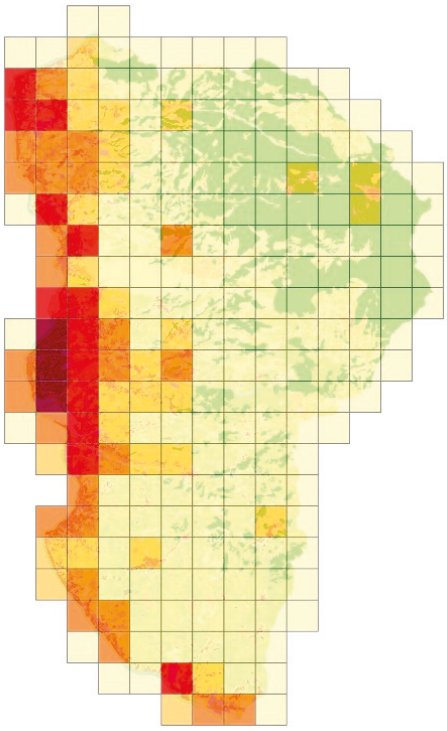


Figure 5. CO_2 emission map of Reggio Calabria FUA. The color gradient represents estimated CO_2 emission intensity for each eco-district, ranging from dark red (highest emissions) to light yellow (lowest emissions).

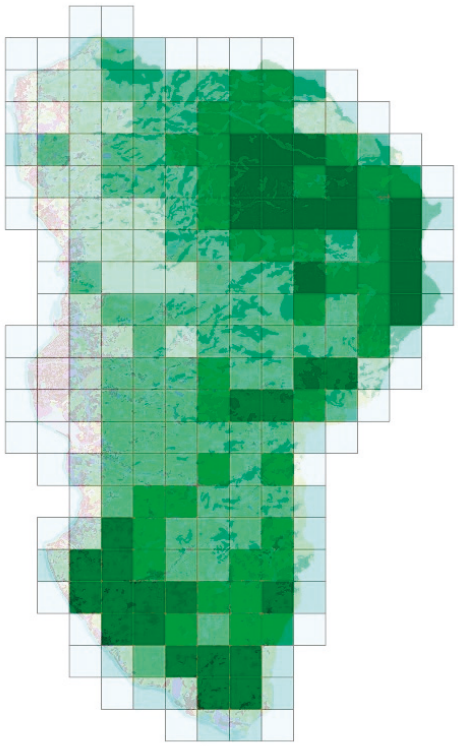


Figure 6. CO_2 sequestration map of Reggio Calabria FUA. The color gradient represents CO_2 sequestration capacity for each eco-district, where dark green areas indicate higher sequestration potential and light green areas indicate lower sequestration capacity.

Interestingly, examining the distribution of eco-districts shows that 123 eco-districts (53%) achieve net sequestration, while 109 eco-districts (47%) are net emitters. This indicates

that over half of these spatial units contribute to carbon mitigation, though often to a limited extent. However, the emission intensity in the net emitter cells is much greater than the sequestration capacity of the net sequestering cells. This disproportion implies that while green and semi-natural spaces are present, their spatial coverage is insufficient to counterbalance the dense and emission-heavy urban zones.

The bipartite spatial network model constructed between eco-districts and land-use types (Figure 7) reveals a highly uneven structure of emissions distribution across Reggio Calabria's urban fabric. By measuring the cumulative CO_2 emissions associated with each district's land-use configuration, we identified a subset of eco-districts that function as structural hubs within the emissions network.

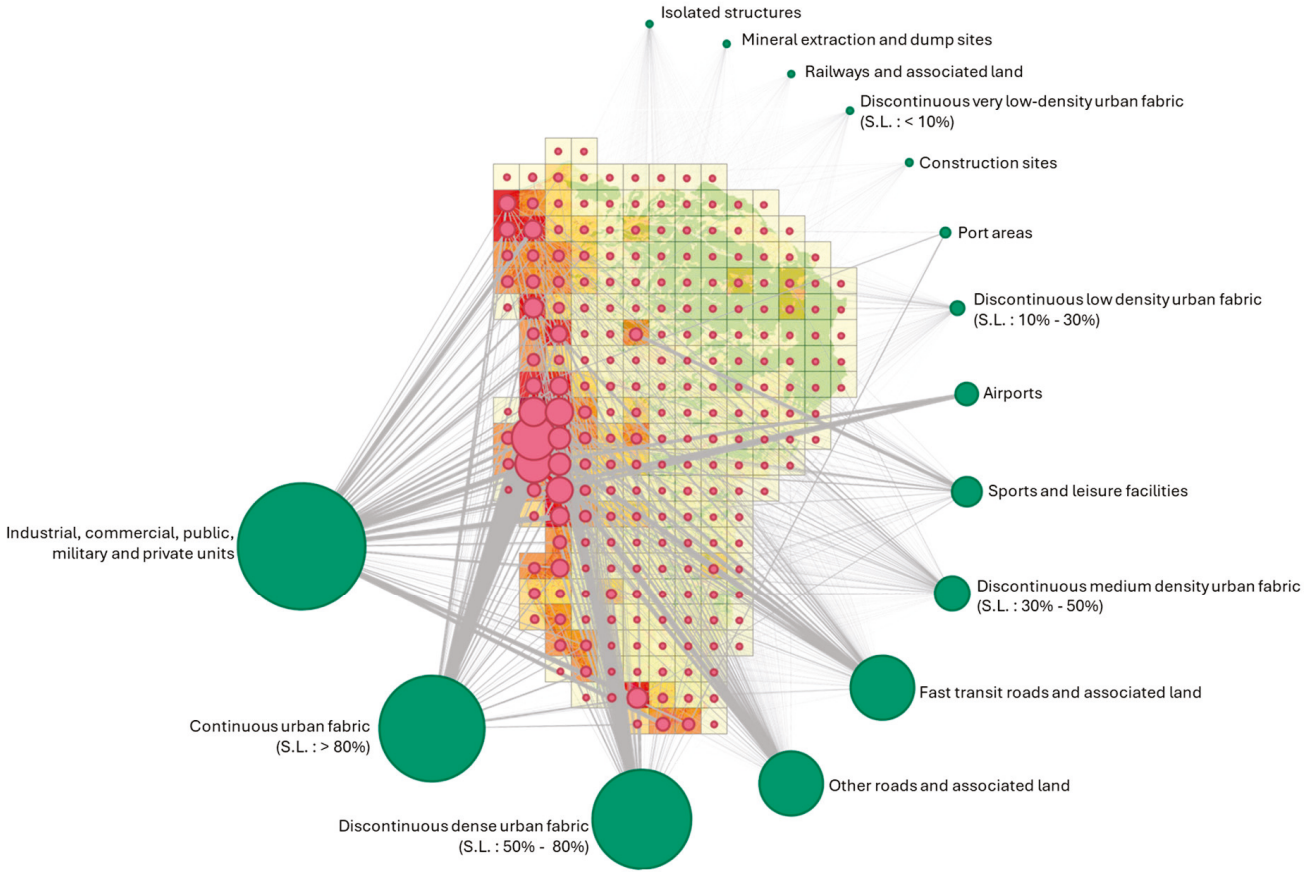


Figure 7. Network visualization of land-use contributions to CO_2 emissions across grid eco-districts over the thematic CO_2 emission map of Reggio Calabria FUA. Legend: Green nodes represent land-use categories and pink nodes represent eco-districts. Node size is proportional to CO_2 emissions (green: by land-use type; pink: by eco-district). Edge width indicates the emission share of each land-use type within a specific eco-district.

Among the 232 eco-districts examined, five are the largest emitters of CO_2 in the city. They are Districts 94, 82, 107, 108, and 72, with the highest emissions combined. Given that the city of Reggio Calabria is located on the west side of this grid, it is clear that the highest emissions will be concentrated in these western districts. Table 3 provides an overview of these districts, their primary land-use types, and indicates potential planning priorities. Figure 8 presents a close comparison of their emission profiles by land-use type, revealing consistent peaks among significant land use functions.

Table 3. The top 5 emission-intensive eco-districts.

Eco-District ID	Total Emissions (Million kg)	Most Dominant Land Use
94	165.8	Continuous urban fabric (S.L.: >80%)
82	133.9	Industrial, commercial, public, military, and private units
107	98.0	Continuous urban fabric (S.L.: >80%)
108	93.3	Continuous urban fabric (S.L.: >80%)
72	87.4	Airports

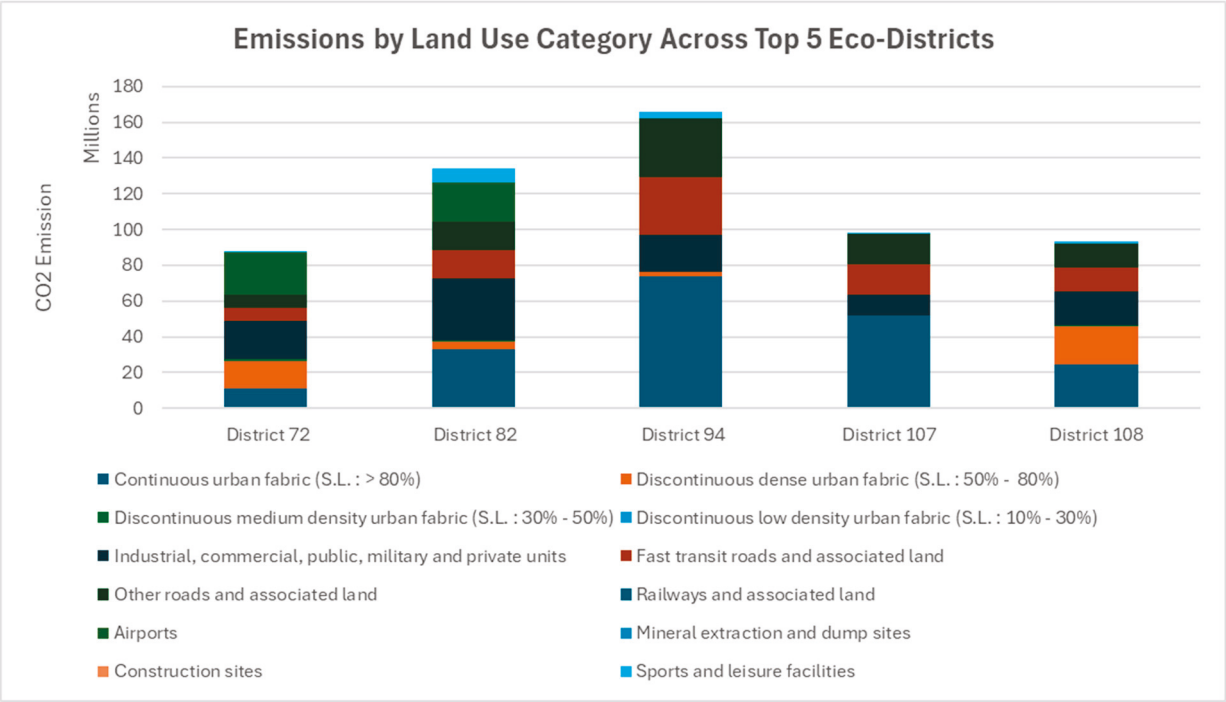


Figure 8. CO_2 emissions (in million kg) by land-use category across the five most emission-intensive eco-districts in Reggio Calabria FUA.

Since the Reggio Calabria FUA is divided into a grid of squares (the eco-districts) stacked next to and above each other, it is logical to hypothesize that the degree centrality will be identical for most districts, with the exceptions being those on the edges.

The network analysis of the urban grid's topology reveals the relationship between a district's connectivity and its emission output. The results from our analysis demonstrate that the highest emitting zones are among those with a high degree of centrality within the network's core, indicating not only large emission loads (weighted degree) but also strong structural embedding (degree/eigenvector). In other words, changes in these districts are likely to generate wider benefits across their neighboring areas. Table 4 shows the centrality metrics of the highest emitting eco-districts identified in the earlier analysis, along with their CO_2 emissions. Eigenvector centrality measures the systemic influence of a district within the network, assigning higher values to districts connected to other highly connected neighbors. Degree centrality indicates the number of directly adjacent districts (those sharing borders). Weighted degree represents the total strength of these adjacency-based connections, reflecting both the number and the intensity of relationships among neighboring districts.

Table 4. Network metrics for the top 5 highest-emitting eco-districts.

Eco-District's Id	Emissions	Eigenvector Centrality	Degree	Weighted Degree
94	1.66×10^8	0.603356371	4	16
82	1.34×10^8	0.618014525	4	16
107	9.80×10^7	0.540203015	4	16
108	9.33×10^7	0.723252115	4	16
72	8.74×10^7	0.720772309	4	16

The analysis of degree centrality shows that all of the highest-emission zones (94, 82, 107, 108, and 72) have a degree of 4. The average degree of the entire network is approximately 3.69.

The eigenvector centrality values for the top emission zones are remarkably high (e.g., 0.60 for Zone 94 and 0.72 for Zone 108). This metric measures a zone's influence by assessing its connections to other highly connected districts. The high values indicate that the high-emission zones are not isolated; they are part of a dense, influential subgraph of the network.

This demonstrates that these areas exhibit the highest aggregated emissions, in addition to being in a central position within the network. Their emissions result from a dense grouping of high-emitting land uses, including industrial land, continuous urban fabric, and transport land. Their centrality means that changes in these districts can affect the emission dynamics of neighboring areas, either through spillover effects or through the redistribution of urban functions.

Further examination of the edges of the network, representing the weighted emission contributions of land-use types to eco-districts, gives a hierarchy of land-use intensity based on CO_2 output (Figure 9). The five leading land-use types responsible for emissions over the urban extent are as follows:

1. Industrial, commercial, public, military, and private units (Total: ~524.7 million kg CO_2);
2. Continuous urban fabric (S.L. > 80%) (Total: ~428.9 million kg CO_2);
3. Discontinuous dense urban fabric (S.L. 50–80%) (Total: ~401.5 million kg CO_2);
4. Other roads and associated land (Total: ~250.9 million kg CO_2);
5. Fast transit roads and associated land (Total: ~250.9 million kg CO_2).

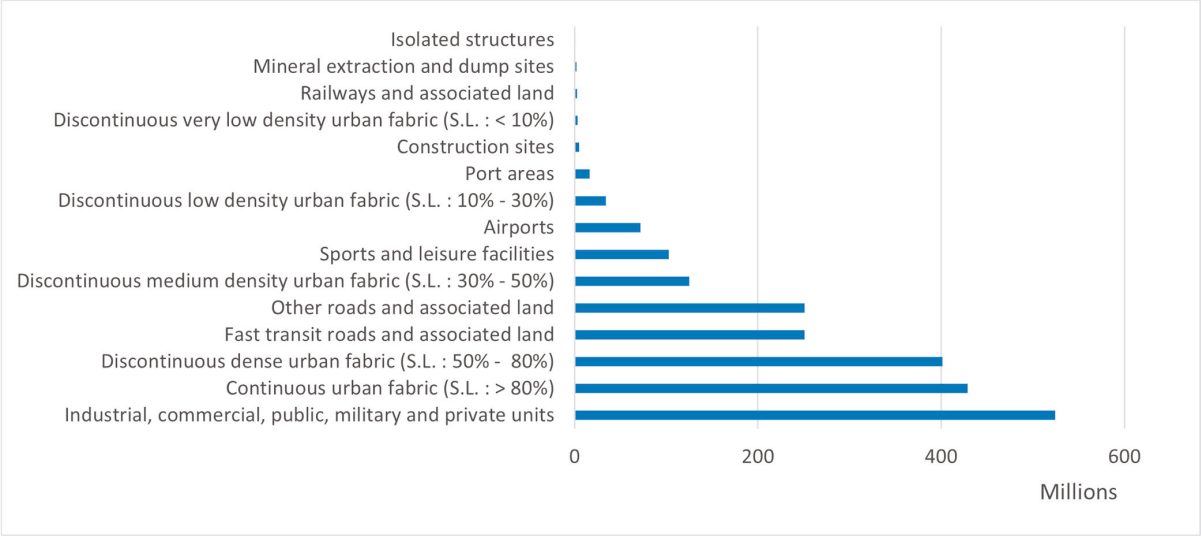


Figure 9. Emissions (in million kg) by land-use type.

Table 5 presents a breakdown of total CO_2 emissions by land-use category across all eco-districts in the Reggio Calabria FUA. Industrial, commercial, public, military, and private units stand out as the most emission-intensive, contributing over 524 million kilograms of CO_2, or about 28.3% of total emissions, despite appearing in only 63 eco-cells. This is followed by continuous urban fabric (S.L. > 80%) and discontinuous dense urban fabric (S.L. 50–80%), which together account for nearly 45% of emissions and are widely distributed across the territory. Road infrastructure, including fast transit roads and other roads, adds over 27% to the city's overall emissions.

Table 5. Emissions by land-use category.

Land-Use Category	Total Emissions (Million kg CO^2)	% of Total Emissions	Eco-Districts Frequency
Continuous urban fabric (S.L.: >80%)	428.92	20%	63
Discontinuous dense urban fabric (S.L.: 50–80%)	401.45	19%	115
Discontinuous medium-density urban fabric (S.L.: 30–50%)	125.27	6%	112
Discontinuous low-density urban fabric (S.L.: 10–30%)	34.10	2%	106
Discontinuous very low-density urban fabric (S.L.: <10%)	3.46	0%	74
Isolated structures	1.13	0%	158
Industrial, commercial, public, military, and private units	524.71	25%	113
Fast transit roads and associated land	250.90	12%	189
Other roads and associated land	250.90	12%	189
Railways and associated land	2.53	0%	38
Port areas	16.68	1%	6
Airports	72.07	3%	4
Mineral extraction and dump sites	2.34	0%	49
Construction sites	5.03	0%	37

The land-use mix of these activities confirms that emission intensity is not a function of the presence of land use but rather how those uses are combined and concentrated in particular districts. For example, industrial areas are comparatively few, yet their influence is concentrated in the eco-districts where they prevail. Road infrastructure, on the other hand, is diffused city-wide, generating dispersed emissions patterns. The integration of land use and network analysis highlights the systemic character of emissions in Reggio Calabria FUA. High-emission districts are defined not only by their land-use composition but also by how emission-intensive uses are spatially organized and interconnected within the urban fabric.

5. Discussion

5.1. Interconnected Nature of Urban Emissions

The results collectively show that urban emissions function as part of a connected spatial system rather than as isolated occurrences. This interconnected nature reflects how neighboring districts and their land-use structures influence each other's carbon outcomes. Such a perspective challenges conventional planning approaches that assess emission sources independently, suggesting instead that interventions in structurally central districts can trigger city-wide mitigation effects. Recognizing these spatial interdependencies allows planners to shift focus from static hotspots to dynamic emission drivers, creating strategies that are both systemic and spatially coordinated.

Importantly, the analysis suggests that emission reduction efforts cannot be confined to high-emitting districts but also to their influence in the network generally. To this end, eco-districts can act as planning units that connect scientific models with zoning policy. Centrality measures, for instance, highlight eco-districts which may not necessarily be emitting the highest level of CO_2 but are structurally central in bridging emission-intensive land use towards the city's territorial organization. Intervention in these structurally fundamental nodes involves greater systemic leverage because improvement in these dimensions is likely to cause spatial ripple effects, either through infrastructure interconnectivity, functional interdependencies, or urban spillovers. This perspective moves the focus from static

emission hotspots to active emission drivers, enabling more effective and targeted planning for spatialized mitigation.

5.2. Multiscale Implications for Urban Planning

With the network analysis, the framework assists in shifting from identifying significant areas to pinpointing specific locations where action is required. The eco-districts indicate where actions can have the most impact due to their high centrality and overall CO_2 emissions. Yet, eco-district level interventions by themselves run the risk of being too general or extensive. To counter this, the framework can be used by urban planners to zoom in on specific eco-communities and eco-cells within the high-priority districts. This multiscale framework allows for hotspots of emissions to be localized and land-use structures to be assessed in greater detail to guide spatially specific interventions.

The spatial framework adapted in this research provides a multiscale foundation for action-oriented climate planning. At the eco-district level, results support their implementation as strategic planning units best adapted to grasping systemic trends and managing spatial flux. Their centrality within the network implies they are optimally placed for long-term intervention.

At finer scales, eco-community and eco-cell scales are important for identifying spatial distinctions and applying real, localized solutions. The ability to isolate single cells with very specific land-use patterns enables planners to zoom into zones in which the introduction of even the smallest land-use change can stimulate measurable emission reductions. This accuracy at the micro-level makes cities able to reconcile strategic goals with operational needs, creating a planning approach that is systemic in scope and place-specific in execution.

Integration of different scales also enables the establishment of ecological compensation mechanisms between territorial cells. The high-emission eco-cells in central districts can be compensated by increased sequestration in adjacent or structurally associated cells, maintaining a less unequal territorial carbon profile and enabling a concerted trajectory toward urban resilience.

Ultimately, this study successfully addresses its core research question: How can a bipartite spatial network linking eco-districts and land-use categories be used to reveal structurally influential districts and pinpoint priority locations for targeted CO_2-mitigation in an urban area? Moreover, the research met its three main objectives by first building the bipartite spatial network between eco-districts and land-use categories. Second, the centrality metrics successfully identified structurally influential eco-districts and dominant emitting land uses. Finally, the analysis of these influential districts and the ability to zoom into lower scales provided a clear basis for suggesting intervention hotspots and proposing spatial actions.

5.3. Methodological Reflection and Scientific Contribution

This study introduces a novel methodological framework that applies bipartite spatial network analysis to urban carbon accounting. Conventional models tend to either estimate emissions by sector or at geographically resolutions, unable to uncover cross-scale structural interdependencies. Conversely, this study combines the land-use emissions' functional logic with the spatial layout of the city, providing a data-driven yet spatial framework for CO_2 mitigation in the city.

The method's scientific validity lies in its ability to reveal relationships that are not visible through traditional emission inventories. By linking land-use categories with eco-districts, the bipartite structure enables a relational understanding of how emissions are distributed and reinforced across the urban system. Furthermore, the use of network

centrality as a proxy for influence and prioritization provides a theoretically grounded way to translate structural properties into actionable planning guidance.

Beyond its analytical innovation, the framework strengthens the interface between carbon accounting and spatial planning practice. It offers a scalable and replicable workflow applicable to other FUAs using standardized datasets such as the Urban Atlas. This enhances the methodological robustness of urban ecosystem service assessments by explicitly incorporating spatial interdependencies.

5.4. Limitations and Future Research

While the spatial and structural dimensions of emissions have been thoroughly explored, in this paper the behavioral and institutional factors that influence emissions over time are not taken into account. For example, whether residents commute to the city, how buildings are used, or the mechanism by which policy in the city promotes green retrofits are outside the current analytical horizon. This exclusion is methodologically justified, as the research sought to isolate the spatial pattern of emissions employing similarly and comparably defined datasets. In doing so, the research creates a replicable and policy-relevant analytical space that can subsequently be generalized when more recent, more dynamic datasets become available.

The model also does not integrate socio-economic overlays since these datasets are typically aggregated at administrative levels that do not align with the eco-district spatial units used in this analysis. Including such data would introduce spatial mismatches and reduce comparability between cities. For this reason, the current study focuses on the physical and functional logic of emissions rather than their socio-economic context. Nevertheless, future research could integrate socio-economic indicators to examine how emission structures intersect with issues of spatial equity, vulnerability, and environmental justice.

The current framework also has a static representation of carbon sequestration and lacks projections of future sequestration or land rehabilitation trends. The choice is both an acknowledgment of current data limitations and an acknowledgment that the study is attempting to construct a spatially explicit rather than predictive framework. Projections of future sequestration capacity would need time-series land-use and vegetation data that are currently not available for the case study. The model is, nevertheless, adaptive and can be adapted to incorporate forecasted land-cover change or rehabilitation scenarios once these data become available, rendering it more useful for climate planning across longer timescales.

Lastly, whereas Reggio Calabria FUA is the appropriate pilot city for medium-sized European urban areas, expanding the methodology to other types of urban settings would make it more applicable.

This research provides a transferable and reproducible framework for structural leverage point identification in urban CO_2 mitigation. The approach extends conventional emission inventories with a spatial network methodology that reveals systemic interdependency. Although behavioral, socio-economic, and temporal dynamics were beyond the scope of this research, the model is dynamic and could develop in tandem with data enhancement to make urban climate policy more integrated, fairer, and forward-looking.

5.5. Approaches for Urban Planning to Address Carbon Emissions

From this spatial network analysis, three key approaches for urban planning can be developed to address carbon emissions:

- Targeted Land Use Reconfiguration

Planners can identify the most emission-heavy eco-cells and target inefficiently used or underutilized land, such as surface parking lots, vacant parcels, and oversized roadways, for redevelopment into green infrastructure. Gradually improving local parks,

urban forests, or green roofs can reduce emissions over time and improve microclimatic conditions.

- Localized Retrofitting and Densification Control

For areas with dense urban development, emissions can be reduced by retrofitting buildings for energy efficiency, controlling densification, and incorporating passive design features. In industrial zones, adopting cleaner technologies or relocating high-emission activities to outer regions with better compensatory capacity can also be effective.

- Ecological Compensation Across the District

Understanding that certain areas cannot be readily changed because of land-use limitations or socio-economic value, planners are able to establish compensation strategies on the eco-district level. Zones with high emissions can be compensated by improving sequestration in lower-emission or neighboring cells within the same district, achieving a practical ecological equilibrium without interfering with essential urban activities.

This ecological compensation idea is further supported by recognizing the contribution of peripheral, pre-urban lands, typically dense in natural and semi-natural land uses. In Reggio Calabria FUA, these lands can act as key ecological resources, with compensatory functions for more urbanized lands with low-carbon sequestration capacity. The spatial network analysis supports that emissions and environmental activities overflow between individual districts, so a change in one district can affect the others' environmental performance. This emphasizes the need for a new planning paradigm that moves beyond administrative boundaries and embraces a functional territorial logic. Urban mitigation strategies would then have to consider not only where emissions are generated but where capacities within the natural world are found, particularly in the surrounding areas, and how activities in one location can exacerbate or counter effects in other locations in the urban system.

This analytical framework highlights how emissions-based planning needs to function at both scales together: employing the eco-district to direct systemic decision-making and the eco-cell to apply site-by-site action. The approach illustrates the necessity of spatial specificity in urban climate strategy formation and offers a basis for cities to operationalize ecosystem services toward achieving their decarbonization ambitions.

6. Conclusions

This study demonstrates that urban CO_2 emissions are not independent phenomena but part of a spatially interconnected system driven by land-use interactions. Supported by a net emission imbalance of approximately 1.85 billion kg CO_2 per year, the bipartite network analysis confirms that a city's carbon footprint results from relational dynamics among eco-districts rather than isolated sources. The study's methodological approach provides a novel and compelling window for the identification of both emission hotspots and structurally central influencer, shifting the focus from static, geographically contained problems to dynamic, system-wide solutions.

The findings reveal that urban CO_2 emissions are not always evenly spread out or solely influenced by the intensity of land use. Rather, certain eco-districts emerge as hubs of centrality in the emissions system, based on their land use and functional connectivity. For instance, Districts 94, 82, 107, 108, and 72 together account for over 500 million kg CO_2 per year, with eigenvector centrality values between 0.54 and 0.72, indicating their structural influence as leverage points for city-wide mitigation. At the scale of these districts, it is possible to identify high-emission intensity areas with dense urban form and industrial use and limited sequestration opportunity.

Through using a dual-scale, network analysis framework, this study presents a new instrument for planners and policymakers seeking to coordinate climate goals into the spatial logic of cities. The method is superior to common emissions mapping due to its quantification not only of where emissions occur, but of how a given place shapes emissions pathways across the city system. This systemic understanding is required to build interconnected, place-targeted strategies that reconcile emission reduction with ecosystem service enhancement.

At a planning scale, the research adds to the emerging discourse on climate-sensitive and ecosystem service-based urbanism. It illustrates the potential of spatial planning to move from static assessments towards evidence-based relational decision-making, where mitigation is localized as well as strategically distributed across space. Incorporating CO_2 emissions and sequestration within a network context also increases the ability of planning to act as an intermediary between environmental objectives and spatial transformation.

The proposed approach is not just analytically but also highly adaptable. It relies on publicly available geospatial data and scalable processes, thus being transferable to other urban agglomerations with similar challenges. Highly spatially diverse and more sustainability-focused cities can benefit greatly from this framework.

In sum, the study suggests the application of multiscale, network-analysis tools that coordinate spatial interventions with environmental performance. In an era where cities across the world are concerned about balancing growth with decarbonization and resilience, methodologies such as the one presented here offer a promising pathway to translate ecosystem service values into actionable and equitable urban policy.

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References

1. Crippa, M.; Guizzardi, D.; Pisoni, E.; Solazzo, E.; Guion, A.; Muntean, M.; Florczyk, A.; Schiavina, M.; Melchiorri, M.; Hutfilter, A.F. Global Anthropogenic Emissions in Urban Areas: Patterns, Trends, and Challenges. *Environ. Res. Lett.* **2021**, *16*, 074033. [CrossRef]
2. United Nations Human Settlements Programme. *Urban Climate Action: The Urban Content of the NDCs—Global Review 2022*; UN-Habitat: Nairobi, Kenya, 2023. [CrossRef]
3. Pu, Y.; Wang, Y.; Wang, P. Driving Effects of Urbanization on City-Level Carbon Dioxide Emissions: From Multiple Perspectives of Urbanization. *Int. J. Urban Sci.* **2022**, *26*, 108–128. [CrossRef]
4. Creutzig, F.; Baiocchi, G.; Bierkandt, R.; Pichler, P.-P.; Seto, K.C. Global Typology of Urban Energy Use and Potentials for an Urbanization Mitigation Wedge. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 6283–6288. [CrossRef] [PubMed]
5. Zarco-Soto, I.M.; Zarco-Periñán, P.J.; Sánchez-Durán, R. Influence of Cities Population Size on Their Energy Consumption and CO_2 Emissions: The Case of Spain. *Environ. Sci. Pollut. Res.* **2021**, *28*, 28146–28167. [CrossRef]
6. Garschagen, M.; Romero-Lankao, P. Exploring the Relationships between Urbanization Trends and Climate Change Vulnerability. *Clim. Change* **2015**, *133*, 37–52. [CrossRef]

7. Das, S.; Choudhury, M.R.; Chatterjee, B.; Das, P.; Bagri, S.; Paul, D.; Bera, M.; Dutta, S. Unraveling the Urban Climate Crisis: Exploring the Nexus of Urbanization, Climate Change, and Their Impacts on the Environment and Human Well-Being–A Global Perspective. *AIMS Public Health* **2024**, *11*, 963. [CrossRef]
8. Eichhorn, S.; Rusche, K.; Weith, T. Integrative Governance Processes towards Sustainable Spatial Development—Solving Conflicts between Urban Infill Development and Climate Change Adaptation. *J. Environ. Plan. Manag.* **2021**, *64*, 2233–2256. [CrossRef]
9. Grafakos, S.; Trigg, K.; Landauer, M.; Chelleri, L.; Dhakal, S. Analytical Framework to Evaluate the Level of Integration of Climate Adaptation and Mitigation in Cities. *Clim. Change* **2019**, *154*, 87–106. [CrossRef]
10. OECD. *Decarbonising Urban Mobility with Land Use and Transport Policies: The Case of Auckland, New Zealand*; OECD Publishing: Paris, France, 2020. [CrossRef]
11. Ghorbany, S.; Hu, M. Urban Embodied Carbon Assessment: Methodology and Insights from Analyzing over a Million Buildings in Chicago. *Carbon Manag.* **2024**, *15*, 2382993. [CrossRef]
12. Kılkış, Ş. Urban Emissions and Land Use Efficiency Scenarios for Avoiding Increments of Global Warming. *Energy* **2024**, *307*, 132174. [CrossRef]
13. Wang, S.-H.; Huang, S.-L.; Huang, P.-J. Can Spatial Planning Really Mitigate Carbon Dioxide Emissions in Urban Areas? A Case Study in Taipei, Taiwan. *Landsc. Urban Plan.* **2018**, *169*, 22–36. [CrossRef]
14. Dadashpoor, H.; Panahi, H. Exploring an Integrated Spatially Model for Land-Use Scenarios Simulation in a Metropolitan Region. *Environ. Dev. Sustain.* **2021**, *23*, 13628–13649. [CrossRef]
15. Raimbault, J. An Interdisciplinary Bibliometric Analysis of Models for Land-Use and Transport Interactions. *arXiv* **2021**, arXiv:2102.13501. [CrossRef]
16. Stokes, E.C.; Seto, K.C. Climate Change and Urban Land Systems: Bridging the Gaps between Urbanism and Land Science. *J. Land Use Sci.* **2016**, *11*, 698–708. [CrossRef]
17. Gómez-Baggethun, E.; Barton, D.N. Classifying and Valuing Ecosystem Services for Urban Planning. *Ecol. Econ.* **2013**, *86*, 235–245. [CrossRef]
18. Mengist, W.; Soromessa, T.; Feyisa, G.L. A Global View of Regulatory Ecosystem Services: Existed Knowledge, Trends, and Research Gaps. *Ecol. Process.* **2020**, *9*, 40. [CrossRef]
19. Skrzypczak, D.; Gorazda, K.; Mikula, K.; Mironiuk, M.; Kominko, H.; Sawska, K.; Evrard, D.; Trzaska, K.; Moustakas, K.; Chojnacka, K. Towards Carbon Neutrality: Enhancing CO2 Sequestration by Plants to Reduce Carbon Footprint. *Sci. Total Environ.* **2025**, *966*, 178763. [CrossRef]
20. Keith, H.; Vardon, M.; Lindenmayer, D.; Mackey, B. Accounting for Carbon Stocks and Flows: Storage and Sequestration Are Both Ecosystem Services. In Proceedings of the 25th Meeting of the London Group on Environmental Accounting, Melbourne, Australia, 7–10 October 2019; pp. 7–10.
21. Kim, J.; Kang, Y.; Kim, D.; Son, S.; Kim, E.J. Carbon Storage and Sequestration Analysis by Urban Park Grid Using I-Tree Eco and Drone-Based Modeling. *Forests* **2024**, *15*, 683. [CrossRef]
22. Haase, D.; Larondelle, N.; Andersson, E.; Artmann, M.; Borgström, S.; Breuste, J.; Gomez-Baggethun, E.; Gren, Å.; Hamstead, Z.; Hansen, R.; et al. A Quantitative Review of Urban Ecosystem Service Assessments: Concepts, Models, and Implementation. *AMBIO* **2014**, *43*, 413–433. [CrossRef]
23. Park, C.; Jeong, S.; Park, M.-S.; Park, H.; Yun, J.; Lee, S.-S.; Park, S.-H. Spatiotemporal Variations in Urban CO2 Flux with Land-Use Types in Seoul. *Carbon Balance Manag.* **2022**, *17*, 3. [CrossRef] [PubMed]
24. Bevilacqua, C.; Sohrabi, P.; Hamdy, N. Spatializing Social Networking Analysis to Capture Local Innovation Flows towards Inclusive Transition. *Sustainability* **2022**, *14*, 3000. [CrossRef]
25. Sahu, P.; Debsarma, C. Climate Change and Urban Environment Sustainability: Issues and Challenges. In *Climate Change and Urban Environment Sustainability*; Disaster Resilience and Green Growth; Pathak, B., Dubey, R.S., Eds.; Springer Nature: Singapore, 2023; pp. 1–13. ISBN 978-981-19-7617-9.
26. Pan, H.; Page, J.; Shi, R.; Cong, C.; Cai, Z.; Barthel, S.; Thollander, P.; Colding, J.; Kalantari, Z. Contribution of Prioritized Urban Nature-Based Solutions Allocation to Carbon Neutrality. *Nat. Clim. Change* **2023**, *13*, 862–870. [CrossRef]
27. World Wide Fund for Nature (WWF) Nature Based Solutions for Mitigation and Adaptation towards Climate Change. Available online: https://wwfeu.awsassets.panda.org/downloads/2023_wwf_report_nbs.pdf (accessed on 16 April 2025).
28. OECD. *Global Monitoring of Policies for Decarbonising Buildings: A Multi-Level Approach*; OECD Urban Studies; OECD: Paris, France, 2024; ISBN 978-92-64-45449-1.
29. Sabet, S.; Farooq, B. Exploring the Combined Effects of Major Fuel Technologies, Eco-Routing, and Eco-Driving for Sustainable Traffic Decarbonization in Downtown Toronto. *Transp. Res. Part A Policy Pract.* **2025**, *192*, 104385. [CrossRef]
30. Shen, J.; Zheng, F.; Ma, Y.; Deng, W.; Zhang, Z. Urban Travel Carbon Emission Mitigation Approach Using Deep Reinforcement Learning. *Sci. Rep.* **2024**, *14*, 27778. [CrossRef]

31. Saarikoski, H.; Primmer, E.; Saarela, S.-R.; Antunes, P.; Aszalós, R.; Baró, F.; Berry, P.; Blanko, G.G.; Goméz-Baggethun, E.; Carvalho, L. Institutional Challenges in Putting Ecosystem Service Knowledge in Practice. *Ecosyst. Serv.* **2018**, *29*, 579–598. [CrossRef]
32. Eraydin, A. "Resilience Thinking" for Planning. In *Resilience Thinking in Urban Planning*; Springer: Dordrecht, The Netherlands, 2012; pp. 17–37. ISBN 978-94-007-5476-8.
33. Chen, S.; Liu, Z.; Chen, B.; Zhu, F.; Fath, B.D.; Liang, S.; Su, M.; Yang, J. Dynamic Carbon Emission Linkages Across Boundaries. *Earth's Future* **2019**, *7*, 197–209. [CrossRef]
34. Milnar, M.; Ramaswami, A. Impact of Urban Expansion and In Situ Greenery on Community-Wide Carbon Emissions: Method Development and Insights from 11 US Cities. *Environ. Sci. Technol.* **2020**, *54*, 16086–16096. [CrossRef]
35. Gallotti, R.; Sacco, P.; De Domenico, M. Complex Urban Systems: Challenges and Integrated Solutions for the Sustainability and Resilience of Cities. *Complexity* **2021**, *2021*, 1782354. [CrossRef]
36. Hamdy, N.; Bevilacqua, C. Assessing the Role of the Blue Economy in the Comprehensive Development of Lagging Coastal Areas. A Case Study of Calabria. In *New Metropolitan Perspectives*; Smart Innovation, Systems and Technologies; Bevilacqua, C., Balland, P.-A., Kakderi, C., Provenzano, V., Eds.; Springer: Cham, Switzerland, 2023; Volume 639, pp. 21–45. ISBN 978-3-031-34210-3.
37. UN-Habitat World Cities Report 2022: Envisaging the Future of Cities. Available online: https://unhabitat.org/world-cities-report-2022-envisaging-the-future-of-cities (accessed on 23 October 2024).
38. URBACT II. Sustainable Regeneration in Urban Areas: URBACT II Capitalisation. Available online: https://www.dotaceeu.cz/Dotace/media/SF/FONDY%20EU/2014-2020/Programy/URBACT/Pokyny%20pro%20p%C5%99%C3%ADjemce%2031_12_2016/Sustainable-regeneration-in-urban-areas_1.pdf (accessed on 13 January 2025).
39. Yang, Y.; Zhang, J.; Huang, J.; Zhao, Y.; Zhao, Q. Urban Density and Spatial Carbon Emission Performance of Megacities in China. *Sci. Rep.* **2024**, *14*, 23862. [CrossRef]
40. Yang, Y.; Takase, T. Spatial Characteristics of Carbon Dioxide Emission Intensity of Urban Road Traffic and Driving Factors: Road Network and Land Use. *Sustain. Cities Soc.* **2024**, *113*, 105700. [CrossRef]
41. Yaacob, N.F.F.; Yazid, M.R.M.; Abdul Maulud, K.N.; Khahro, S.H.; Javed, Y. Spatio-Temporal Analysis of CO2 Emissions from Vehicles in Urban Areas: A Satellite Imagery Approach. *Sustainability* **2024**, *16*, 10765. [CrossRef]
42. Wagner, F.; Nachtigall, F.; Franken, L.; Milojevic-Dupont, N.; Pereira, R.H.M.; Koch, N.; Runge, J.; Gonzalez, M.; Creutzig, F. Using Machine Learning to Understand Causal Relationships between Urban Form and Travel CO_2 Emissions across Continents. *arXiv* **2023**, arXiv:2308.16599. [CrossRef]
43. Tang, M.; Hu, F. Land Urbanization and Urban CO2 Emissions: Empirical Evidence from Chinese Prefecture-Level Cities. *Heliyon* **2023**, *9*, e19834. [CrossRef] [PubMed]
44. Hu, Y.; Sun, J.; Zheng, J. Spatiotemporal Analysis of Urban Carbon Metabolism and Its Response to Land Use Change: A Case Study of Beijing, China. *Atmosphere* **2023**, *14*, 1305. [CrossRef]
45. Wei, L.; Zeng, B. Urban Technology Transfer, Spatial Spillover Effects, and Carbon Emissions in China. *Sustainability* **2024**, *16*, 9662. [CrossRef]
46. Fu, H.; Li, B.; Liu, X.; Zheng, J.; Yin, S.; Jiang, H. Spatio-Temporal Coupling Evolution of Urbanisation and Carbon Emission in the Yangtze River Economic Belt. *Int. J. Environ. Res. Public Health* **2023**, *20*, 4483. [CrossRef]
47. Lu, Y.; Zhai, G.; Zhou, S.; Shi, Y. Risk Reduction through Urban Spatial Resilience: A Theoretical Framework. *Hum. Ecol. Risk Assess. Int. J.* **2021**, *27*, 921–937. [CrossRef]
48. Zetterberg, L.; Eriksson, M.; Ravry, C.; Santosa, A.; Ng, N. Neighbourhood Social Sustainable Development and Spatial Scale: A Qualitative Case Study in Sweden. *Local Environ.* **2023**, *28*, 793–810. [CrossRef]
49. Ye, Y. Sino-Singapore Tianjin Eco-City (Case: CHN-Tianjin). Available online: https://atlasofurbantech.org/cases/chn-tianjin/ (accessed on 22 April 2025).
50. Shi, Y.; Zheng, B.; Wang, Z.; Zheng, J. Mixed Land Use and Its Relationship with CO_2 Emissions: A Comparative Analysis Based on Several Typical Development Zones in Shanghai. *Land* **2023**, *12*, 1675. [CrossRef]
51. Chuai, X.; Xu, H.; Liu, Z.; Xiang, A.; Luo, Y.; Mao, W.; Wang, T.; Ye, X.; Miao, L.; Zhao, R. Promoting Low-Carbon Land Use: From Theory to Practical Application through Exploring New Methods. *Humanit. Soc. Sci. Commun.* **2024**, *11*, 727. [CrossRef]
52. Li, Q.; Chen, X.; Jiao, S.; Song, W.; Zong, W.; Niu, Y. Can Mixed Land Use Reduce CO2 Emissions? A Case Study of 268 Chinese Cities. *Sustainability* **2022**, *14*, 15117. [CrossRef]
53. Morelli, C.; Maranzano, P.; Otto, P. Spatiotemporal Clustering of GHGs Emissions in Europe: Exploring the Role of Spatial Component. *arXiv* **2025**, arXiv:2503.11909. [CrossRef]
54. Baur, A.H.; Förster, M.; Kleinschmit, B. The Spatial Dimension of Urban Greenhouse Gas Emissions: Analyzing the Influence of Spatial Structures and LULC Patterns in European Cities. *Landsc. Ecol.* **2015**, *30*, 1195–1205. [CrossRef]
55. EEA Urban Atlas Land Cover/Land Use 2018 (Vector), Europe, 6-Yearly, July 2021. Available online: https://sdi.eea.europa.eu/catalogue/copernicus/api/records/fb4dffa1-6ceb-4cc0-8372-1ed354c285e6 (accessed on 23 March 2025).

56. ENEA SIAPE—Sistema Informativo sugli Attestati di Prestazione Energetica. Available online: https://siape.enea.it/ (accessed on 22 January 2025).
57. International Union of Railways (UIC) Carbon Footprint of Railway Infrastructure: Comparing Existing Methodologies on Typical Corridors; Recommendations for a Harmonised Approach. Available online: https://uic.org/IMG/pdf/carbon_footprint_of_railway_infrastructure.pdf (accessed on 13 March 2025).
58. Enea, D.; Mastrilli, A. Sustainable Planning: The Case Study of the Strait of Messina Ports. *Environ. Sci. Pollut. Res.* **2024**, *31*, 15348–15363. [CrossRef] [PubMed]
59. Fregola, R.A.; Ciccolella, A.; Festa, V.; Ruggieri, G.; Schingaro, E.; Tursi, F.; Ventruti, G. Review of Polymetallic Mineralization in the Sila and Serre Massifs (Calabria, Southern Italy). *Minerals* **2023**, *13*, 439. [CrossRef]
60. Ralph, J.; Von Bargen, D.; Martynov, P.; Zhang, J.; Que, X.; Prabhu, A.; Morrison, S.M.; Li, W.; Ma, X. Metropolitan City of Reggio Calabria, Calabria, Italy. Available online: https://www.mindat.org/loc-31470.html (accessed on 3 February 2025).
61. Brilli, L.; Toscano, P.; Carotenuto, F.; Di Lonardo, S.; Di Tommasi, P.; Magliulo, V.; Manco, A.; Vitale, L.; Zaldei, A.; Gioli, B. Long-Term Investigation of Methane and Carbon Dioxide Emissions in Two Italian Landfills. *Heliyon* **2024**, *10*, e29356. [CrossRef]
62. Weigert, M.; Melnyk, O.; Winkler, L.; Raab, J. Carbon Emissions of Construction Processes on Urban Construction Sites. *Sustainability* **2022**, *14*, 12947. [CrossRef]
63. Groth, P.; Miller, R.; Nadkarni, N.; Riley, M.; Shoup, L. Quantifying the Greenhouse Gas Benefits of Urban Parks. Available online: http://cloud.tpl.org/pubs/benefits_greenhouse_gases_and_parks_whitepaper.pdf (accessed on 22 July 2025).
64. European Climate Change Programme (ECCP) Agricultural Soils-Final Report. Available online: https://climate.ec.europa.eu/system/files/2016-11/finalreport_agricsoils_en.pdf (accessed on 13 February 2025).
65. Lopez-Bellido, P.J.; Lopez-Bellido, L.; Fernandez-Garcia, P.; Muñoz-Romero, V.; Lopez-Bellido, F.J. Assessment of Carbon Sequestration and the Carbon Footprint in Olive Groves in Southern Spain. *Carbon Manag.* **2016**, *7*, 161–170. [CrossRef]
66. Scandellari, F.; Caruso, G.; Liguori, G.; Meggio, F.; Palese, A.M.; Zanotelli, D.; Celano, G.; Gucci, R.; Inglese, P.; Pitacco, A. A Survey of Carbon Sequestration Potential of Orchards and Vineyards in Italy. *Eur. J. Hortic. Sci.* **2016**, *81*, 106–114. [CrossRef]
67. Intergovernmental Panel on Climate Change (IPCC) Land Use, Land-Use Change, and Forestry—Chapter 3: Projecting Land-Use Change. Available online: https://archive.ipcc.ch/ipccreports/sres/land_use/index.php?idp=28 (accessed on 2 March 2025).
68. Pan, Y.; Birdsey, R.A.; Fang, J.; Houghton, R.; Kauppi, P.E.; Kurz, W.A.; Phillips, O.L.; Shvidenko, A.; Lewis, S.L.; Canadell, J.G.; et al. A Large and Persistent Carbon Sink in the World's Forests. *Science* **2011**, *333*, 988–993. [CrossRef]
69. Xu, W.; Zhang, B.; Xu, Q.; Gao, D.; Zuo, H.; Ren, R.; Diao, K.; Chen, Z. Enhanced Carbon Storage in Mixed Coniferous and Broadleaf Forest Compared to Pure Forest in the North Subtropical–Warm Temperate Transition Zone of China. *Forests* **2024**, *15*, 1520. [CrossRef]
70. Gratani, L.; Varone, L.; Ricotta, C.; Catoni, R. Mediterranean Shrublands Carbon Sequestration: Environmental and Economic Benefits. *Mitig. Adapt. Strateg. Glob. Change* **2013**, *18*, 1167–1182. [CrossRef]
71. Canu, D.M.; Ghermandi, A.; Nunes, P.A.; Lazzari, P.; Cossarini, G.; Solidoro, C. Estimating the Value of Carbon Sequestration Ecosystem Services in the Mediterranean Sea: An Ecological Economics Approach. *Glob. Environ. Change* **2015**, *32*, 87–95. [CrossRef]
72. Taylor, S.; Gilbert, P.J.; Cooke, D.A.; Deary, M.E.; Jeffries, M.J. High Carbon Burial Rates by Small Ponds in the Landscape. *Front. Ecol. Environ.* **2019**, *17*, 25–31. [CrossRef]
73. Malak, D.A.; Marín, A.I.; Trombetti, M.; Roman, S.S. *Carbon Pools and Sequestration Potential of Wetlands in the European Union*; ETC/ULS Report No. 10/2021; European Topic Centre on Urban, Land and Soil Systems: Viena, Austria; Malaga, Spain, 2021; ISBN 978-3-200-07433-0. [CrossRef]

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Resilience and Liveability as Drivers of Sustainability: The Case of UBC's Public Spaces

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Abstract

Environmental sustainability and resilience have become urgent priorities in contemporary urban planning as cities confront the disruptive impacts of climate change, extreme weather, and global health crises. Within this framework, university campuses increasingly act as catalysts for sustainable urban transformation. This research, developed within the *LOVE Sapienza* and *NARRATES* projects, seeks to identify the key factors that enhance the liveability of campus public spaces and to propose a dedicated methodology, supported by the case study of the University of British Columbia (UBC) in Vancouver. The proposed approach integrates spatial analyses, field observations, and perceptual mapping aligned with the principles of the Charter for Resilient and Liveable Public Spaces. UBC exemplifies how biophilic design, inclusive governance, and art-based placemaking can strengthen resilience, social cohesion, and cultural identity. The study contributes a transferable framework for designing and managing campus public spaces as drivers of sustainability and urban regeneration.

Keywords: resilience; liveability; campus public spaces; sustainability

1. Introduction

Environmental sustainability and resilience have become urgent priorities in contemporary urban planning, particularly as cities increasingly face the disruptive impacts of climate change, extreme weather events, and global health crises. These challenges represent not only economic and infrastructural threats but also profound risks to human well-being. This has generated a growing imperative to rethink how urban systems are designed, governed, and maintained. Urban design has emerged as a crucial discipline for addressing such complexity, shaping urban transformations that are ecologically sustainable, liveable, socially inclusive, and adaptable to future uncertainties. The integration of green infrastructure, flexible public spaces, and art now constitutes a cornerstone of strategies aimed at enhancing the liveability and resilience of increasingly dense and vulnerable urban areas [1].

Within this framework, the public spaces of university campuses are assuming a progressively more significant role. No longer isolated zones devoted exclusively to academia, campuses today function as dynamic urban ecosystems—places where diverse populations gather for education, socialization, work, leisure, and cultural exchange. Their spatial, social, and environmental functions are increasingly aligned with urban priorities, positioning them as key sites for advancing climate adaptation, community building, and sustainable infrastructures [2].

Historically, however, university campuses were conceived as insular environments, focused solely on academic activities and characterized by minimal interaction with the

surrounding city. In Europe, for example, medieval universities often adopted cloister-like layouts that emphasized separation from everyday urban life: models such as Oxford and Cambridge epitomized this approach, privileging intellectual isolation [3,4]. By contrast, in recent decades, the role of campuses has profoundly evolved [5–8]: increasingly integrated into the urban fabric, they reflect broader social transformations associated with urbanization, sustainability, and the opening of higher education to public and social functions [9,10]. Today, universities are recognized as key actors in urban contexts, and their public spaces—green areas, plazas, pedestrian networks, and courtyards—are designed not only to serve academic needs but also to foster social interaction, community engagement, and environmental sustainability [11–14]. The central challenge lies in balancing the traditional academic mission with the growing role of campuses as social and cultural hubs that actively contribute to urban life. Their public spaces operate as multifunctional settings for informal learning, relaxation, and socialization for students and faculty, while simultaneously serving as open resources for city residents, offering cultural, recreational, and social opportunities [15–17]. Building on these premises, the present study—conducted within the framework of two research projects both funded by Sapienza Università di Roma—LOVE Sapienza: Livable, enjOyable and attractiVE spaces for the community, under the Author's responsibility, and University and Urban Regeneration: Redesigning Neglected Spaces and Routes with Sapienza as a Driver (NARRATES), of which the Author is Responsible for the Architectural and Urban Regeneration Line of Research—seeks to identify the key factors that enhance the liveability of campus public spaces and to propose a dedicated methodology, supported by the case study of the University of British Columbia (UBC) in Vancouver.

The aims of LOVE Sapienza include analyzing international best practices of public spaces in universities and campuses, examining Sapienza's sites, and proposing guidelines for the enhancement and/or design of open public spaces in Sapienza's facilities, with attention to urban liveability, health, and flexibility. The aims of NARRATES include regenerating underused public spaces in Rome through a sustainable network for non-motorized and collective mobility connecting Sapienza University with key urban hubs and promoting new "narratives" of sustainable places and behaviors that strengthen the university–city relationship.

The original methodology—which was partially used in the aforementioned research projects—developed integrated spatial analyses, field observations, and alignment with the principles of the Charter for Resilient and Liveable Public Spaces, elaborated from the case studies.

The Vancouver campus of UBC represents a particularly significant example of this evolution. Situated within an ecologically sensitive context, it has evolved into a multifunctional environment where sustainability, climate resilience, community, and artistic expression are deeply interwoven. Through biophilic design, inclusive placemaking, and long-term climate planning, the campus not only mitigates ecological risks but also cultivates a vibrant social and cultural community. Its trajectory illustrates how post-secondary institutions can guide urban transformation by promoting public health, civic participation, and environmental stewardship.

Resilience constitutes a central theme in UBC's development, as the university addresses growing risks such as wildfires, heatwaves, and heavy rainfall through its Resilience Strategy. Notable initiatives include the establishment of "Resilience Hubs"—multifunctional spaces that provide support during emergencies (e.g., cooling centers or distribution hubs for essential goods) while also serving as everyday meeting places designed to ensure accessibility, energy efficiency, and social inclusion. From an environmental standpoint, UBC positions itself as a living laboratory: its Climate Action Plan

aims for carbon neutrality by the mid-century through district energy systems, advanced building standards (LEED Gold and beyond), integrated water management, resilient landscapes, and zero-waste infrastructures.

Community engagement is embedded in the Engagement Charter, which sets out principles of transparency and inclusion, involving students, staff, Indigenous communities such as the Musqueam, and neighboring municipalities.

Indeed, UBC's Indigenous Strategic Plan (ISP) embeds reconciliation within all aspects of campus life, guiding actions that honour Indigenous rights, knowledge, and presence. A key focus—"Enriching our spaces" (Goal 5)—promotes the integration of Indigenous art, design principles, and cultural narratives into public spaces, ensuring that the campus reflects Indigenous heritage and fosters inclusivity. Through collaboration with the Musqueam and other Indigenous Nations, UBC's open areas, pathways, and artworks become sites of dialogue, remembrance, and respect. These interventions transform the campus into both a learning environment and a landscape of reconciliation, where spatial design and cultural expression advance intercultural understanding and shared stewardship [18].

The campus's social infrastructures are conceived as fundamental to well-being: open spaces, greenways, and pedestrian paths encourage social interaction and physical activity; multimodal transport systems reduce emissions; childcare facilities, residences, and recreational centers ensure a balanced and accessible environment.

Finally, the arts play an essential role in UBC's cultural landscape. Public art—with particular attention to Indigenous expression—is integrated into the built environment to stimulate dialogue and cultural memory. Galleries, performance venues, and installations serve not only the university community but the wider region, reinforcing the campus's role as a cultural hub (University of British [18–20]. This case demonstrates how contemporary campuses, by reconfiguring their role within cities, can reconcile academic, social, and ecological objectives. Their public spaces, increasingly crucial, shape the liveability and resilience not only of university communities but also of the cities that host them. The paper is structured as follows: Section 2 discusses the main components of a resilient and liveable campus; Section 3 illustrates the methodology for analyzing and designing campus public spaces; Section 4 presents the case study; Section 5 offers the observations; and finally, Section 6 concludes the study.

2. Universities and Campus Public Spaces: Resilience and Liveability Factors

The design of public spaces within university campuses must respond to the complex and evolving needs of a heterogeneous user base, comprising students, faculty, staff, and residents. In high-density urban environments, where land availability is often constrained, universities frequently face spatial competition from other land uses [21–23].

As a result, the allocation of land for public open space is limited, necessitating design strategies that maximize spatial efficiency and multifunctionality within compact footprints. The need to reconcile diverse expectations—ranging from students seeking environments conducive to study and socialization, to residents utilizing campus areas for leisure and recreation—further complicates spatial planning. Addressing these competing demands requires a carefully calibrated approach that integrates resilience, adaptability and flexibility into spatial design [24].

In addition to programmatic versatility, public space design must prioritize core principles of safety, comfort, and accessibility. The provision of well-lit and clearly legible circulation paths is essential to ensure perceived and actual safety, particularly during non-daylight hours. Furthermore, incorporating adequate seating, shaded zones, and

protection from adverse weather conditions contributes to prolonged and equitable use of outdoor spaces. Crucially, accessibility must be approached through an inclusive lens, ensuring universal access for individuals with disabilities. When successfully implemented, these strategies foster not only usability but also broader outcomes such as psychological well-being, social connectivity, and a sense of belonging within the campus community.

2.1. Resilience

The concept of resilience, together with that of adaptation, describes the capacity of a system to absorb shocks, reorganize, and maintain its core functions without losing identity or purpose. Originating in the field of ecology with Holling's seminal studies (1973) and later extended across a wide range of disciplines—from spatial planning to psychology, sociology, and economics—it has become a transversal category, useful for interpreting the complexity of contemporary societies and their vulnerabilities. Within this research, resilience is operationally defined as the measurable capacity of the campus environment to prevent, withstand, and recover from environmental, infrastructural, and social disruptions through integrated spatial, technological, and community-based strategies. Resilience does not merely denote a passive reaction to crises; rather, it is understood as a dynamic process involving prevention, adaptation, and transformation [25].

In the context of university campuses, resilience acquires a distinctive relevance, as these environments operate as "miniature cities" characterized by heterogeneous populations and a concentration of educational, social, cultural, and residential functions. The COVID-19 pandemic represented another major test of resilience: campuses that had already integrated outdoor learning environments—such as the University of British Columbia in Vancouver—were able to cope more effectively with the disruption, experiencing only a brief interruption of in-person teaching [19]. University public spaces are not simply are as of transit, but multifunctional platforms that support community life and foster social cohesion. Squares, green corridors, libraries, courtyards, and communal areas function as social infrastructures that reduce isolation and strengthen bonds among individuals and groups, contributing to the construction of belonging and collective identity [26]. At the same time, these spaces play a crucial environmental role by mitigating the effects of climate change through nature-based and integrated solutions such as sustainable urban drainage, vegetative shading, permeable surfaces, and biodiversity enhancement [27]. In this sense, environmental and social resilience are intertwined, producing places capable of accommodating everyday needs while serving as critical infrastructures during times of crisis.

The application of resilience to university spaces is closely linked to the notion of preventive resilience, which presupposes strategic investments, long-term planning, and inclusive governance [28,29]. This approach requires not only the identification of potential vulnerabilities, but also particular attention to groups most at risk during crises. On campuses, these may include international students, individuals living in collective residences, persons with disabilities, or those in precarious economic conditions. Social resilience thus translates into universal accessibility, equitable distribution of resources, attention to mental health, and enhanced perceived safety [30]. Resilient spaces are inherently inclusive: they accommodate cultural and social diversity, promote dialogue and participation, and strengthen networks of mutual support.

Mobility is another key dimension. Reducing automobile dependency forms an integral part of resilience: campuses that prioritize walkability, cycling, and public transport not only deliver environmental benefits but also provide safer and more continuous flows under crisis conditions. Public spaces thereby become connective corridors that integrate multiple modes of mobility and guarantee legible, safe, and redundant routes, avoiding

single points of vulnerability [31]. In recent years, increasing attention has been paid to designing spaces that serve everyday academic, social, and cultural functions but can rapidly transform into shelters and support centres during emergencies. Such spaces can provide protection against extreme weather events, distribute food and water, and ensure energy and information connectivity in the event of service disruptions. Within university campuses, libraries, student centres, and gyms can perform these dual roles, reinforcing the conception of public space as critical infrastructure with both ordinary and extraordinary functions.

Resilience in public space also encompasses cultural and symbolic dimensions. Access to nature and high-quality landscapes directly influence psychological well-being, reducing stress while supporting concentration and creativity [32]. Tree-lined pathways, community gardens, and teaching orchards create regenerative environments that strengthen a sense of community. In parallel, public art, collective events, and cultural celebrations consolidate the identity of the campus as a locus of shared memory and social innovation.

2.2. Well-Being

Liveability is operationally defined here as the set of environmental and social conditions that support human well-being, comfort, and inclusivity within the campus context. Main factors include thermal comfort, perceived safety, accessibility score, and health-related quality of life. This concept has gained increasing relevance in urban planning as cities seek to create environments that enhance human well-being. Within university campuses, liveability [33] is crucial not only for students, faculty, and staff who spend significant time in these spaces, but also for the broader urban communities that interact with campus facilities [34]. Universities are no longer solely educational institutions; they now function as social, cultural, and economic actors within cities, shaping the urban landscape and fostering community well-being.

The contribution of public spaces to individual physical and psychological health is well documented in environmental and urban studies. In the campus context, one of the most significant determinants of liveability is the integration of green infrastructure. Numerous studies highlight the benefits of natural environments—parks, gardens, and vegetated open spaces—for mental health and psychosocial well-being. Exposure to such settings is associated with reduced stress, improved mood, and strengthened social cohesion, particularly through informal social interactions [1]. Among these spatial typologies, the concept of "healing gardens" has gained prominence. Incorporating trees, flowering plants, and water features, they offer restorative experiences that provide refuge from academic pressures. Evidence shows that such spaces support cognitive restoration and emotional resilience among students and staff [22,35]. More broadly, the presence of natural settings contributes to calmness and focus, both positively correlated with academic performance and psychological health. Physical activity represents another essential dimension of liveability, closely tied to both mental and physical health. Walking paths, sports fields, outdoor fitness installations, and open activity zones encourage daily movement and exercise, improving cardiovascular health, reducing risks of chronic illness, and enhancing emotional stability [36,37]. These spaces thus function not only as recreational amenities but as critical components of public health infrastructure [38].

Green and open spaces also provide micro-breaks that counteract stress-induced fatigue in demanding academic environments. This aligns with biophilic theory, which posits an innate human affinity with nature and explains the calming effects of natural settings. Empirical evidence links time spent in nature to reduced cortisol levels and improved emotional well-being.

Beyond individual outcomes, campus public spaces play a social role, fostering inclusive and cohesive communities. They provide platforms for casual, unstructured encounters that promote interpersonal connections and reduce isolation—an issue frequently observed in academic contexts [35]. Plazas, seating areas, and outdoor cafés enable interaction across disciplinary, cultural, and generational boundaries, enriching the social fabric of the university. In doing so, they contribute both to individual well-being and to the cultivation of a supportive, diverse campus culture.

2.3. Connectivity

Connectivity is a factor that is necessary to open the campus to the city and create a social sustainability.

Historically, university campuses were conceived as insular environments, reinforcing the notion of academia as a world detached from everyday urban life. Contemporary urban dynamics—marked by population growth, densification, and shifting socio-economic priorities—have transformed this paradigm. Today, the boundaries between campus and city are increasingly porous, requiring a reconceptualization of the university's role within the broader urban ecosystem.

A key driver of this shift is the recognition of universities as catalysts for urban regeneration, particularly in areas lacking accessible public infrastructure or facing socio-economic challenges [37]. Many institutions have therefore embraced the "open campus" model, reimagining their estates as multifunctional, publicly accessible environments that provide value beyond the academic community. By integrating green infrastructure, cultural amenities, and socially oriented services, these campuses actively contribute to urban liveability [38,39].

This model is especially relevant in cities with limited public space. Universities often hold large land assets, and by opening portions of their estates for public use, they help address urban deficits in recreation, ecology, and social infrastructure. Moreover, through the development of connective elements—pedestrian corridors, bicycle lanes, bridges, and transitional nodes—campuses foster physical and symbolic integration with their urban surroundings.

Designing for connectivity requires prioritizing inclusivity. Universal design principles must be applied to pedestrian paths, seating, and gathering spaces, ensuring accessibility for people of all ages and abilities. Locating green spaces near academic buildings, residences, and public transport nodes further enhances usability and equitable access [1].

Connectivity also extends to programmatic strategies. Universities that host cultural events, community outreach programs, and open-access learning initiatives contribute to intellectual and social enrichment beyond academia. Such activities foster reciprocal exchanges between universities and their cities, strengthening civic legitimacy and reinforcing their role as drivers of cultural vitality. In this evolving model, the campus emerges as both a spatial and societal interface—one that advances educational goals while supporting urban resilience, liveability, and community engagement.

2.4. Sense of Community

The *Sense of community* in Campus public spaces–including furniture and equipment-is important to create interactions not only for students, faculty, and staff, but also for urban populations that engage with campus facilities [34,35]. Public spaces are central to this framework, functioning as enablers of community-building and informal social interaction. They play a critical role in shaping what Oldenburg defines as "third places"—neutral settings beyond home and work that facilitate inclusive encounters across diverse groups [40–42]. On campuses, the relevance of third places is amplified

by population diversity and fluidity. Students, faculty, staff, and visitors embody a wide spectrum of cultural, social, and economic backgrounds. Campus life encompasses overlapping communities—some permanent, others transient—ranging from formal institutional structures to informal networks organized around shared interests or digital platforms. These dynamics demand shared and accessible environments where both planned and serendipitous encounters can occur [35].

Spaces such as plazas, libraries, cafés, and outdoor seating areas are thus essential for cultivating a vibrant and cohesive campus culture. They not only facilitate daily socialization but also support intercultural exchange, emotional belonging, and the development of interpersonal networks. Designing such spaces requires grounding in principles of inclusivity and diversity, ensuring responsiveness to a variety of user needs and practices.

Inclusive design extends beyond physical accessibility to social and cultural accessibility. This entails flexibility—providing quiet areas alongside active zones, formal and informal seating, and opportunities for both individual and collective use [1]. Cultural sensitivity is equally important: for international students and visitors, elements such as culturally resonant vegetation, public art, or food offerings can foster familiarity and comfort. Through these strategies, campus public spaces become environments where diversity is acknowledged and celebrated, strengthening community ties and enhancing the overall liveability of the campus.

3. Methodology

In recent decades, the understanding of university spaces has evolved beyond their traditional role as functional supports for teaching and research (Figure 1).

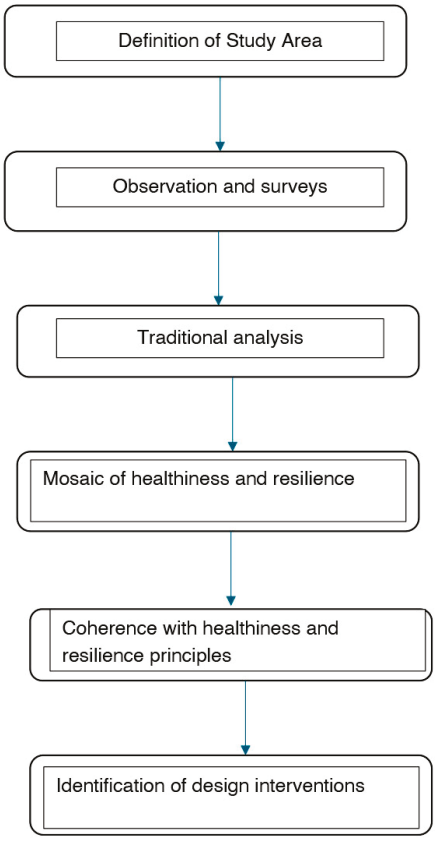


Figure 1. Methodological flow chart (Source: Author's Elaboration).

They are now increasingly regarded as complex environments that influence psychological and physical well-being, quality of life, and the sociality of academic communities. Within this framework, it becomes necessary to employ a methodology conceived as an innovative tool for the analysis, design, and transformation of university public spaces. This methodology is grounded in an integrated approach that combines direct surveys, cartographic tools, and universal principles of healthiness and urban liveability [40]. The methodological framework is articulated into six sequential phases, designed to ensure a logical progression from observation to design proposal.

Phase 1 consists of defining the study area within the campus. This preliminary step is essential to circumscribe the scope of investigation, establishing the physical and functional boundaries of the university public space under analysis. Through site visits and preliminary observations, the main gathering areas, circulation routes, and connection nodes are identified, providing the operational basis for subsequent analyses.

Phase 2 focuses on the systematic observation and classification of the physical, social, and perceptual characteristics of public spaces, as well as the movements and behaviours of people traversing them. Quantitative and qualitative data are collected on flows, activities, and user categories, distinguishing among students, faculty, technical staff, visitors, and members of the surrounding community. The observation framework (Table 1) records the type of activity (leisure, transit, sports, work), the quantity of people, and their frequency and pace of movement, each evaluated on a Low–Medium–High scale. This allows for a comparative analysis of intensity, rhythm, and spatial distribution of use.

Table 1. People and Activities Survey.

Activity	People	Quantity of People	Frequency	Pace
Leisure, transit, sports, work	Locals, students, visitors, professors, workers	Low, medium, high	Low, medium, high	Fast, moderate, slow

Simultaneously, the perceptual dimension of space is explored through on-site and survey-based assessments that capture users' sensory experiences (Table 2). Visual, acoustic, olfactory, tactile, gustatory, and mixed perceptions are documented, each rated in terms of quantity (Low–Medium–High) and quality (Pleasant–Neutral–Disturbing). This dual evaluation recognizes that environmental quality derives not only from measurable physical parameters but also from the subjective sensations and affective responses elicited by place.

Table 2. Perceptions Survey.

	Visual Perception	Acoustic Perception	Olfactory Perception	Gustatory Perception	Tactile Perception	Mixed Perception
Quantity: Low, Medium, High						
Quality: Pleasant, Disturbing, Neutral						

The phase also includes the cataloguing of facilities, equipment, and furnishings (Table 3), assessing their type, characteristics, and maintenance status using the same Low–Medium–High scale. Special attention is given to sustainability-oriented devices—such as solar-powered lighting or recycling bins—and to artistic or symbolic

elements like sculptures or street art, which contribute to the identity and inclusiveness of the space.

Table 3. Facilities and Equipment Survey.

	Access (Free, with Steps, Turnstiles, etc.)	**Pathways (Pedestrian, Cycling, etc.)**	**Urban Furniture (Bins, Light Poles, etc.)**	**Equipment (Play-ground, Sports, etc.)**	**Sustainability-Oriented Equipment (Solar-Powered Poles, Recycling Bins, etc.)**	**Transport Means (Cars, Bikes, Scooters, Metro)**	**Artistic Products (Sculptures, Street Art, etc.)**
Type							
Maintenance Status: Low, medium, high							

Overall, Phase 2 provides a multi-layered understanding of campus public spaces by combining behavioural observation, sensory perception, and infrastructural assessment. The use of standardized parameters (Low–Medium–High) ensures comparability across sites and facilitates the translation of empirical observations into design and management guidelines.

Phase 3 involves traditional cartographic and morphological analysis. This stage examines the physical components of the campus context—roads, green areas, buildings, and infrastructures—placing them within an overall vision. It is a crucial step for understanding the relationship between the academic space and the surrounding urban fabric, as well as for highlighting the potential and criticalities of the existing morphological structure.

Phase 4 identifies the elements of healthiness and resilience within the campus public spaces by superimposing the information collected in the previous phases. The objective is to create a composite map highlighting which areas are healthier and more resilient, and which require corrective interventions. This synthesis provides the foundation for comparative evaluation.

Phase 5 consists of assessing the degree of healthiness and resilience by verifying coherence with guiding principles. These principles, constituting a "Charter for Resilient and Liveable Campuses," span material needs—such as cleanliness, maintenance, and removal of architectural barriers—as well as immaterial aspects, including place identity, educational functions, the presence of art, and the use of digital technologies for heritage enhancement.

The principles include:

- Ensuring accessibility for all potential campus users;
- Eliminating architectural barriers that discourage use;
- Balancing natural, landscape, and infrastructural elements;
- Designing flexible, adaptable spaces that can serve in both ordinary and emergency conditions;
- Guaranteeing adequate natural and artificial lighting while minimizing artificial light pollution;
- Maintaining cleanliness and proper upkeep;
- Creating a sense of safety and protection for those walking, studying, or resting in public spaces;
- Reducing or eliminating noise generated by transport systems;
- Providing adequate cycling lanes and internal–external campus connections;
- Using natural, preferably local, materials;

- Incorporating water features that foster vitality;
- Ensuring usability in diverse weather and seasonal conditions;
- Preserving both place identity and intangible site characteristics;
- Supporting varied functions such as play, relaxation, and walking;
- Facilitating physical activity with equipment or dedicated spaces;
- Promoting art in its various forms;
- Encouraging participation and a sense of belonging;
- Implementing effective wayfinding systems;
- Paying attention to waste separation and recycling;
- Recognizing healthy nutrition as an essential principle of campus sustainability.

This verification not only measures compliance with shared standards but also identifies criticalities and opportunities for improvement.

Phase 6 culminates in the identification of design interventions, elaborated on the basis of collected data. These interventions must align with the Charter's principles and integrate coherently with the university's strategic development plans. The final outcome is a comprehensive mosaic that not only represents the current state of public spaces but also outlines potential pathways for their transformation.

4. UBC Vancouver Campus

The methodology was tested on several exemplary university campuses whose public spaces represent key indicators of environmental and social quality for both academic communities and visitors. These include University of British Columbia (UBC Vancouver), Søndre Campus (Copenhagen), WU Vienna University of Economics and Business, University College Dublin (UCD), Wuhan University, Xi'an University of Architecture and Technology (XAUAT), and the University of California campuses at Berkeley and San Francisco–Mission Bay.

The comparative analysis of Søndre Campus, WU Vienna, and UCD highlights how European campuses function as resilient, inclusive, and liveable urban ecosystems. Each demonstrates strong connectivity with its urban surroundings through open spatial structures, pedestrian and cycling networks, and integration with public transport. Field observations and surveys confirm that these environments promote well-being through accessible, green, and multisensory spaces fostering study, leisure, and social interaction. Users value biodiversity-oriented landscapes, shaded seating, and multifunctional plazas enhancing comfort and year-round usability. Despite this, exposure to weather extremes underscores the need for more adaptive and climate-responsive design. In the North American context, UC Berkeley and UCSF Mission Bay offer two complementary models. Berkeley's historic campus, embedded in the urban fabric, embodies a hybrid ecosystem where cultural memory, civic activism, and nature coexist. Mission Bay, conversely, represents a paradigm of health urbanism, integrating research, clinical care, and community well-being within a sustainable spatial framework. In China, Wuhan University and XAUAT demonstrate distinct yet convergent approaches. Wuhan integrates its campus within the natural landscape of Luojia Hill and East Lake, fostering contemplative and environmental harmony, while XAUAT's design uses courtyards and experimental gardens as pedagogical spaces, merging learning, research, and social interaction. Among these case studies, the case of UBC Vancouver is of particular interest and will be illustrated in detail below. It represents a campus where public spaces embody resilience and liveability for all, in line with the broader planning principles of the city.

The University of British Columbia (UBC), headquartered in Vancouver, constitutes one of the most significant examples of a North American campus designed and managed according to advanced principles of environmental and social sustainability. The study

area corresponds to the main campus, located on the Point Grey Peninsula, an extensive site combining academic, residential, cultural, and sports functions, interwoven with a complex system of open public spaces. The delimitation follows a dual logic: on the one hand, the physical and administrative boundaries of the campus, regulated by controlled access; on the other, the perception of the public spaces actually used by users. Within this perimeter, particular importance is given to central plazas (such as Martha Piper Plaza), pedestrian and cycling greenways, courtyards within academic buildings, equipped green areas, commons, outdoor sports facilities, and informal recreational spaces. A specific focus is directed toward the relationship with the surrounding context: UBC stands on the unceded traditional territory of the Musqueam community, which confers a functional, environmental, and cultural-symbolic value to its public spaces. Artistic installations, Indigenous works, and participatory processes aimed at recognizing local cultural heritage are thus integral to the study area definition. Phase 1 therefore produces a clear delimitation of the study area, comprising the main public spaces, slow-mobility corridors, and activity nodes guiding population flows.

Phase 2 relies on direct and indirect surveys to map activities, flows, perceptions, and material provisions. Data sources include field visits and survey-based investigations, which provided both qualitative and quantitative information on the use and perception of public spaces.

The campus population is highly heterogeneous, including undergraduate and graduate students, researchers, faculty, technical and administrative staff, visitors, and members of local communities.

The intensity of use varies according to the time of day and the academic calendar: daytime is characterized by circulation and study/work activities; breaks coincide with social and recreational practices, while specific areas host sports, leisure, and cultural events. Movement rhythms are diverse: fast along classroom–library connections, moderate along greenways, and slow in plazas and commons where pauses prevail.

Sensory perceptions reveal an overall positive image: visually, modern buildings alternate with green landscapes and panoramic views of the ocean and mountains; acoustically, the environment is generally pleasant due to limited car traffic, although higher noise levels are recorded near main road nodes; natural scents of grass and wood positively influence olfactory perception; tactile sensations are enhanced by the use of natural materials such as wood and stone in pavements and furnishings.

Equipment includes benches, waste-sorting bins, lighting, bike racks, playgrounds, and sports facilities (Figures 1–6). Sustainable technologies such as solar lighting, rainwater management systems, and digital information panels are widespread, while maintenance standards remain consistently high.

Artistic and cultural features—particularly Indigenous installations—endow public spaces with a strong cultural identity: far from mere decoration, public art stimulates reflection, belonging, and recognition of local communities. Example tables are represented in the following (Tables 4–6).

Cartographic and morphological analysis allows the identification of the campus's physical and infrastructural elements and their alignment with healthiness objectives (Figure 7). The system appears compact, with clear distinctions among central academic areas, student residences, sports facilities, and services. The open-space network functions as green infrastructure connected both to surrounding natural areas and to internal mobility systems. Main entrances are designed to favour multimodal transport—bus, cycling, and pedestrian flows—while reducing car dependency through greenways and progressive pedestrianization of internal streets. Landscape integration is of great value: proximity to the ocean and forests enhances aesthetic attractiveness, strengthens perceptions of health-

iness, and provides daily opportunities for contact with nature. District energy systems and LEED Gold building standards demonstrate an advanced sustainability approach, while the innovative *Resilience Hubs* provide spaces for ordinary social activities that can be rapidly transformed into community support centres during emergencies. This phase systematically maps material and infrastructural components, confirming alignment with sustainability goals and highlighting resilience as a guiding criterion.



Figure 2. UBC Campus public space, perspective view of the landscape (Source: Author's Archive).



Figure 3. UBC Campus public space, detail of bicycle parking area (Source: Author's Archive).



Figure 4. UBC Campus, detail of a symbolic sculpture on the pavement (Source: Author's Archive).



Figure 5. UBC Campus area for relaxing (Source: Author's Archive).

Table 4. Campus Core People and Activities Survey.

Activity	People	Quantity of People	Frequency	Pace
Leisure, transit	students, visitors, professors, staff	medium	medium	slow



Figure 6. UBC Campus indigenous sculpture (Source: Author's Archive).

Table 5. Campus Core Perceptions Survey.

	Visual Perception	**Acoustic Perception**	**Tactile Perception**	**Mixed Perception**
	Landscape-ocean and mountains	Voice of people	Grass	serenity
Quantity: Low, Medium, High	Medium	Medium	Medium	Medium
Quality: Pleasant, Disturbing, Neutral	Pleasant	Neutral	Pleasant	Pleasant

Table 6. Campus Core Facilities and Equipment Survey.

	Access (Free, with Steps, Turnstiles, etc.)	**Pathways (Pedestrian, Cycling, etc.)**	**Urban Furniture (Bins, Light Poles, etc.)**	**Sustainability-Oriented Equipment (Solar-Powered Poles, Recycling Bins, etc.)**	**Artistic Products (Sculptures, Street Art, etc.)**
Type	Free	Pedestrian	Benches, light poles	Solar-powered poles	Indigenous installations
Maintenance Status: Low, medium, high	High	High	High	High	High

Phase 5 synthesizes evidence from surveys and cartographic analysis to identify factors underpinning UBC's resilience and liveability. Key strengths include: Environmental quality, expressed through abundant green spaces, connection with surrounding nature, and use of natural, sustainable materials;

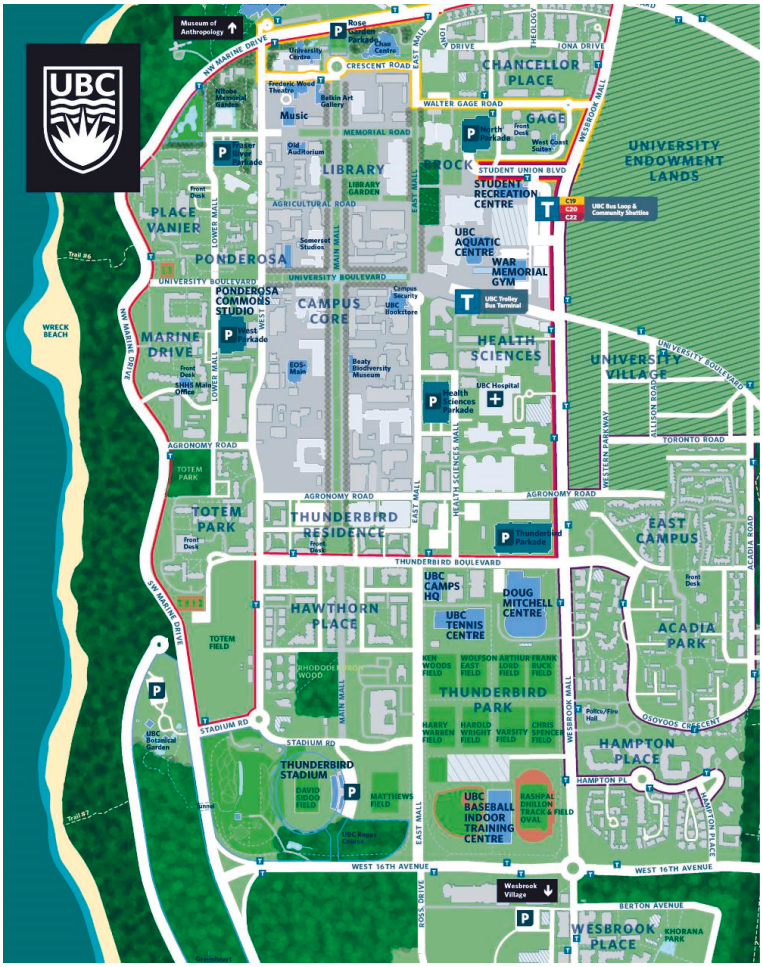


Figure 7. UBC Campus plan (Source: https://maps-vancouver.com/ubc-campus-map, accessed on 30 October 2025).

Mobility, with an extensive network of pedestrian and cycling paths and reduced car use; Social accessibility, reflected in inclusive gathering spaces and participatory processes involving students, staff, and the Musqueam community; Resilience and safety, demonstrated by the presence of Resilience Hubs and sustainable energy infrastructures; Cultural value, shaped by a visual and symbolic identity reinforced through public and Indigenous art.

Challenges remain, however: limited coverage reduces year-round usability; residual architectural barriers persist in secondary areas; there is demand for more light sports and informal social facilities; and some traffic nodes generate noise levels that compromise acoustic comfort.

Verification against the Charter principles confirms that UBC transmits widespread feelings of well-being and happiness, supported by abundant greenery, perceived safety, and vibrant social life. Spaces are not limited to students but also attract families, children, and seniors, particularly in green and cultural areas, confirming intergenerational inclusivity. Accessibility measures are largely effective, though some barriers remain in older facilities. Balance between natural elements and infrastructure is well achieved, lighting is adequate though sometimes excessive, and maintenance is consistently high. Noise is reduced in central areas but persists near traffic corridors. Cycling infrastructure is widespread, though intersections require improvements. Sensory quality is enriched by natural scents and tactile use of local materials. Public spaces support a moderate rhythm of daily activities, with ample opportunities for pause, walking, and socialization,

though seasonal usability declines in winter due to harsh, rainy weather. Campus identity is strongly preserved through ties with the Musqueam community and Indigenous art. Functional diversity is ensured by a variety of study, leisure, sports, and cultural areas, though light physical activities could be better supported by specific equipment. Public art is highly valued, and playful, interactive elements could be expanded. Educational functions are enriched by panels, museums, and learning trails, complemented by digital technologies enabling interactive engagement.

Phase 6 translates findings into concrete design interventions. For UBC, priority actions include:

Development of climate-adaptive infrastructures such as lightweight canopies, pergolas, and covered multifunctional areas; introduction of more water elements (fountains, reflecting pools, interactive installations) to reinforce sensory and symbolic dimensions; completion of universal accessibility, eliminating residual barriers and redesigning secondary routes inclusively; expansion of sports and fitness facilities (e.g., gentle exercise areas, yoga spaces, fitness trails); enrichment of public art, integrating interactive and playful installations; strengthening of cycling infrastructure, focusing on safer intersections and increased bike parking; implementation of digital tools for communication and storytelling, to promote cultural heritage and community belonging.

These interventions are fully consistent with the strategies of *Campus Vision 2050* [20,43] already underway at UBC in the fields of sustainability, resilience, and inclusion. Collectively, they consolidate the image of the campus as an international model of healthy, liveable, and joyful public space [44].

5. Observations on the Case Study

UBC has developed as a complex urban ecosystem, capable of integrating academic, residential, cultural, and recreational functions within a high-value landscape setting. In this perspective, resilience and liveability are not ancillary outcomes but guiding criteria that inform the entire life cycle of public space: from morphological layout to material choices, from water management to programming and use, through to the construction of identity and belonging. The underlying premise is that an environment able to host everyday practices under ordinary conditions—study, encounter, play, movement, contemplation—is also an environment that, under extraordinary conditions, can absorb shocks, reorganize, and ensure continuity of essential services.

In terms of climate adaptation, the resilience strategy takes shape through infrastructures that connect physical and social dimensions. The Resilience Hubs represent the fulcrum of this vision: hybrid places that, in normal times, support programs for well-being, sociality, and learning, while, in emergencies, reconfigure as cooling centres and hubs for the distribution of water and food, and for access to energy and information. Their effectiveness depends not only on technical solutions (energy efficiency, emergency systems, network redundancy), but also on universal accessibility, proximity to pedestrian flows, and symbolic recognizability, so that they are perceived as common goods rather than sector-specific facilities.

Campus liveability is supported by a coherent network of open spaces that privileges walking and cycling. Greenways, plazas, and commons are conceived as devices for ecological and social continuity: by connecting buildings and amenities, they sustain active mobility, multiply opportunities for informal encounter, and increase perceived safety through the steady presence of users and legible routes. Within this light infrastructure, the use of natural, locally sourced materials (wood, stone), vegetative shading, permeable surfaces, and distributed stormwater management mitigates heat islands, runoff, and environmental

stress, translating biophilic design principles into accessible sensory experiences—scents of grass and wood, tactile textures, and views toward the ocean and forests.

The cultural dimension is another structural lever of resilience. Collaboration with the Musqueam community and the integration of public art—with particular emphasis on Indigenous works—acknowledge the identity of place and activate a pedagogy of space that connects memory, care, and territorial justice. Far from mere decoration, art functions as a language of mediation and cohesion: it marks routes, renders nodes recognizable, produces shared narratives, and strengthens symbolic anchoring as well as the quality of experience.

To enhance the analytical and operational clarity of the case study, the identified strengths and challenges can be systematized through a priority matrix that evaluates each proposed action according to its impact and feasibility, and associates it with a suggested timeframe (short, medium, or long term). High-impact and high-feasibility actions include the expansion of shaded and permeable areas, the improvement of cycling networks, and the integration of interactive public art—all of which can generate tangible benefits for comfort, mobility, and cultural inclusion within a short to medium horizon. Medium-impact interventions with lower feasibility, such as the extension of resilience hubs or the implementation of advanced stormwater systems, would require longer-term planning and additional funding.

6. Conclusions

The paper has illustrated the main factors of liveability and resilience in campus public spaces, together with an original methodology for their analysis and design. Among the case studies, the best practice of the University of British Columbia (UBC) in Vancouver was examined, revealing that resilience and liveability are not merely desirable attributes but structural components of a sustainability framework capable of enduring over time. The most significant outcome lies not in the sum of individual interventions, but in the systemic quality that interrelates them: legible and connected open spaces, inclusive governance, a culture of place, ecological resource management, and climate adaptation capacity. This interweaving generates positive externalities across multiple dimensions—environmental, social, health-related, and educational—consolidating the campus as a civic platform that promotes public well-being beyond institutional boundaries.

From a theoretical perspective, the UBC case confirms that resilience extends beyond resistance to disturbances, incorporating institutional learning and the redefinition of practices of use. Liveability, in turn, transcends aesthetic or perceptual aspects to function as an everyday infrastructure encompassing active mobility, shading and microclimatic comfort, spaces for rest and encounter, universal accessibility, and perceived safety. When these elements are coherently coordinated and properly maintained, the university campus becomes a device capable of reducing vulnerabilities, generating social capital, and enabling healthy behaviours. The integration of art and place memory—particularly through dialogue with the Musqueam community—demonstrates that culture forms part of the cognitive security of space: it orients, includes, and empowers.

From a methodological standpoint, the proposed approach has proven effective in organizing heterogeneous data—field surveys, sensory perceptions, and cartographic analyses—and translating them into actionable strategies. Its added value lies not only in the sequencing of phases but also in the iterative possibility of revisiting results through the lens of the Charter of Resilient and Liveable Campuses. This verification distinguishes between superficial compliance and genuinely experienced quality, preventing sustainability from being reduced to certifications or performance standards disconnected from everyday life. The integration of both quantitative and qualitative dimensions—metrics

and narratives such as indicators, perception maps, and climate diaries—emerges as crucial for informed, context-sensitive decision-making that accounts for seasonal dynamics and diverse social needs.

From a theoretical contribution standpoint, the integration of the Curriculum + Charter represents a transferable and comparable framework for campus planning. It provides a replicable structure linking educational content (the Curriculum) with spatial and operational principles (the Charter), enabling institutions to evaluate and design their public spaces through a shared matrix of criteria. This framework can serve as a reference model adaptable to diverse cultural and environmental contexts, fostering cross-campus benchmarking and knowledge exchange in the field of sustainable campus development.

From an operational perspective, the UBC experience suggests three strategic trajectories that campuses—and, more broadly, large public estates—can adopt to reconcile adaptation, equity, and spatial quality. The first concerns the climatic maintenance of open spaces, moving beyond routine care toward seasonal management that includes permeable surfaces, lightweight shelters, wind screens, and low-impact thermal comfort devices. The second involves water as both environmental and cultural infrastructure: not only the technical management of stormwater, but also the staging of water cycles through educational and experiential installations such as fountains, small cascades, and visible collection systems. The third relates to slow mobility as a universal service, through protected cycling networks, continuous sidewalks, inclusive wayfinding, and micro-areas for gentle physical activity near residences and classrooms.

Looking ahead, the proposed methodology offers a scalable framework adaptable to other university campuses and large institutional estates worldwide. By integrating environmental performance with social and cultural dimensions, it provides a replicable model for the design and management of resilient and liveable public spaces. Nonetheless, certain limitations must be acknowledged: the study's focus on a single case—the UBC Vancouver campus—may not capture the full diversity of geographical, climatic, or governance contexts elsewhere, and the predominance of qualitative data calls for further quantitative validation. Future research could therefore expand the empirical base and test the framework across different cultural and environmental settings, including healthcare facilities, research parks, and civic precincts, where similar dynamics of coexistence, mobility, and adaptation define the everyday landscape of collective life.

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References

1. Hami, A.; Abdi, M. Natural elements and their influence on student study areas in university campuses. *Environ. Psychol. Rev.* **2021**, *31*, 45–60.
2. Haar, S. *The City as Campus: Urbanism and Higher Education in Chicago*; University of Minnesota Press: Minneapolis, MN, USA, 2011.
3. Turner, P.V. *Campus: An American Planning Tradition*; MIT Press: Cambridge, MA, USA, 1984.
4. Ulrich, R.S. View through a window may influence recovery from surgery. *Science* **1984**, *224*, 420–421. [CrossRef] [PubMed]
5. Gumprecht, B. The campus as a public space in the American college town. *J. Hist. Geogr.* **2007**, *33*, 72–103. [CrossRef]
6. Austin, D.; Solano, T.; Chen Austin, M. Synergistic Effects of Bioclimatic Strategies on Microclimate Improvement: A Numerical–Experimental Study at University Campus Scale. *Sustainability* **2025**, *17*, 8867. [CrossRef]
7. McNeill, D. Urban Geography III: Universities and their spaces. *Prog. Hum. Geogr.* **2024**, *48*, 103–110. [CrossRef]
8. Mohammed, A.M.S.; Ukai, T.; Hall, M. Towards a sustainable campus-city relationship: A systematic review of the literature. *Reg. Sustain.* **2022**, *3*, 53–67. [CrossRef]
9. Sugiarto, A.; Lee, C.W.; Huruta, A.D. A Systematic Review of the Sustainable Campus Concept. *Behav. Sci.* **2022**, *12*, 130. [CrossRef]
10. Bromley, R. On and off campus: Colleges and universities as local stakeholders. *Plan. Pract. Res.* **2006**, *21*, 1–24. [CrossRef]
11. Fassi, D.; Galluzzo, L.; Rogel, M. Opening the campus: The Milano Bovisa experience. *Des. J.* **2016**, *19*, 501–517.
12. Ali, M.; Kim, Y. Can a university campus work as a public space in the metropolis of a developing country? The case of Ain-Shams University, Cairo, Egypt. *Sustainability* **2020**, *12*, 7229. [CrossRef]
13. University of Pennsylvania. *Penn Connects: A Vision for the Future*; University of Pennsylvania Press: Philadelphia, PA, USA, 2011.
14. Wagner, G. Green Campus: The Role of Sustainability at WU Vienna. *Environ. Res. Lett.* **2016**, *11*, 065001.
15. Way, H. University of Chicago's expansion: An integrated campus in an urban setting. *J. Urban Des.* **2018**, *23*, 569–585.
16. Bagnato, V.P. The university campus' open spaces between rituality and non-normativity. *FORUM A+P* **2021**, *22*, 62–69. [CrossRef]
17. Lester, R.K.; Piore, M.J. Universities as public spaces. In *Innovation—The Missing Dimension*; Harvard University Press: Cambridge, MA, USA, 2006.
18. Rashidi, A. University-city integration: A socio-cultural and economic relationship. *J. Urban Stud.* **2013**, *50*, 948–965.
19. UBC. UBC Indigenous Strategic Plan. 2023. Available online: https://oisi-2023.sites.olt.ubc.ca/files/2024/02/FINAL-ISP-BIG-booklet-version-2.0.pdf (accessed on 20 October 2025).
20. UBC. *Outdoor Learning Spaces and COVID-19 Response*; University of British Columbia: Vancouver, BC, Canada, 2020.
21. UBC. UBC Vancouver campus plan, 2020b. Available online: https://planning.ubc.ca/sites/default/files/2020-12/PLAN_UBC_VCP-Part2-2020Update_0.pdf (accessed on 20 October 2025).
22. Dober, R.P. *Campus Design*; John Wiley, Sons: New York, NY, USA, 1992.
23. Dong, W.; Wu, J.; Chen, Y.; Zhou, X. A bibliometric review of research on the perceptions of campus public spaces. *Buildings* **2023**, *13*, 501. [CrossRef]
24. Działek, J.; Homiński, B.; Miśkowiec, M.; Świgost-Kapocsi, A.; Gwosdz, K. The assessment of the quality of campus public spaces as key parts of the learning landscape: Experience from a crowdsensing study on the Third Campus of Jagiellonian University, Krakow, Poland. *Urban Des. Int.* **2024**, *29*, 77–92. [CrossRef]
25. Fassi, D.; Galluzzo, L.; Rogel, M. Hidden public spaces: When a university campus becomes a place for communities. In *Future Focused Thinking, Proceedings of the DRS International Conference, Brighton, UK, 27–30 June 2016*; Lloyd, P., Bohemia, E., Eds.; Design Research Society: London, UK; pp. 27–30.
26. Zolli, A.; Healey, A.M. *Resilience: Why Things Bounce Back*; The Free Press: New York, NY, USA, 2012.
27. Vale, L.J.; Campanella, T.J. *The Resilient City: How Modern Cities Recover from Disaster*; Oxford Scholarship Online: Oxford, UK, 2005.
28. Pickett, S.T.A.; Cadenasso, M.L.; Grove, J.M. Resilient cities: Meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms. *Landsc. Urban Plan.* **2004**, *69*, 369–384. [CrossRef]
29. Russo, M. Rethinking resilience, design the city through its metabolism. *TECHNE J. Technol. Archit. Environ.* **2018**, *15*, 39–44.
30. Davoudi, S.; Shaw, K.; Haider, L.J.; Quinlan, A.E.; Peterson, G.D.; Wilkinson, C.; Fünfgeld, H.; McEvoy, D.; Porter, L. Resilience: A Bridging Concept or a Dead End? *Plan. Theory Pract.* **2012**, *13*, 299–333. [CrossRef]
31. Ojerio, R.; Moseley, C.; Lynn, K.; Bania, N. Limited Involvement of Socially Vulnerable Populations in Federal Programs to Mitigate Wildfire Risk in Arizona. *Nat. Hazards Rev.* **2011**, *12*, 28–36. [CrossRef]
32. Borsekova, K.; Nijkamp, P. *Resilience and Urban Disasters*; Edward Elgar Publishing: Cheltenham, UK, 2019.
33. Vale, J.L. The politics of resilience cities: Whose resilience and whose city? *Build. Res. Inf.* **2014**, *42*, 191–201. [CrossRef]
34. Sepe, M. *Designing Healthy and Liveable Places*; Routledge: London, UK; New York, NY, USA, 2023.

35. Soares, I.; Weitkamp, G.; Yamu, C. Public spaces as knowledgescapes: Understanding the relationship between the built environment and creative encounters at Dutch university campuses and science parks. *Int. J. Environ. Res. Public Health* **2020**, *17*, 7421. [CrossRef]
36. Lau, S.S.; Yang, F. Introducing healing gardens into a compact university campus: Design natural space to create healthy and sustainable campuses. *Landsc. Res.* **2009**, *34*, 55–81. [CrossRef]
37. Gehl, J. *Life Between Buildings: Using Public Space*; Island Press: Washington, DC, USA, 2006.
38. Tjora, A.; Scambler, G. *Cafe Society: Coffee Bars, the Urban Public and the Politics of Space*; Palgrave Macmillan: Cham, Switzerland, 2018.
39. Jensen, O.B. *Mobilities and Design: Urban Design for Mobile Situations*; Routledge: London, UK; New York, NY, USA, 2016.
40. Bersanti, E.; Crudeli, A.; Lanini, L.; Marcheschi CSepe, M. Living the University, Guidelines for new campuses and public spaces for sustainable urban livability. *Agathon—Int. J. Archit. Art Des.* **2025**, *17*, 59–72.
41. Bringle, R.G.; Hatcher, J.A. Campus-Community Partnerships: The Terms of Engagement. *J. Soc. Issues* **2002**, *58*, 503–516. [CrossRef]
42. Oldenburg, R. *The Great Good Place*; Da Capo Press: Cambridge, MA, USA, 1999.
43. AAVV. Campus Vision 2050, 2025. Available online: https://planning.ubc.ca/vision (accessed on 20 October 2025).
44. Zhu, Q.; Fang, X. Exploring the Application of Neurostructural Principles to the Design of Public Spaces on University Campuses. *Land* **2024**, *13*, 1978. [CrossRef]

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The Divergent Geographies of Urban Amenities: A Data Comparison Between OpenStreetMap and Google Maps

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Abstract

Urban models support sustainable, resilient, and equitable planning, but their validity hinges on underlying spatial data. This study examines the epistemological and technical consequences of relying on two dominant yet divergent platforms—OpenStreetMap (OSM) and Google Maps—for extracting proximity-based amenities within the 15-min city framework. Across four European contexts—Versilia, Gothenburg, Nice, and Vienna—we compare (i) data completeness and spatial coverage; (ii) semantic categories; and (iii) the effects of data heterogeneity on accessibility modelling. Findings show that OSM, while semantically consistent and openly accessible, systematically underrepresents peripheral amenities, introducing bias towards urban cores in accessibility metrics. Conversely, Google Maps provides broader coverage but is constrained by dependencies on extraction methods, opaque data structures, and ambiguous classification schemes, which hinder reproducibility, reduce interpretability, and limit its analytical robustness. These divergences yield distinct accessibility landscapes and competing readings of functionality and spatial equity. We argue that data source choice and protocol design are epistemological decisions and advocate transparent, hybrid strategies with cross-platform semantic harmonisation to strengthen robustness, equity, and policy relevance.

Keywords: OpenStreetMap; google maps; volunteered geographic information; spatial data quality; big-data; 15-min city; proximity-based planning; data-driven urban modelling; decision support systems (DSS)

1. Introduction

In recent years, the concept of the 15-Minute City has gained widespread traction as a framework for sustainable urban transformation. Popularised by Moreno et al. [1], it envisions urban environments where essential services and amenities are accessible within a 15-min walk or bike ride, thereby promoting proximity, local vibrancy, and environmental efficiency. Despite its appeal, operationalising this concept in spatial analyses and decision-support systems (DSS) remains methodologically challenging. As Pezzica et al. [2] highlight, persistent uncertainties affect both the selection of urban functions to include and the spatial granularity of the analytical units—such as whether isochrones should be generated from grid-based centroids or user-specific origins.

An equally critical, yet comparatively underexplored, issue concerns the quality, completeness, and internal consistency of the spatial datasets on which proximity models depend. The robustness of urban accessibility assessments is directly contingent upon

the reliability of these underlying datasets. Pezzica et al. [2], for example, adopted OpenStreetMap (OSM) as their primary data source, applying both strict and broad amenity classifications, but noted persistent sensitivities to tagging inconsistencies. Similarly, Mara et al. [3] documented the misrepresentation of commercial activities in Versilia, prompting a manual survey to validate correlations with centrality measures. While such ground-truthing offers valuable accuracy, it is impractical for multiscale planning frameworks. Complementary platform audits also indicate that online maps provide uneven and selective coverage of on-the-ground businesses. In a field-validated study of smaller US cities, Quinn and Condon [4] show that Latino-oriented local businesses are less frequently included across popular platforms than national chains and that coverage is lower in high-Latino areas; they also note residual "defunct" venues and visibility effects linked to platform ranking. These findings suggest that platform logics and contributor ecologies can condition which amenities are even eligible to be counted—introducing distributional bias upstream of any proximity model. Taken together with tagging sensitivities in OSM [2] and local misclassification issues [3], this makes the integrity of digital spatial data—and, at minimum, a nuanced understanding of their structures, provenance, and limitations—a foundational concern not only for proximity-based models, but for evidence-based urban analytics more broadly. Yet, the systematic implications of dataset choice, extraction protocols, and inherent variability remain insufficiently examined.

Among the most widely used spatial data infrastructures in urban research are OpenStreetMap and Google Maps [5]. Both provide extensive geographic coverage, frequent updates, and machine-readable formats, making them central to accessibility modelling, mobility analysis, land-use characterisation, and urban form assessment. However, few studies have directly compared these datasets [6–9], and even fewer have examined how divergences in data structure, categorisation logic, or retrieval protocols shape modelling outcomes—particularly in proximity-based frameworks such as the 15-min city. Key questions remain unresolved: Are these sources functionally interchangeable? Do their discrepancies manifest uniformly across different urban morphologies and socio-spatial contexts? Is one demonstrably more complete, reliable, or fit-for-purpose than the other?

This paper addresses these questions through a comparative evaluation of OSM and Google Maps, focusing on their capacity to represent urban amenities central to the 15-min city framework. The aim is to assess the extent to which spatial data source selection influences both the analysis and operationalisation of urban proximity in planning practice. Three analytical dimensions guide the study:

1. **Data volume** and **spatial consistency** across multiple geographical scales;
2. **Semantic divergence** in the categorisation and retrieval of core urban functions;
3. **Impacts on applied urban modelling**, with specific reference to 15-min accessibility potential.

The empirical analysis spans four diverse urban contexts: northern Versilia (Italy), Gothenburg (Sweden), Nice (France), and Vienna (Austria). Through buffer-based sampling, semantic harmonisation, and functional classification, the study demonstrates how alternative datasets generate systematically different representations of local accessibility—in both the volume of amenities identified and the granularity of typological detail.

The remainder of the paper is organised as follows. Section 2 reviews the two platforms, outlining their core characteristics and comparability issues. Section 3 introduces the case study contexts. Section 4 presents the methodological framework. Section 5 reports empirical results across the three analytical dimensions, while Section 6 discusses implications for data-driven spatial modelling, evidence-based planning, and proximity-oriented urban policy.

This contribution advances research on sustainable, resilient, and equitable urban development by interrogating the data infrastructures that underpin proximity-based planning and decision-support systems. Sustainable outcomes depend not only on persuasive concepts such as the 15-min city, but on reliable, transparent, and reproducible measurements of accessibility and functional mix. By showing that the choice between OpenStreetMap and Google Maps is not a neutral technical step—but an epistemological decision that reshapes counts, spatial distributions, and amenity typologies across distinct European contexts—this study foregrounds the governance of digital data as a first-order issue for urban analytics. In particular, we demonstrate how scale sensitivity and retrieval logics (Section 5.2), semantic misalignment (Section 5.3), and downstream modelling effects within 15-min isochrones (Section 5.4) can bias assessments toward dense cores and commercially salient venues, risking misallocation of resources and under-servicing of peripheral areas. Situating accessibility indicators within this critical lens strengthens their validity for SDG-oriented monitoring and for evidence-based planning that pursues both environmental benefits (e.g., reduced travel demand) and social justice (e.g., fair provision of daily services).

2. Datasets Properties and Extraction Criteria

This study focuses on two of the most widely used geospatial platforms in urban research: OpenStreetMap (UK) and Google Maps (USA). Both are primary sources of spatial big data in contemporary urban analysis due to their extensive global coverage, frequent updates, and programmatic accessibility [10,11]. Despite their shared prominence, they differ fundamentally in governance models, data structures, and semantic frameworks—differences that have direct implications for the operationalisation of proximity-based urban models.

2.1. OpenStreetMap

OSM is the most prominent example of Volunteered Geographic Information (VGI), a data paradigm grounded in crowdsourced contributions. Its data model is built on three core primitives—nodes, ways, and relations—each annotated with tags expressed as key–value pairs. This tag-based schema offers high semantic flexibility but lacks uniform standardisation, leading to variability across regions and applications [12]. As an open-source platform, OSM allows free upload, editing, and download of geospatial data, enabling rapid updates and detailed local mapping. However, this participatory structure also introduces heterogeneity and inconsistency due to variations in contributors' expertise, priorities, and mapping coverage [13].

OSM data can be obtained through multiple channels: the official *OpenStreetMap.org* export tool, the *PlanetOSM* database, and third-party extracts such as *GeoFabrik.de* and *BBBike.org*. For targeted feature retrieval, the *Overpass API* (via Overpass Turbo) or the *QuickOSM* plugin in QGIS enables spatially and semantically filtered queries. In this study, data were retrieved using *QuickOSM* within QGIS, selected for its ability to execute fine-grained, area-specific queries tailored to both the semantic and spatial requirements of the analysis.

2.2. Google Maps

Google Maps is the most widely used commercial geospatial platform globally [14]. While it incorporates user-generated content, it is not strictly VGI; rather, it combines proprietary datasets with crowdsourced inputs, subject to centralised validation and governance. User engagement—particularly from verified business owners—plays a significant role in determining place visibility and ranking [15]. A key functional distinction is its

dynamic marker rendering, which adjusts the visibility of places based on zoom level, contextual relevance, and proximity.

Access to structured Google Maps data requires the Google Maps Platform API, which supports controlled queries within defined usage limits [16]. In this study, data were accessed through the API via the Python Console (v3.9.5) in QGIS. The *NearbySearch* function was employed, which returns places of interest located within a specified radius from given coordinates. This method was deliberately chosen to ensure objectivity and reproducibility by relying exclusively on Google's internal *Place Type* classification, avoiding the subjective variability inherent in keyword-based *TextSearch* queries. From the API response, only three fields were retained—*Name*, *Address*, and *PrimaryType*—ensuring focus on attributes directly relevant to semantic alignment.

2.3. Semantic Alignment Across Platforms

Direct comparison between OSM and Google Maps requires a harmonised classification framework. No universally accepted taxonomy of urban amenities exists, and the two platforms use fundamentally different categorisation logics: OSM's community-driven tag schema versus Google's centrally managed *Place Types*. Within the 15-min city framework, Moreno et al. [1] proposed six broad functional dimensions (residential, work, commerce, healthcare, education, and entertainment), but these categories are too generic to support precise cross-platform matching [17].

To address this, we adopted the macro-categories proposed by Papadopoulos et al. [16], derived from a systematic review of 15-min city literature. These categories serve as an intermediate classification layer, enabling semantic alignment between heterogeneous taxonomies. For OSM, tag matching was guided by the official *OSM Map Features* documentation [18]. For Google Maps, matching was based on the *Place Types* listed in Table A in the Google Maps Places API documentation [19] (as updated 7 November 2024). The resulting classification comprises seven macro-categories (Table 1), encompassing the core amenities relevant to proximity-based accessibility assessments: health services, entertainment facilities, retail services/trade, sports facilities, restaurants, economic facilities, and food/grocery stores.

Table 1. Categorization of selected urban amenities adapted conceptually from Papadopoulos et al. [17].

Macro Categories	Urban Amenities
Health services	Pharmacies, hospitals, medical offices and medical stores
Entertainment facilities	Bars, cinemas, casino and bookmakers
Retail services/trade	Goods stores, private agencies and offices, crafts and malls
Sports facilities	Sport and fitness centres
Restaurants	Restaurants and fast food
Economic facilities	Banks and ATM
Food/grocery stores	Supermarkets and food stores

3. Case Studies

This study examines four European urban contexts drawn from the *Evolutive Meshed Compact City* (EMC^2) Project [20], developed under the *Driving Urban Transitions* (DUT) Partnership: the **Versilia conurbation** (Italy), **Nice** (France), **Gothenburg** (Sweden), and **Vienna** (Austria). The selection balances geographical diversity with variation in urban morphology, while retaining a degree of comparability in development trajectories and spatial configurations. Together, these cases span a spectrum of urban forms—from coastal linear conurbations to radial-concentric capitals—providing a robust basis for testing

both the EMC^2 framework and, more specifically, the consistency, completeness, and interpretability of spatial datasets across distinct territorial and cultural contexts.

3.1. Versilia (Italy)

Versilia is a linear coastal conurbation comprising several municipalities along the northern Tuscan coast. Until the mid-20th century, these municipalities maintained administrative and spatial autonomy; post-war expansion gradually merged once-separate urban fabrics into a continuous built environment [3]. Morphologically, Versilia extends transversally from the Tyrrhenian coastline to the Apuan Alps, while longitudinally linked by a continuous infrastructural corridor [3]. Its average residential density is relatively low (≈800 inhabitants/km^2 [21]), reflecting a dispersed settlement pattern in which compact historic centres are embedded within a broader suburban continuum. This heterogeneous spatial structure makes Versilia a critical test case for evaluating the granularity and spatial coherence of OpenStreetMap and Google Maps amenities data in low-density Italian suburban contexts.

3.2. Nice (France)

Nice anchors the *Métropole Nice Côte d'Azur*, a conurbation of multiple Mediterranean municipalities. Like Versilia, its urban fabric extends transversally from the coast to the foothills of the Maritime Alps. However, Nice functions as a major metropolitan centre with a markedly higher population density (4622.3 inhabitants/km^2 [22]) and a more hierarchical urban structure. Its growth trajectory spans Roman origins to modern expansion, progressively incorporating neighbouring municipalities [23]. The combination of a dense core, polycentric development, and strong tourism orientation makes Nice particularly relevant for assessing how geospatial platforms represent commercial and service-oriented land uses in high-density French coastal environments.

3.3. Gothenburg (Sweden)

Gothenburg, Sweden's second-largest city and Scandinavia's largest port, shares with the Italian and French cases a coastal setting and, with Nice, metropolitan status. The city developed along the Göta River following a radio centric pattern from its medieval core. Eighteenth-century expansion introduced a semi-circular fortification ring and an orthogonal street-and-canal grid [24,25]. Twentieth-century decentralisation and housing policies produced suburban neighbourhoods interspersed with hilly, vegetated terrain [26]. Despite its economic significance, Gothenburg maintains a relatively low average population density of 1291.6 inhabitants per km^2 [27]. Despite its economic importance, Gothenburg maintains a relatively low average density (1291.6 inhabitants/km^2 [27]). Its mixed land-use pattern and topographical complexity make it a useful context for testing platform performance in mapping amenities across dispersed, low-density urban landscapes.

3.4. Vienna (Austria)

Vienna, Austria's capital and one of its nine federal states, exhibits a highly structured radial–concentric urban form shaped by successive historical layers. The medieval core was first enclosed by defensive walls, later replaced in the 18th century by the *Ringstraße* boulevard, which today delineates central districts from subsequent expansions [28]. Nineteenth-century industrialisation drove outward growth and densification, yielding a metropolitan form characterised by both functional centrality and morphological coherence. With a density of 4655.0 inhabitants/km^2 [29], Vienna ranks among Europe's most densely populated cities. As a high-density, historically layered capital, it serves as a valuable benchmark for assessing dataset completeness and classification consistency in complex, mature urban systems.

4. Methodology

The methodological framework adopts a sequential, multi-scalar design to evaluate OpenStreetMap (OSM) and Google Maps from both quantitative and qualitative perspectives. Analyses are conducted at both the urban and micro-urban scales, addressing data variability, spatial consistency, semantic divergence, and modelling implications. The workflow comprises **four sequential analytical steps**, each targeting a distinct dimension of comparison. This section delineates the methodological framework and provides a detailed description of each step, while the subsequent section presents the corresponding results following the same structure.

4.1. Step 1: Baseline Data Extraction and Cross-Platform Volume Comparison

The first step assesses **data completeness and spatial consistency** across the two platforms at the full urban scale. For each case study, amenities corresponding to the macro-categories in Table 1 were extracted within an 8000 m radius encompassing the main urban context. For Vienna and Gothenburg data were downloaded from the city centre barycentre, in the case of Nice, the entire municipal area was included, while for the Versilia case, the municipalities of Carrara, Massa, and Montignoso were considered. This stage establishes baseline counts and distributions, allowing the identification of systematic cross-platform differences potentially linked to contextual (e.g., morphology, density) or platform-specific factors.

4.2. Step 2: Sensitivity to Spatial Extent and Radial Displacement

The second step evaluates scale sensitivity by repeating the data retrieval at progressively smaller radii—5000 m, 2500 m, and 1200 m—using the same extraction points as in Step 1. For OSM, queries were executed via the *QuickOSM* QGIS plugin; for Google Maps, separate API requests were issued for each radius. The comparison was then conducted within the smallest buffer (1200 m, by clipping the areas of larger radii) allowing for standardized cross-case and cross-platform evaluation (Figure 1a).

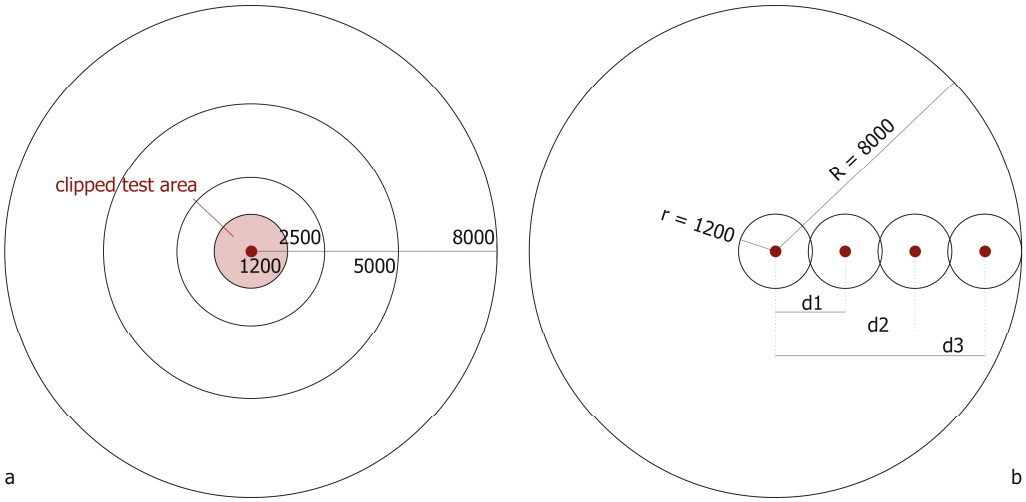


Figure 1. Schematic representation of the methodology used to assess sensitivity to spatial extent (**a**) and to radial displacement (**b**).

Additionally, to assess the potential impact of **distance from the extraction point** on data quality or completeness, an exploratory radial displacement test was performed: data within a fixed 1200-m radius were extracted along a transect extending outward from the original extraction point and compared with the 8000-metre radius download,

allowing for detection of spatial biases in data density or classification across concentric zones (Figure 1b).

4.3. Step 3: Semantic Divergence Analysis

The third step examines **classification inconsistencies** by focusing on three amenity types—pharmacies, bookstores, and bars—selected for their relevance to daily life in the 15-min city, their potential semantic ambiguity, and their representation in both platforms. For each amenity type, counts, spatial distributions, and co-location patterns were compared across datasets. This targeted approach highlights the operational implications of divergent tagging conventions (OSM) and place-type classifications (Google Maps) without requiring a full crosswalk between the two systems.

4.4. Step 4: Modelling Implications for the 15-Minute City

The fourth step integrates findings from Steps 1–3 into an accessibility modelling exercise aligned with the **15-min city framework**. For each case study, pedestrian-based 15-min isochrones were generated from representative suburban locations, using a standard 1200 m walking radius [1,30]. All amenities from Table 1 falling within these isochrones were included. This final step evaluates how differences in dataset completeness, semantic alignment, and spatial consistency translate into divergent accessibility outcomes—directly informing the reliability of proximity-based urban models.

5. Results and Discussion

5.1. Dataset Comparison at the Urban Scale: Quantity and Spatial Distribution

The first analytical step evaluates aggregate differences between OpenStreetMap and Google Maps at the urban scale, examining the outcomes when all selected macro-categories are extracted in bulk across extended urban areas.

Across all four case studies, OSM systematically returns a greater number of features than GM (Table 2, Figure 2). The largest discrepancies occur in Nice and Vienna, where OSM produces more than twice the number of entries returned by GM. Gothenburg exhibits a smaller yet substantial gap, while in Versilia the two datasets yield comparable totals.

Table 2. Quantitative assessment of the downloaded urban places at the macro scale.

Case Studies	Google Maps	OpenStreetMap	*SMAPE* (%)
Versilia	1922	2639	31
Nice	2662	13,599	135
Gothenburg	2402	7127	99
Vienna	2921	35,660	170

Importantly, differences are not confined to counts. Even in point-of-interest–dense areas, the spatial distribution of amenities differs markedly between platforms, suggesting divergent underlying logics for place inclusion, placement, and representation.

To quantify these differences, the Symmetric Mean Absolute Percentage Error (*SMAPE*) was applied (Equation (1)) to the total values of the two datasets, in order to measure their relative deviation. Lower *SMAPE* values indicate closer numerical agreement, while higher values signify substantial divergence in extracted quantities.

$$SMAPE\ (\%) = \frac{|OSM\ value - GM\ value|}{\frac{OSM\ value + GM\ value}{2}} \times 100 \quad (1)$$

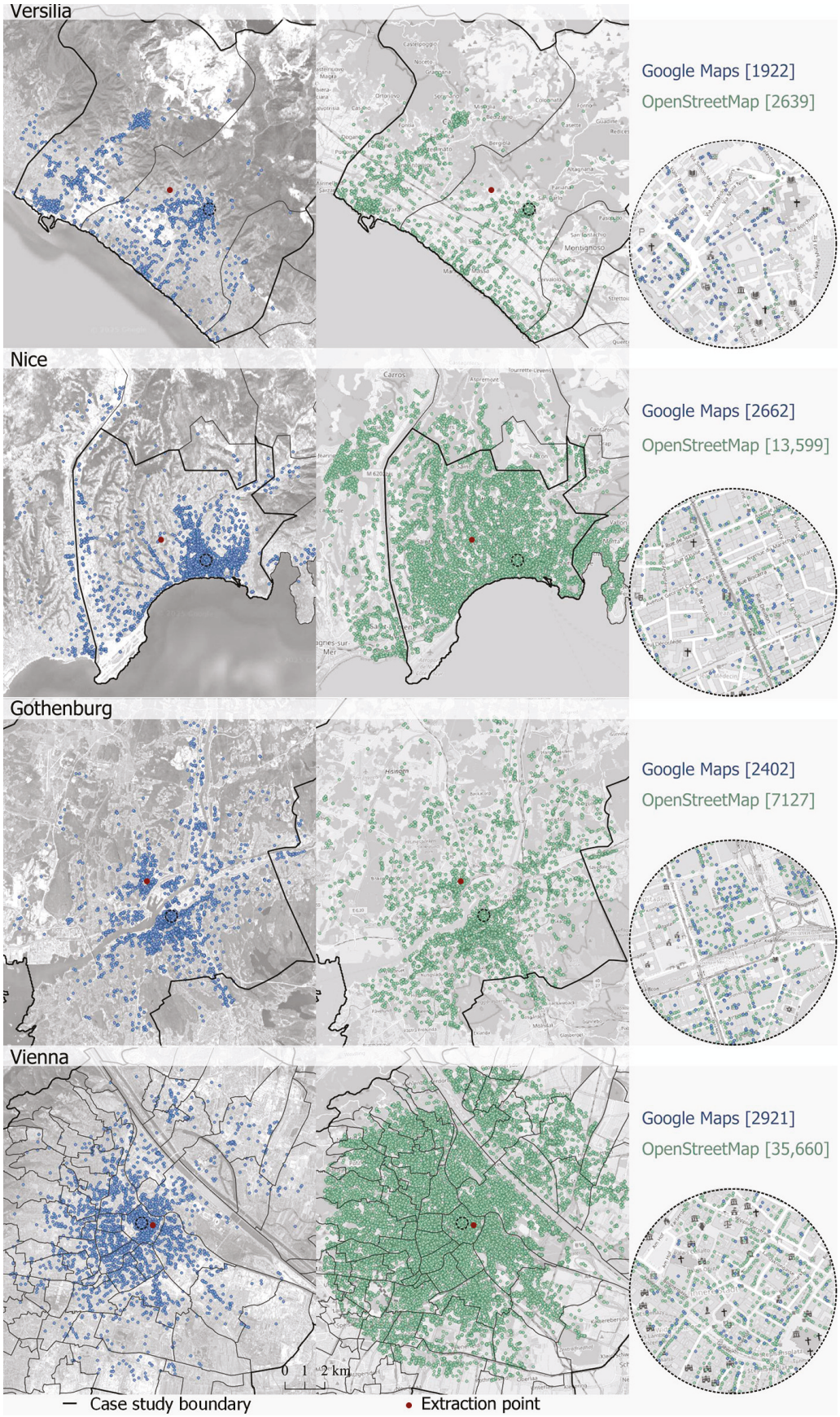


Figure 2. Spatial distribution of the downloaded urban places at the macro scale.

The *SMAPE* values (Table 2) confirm strong divergence in Nice (135%) and Vienna (170%), moderate differences in Gothenburg (99%), and relatively close alignment in Versilia (31%). While these patterns are not generalisable given the limited case set, some interpretative insights emerge. Both Nice and Vienna are among the most populous and densely inhabited cities in their respective countries, and both attract substantial tourist inflows [31]. These conditions may foster more active OSM mapping communities—although the underlying drivers remain to be fully investigated—thereby increasing data richness through crowdsourced contributions.

However, closer inspection reveals that a substantial share of OSM features in these cities are private swimming pools—7075 of 13,599 in Nice and 4970 of 35,660 in Vienna—often located within residential properties. This highlights a fundamental operational difference: in such cases, the OSM dataset includes physically verifiable locations—such as swimming pools but also pitches and other facilities –, regardless of public accessibility or commercial relevance, whereas GM primarily contains recognised points of interest—places with public-facing functions or visibility within its service ecosystem.

This distinction has methodological consequences. Bulk extractions from global spatial datasets can yield substantially different results not because of geographic coverage gaps, but due to differences in inclusion criteria. In this case, swimming pools provide a striking example, though likely not an isolated one, as similar patterns may well be observed in other categories. A close and systematic examination of individual types of urban amenities, together with the associated data cleaning, lies beyond the scope of this paper, which is instead concerned with highlighting discrepancies between datasets. For this reason, we chose not to alter the original dataset. Hence, without accounting for platform-specific data logic, analyses risk misinterpretation. The next subsections explore additional factors—such as extraction radius and classification frameworks—that may further explain and amplify these discrepancies.

5.2. Dataset Comparison at the Urban Scale: Sensitivity to Spatial Extent and Distance from the Extraction Point

To assess how spatial extent influences dataset completeness, amenities were extracted from Google Maps and OSM across concentric buffers of 8000, 5000, 2500, and 1200 m from the original extraction points. While *SMAPE* quantifies the discrepancy between the two datasets, it does not indicate which is richer. To capture the direction of the discrepancy, the non-standard *SMAPE* (*nsSMAPE*, Equation (2)) is introduced. It omits the absolute value in the numerator, allowing the sign of the value to indicate whether the Google dataset is richer (negative values) or poorer (positive values) than the OSM dataset.

$$nsSMAPE\ (\%) = \frac{OSM\ value - GM\ value}{\frac{OSM\ value + GM\ value}{2}} \times 100 \quad (2)$$

Overall trends show *SMAPE* decreasing with smaller radii (Table 3), suggesting stronger cross-platform alignment at finer scales. This trend is most consistent in Vienna, while Nice and Gothenburg show a slight *SMAPE* increase at 1200 m, though still lower than at 5000 m. Versilia diverges from this pattern: at smaller radii, GM consistently returns more amenities, yielding negative *nsSMAPE* values. Similar GM dominance at small extents is also seen in Gothenburg, whereas OSM retains higher counts at all scales in Nice and Vienna. High *SMAPE* values in Vienna and Nice reflect OSM's dense coverage in these high-population, high-tourism contexts—again suggesting potential links between population density, civic engagement, and VGI dataset richness. Further confirmation of this trend is provided by the different location of the data extraction point across the four cases: situated in dense central areas in Gothenburg and Vienna, and in more peripheral, less dense areas

in Versilia and Nice. To standardise spatial coverage across scales, each case's datasets were clipped to the smallest (1200 m) radius. OSM counts remained stable regardless of original download radius, while GM counts increased as the radius decreased (Figure 3). Within these clipped areas OSM consistently exceeds Google Maps in Vienna and Nice, while Google Maps exhibits greater density in Gothenburg and Versilia at smaller radii. This indicates a key architectural difference: **OSM's data retrieval is radius-independent, whereas GM's is scale-sensitive**, likely due to internal ranking and zoom-level constraints (Figure 4).

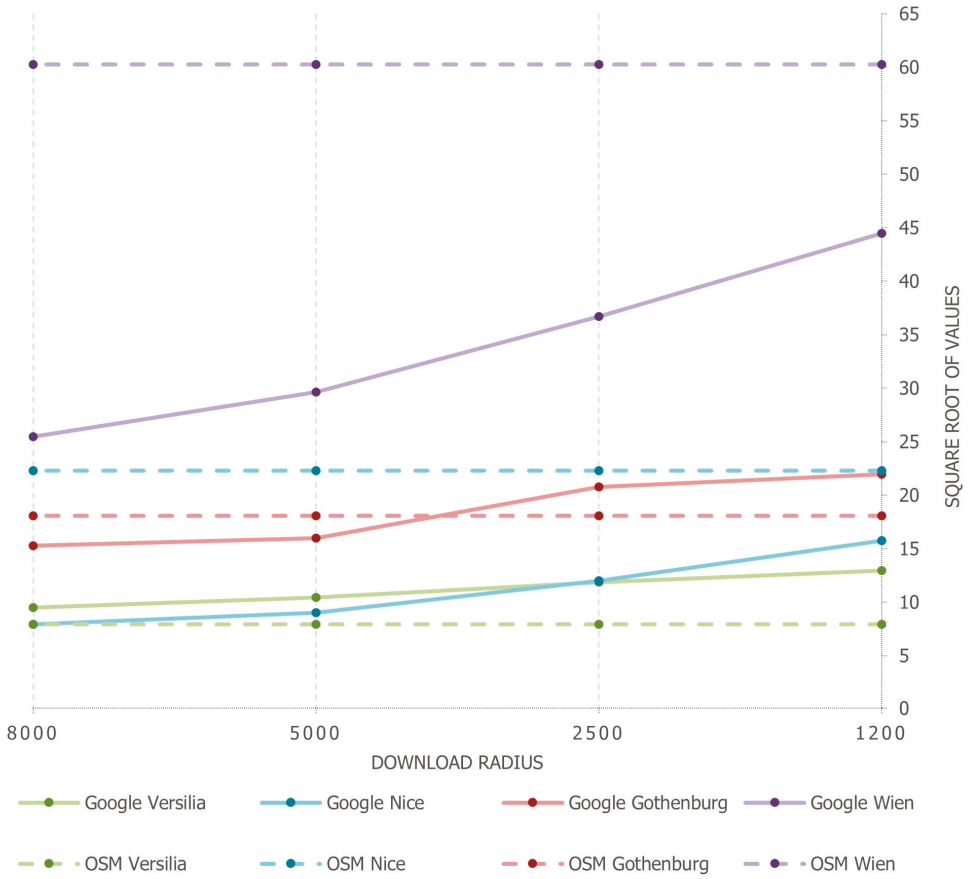


Figure 3. Trend in the number of retrieved urban amenities across different download metric radii within the clipped test area.

Table 3. Retrieved urban amenities within varying metric radii.

Case Studies	Database	8000-m Radius	5000-m Radius	2500-m Radius	1200-m Radius
Versilia	Google Maps	1922	1761	951	168
	OpenStreetMap	2639	1615	380	63
	nsSMAPE (%)	31	−9	−86	−100
Nice	Google Maps	2662	2604	2106	248
	OpenStreetMap	13,599	9864	3264	496
	nsSMAPE (%)	135	116	43	67
Gothenburg	Google Maps	2402	2227	1031	483
	OpenStreetMap	7127	5224	1013	327
	nsSMAPE (%)	99	80	−2	−39
Vienna	Google Maps	2921	2880	2580	1979
	OpenStreetMap	35,660	24,382	10,022	3628
	nsSMAPE (%)	170	158	118	59

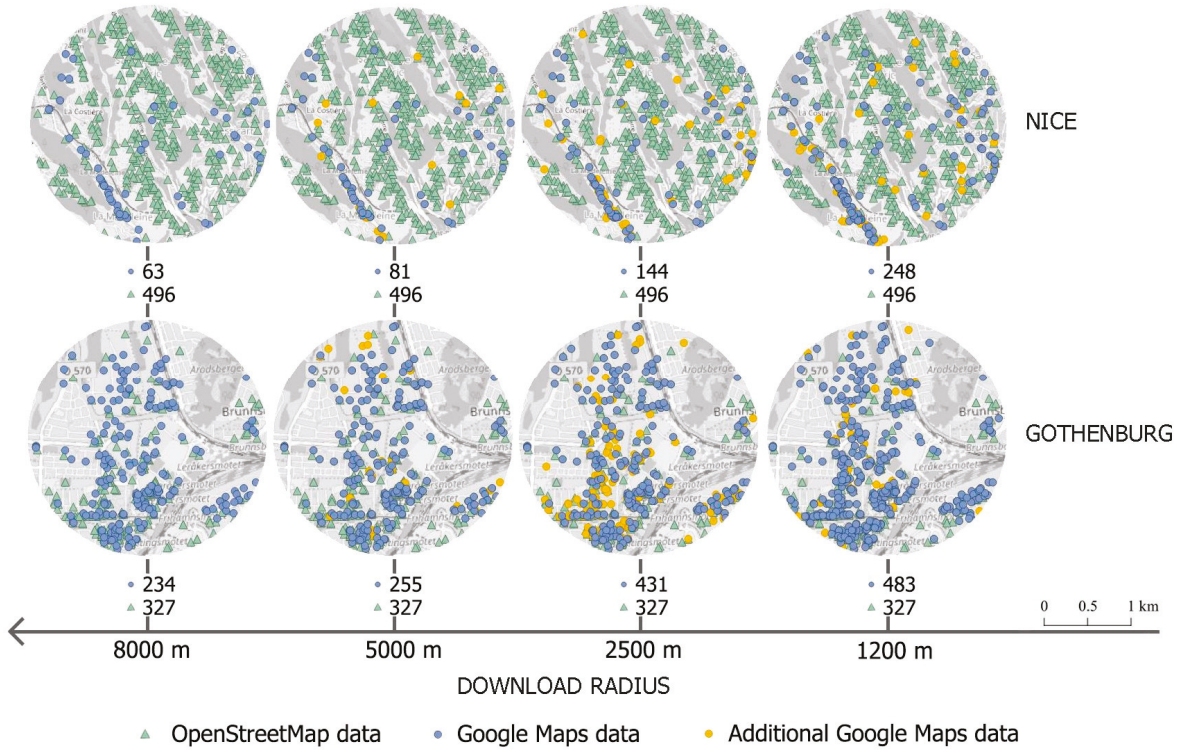


Figure 4. Spatial distribution of urban amenities retrieved within decreasing metric radii (left to right) in the test areas of Gothenburg and Nice. Yellow markers highlight additional amenities identified via Google Maps at each radius, relative to the set retrieved at the immediately larger radius (the preceding circle on the left).

5.2.1. Distance from the Extraction Point

We first show that downloaded place counts vary with the size of the extraction area, reflecting Google Maps' retrieval process and ranking mechanisms (which prioritize POIs based on user interaction) [14]. We then test whether the distance between the extraction point, and POIs further affects the completeness of the Google Maps dataset (Figure 5). The *Percentage Change* metric (Equation (3)) measures deviation between these datasets for each location, by quantifying how the density of POIs retrieved at each local 1200-m buffer compares to that of the corresponding area in the 8000-mdataset. High positive values indicate that smaller-radius queries yield more amenities than the same location's clipped section from the larger-radius download.

$$Percentage\ Change(\%) = 100 \times \frac{|GM_{1200\mathrm{m}} - GM_{8000\mathrm{m}}|}{GM_{8000\mathrm{m}}} \quad (3)$$

Results consistently show that local downloads at 1200 m—regardless of the extraction point's specific location—produce richer datasets than the corresponding clipped sections of the 8000-m download, thereby confirming the trend identified in the previous section.

However, the *Percentage Change* is not strictly increasing with distance from the centre, suggesting that no monotonic relationship exists between centroid distance and data completeness. Notably, in 9 out of 12 cases, the metric increases from dn to dn+1, indicating a general trend of growing divergence with increasing distance from the barycentre. This pattern, however, is not observed in Versilia, Nice, and Gothenburg, where the *Percentage Change* at distance $d1$ exceeds that recorded at $d0$, deviating from the expected progression.

A closer examination reveals a possible explanation for this potential outlier. In Versilia, Nice and Gothenburg, the *d*1 extraction buffers intersect areas with a higher presence of POIs compared to those at *d*0, resulting in richer 1200-m downloads (Figure 5). Conversely, in Vienna, both *d*0 and *d*1 fall within uniformly dense urban areas, leading to more consistent retrievals across distances.

As highlighted in Anselmi et al. [32], a key limitation in Google's data retrieval mechanism lies in its cap of approximately 60 POIs per *PlaceType* per request. Consequently, in high-density zones where specific categories surpass this threshold, the downloaded dataset underrepresents the actual amenity landscape available within Google's full database. This limitation likely contributes to the non-monotonic behaviour of the Percentage Change function observed in Nice, Gothenburg, and Versilia—where the number of POIs retrieved at *d*1 surpass those at *d*0.

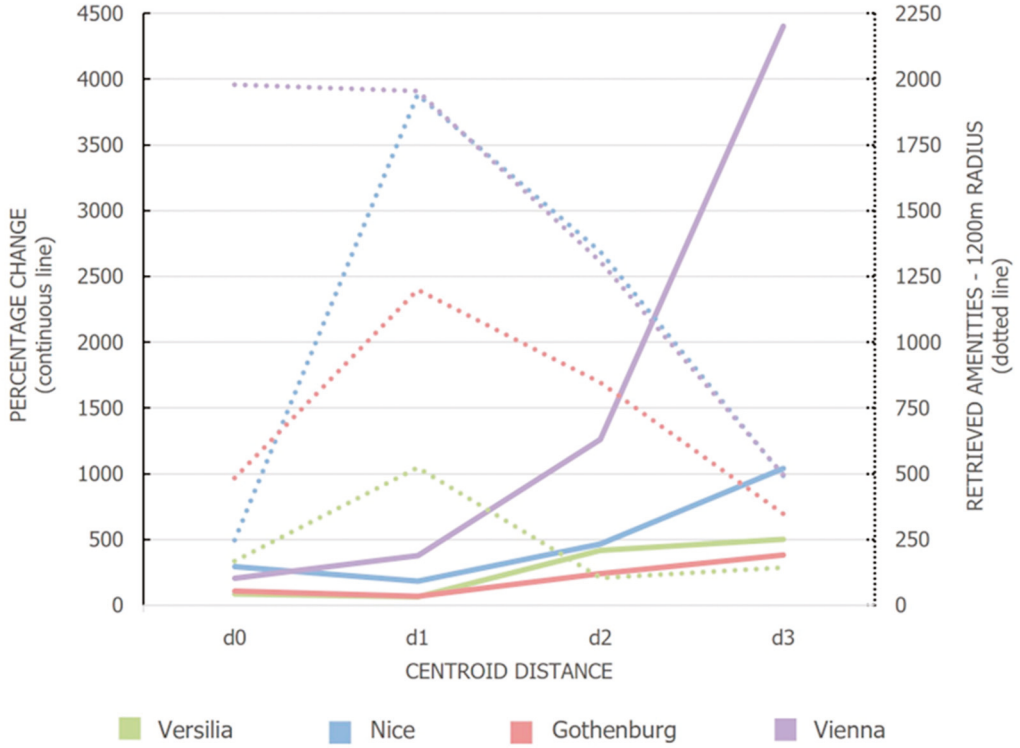


Figure 5. Percentage Change in Google Maps data between 8000- and 1200-m radii vs. distance from the 8000-metre centroid.

To illustrate this phenomenon, Figure 6 presents the case of Versilia: while the *d*0-centred areas show comparable POI counts among the 1200 m- and the 8000 m clipped- extraction, the peripheral *d*3-centred area demonstrates a stark discrepancy, with the 8000 m clipped download capturing significantly fewer amenities than the localized 1200-m extraction. These patterns imply that Google Maps retrievals lose spatial consistency as the distance from the query centre increases, particularly when large-scale urban extents are involved. Alongside the ranking algorithm, which reflects user interaction with the platform, the spatial positioning of POIs relative to the requester—that is, the extraction point—emerges as a key element in the logic governing the retrieval of places in Google Maps.

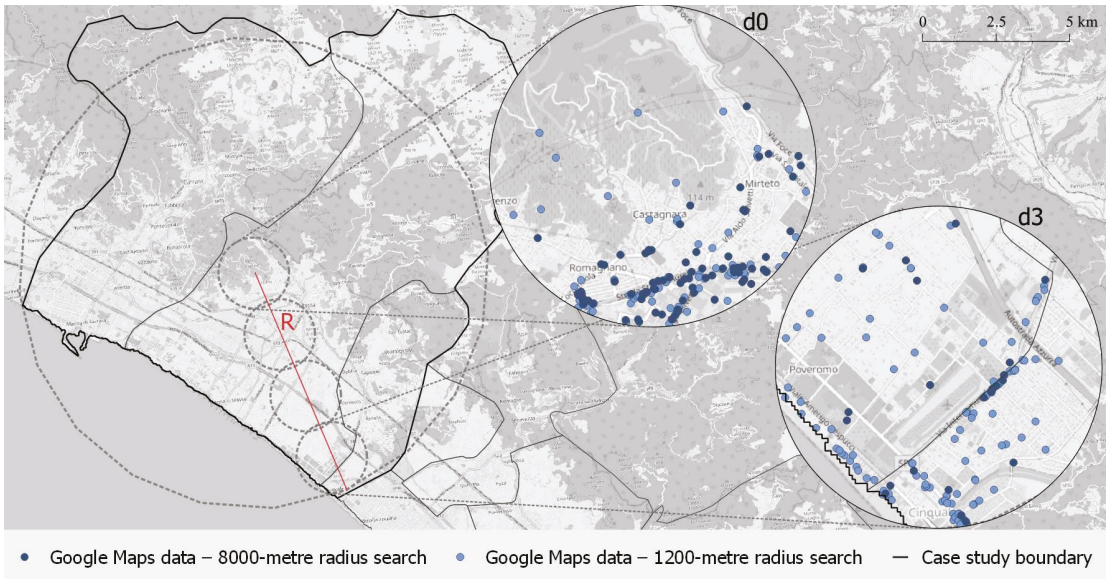


Figure 6. Accuracy loss in Google Maps data with distance from search centre: the Versilia case study.

5.2.2. Implications

Overall, these findings highlight a critical limitation in using Google Maps for urban-scale bulk downloads: broader-radius queries introduce distortions, especially at the periphery, due to algorithmic biases and ranking filters. In contrast, downloads with a smaller radius yield more accurate and spatially consistent datasets, although they may still be affected by additional category-related distortions, as highlighted by Anselmi et al. [32]. OpenStreetMap, by comparison, shows no sensitivity to either radial extent or distance from centroid, confirming its internal consistency and suitability for uniform spatial sampling.

5.3. Semantic Divergence and the Representation of Key Urban Functions

This stage of the analysis examines how semantic categorisation influences the representation of urban amenities in OSM and Google Maps. A marker-based approach was used to assess the consistency, completeness, and spatial overlap of specific place types, focusing on how classification frameworks shape coverage and reliability. Three urban amenities—selected for their everyday relevance and relatively straightforward cross-platform mapping—were analysed: pharmacies (OSM value = pharmacy, GM place type = pharmacy), bookstores (OSM value = books, GM place type = book_store), and bars (OSM value = bar, GM place type = bar). Given the findings from Section 5.2, the comparison was conducted within a 1200 m radius, where GM data had previously shown greater completeness.

5.3.1. Quantitative Trends

nsSMAPE values for these markers are often negative, indicating that OSM generally underrepresents these functions compared to Google Maps—contrary to aggregate patterns at larger scales. However, no consistent spatial trend emerges across the cities. Figure 7 illustrates that the datasets are not simple subsets of each other: in most cases, there is substantial spatial divergence between the two sources, even when amenity counts are similar. Exceptions include bookstores in Nice, pharmacies in Versilia and Vienna, and bars in Gothenburg—though the latter displays notably sparse coverage. In contrast, spatial mismatch is evident in most other cases, including pharmacies and bookstores in Gothenburg, where the absolute counts are equal, but locations differ.

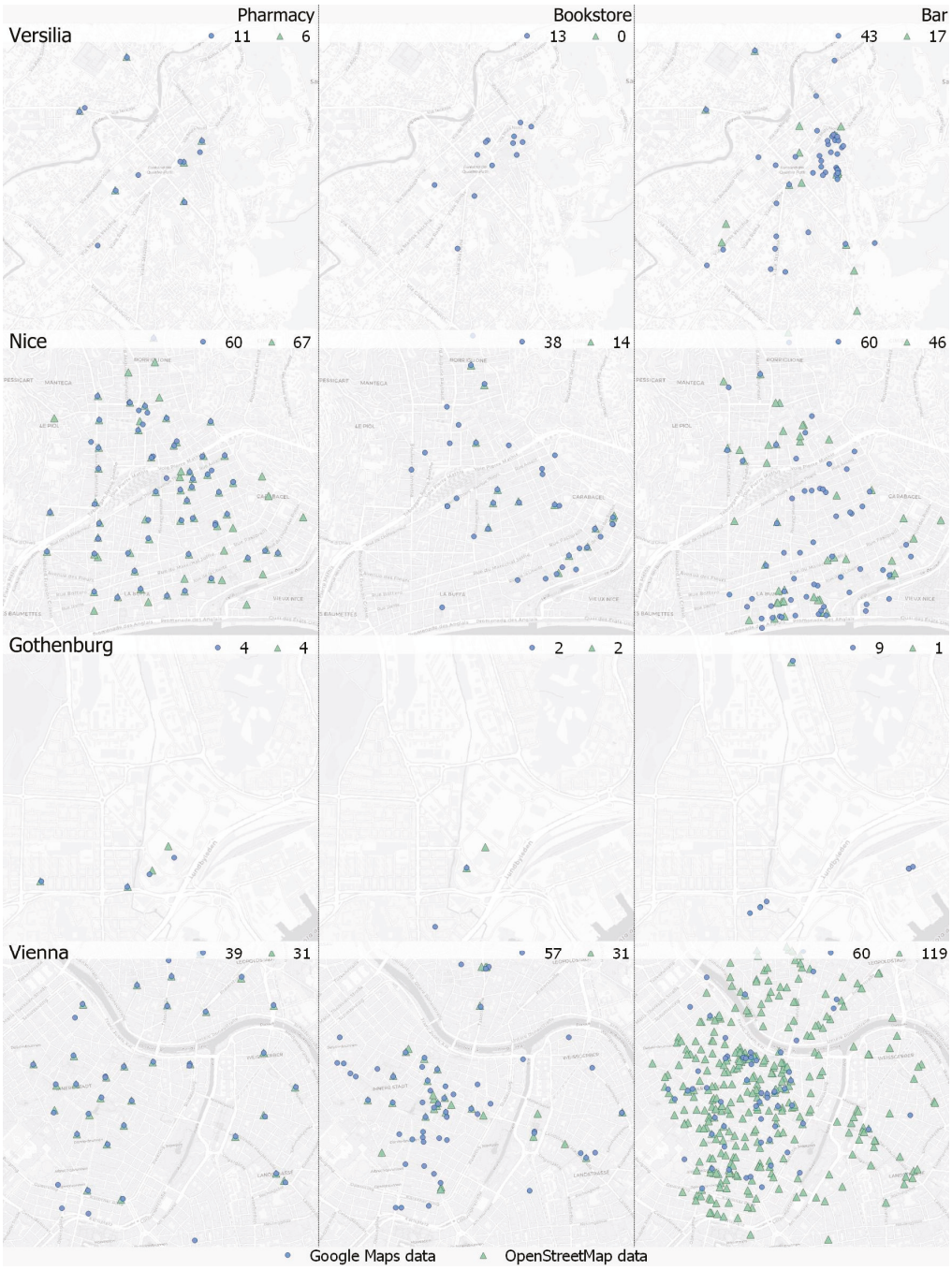


Figure 7. Comparison of place marker representation at local scale (1200-m radius) between the two data sources.

Among all cases, Versilia exhibits the highest average *SMAPE* values, driven by a significant underrepresentation in OSM across all three categories.

5.3.2. Semantic Complexity

Although the three selected markers—pharmacies, bookstores, and bars—may appear semantically unambiguous, closer inspection of the categorisation systems used by OpenStreetMap (OSM Map Features) and Google Maps (Google Maps Platform) reveals notable divergences. While both platforms provide taxonomies, these are neither mutually aligned nor internally consistent. As a result, one-to-one correspondence between categories is often unattainable in practice, despite superficial semantic similarities.

This complexity stems from several factors. As noted by Biljecki et al. [33], variations in language, cultural context, and socio-spatial interpretations shape how amenities are perceived and tagged. For instance, the category "bar" may encompass vastly different establishments across countries and platforms—ranging from cafés to nightclubs—leading to inconsistencies in visibility, classification, and retrieval.

Table 4 details the entries associated with each selected marker across the platforms. Bookstores exhibit consistent, unique tag associations in both databases. Pharmacies show moderate variation, with some extended forms ("pharmacy+") leading to higher counts—particularly in Vienna, where the broader interpretation results in a near doubling of retrieved data. Bars, however, reveal significant semantic divergence. Their classification encompasses a wide array of related place types, leading to inflated results: in some cities, retrieved bar data are three to four times higher when using extended tagging schemes (Table 5). The case of Gothenburg is especially illustrative. While bookstores and pharmacies display minimal variation across platforms and classification schemes, bars exhibit high *SMAPE* values and substantial numerical discrepancies. Under an extended categorisation, bar-related entries are nine times higher in Google Maps and up to seventeen times higher in OSM.

Table 4. Semantic ambiguity in the definition of the urban categories: list of considered tags.

Marker	Google Maps	OpenStreetMap
Pharmacy	"pharmacy"	"pharmacy"
Pharmacy+	"pharmacy", "drugstore"	"pharmacy", "herbalist", "nutrition_supplements"
Bookstore	"book_store"	"books"
Bar	"bar"	"bar"
Bar+	"bar", "cafe", "coffee_shop", "cafeteria", "cat_cafe", "dog_cafe", "tea_house", "internet_cafe", "bar_and_grill", "pub", "wine_bar"	"bar", "café", "internet_cafe", "biergarten", "pub"

Table 5. Semantic ambiguity in the definition of the urban categories: quantitative assessment at the local scale.

Case Studies	Marker	Google Maps	OpenStreetMap	*nsSMAPE* (%)
Versilia	Pharmacy	11	6	−58
	Pharmacy+	12	6	−67
	Bookstore	13	0	−200
	Bar	43	17	−87
	Bar+	120	32	−116
Nice	Pharmacy	60	67	11
	Pharmacy+	64	68	6
	Bookstore	38	14	−92
	Bar	60	46	−26
	Bar+	176	162	−8
Gothenburg	Pharmacy	4	4	0
	Pharmacy+	4	6	40
	Bookstore	2	2	0
	Bar	9	1	−160
	Bar+	78	17	−128
Vienna	Pharmacy	39	31	−23
	Pharmacy+	72	33	−74
	Bookstore	57	31	−59
	Bar	60	119	66
	Bar+	166	337	68

5.3.3. Internal Classification Ambiguities

From a technical standpoint, the internal classification within each downloaded entry introduces an additional layer of complexity. OSM allows at most two tags per key for a single item, but the same element can appear under multiple keys depending on the recorded attributes. Google Maps, similarly, includes multiple labels per location, derived from both PrimaryTypes and additional descriptors. While this increases retrieval flexibility, it also introduces ambiguity: a single feature may fall under several categories without a clear indication of its primary function. For applications requiring fine-grained typologies, such ambiguity complicates the consistent use of these databases in discrete functional models.

Despite this possibility, it was observed that such ambiguity is relatively limited in OSM. In contrast, for GM, the place types associated with each retrieved feature are never unique. This could arguably be seen as a strength of Google Maps, as the broader categorization may support the identification of all relevant amenities linked to a given location. However, in this study, to ensure a rigorous and non-discretionary procedure, only the first label listed in Table A from the Google Maps Platform was used to assign the corresponding macro-category.

5.3.4. Technical Constraints

A further limitation of Google Maps also emerges. Close inspection of the data revealed that in 3 out of 12 cases, the number of registered activities was exactly 60 units. This reflects the limitation discussed in Section 5.2, and is likely to have also affected the extraction of categories in their extended forms (e.g., pharmacy+ and bar+ in Nice, and bar+ in Vienna). Without this technical constraint, one could reasonably expect—consistent with the overall trend—that the number of activities retrieved from Google would exceed those retrieved from OSM.

5.3.5. Implications

These findings underscore the importance of understanding data semantics and classification granularity when selecting datasets for urban modelling purposes. Seemingly comparable categories may yield non-overlapping spatial realities, which could lead to misleading conclusions if not critically assessed in advance. Moreover, semantic alignment between platforms does not guarantee spatial consistency or completeness. Therefore, for fine-grained urban modelling dataset selection must consider not only coverage and density, but also the semantic architecture of the source.

5.4. The Impact of Data on Urban Modelling: The 15-Minute City

The preceding analyses reveal substantial divergences between GM and OSM across multiple dimensions: data volume, spatial distribution, semantic categorisation, and sensitivity to scale and proximity. While both platforms are widely used in urban research due to their coverage, regular updates, and relative accessibility, the differences observed are methodologically significant. As shown, the choice of dataset can materially influence modelling outputs, particularly in frameworks that rely on precise locational accuracy and comprehensive coverage.

The 15-min city model—taken here as an applied test case for proximity-based planning—offers a clear illustration of this effect. In accessibility assessments, the spatial distribution and typological classification of amenities directly shape perceptions of urban vibrancy and liveability [34]. Divergences in service representation between platforms can therefore produce markedly different readings of suburban accessibility and functional diversity.

5.4.1. Analytical Approach

A supply-based approach was adopted to discuss the impact of databases on proximity-based assessment in selected suburban areas in four case studies—Versilia, Nice, Gothenburg, and Vienna—by evaluating the presence of amenities (listed in Table 1) within 15-min walking catchments. Rather than relying on a user-based or grid-centroid method—whose arbitrariness has been shown to influence results [2]—this study examines a predefined suburban area in each city independently of base grid or origin assumptions. The areas have been chosen in the first peri-central rings contiguous to the historic cores, characterized by lower residential density and building coverage than the core areas while still exhibiting a functional mix and good accessibility, according to the guidelines of the DUT Emc2 project. Amenities were extracted using a 1200 m buffer—the standard walking distance approximation for a 15-min city [30] and, as established in Section 5.2, the most reliable radius for balanced dataset retrieval.

Table 6 summarises the number of amenities (as defined in Table 1) retrieved within each isochrone. In Versilia and Nice, Google Maps consistently reports a higher number of amenities. Gothenburg shows comparable values across platforms, with a low *SMAPE* score. Vienna, conversely, displays a predominance of OSM data. These contrasting patterns are visualised in Figure 8, which highlights the particularly divergent cases of Versilia and Vienna: the former showing OSM underrepresentation, the latter revealing an exceptionally high level of OSM data density.

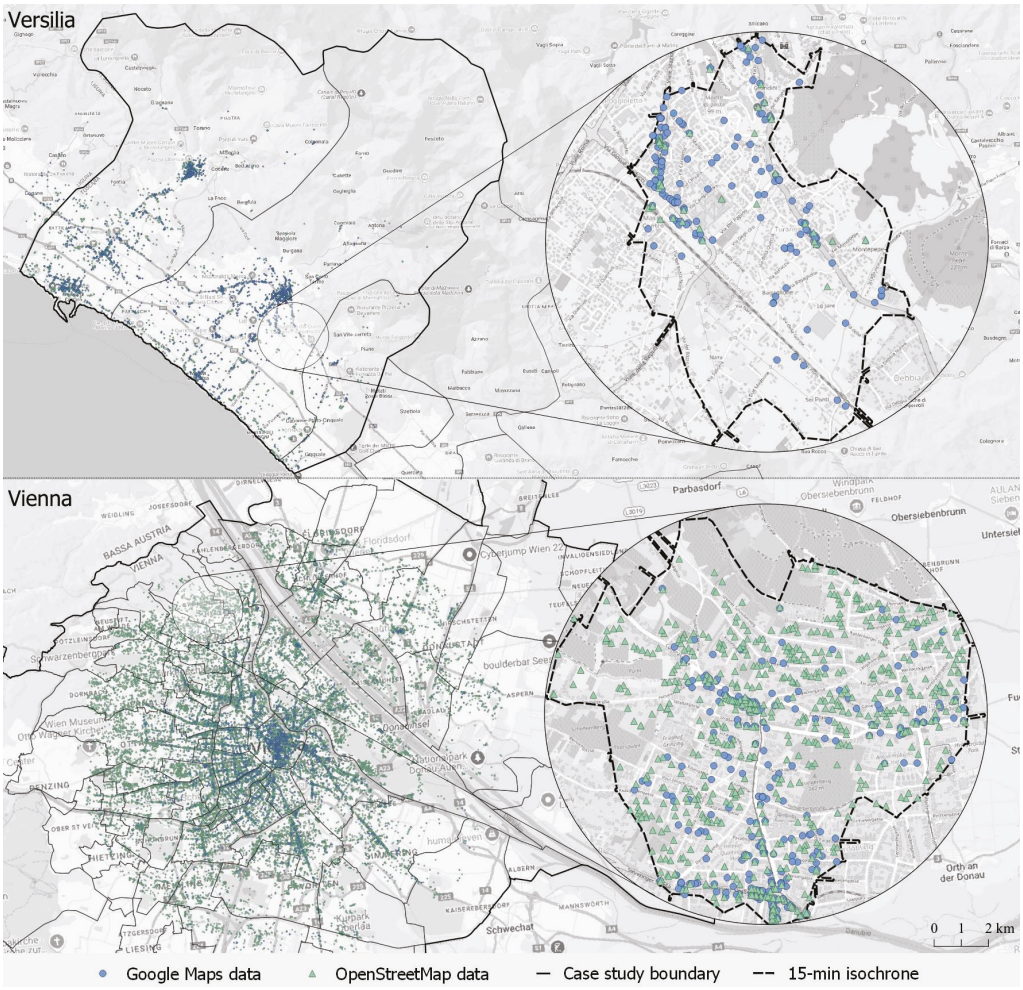


Figure 8. Comparison of place retrieval within 15-min isochrones in suburban areas of Versilia and Vienna.

Table 6. Quantitative comparison of the two data sources within 15-min isochrones in suburban case study areas, based on the distribution of selected urban amenities.

Case Studies	Google Maps	OpenStreetMap	*SMAPE* (%)
Versilia	171	47	114
Nice	311	39	155
Gothenburg	155	112	32
Vienna	319	693	74

5.4.2. Interpretation and Limitations

These results do not imply that one platform offers a more accurate reflection of on-the-ground reality. The observed discrepancies underscore the need for caution when interpreting accessibility scores derived from open data sources. Despite the effort required and the subjective variables it entails, without field validation it remains impossible to determine the reliability of either dataset [35]. Future work should incorporate empirical ground-truthing—or alternative validation strategies—to calibrate digital datasets for proximity-based modelling. Without this step, outputs risk overestimating or underestimating accessibility, depending on platform biases.

5.4.3. Typological Composition

Using the Papadopoulos et al. [16] classification framework (Section 2), the analysis also compared the functional mix of amenities in each isochrone. The contrast between Versilia and Vienna is instructive. In Versilia, OSM returns a sparse dataset, limiting the capacity to detect a diverse mix of urban functions. In Vienna, by contrast, OSM presents a rich dataset, yet this abundance introduces its own challenge: several retrieved amenities—such as recreational facilities (e.g., private swimming pools)—fall outside the intended scope of analysis. While these features reflect real and functionally relevant spaces, their inclusion highlights the need for careful control over category filtering when assessing accessibility or functional diversity.

These variations substantially influence the interpretation of an area's functional character. As shown in Table 7, in Versilia all considered categories are well represented in Google Maps, with a marked prevalence of retail and trade activities—an aspect that does not emerge from OpenStreetMap. In Vienna, the strong presence of sport facilities—driven primarily by the inclusion of private swimming pools (specifically, 485 out of 518 sport-related entries)—suggests a distinct sporting vocation for the area. In contrast, Google Maps indicates a predominance of commercial activities and health services. A further layer of complexity arises from entries assigned to ambiguous or residual categories such as "other" or "generic". These encompass activities either not explicitly requested or lacking precise semantic attribution, rendering them unclassifiable within the adopted framework. Their presence not only complicates comparison between datasets but also underscores the risk of overestimating functional richness due to poorly defined or inconsistently applied tags.s5.4.4. Implications for ModellingsUltimately, the reliability of proximity-based urban models—whether for the 15-min city or similar frameworks—depends on three intertwined conditions:

- Data completeness—ensuring full coverage of relevant amenities;
- Semantic clarity—avoiding misclassification or over-generalisation;
- Functional relevance—excluding features outside the intended analytical scope.

As this analysis shows, data quality issues can manifest as **absence** (underrepresentation), **excess** (overrepresentation of marginal features), or **ambiguity** (poorly defined categories). Each can distort modelling outputs if left unchecked. Automated top-down extractions must therefore be complemented by critical pre-processing—including tag

review, category filtering, and validation against independent sources—before integration into decision-support systems.

Table 7. Selected categories observed within 15-min city isochrones in suburban contexts.

Case Studies	Place Categories	Google Maps	OpenStreetMap
Versilia	Total places	171	47
	Economic facilities	3	3
	Entertainment facilities	9	7
	Food/grocery stores	19	6
	Health services	27	6
	Restaurants	11	4
	Retail services/trade	72	11
	Sports facilities	4	10
	Other	14	0
	Generic	12	0
Vienna	Total places	319	693
	Economic facilities	6	5
	Entertainment facilities	18	12
	Food/grocery stores	24	15
	Health services	89	38
	Restaurants	31	38
	Retail services/trade	117	67
	Sports facilities	9	518
	Other	8	0
	Generic	17	0

5.5. Data Gaps and Biases in Digital Mapping

The analyses and the results developed within this research—an initial step toward assessing the practical reliability of big data for urban-planning applications—quantitatively corroborate patterns reported in prior work: digital mapping datasets embed systematic gaps and biases driven by mapping procedures, internal visibility mechanisms and by the economic–social salience of mapped places [36].

OpenStreetMap and Google Maps represent two structurally distinct models of geographic data production, each characterised by specific omissions and biases. OSM, sustained by volunteer contributions and an anti-commercial ethos, provides free and openly accessible data, but its soundness is questionable, and its completeness is highly uneven, with coverage being potentially underrepresented in peripheral and disadvantaged zones [37]. Participation is markedly skewed—the familiar 90–9–1 pattern [38], and contributors tend to maintain a consistent geographic focus over time, reinforcing existing inequalities [37,39–41].

By contrast, Google Maps is a proprietary platform built on closed datasets, third-party sources, and machine-learning models. It provides extensive consumer-facing services but operates under commercial constraints. Platform governance strongly shapes data visibility and the mechanisms for access and download: ranking algorithms, Business Profile verification, user reviews, and API result caps privilege prominent or commercially active venues, while community spaces, low-visibility facilities, recently opened activities or specific types of amenities are harder to retrieve, especially in competitive urban contexts [4,14,41].

Beyond these intrinsic limitations, competitive dynamics between the two platforms further accentuate asymmetries: the expansion of Google Maps has been linked to a reduction in overall OSM contributions, as many potential new users turn to Google Maps instead [42]. At the same time, a smaller group of established contributors intensifies their efforts, motivated by ideological commitment to the open-source ethos and, to some extent, by community

interaction [43]. These social, spatial, and temporal filters determine which amenities become analytically visible and, in turn, cascade into 15-min accessibility outcomes.

6. Conclusions and Further Developments

This study critically examined how differences between two of the most widely used spatial datasets—OpenStreetMap (OSM) and Google Maps (GM)—shape the modelling of urban phenomena, with a specific focus on accessibility analyses within the 15-min city framework. By systematically comparing the two platforms across four European cities—Versilia, Gothenburg, Nice, and Vienna—this research demonstrates that dataset choice is far from a neutral technical step. Instead, it has a measurable and often substantial influence on both the quantitative assessment of service proximity and the qualitative interpretation of functional urban identity.

The findings point to three major areas of divergence between the datasets. First, **data volume and spatial consistency** vary substantially by platform and location. Google Maps tends to yield higher place counts exclusively at finer spatial scales, reflecting its sensitivity to the representation level. OSM, while more consistent in its tagging structure, tends to underrepresent certain functions—especially in peripheral or less densely mapped areas—and includes elements that may have low relevance for urban planning purposes, highlighting the need for careful evaluation of data characteristics and contextual significance.

Second, **semantic categorisation** plays a critical role. Even for apparently straightforward amenities such as pharmacies, bookstores, and bars, substantial inconsistencies were observed in how categories are defined, structured, and retrieved across the two platforms. These semantic mismatches complicate both data integration and model comparability, especially in contexts requiring fine-grained functional distinctions.

Third, and most crucially, these differences **cascade into the modelling process itself**. Using the 15-min isochrone as a lens, the study revealed that accessibility scores and spatial interpretations of urban vibrancy vary not only in magnitude but also in meaning depending on the data source used. This is particularly relevant in decision-support systems and planning workflows, where data-driven insights are translated into spatial strategies.

In practice, much applied work relies on a single platform—typically OSM or Google Places—often with minimal justification and without cross-source sensitivity checks. Taken together, these findings show why that choice is not neutral. On the contrary, they reflect **distinct epistemological models of the urban**: one rooted in participatory, volunteer-based mapping; the other governed by commercial logic and algorithmic visibility. Each has its own strengths and limitations. While it remains unclear which of the two more accurately reflects real-world conditions, it is likely that both diverge, in different ways, from the urban reality they aim to represent—a question that is currently being explored in ongoing research.

Specific findings that could drive the use of these datasets or stimulate further research are

- Functional non-equivalence. OSM and GM differ fundamentally in structure, category logic, and extraction protocols, with direct consequences for modelling outputs;
- Scale sensitivity. OSM retrievals are insensitive to search radius or centroid distance; GM retrievals vary with spatial extent, losing consistency over larger urban areas;
- Semantic misalignment. No one-to-one category correspondence exists; even overlapping primary tags rarely match spatially or quantitatively, complicating DSS integration.

For planners, spatial analysts, and policymakers, the implications are clear: **data selection must be treated as an explicit modelling decision**, not a neutral technical step. Proximity-based frameworks like the 15-min city depend on more than conceptual clarity—they rely on data infrastructures that are themselves uneven, contingent, and

often opaque. A thorough analysis of the operating mechanisms of the selected database, the pre-filtering of features according to research objectives, and the adoption of smaller search radius are strongly recommended.

Situated within the broader agenda of sustainable urban transitions and evidence-based planning, our findings have three implications. First, environmental efficacy: credible proximity metrics are prerequisites for demand-side measures that reduce car dependence and emissions; our cross-platform tests identify when and why such metrics may over- or under-estimate reachable amenities (Sections 5.1 and 5.2). Second, social equity: platform biases—underrepresentation of peripheral amenities in OSM and ranking/visibility filters in Google Maps—translate into unequal analytical visibility of everyday services, with consequences for spatial justice and targeted investment (Sections 5.3 and 5.4). Third, governance and reproducibility: transparent protocols, hybrid sourcing, and cross-platform semantic harmonisation operationalise open, auditable evidence for planning, aligning with the journal's emphasis on robust methods for policy-relevant sustainability research. By treating spatial data selection as an explicitly theory-laden modelling choice, the study provides practitioners with concrete levers—radius design, semantic controls, and validation checkpoints—to improve DSS reliability and, ultimately, the robustness and fairness of proximity-based interventions.

Future research should pursue several key directions. First, the integration of ground-truth datasets is needed to benchmark the representational accuracy of both platforms and to assess how data quality correlates with urban form, city function, or specific amenity types. Second, there is a pressing need to develop a harmonised and extensible categorisation schema capable of bridging semantic mismatches and enabling robust cross-platform comparisons. Third, hybrid approaches that leverage the complementary strengths of both OSM and Google Maps should be explored, alongside the development of validation protocols tailored to distinct urban contexts. Lastly, more fine-grained, intra-urban analyses should be prioritised, moving beyond citywide generalisations to account for the heterogeneity of urban space and to support more context-sensitive modelling of accessibility and proximity. By foregrounding the epistemic and technical implications of data choice, this study positions spatial data selection as a critical, theory-laden decision in urban analytics—one that directly shapes the narratives, priorities, and policy interventions derived from data-driven models.

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References

1. Moreno, C.; Allam, Z.; Chabaud, D.; Gall, C.; Pratlong, F. Introducing the "15-minute city": Sustainability, resilience and place identity in future post-pandemic cities. *Smart Cities* **2021**, *4*, 93–111. [CrossRef]
2. Pezzica, C.; Altafini, D.; Mara, F.; Chioni, C. Travel-time in a grid: Modelling movement dynamics in the "minute city". In Proceedings of the International Conference on Innovation in Urban and Regional Planning, L'Aquila, Italy, 6–8 September 2023; Springer Nature: Cham, Switzerland, 2023; pp. 657–668. [CrossRef]
3. Mara, F.; Anselmi, C.; Deri, F. Urban systems, when they conurbate: The diachronic-configurational approach to detect the shifting of centrality in Versilia. *URBAN Des. Int.* **2025**, 1–22. [CrossRef]
4. Quinn, S.; Condon, D. Inclusion of Latino-oriented local businesses in popular online maps: An empirical study in the Inland Northwest of the United States. *J. Community Inform.* **2022**, *18*, 84–114. [CrossRef]
5. Martinez, J.; Mahajan, S. Smart cities and access to nature: A framework for evaluating green recreation space accessibility. *IEEE Access* **2023**, *11*, 102014–102024. [CrossRef]
6. Zhou, Q.; Lin, H. Investigating the completeness and omission roads of OpenStreetMap data in Hubei, China by comparing with street map and street view. *ISPRS-Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2020**, *XLIII-B4-2020*, 299–306. [CrossRef]
7. Ćmielová, B.; Pánek, J. Visual comparison of web map changes of OpenStreetMap and commercial online-map providers: A research note. *Int. J. E-Plan. Res.* **2016**, *5*, 40–54. [CrossRef]
8. Franzini, M.; Annovazzi-Lodi, L.; Casella, V. Assessment of the Completeness of OpenStreetMap and Google Maps for the Province of Pavia (Italy). In Proceedings of the 6th International Conference on Geographical Information Systems Theory, Applications and Management, Prague, Czech Republic, 7–9 May 2020; pp. 270–277. [CrossRef]
9. Zhou, Q.; Zhang, Y.; Chang, K.; Brovelli, M.A. Assessing OSM building completeness for almost 13,000 cities globally. *Int. J. Digit. Earth* **2022**, *15*, 2400–2421. [CrossRef]
10. Yu, D.; Fang, C. Urban remote sensing with spatial big data: A review and renewed perspective of urban studies in recent decades. *Remote Sens.* **2023**, *15*, 1307. [CrossRef]
11. Boeing, G. Spatial information and the legibility of urban form: Big data in urban morphology. *Int. J. Inf. Manag.* **2021**, *56*, 102013. [CrossRef]
12. Mooney, P.; Minghini, M. A Review of OpenStreetMap Data. In *Mapping and the Citizen Sensor*; Foody, G., See, L., Fritz, S., Mooney, P., Olteanu-Raimond, A.-M., Fonte, C.C., Antoniou, V., Eds.; Ubiquity Press: London, UK, 2017; pp. 37–59. [CrossRef]
13. Ballatore, A.; Zipf, A. A conceptual quality framework for volunteered geographic information. In Proceedings of the Spatial Information Theory: 12th International Conference (COSIT), Santa Fe, NM, USA, 12–16 October 2015; Springer International Publishing: Cham, Switzerland, 2015; pp. 89–107. [CrossRef]
14. Panko, R. The Popularity of Google Maps: Trends in Navigation Apps in 2018. *Manifest* **2018**, *10*. Available online: https://themanifest.com/app-development/trends-navigation-apps (accessed on 12 June 2025).
15. Google Business Profile Help. Available online: https://support.google.com/business/answer/7091?hl=enref_topic=11515681sjid=11575979098544691654-EU (accessed on 12 May 2025).
16. Places API Overview. Google Maps Platform. Available online: https://developers.google.com/maps/documentation/places/web-service (accessed on 12 May 2025).
17. Papadopoulos, E.; Sdoukopoulos, A.; Politis, I. Measuring compliance with the 15-min city concept: State-of-the-art, major components and further requirements. *Sustain. Cities Soc.* **2023**, *99*, 104875. [CrossRef]
18. Map Features. Available online: https://wiki.openstreetmap.org/wiki/Map_features (accessed on 19 February 2025).
19. Place Types. Google Maps Platform Documentation. Available online: https://developers.google.com/maps/documentation/places/web-service/place-types#table-a (accessed on 13 February 2025).
20. Fusco, G.; Pont, M.B.; Cutini, V.; Psenner, A. Guiding principles for the 15-minute city in peripheral areas: The emc2 model. *Game Chang. Plan. Just Sustain. Urban Reg.* **2024**, *36*, 690–707.
21. AdminStat Italy. Available online: https://ugeo.urbistat.com/AdminStat/it/it/demografia/dati-sintesi/massa-carrara/45/3 (accessed on 20 March 2025).
22. AdminStat France. Available online: https://ugeo.urbistat.com/AdminStat/it/fr/demografia/dati-sintesi/alpes-maritimes/6/3 (accessed on 20 March 2025).
23. Moak, D.G. Une ville des jardins: The Consiglio d'Ornato and the Urban Transformation of Nice (1832–1860). *J. Urban Hist.* **2019**, *45*, 786–812. [CrossRef]
24. Goteborg, Treccani. Available online: https://www.treccani.it/enciclopedia/goteborg/ (accessed on 20 March 2025).
25. Stavroulaki, I.; Marcus, L.; Pont, M.B. *GIS-Based Time Model. Urban Development in Gothenburg, 1960 to Present*; Chalmers University of Technology: Gothenburg, Sweden, 2019. Available online: https://research.chalmers.se/publication/514518/file/514518_Fulltext.pdf (accessed on 7 August 2025).
26. Cereda, V. Compact City and Densification Strategies. The Case of Gothenburg. Master's Thesis, European Spatial Planning and Regional Development, Blekinge Institute of Technology, Blekinge County, Sweden, 11 May 2009.

27. World Population Review. Available online: https://worldpopulationreview.com/cities/sweden/gothenburg#city-size-and-population-density (accessed on 20 March 2025).
28. Suitner, J. Vienna's planning history: Periodizing stable phases of regulating urban development, 1820–2020. *Plan. Perspect.* **2021**, *36*, 881–902. [CrossRef]
29. AdminStat Austria. Available online: https://ugeo.urbistat.com/AdminStat/it/at/demografia/dati-sintesi/wien/9/2 (accessed on 20 March 2025).
30. Yamu, C.; Garau, C. The 15-Minute City: A Configurational Approach for Understanding the Spatial, Economic, and Cognitive Context of Walkability in Vienna. In Proceedings of the 22nd International Conference on Computational Science and Its Applications, Malaga, Spain, 4–7 July 2022; Gervasi, O., Murgante, B., Hendrix, E.M.T., Taniar, D., Apduhan, B.O., Eds.; Springer International Publishing: Cham, Switzerland, 2022; pp. 387–404. [CrossRef]
31. Euromonitor. Top 100 City Destinations Index. 4 December 2024. Available online: https://www.euromonitor.com/top-100-city-destinations-index/report (accessed on 6 January 2025).
32. Anselmi, C.; Mara, F.; Deri, F. Big-data Reliability in Informing the 15-Min City Modelling: A Comparison Between OpenStreetMap and Google Maps. In *International Conference on Computational Science and Its Applications*; Springer Nature: Cham, Switzerland, 2025; pp. 325–341. [CrossRef]
33. Biljecki, F.; Chow, S.Y.; Lee, K. Quality of crowdsourced geospatial building information: A global assessment of OpenStreetMap attributes. *Build. Environ.* **2023**, *237*, 110295. [CrossRef]
34. Boeing, G.; Higgs, C.; Liu, S.; Giles-Corti, B.; Sallis, J.F.; Cerin, E.; Lowe, M.; Adlakha, D.; Hinckson, E.; Moudon, A.V.; et al. Using open data and open-source software to develop spatial indicators of urban design and transport features for achieving healthy and sustainable cities. *Lancet Glob. Health* **2022**, *10*, e907–e918. [CrossRef] [PubMed]
35. Deri, F.; Mara, F.; Anselmi, C. Crowdsourced Data for Urban Planning: A Critical Evaluation of OpenStreetMap Accuracy and Completeness. In *International Conference on Computational Science and Its Applications*; Springer Nature: Cham, Switzerland, 2025; pp. 403–420. [CrossRef]
36. León, L.F.A. *The Map in the Machine: Charting the Spatial Architecture of Digital Capitalism*; University of California Press: Oakland, CA, USA, 2024.
37. Herfort, B.; Lautenbach, S.; Porto de Albuquerque, J.; Anderson, J.; Zipf, A. A spatio-temporal analysis investigating completeness and inequalities of global urban building data in OpenStreetMap. *Nat. Commun.* **2023**, *14*, 3985. [CrossRef] [PubMed]
38. Nielsen, J. The 90-9-1 Rule for Participation Inequality in Social Media and Online Communities, 2006. Available online: https://www.nngroup.com/articles/participation-inequality/?utm_source=chatgpt.com (accessed on 12 June 2025).
39. Blurify. Google Maps vs OpenStreetMap: Which One Is Better for Your Project? 2025. Available online: https://blurify.com/blog/google-maps-vs-openstreetmap/ (accessed on 12 June 2025).
40. Thebault-Spieker, J.; Hecht, B.; Terveen, L. Geographic Biases are 'Born, not Made' Exploring Contributors' Spatiotemporal Behavior in OpenStreetMap. In Proceedings of the 2018 ACM International Conference on Supporting Group Work, Sanibel, FL, USA, 7–10 January 2018; pp. 71–82.
41. Haklay, M. How good is volunteered geographical information? A comparative study of OpenStreetMap and Ordnance Survey datasets. *Environ. Plan. B Plan. Des.* **2010**, *37*, 682–703. [CrossRef]
42. Nagaraj, A.; Piezunka, H. How competition affects contributions to open source platforms: Evidence from OpenStreetMap and Google maps. *Work. Pap.* **2020**, 58.
43. Bhandari, A.; Noone, R. Support local: Google Maps' local guides platform, spatial power and constructions of "the local". *Commun. Cult. Crit.* **2023**, *16*, 198–207. [CrossRef]

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Spatial Joining of Traffic Data from Big Data Platforms in Simulation Tools Used to Model Urban Road Networks

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Abstract

Traffic simulation models are widely used in transportation analysis, often oriented toward keeping urban systems sustainable from various points of view, ranging from energy consumption to air quality. However, their accuracy depends on the quality of the data used to represent both the road network and travel demand. Although open-source datasets can be used to develop simulation networks and observed traffic information is available from big-data platforms, integrating these heterogeneous datasets remains challenging. Indeed, different road segmentation schemes may be used across different platforms, and common identifiers are often not adopted. This study proposes a GIS-based framework for spatially joining traffic data from big-data platforms with road networks used in traffic simulation models. The methodology integrates a microscopic simulation network derived from OpenStreetMap and implemented in SUMO with traffic data obtained from the TomTom Traffic Stats service. The workflow is implemented in QGIS (3.34 prizren) and combines spatial buffering, directional filtering, overlap analysis, and hierarchical match cleaning to associate traffic segments with the corresponding simulation network edges. The framework is applied to an urban case study in the city of Biella, Italy. Results show that more than 80% of the simulation network edges can be successfully linked with traffic segments, enabling the integration of hourly traffic indicators such as travel time and speed. The resulting dataset supports several applications, including network calibration, simulation validation, detector placement, and traffic demand estimation, contributing to the development of more reliable traffic simulation models for comparing and selecting sustainable urban mobility actions within the transportation planning process.

Keywords: road network matching; traffic simulation; floating car data; sustainable mobility; GIS-based data integration

1. Introduction

Traffic simulation models, including macroscopic, mesoscopic, and microscopic approaches, play a fundamental role in transportation analysis and support a wide range of applications [1]. These range from transportation planning and traffic management to road safety assessment, energy consumption, emissions and air quality analysis [2–4], vulnerability analysis of road networks [5–7], and the development of testing operations for connected and autonomous vehicle technologies. Simulated urban traffic models can also support socio-demographic studies by enabling the analysis of traffic flows and the identification of residential and industrial districts [8]. In addition, simulation tools are

increasingly used in research related to vehicular ad hoc networks (VANETs), which support autonomous driving, road safety applications, and hazard information services [9]. These technologies are often investigated through large-scale regional simulations because real-world testing is difficult to reproduce, extremely costly at large scales, and may pose safety risks to users. Recently, traffic simulation has become an important tool for assessing the vulnerability of transportation networks in case of disruptions such as flooding events, natural hazards, and man-made disasters. By simulating baseline and disrupted scenarios, researchers can estimate the impacts of infrastructure failures on mobility, congestion patterns, accessibility, and traffic redistribution across the network. Recent studies have further demonstrated how flood-induced disruptions can generate cascading effects on urban mobility systems through both mesoscopic and agent-based traffic simulations [6,10]. However, the reliability of such analyses depends on the accuracy of the underlying traffic simulation models, which must be properly calibrated and validated using observed data.

A traffic simulation model generally requires three key types of inputs: (i) network data describing functions of road facilities, (ii) additional traffic infrastructure elements such as signals or detectors, and (iii) traffic demand data representing travel patterns, typically expressed by origin–destination (O–D) matrices [11]. Developing an accurate network model requires detailed information about road attributes such as road classification, number of lanes, speed limits, traffic direction, and link length. These datasets are often obtained from official geoportals or open-access platforms such as OpenStreetMap (OSM). However, open-source network data may contain inconsistencies or missing attributes and, therefore, often require a careful calibration and validation process before being used in traffic simulation models. Demand modeling is typically based on O–D matrices that describe the number of trips between traffic analysis zones. These matrices are traditionally derived from travel surveys, census data, or other aggregated statistics. Such data sources can also be used to calibrate and validate traffic simulation models. For example, Shahdani et al. validated a mesoscopic traffic simulation developed to analyze the vulnerability of the road network in the Santarém region, Portugal, using average daily travel time data obtained from Infraestruturas de Portugal [5]. Nevertheless, calibration and validation based solely on demographic or survey data remain challenging because high-resolution real-world measurements are often limited or unavailable.

Recent advances in communication technologies and data collection methods have enabled the emergence of floating car data (FCD), which provides large-scale observations of vehicle trajectories, speeds, travel times, and route choices. With increasing penetration rates, these traffic datasets from service providers have become widely available. These datasets can also provide derived information such as traffic density, congestion levels, and travel time reliability with significantly higher spatial resolution than traditional fixed traffic detectors [12–14]. For instance, Salvo et al. developed a data-driven microsimulation framework combining the Dynasim simulation model with real-time traffic data from the TomTom platform [15] to evaluate emergency management strategies in Palermo, Italy. Their study demonstrated how FCD traffic data can support the analysis of congestion dynamics and rerouting behavior during flood events [16]. More recently, large-scale traffic datasets have also been increasingly used in data-driven traffic analysis, congestion prediction, and intelligent transportation system (ITS) applications. Recent studies have explored machine learning and deep learning approaches to analyze urban traffic conditions and support real-time mobility management using heterogeneous traffic datasets [17]. These developments further highlight the importance of integrating traffic data from different platforms into traffic simulation and traffic analysis environments.

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Despite the growing availability of traffic datasets, integrating these data sources with traffic simulation networks remains a major challenge. Simulation networks are frequently constructed from open-source datasets such as OSM and converted into formats compatible with simulation platforms. However, traffic information provided by commercial platforms is typically structured around proprietary road segment definitions that do not align directly with those in simulation networks. Even when both datasets contain geographic coordinates, the segments representing the same road may differ significantly in length, segmentation, geometry, or spatial alignment. Consequently, a direct attribute join between these datasets is usually not possible. An essential step for integrating traffic datasets with simulation networks is therefore the matching or conflation of road networks derived from heterogeneous sources.

Several studies have addressed the problem of matching road networks from heterogeneous datasets. Guo et al. proposed a stroke-based matching approach that reconstructs road segments into continuous strokes and evaluates similarity using geometric, topological, and structural constraints to identify relationships such as 1:1, 1:N, and M:N across datasets with different scales [18]. Hacar and Gökgöz developed a semi-automated approach that assigns similarity scores based on geometric and topological indicators and iteratively adjusts the weights of these measures according to their matching efficiency [19]. Wu et al. formulated road matching as an optimization problem and solved it using a minimum-cost network flow model combined with relaxation constraints such as angle and shortest-path consistency [20]. Zuo et al. introduced a hierarchical framework based on Delaunay triangulation that converts road networks into triangular meshes and identifies corresponding structures using probabilistic relaxation techniques [21]. Hackeloeer et al. proposed an iterative hierarchical conflation approach exploiting topological and geometric relationships across heterogeneous road datasets [22], while Zhang et al. developed an automatic conflation framework combining road network matching, geometric transformation, topological remodeling, and error correction procedures for integrating heterogeneous routing datasets [23]. More recently, Veihelmann et al. applied machine learning techniques, specifically a decision tree classifier based on geometric similarity features, to match floating car data with OSM networks to support microscopic traffic simulation. Their framework integrated high-resolution probe-count data with simulation networks to generate detector-based traffic information and improve the calibration and validation of large-scale microscopic simulations [12]. Open-source conflation platforms such as Hootenanny [24] have also been developed to integrate heterogeneous map datasets into unified representations through rule-based and machine learning-assisted procedures.

Although these approaches can achieve high matching accuracy, several limitations remain for traffic simulation applications. Many methods rely on complex optimization procedures or machine learning models that require labeled training datasets, extensive parameter tuning, or computationally intensive processing. Furthermore, several conflation approaches primarily focus on generating unified map representations rather than preserving the original structure of simulation networks. However, in traffic simulation workflows, preserving simulation network geometry is important because detector placement, calibration procedures, and traffic analysis are often directly linked to predefined simulation edges. In addition, one-to-many relationships between traffic segments and simulation edges are common when integrating floating car data with simulation networks, but these relationships are not always explicitly addressed in existing approaches. Therefore, a gap remains for a practical and transferable framework that integrates heterogeneous traffic datasets from different sources with simulation networks, preserves the original simulation structure, and enables direct use in simulation-oriented applications.

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To address this gap, this study proposes a GIS-based spatial framework for integrating heterogeneous traffic datasets with road networks used in traffic simulation models. The proposed methodology focuses on a practical and transferable workflow based on spatial relationships, directional consistency, and geometric overlap rather than complex optimization or machine learning techniques. Implemented using standard GIS tools, specifically QGIS, the framework enables integrating traffic datasets with simulation networks while preserving the original simulation geometry and explicitly handling one-to-many relationships between traffic segments and simulation edges. In addition, the framework introduces a detector-based representation of multiple matches to support simulation-oriented applications. The methodology is applied and validated using case studies based on floating car data integrated with simulation networks derived from OSM. This facilitates the preparation of enriched and calibrated simulation environments for applications including traffic analysis, network performance evaluation, and the development of more reliable models for sustainable urban mobility analysis and urban mobility scenario modeling.

The remainder of the paper is structured as follows. Section 2 describes the datasets used and the study area in which the methodology is applied. Section 3 outlines the proposed methodology and framework of the study. Section 4 presents the results and discusses the potential applications of the merged datasets. Finally, Section 5 provides the conclusions and recommendations for future research.

2. Data and Study Area

This section describes the datasets used in the study and the geographic area selected for the proposed framework's application.

2.1. Simulation Network Derived from OSM

The road network used in the traffic simulation is derived from OSM and generated using the OSM Web Wizard, an integrated tool within the SUMO (Simulation of Urban MObility) platform [1]. This tool consists of a set of Python 3.12 scripts to automatically download and convert OSM road data into a network format compatible with the simulation environment. During this process, road elements are imported according to their classifications, permitted vehicle types, and the simulation configuration defined for the selected geographic area. The resulting configuration includes a network file (osm.net.xml) that represents the road infrastructure of the selected study area within a rectangular bounding box. To obtain a network that matches the exact shape of the study area, the downloaded network was further processed with the NETEDIT tool. By importing both the network file and a polygon shapefile representing the study area boundary, the network was clipped to the desired spatial extent.

For spatial analysis and integration with external datasets, the network was converted into GeoJSON format using the net2geojson.py tool. This conversion exports only the network edges, excluding junctions and connections, as the objective of this study is to match network edges with traffic datasets. The resulting GeoJSON dataset contains several attributes associated with each edge, including the OSM identifier (edge ID), element type (edge), permitted vehicle types (allow), road name, number of lanes, and maximum allowed speed. Additionally, the length of each edge was calculated and appended to the dataset by parsing both the osm.net.xml network file and the GeoJSON dataset using a custom Python script (Add_length_SUMO.py), which extracts the geometric length of each edge and adds it to the attribute table. The final dataset was then imported into QGIS for further spatial analysis and integration with the FCD traffic dataset.

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2.2. Traffic Data Description and Processing

Traffic data used in this study were obtained from the TomTom Traffic Stats, Area Analysis platform [15], which provides aggregated traffic information derived from anonymized GNSS devices installed on board. Observations are aggregated to generate statistical traffic indicators for predefined road segments within a selected geographic area.

The dataset is in the Orbis map format, which represents the proprietary road network used for traffic analytics on the platform. The data were downloaded for the selected study area through the Traffic Stats portal and provided as a shapefile containing the road network geometry, together with additional attribute tables describing hourly traffic statistics. The network shapefile contains the geometric representation of road segments and includes attributes such as the segment identifier, segment length, functional road class (FRC), speed limit, and street name. Each segment is uniquely identified by an ID, which links the network geometry to additional tables containing traffic information.

Traffic statistics are provided in separate tables for different time intervals, with hourly aggregation used in this dataset, including several traffic indicators derived from FCD measurements, such as average travel time, median travel time, average speed, harmonic average speed, speed standard deviation, percentile speeds, and the number of observations used in the calculations, allowing the characterization of traffic conditions across different times of the day.

2.3. Study Area

The study area selected for this analysis is located in the central part of the city of Biella, in the Piedmont region of northern Italy. The area was selected as a representative urban environment where traffic simulation models can be used to evaluate traffic management strategies. To develop a reliable microscopic traffic simulation model, it is necessary to calibrate and validate it using observed traffic data. However, before such calibration can be performed, traffic data from external sources must be integrated with the road network used in the simulation model. Therefore, the first step consists of merging the simulation network with traffic datasets, which represents the primary objective of this study.

After clipping the network to the study area boundary, the simulation network contains 194 nodes and 360 edges. The road network comprises multiple road classes, including secondary, tertiary, residential, and unclassified roads. A comparable road network was also obtained from the FCD platform, which contains 366 road segments within the same study area.

Although the number of segments is similar between the two datasets, important differences exist. In several locations, the traffic dataset provides finer road segmentation, resulting in multiple traffic segments corresponding to a single edge in the simulation network. Conversely, some residential and unclassified roads present in the simulation network are not included in the observed traffic dataset, which partly explains the discrepancy between the two networks.

Figure 1 illustrates the simulation network edges exported as a GeoJSON dataset, which includes only the road segments and excludes junctions and connections. Figure 2 presents the corresponding FCD road network covering the same study area.

The traffic data used in this study correspond to weekday traffic conditions during the Autumn–Winter period from September 2024 to March 2025, aggregated at hourly time intervals.

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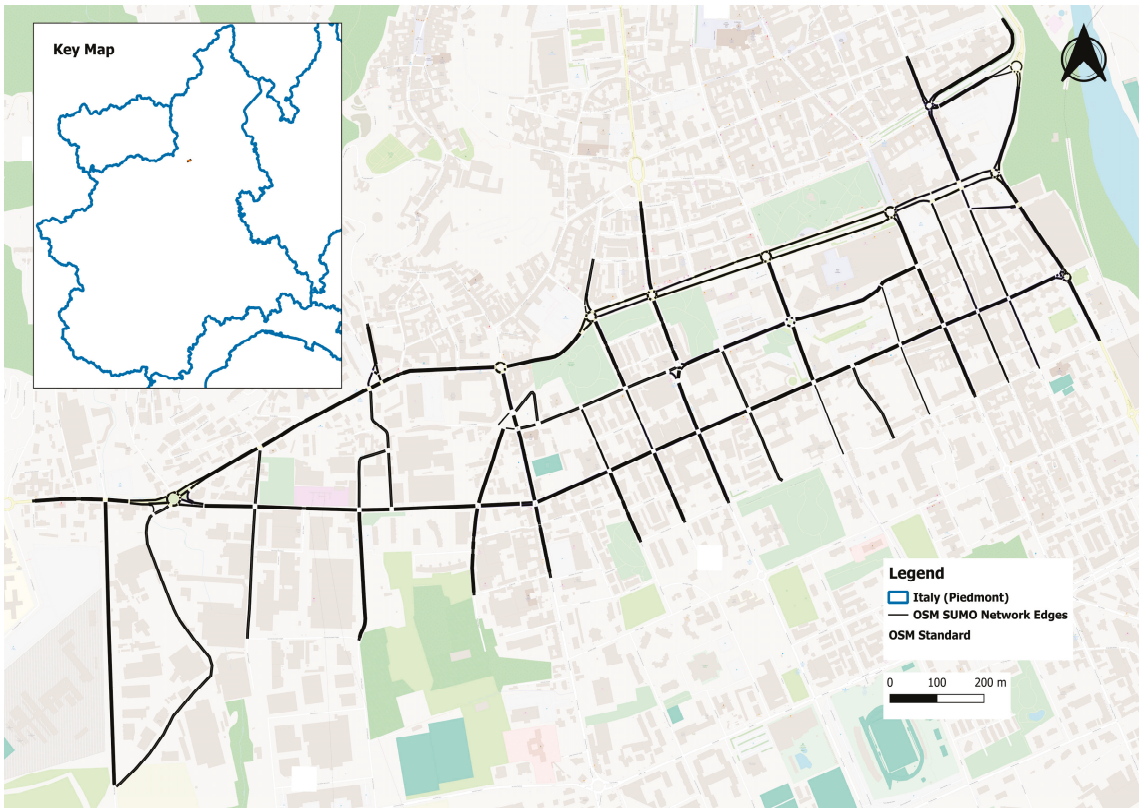


Figure 1. Simulation road network edges in the selected study area.

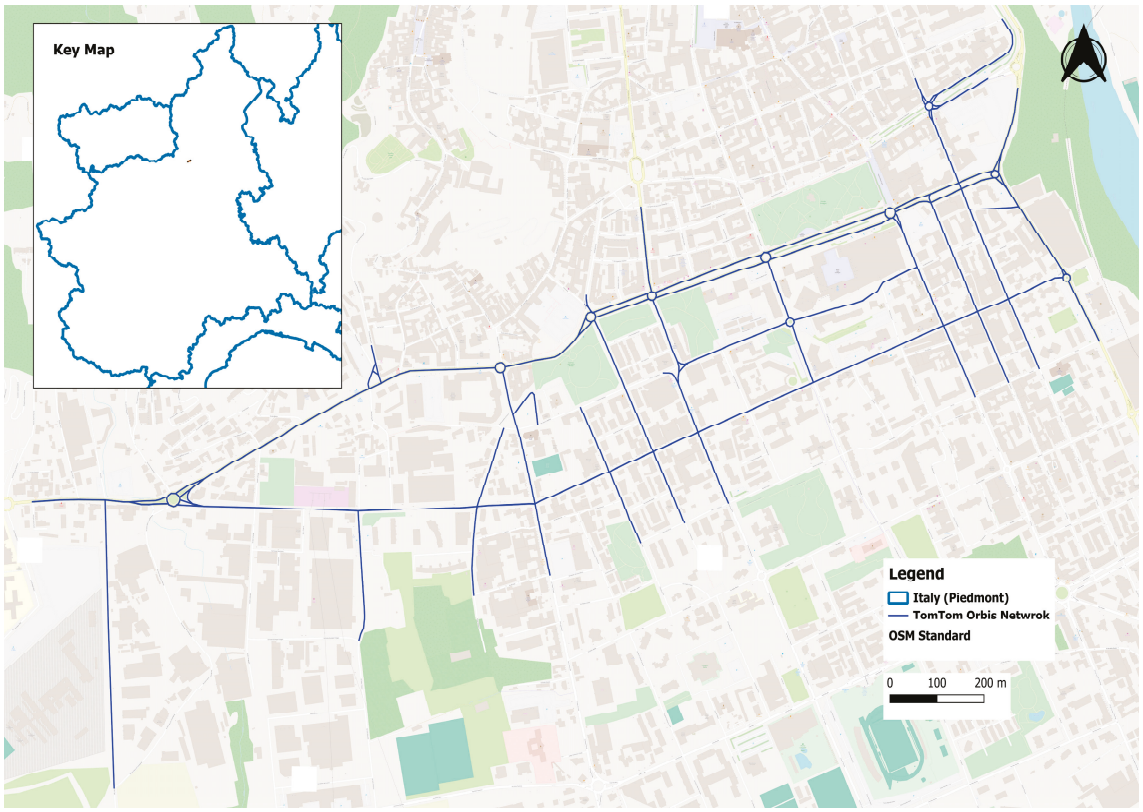


Figure 2. FCD road network in the selected study area.

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2.4. Dataset Differences and Integration Objectives

Although both datasets represent the same underlying road infrastructure, several structural differences exist between the OSM-derived simulation network and the FCD traffic network, requiring a specific process to integrate traffic information between the two datasets.

First, the two networks do not share a common identifier field. Edges in the simulation network are identified by unique IDs generated during the network conversion process, whereas the FCD dataset uses proprietary segment identifiers. Consequently, a direct attribute join between the two datasets is not possible. Second, road segmentation differs between the datasets. In many cases, a single edge in the simulation network corresponds to multiple segments in the traffic dataset, while in other cases multiple simulation edges correspond to a single segment. These 1:N and N:1 relationships complicate the direct transfer of traffic attributes between the networks.

Another issue to be managed is the edge directions. In the simulation network, each direction is represented by a separate edge. In contrast, the traffic dataset often represents bidirectional roads using two vectors along the same geometric line, resulting in overlapping directional information. Furthermore, slight geometric differences exist between the two datasets, including variations in segment length, spatial alignment, and road curvature. These discrepancies arise because the networks are generated from different mapping processes and data sources.

These differences highlight the need for a spatial matching procedure capable of linking traffic segments with the corresponding edges of the simulation network. Figure 3 illustrates an example of spatial differences between the two networks in the study area, highlighting differences in segmentation and geometric representation.

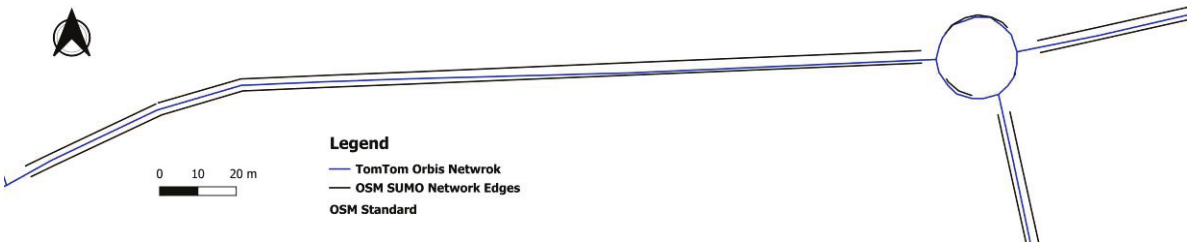


Figure 3. Example of spatial differences between simulation network edges and the FCD road segments in the study area.

3. Methodology

The methodology adopted to harmonize traffic data with the simulation road network is illustrated in Figure 4. The framework consists of three main stages: preparation of the simulation road network, preparation of the FCD road network, and spatial matching and filtering to associate traffic segments with the corresponding edges of the simulation network. All spatial processing steps were performed using QGIS.

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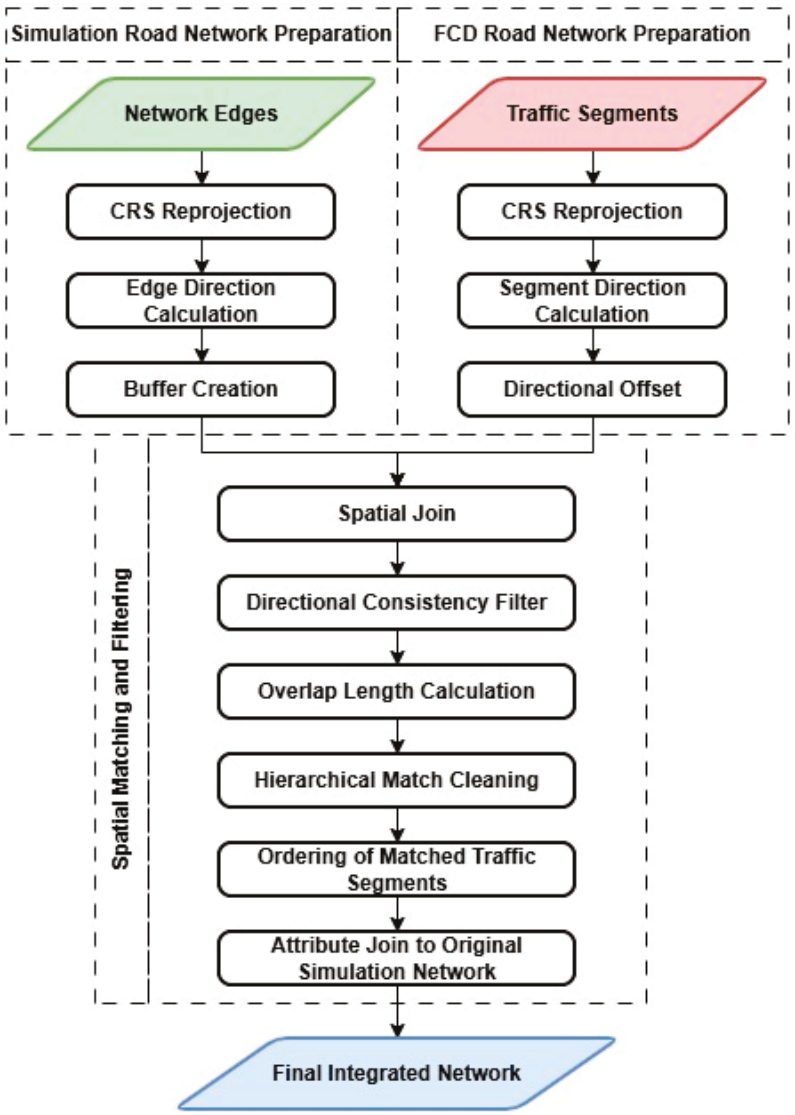


Figure 4. Workflow of the methodology for integrating traffic data with the simulation network.

3.1. Simulation Road Network Preparation

The simulation network edges, exported in GeoJSON format using the WGS84 coordinate reference system (EPSG:4326) explained in Section 2.1, are imported into QGIS for further spatial processing. For compatibility with other datasets used in the analysis, particularly the FCD road network, the layer is converted to a Shapefile, although the workflow could also be performed directly using GeoJSON layers.

The dataset is then reprojected from WGS84 (EPSG:4326) to UTM Zone 32N (EPSG:32632), which is appropriate for northern Italy and enables spatial operations to be performed using metric units. This step is necessary because subsequent geometric operations, such as buffer creation, length calculations, and spatial overlap analysis, require measurements in meters rather than degrees.

To characterize the direction of each edge, a directional attribute (azimuth) is computed based on the start and end points of the edge geometry using the QGIS Field Calculator. This operation assigns a directional value to each edge representing its orientation within the range of 0–360°, consistent with standard azimuth conventions.

Finally, a 3 m buffer is generated around each edge using flat end caps and without dissolving adjacent features. The buffer accounts for geometric discrepancies between datasets and ensures that nearby traffic segments can be captured during the subsequent spatial

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matching process. This value is selected based on initial visual inspection and preliminary trial analyses of geometric misalignment between the datasets. The buffer size can be adjusted depending on the degree of misalignment and should be large enough to capture as many potential matches as possible. Including segments with opposite directions does not introduce issues, as these are removed during directional filtering. However, excessively large buffers may capture adjacent parallel links with similar directions (e.g., service roads and main corridors), which can lead to incorrect matches due to high directional consistency and overlap ratios.

3.2. FCD Road Network Preparation

The FCD road network data is downloaded from the ORBIS map in Shapefile format using the WGS84 coordinate reference system (EPSG:4326). The dataset is then imported into QGIS for spatial preprocessing.

To ensure consistency with the simulation road network, the dataset is reprojected to UTM Zone 32N (EPSG:32632). Using the same projected coordinate reference system allows all subsequent spatial operations to be performed in metric units and ensures geometric compatibility between the two datasets.

A directional attribute (azimuth) is then computed for each segment based on the start and end points of the segment geometry using the QGIS Field Calculator. This results in orientation values ranging from 0° to 360°, consistent with the convention used for the simulation network.

In this dataset, bidirectional roads are represented by two overlapping line features, each corresponding to a different travel direction. To avoid spatial ambiguity, a 1.5 m right-side offset is applied using the QGIS Geometry by Expression tool. This offset separates the two directional representations geometrically while preserving their directional attributes, allowing them to be distinguished during the spatial matching stage. The value is determined based on the typical lateral displacement observed between segments and is sufficient to separate overlapping features and slightly shift them toward lane centers. When segments are already spatially separated, the offset does not significantly alter their correspondence with the simulation network.

The buffer and offset values are defined based on an initial inspection of geometric alignment between datasets and can be adjusted to balance the inclusion of candidate matches and the reduction in false associations. In practice, the buffer size plays a more critical role in capturing potential matches during the spatial join phase, while the offset primarily serves to separate overlapping directional features. An appropriate buffer value depends on the degree of geometric misalignment and should be selected to maximize candidate capture while limiting the inclusion of unrelated parallel links.

3.3. Spatial Matching and Filtering

After preparing both datasets, a spatial matching procedure is applied to associate traffic segments with the corresponding edges of the simulation network. The process includes spatial joining, directional filtering, overlap-based selection, and ordering of matched segments.

3.3.1. Spatial Join

A Join by Location operation is performed in QGIS to associate the simulation network with the traffic dataset. The 3 m buffer layer generated around the network edges is used as the input layer, while the offset traffic segments is used as the join layer. The spatial predicate Intersects is applied, and the join is configured as a one-to-many relationship.

Through this operation, attributes from the traffic dataset, particularly the segment identifier, are transferred to the buffered network layer. If an edge does not intersect any

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segment, no attributes are assigned. Otherwise, due to differences in network segmentation, the join may produce either one-to-one or one-to-many relationships, where a single simulation edge corresponds to one or multiple segments.

3.3.2. Directional Consistency Filtering

Because spatial proximity alone may associate simulation network edges with traffic segments representing an opposite travel direction, a directional consistency filter is applied. The angular difference between the orientation of each edge and the corresponding segment is computed to verify whether the two geometries represent a similar direction of travel.

A new attribute representing the angular difference is calculated to measure the absolute difference between the edge direction and the segment direction, while accounting for the circular nature of angular measurements (0–360°). The resulting value ranges between 0° and 180°, representing the minimum directional difference between the two geometries.

Based on this measure, valid matches are identified using a directional threshold of 45°. Matches with an angular difference of 45° or less are retained to ensure directional consistency between the paired geometries while allowing a tolerance for geometric variability. This threshold represents a balance between maintaining consistent travel direction and accounting for curvature or irregularities in road geometry. In addition, cases in which no segment is associated with an edge are preserved to maintain complete simulation network coverage for subsequent analysis.

3.3.3. Overlap Length Calculation

Despite the directional filtering step, some edges may still be associated with multiple segments. This situation typically occurs near intersections where edges are relatively short or where the spatial buffer captures the endpoints of adjacent segments. To distinguish the most relevant matches, the geometric overlap length between edges and segments is computed.

An intersection operation is performed between the offset FCD dataset and the buffer-joined layer. The resulting geometries represent the overlapping portions between the two datasets. For each intersecting feature, the overlap length is calculated and stored as an attribute.

The computed overlap length is then associated with the corresponding edge–segment pair in the joined dataset. To normalize this measure, an overlap ratio is calculated by dividing the overlap length by the total length of the corresponding traffic segment. This ratio represents the proportion of each segment that overlaps with the corresponding simulation network edge and provides a quantitative indicator for selecting the most representative match.

3.3.4. Hierarchical Match Cleaning

To resolve cases where multiple segments remain associated with a single simulation network edge, a hierarchical selection procedure is applied. This procedure combines directional consistency, overlap ratio, and edge length criteria to retain the most appropriate matches while preserving complete network coverage.

First, edges that do not intersect any segment are retained without modification. If an edge is associated with only one segment, the match is preserved directly.

For edges with multiple potential matches, the selection depends on edge length. For edges longer than or equal to 10 m, traffic segments covering at least 45% of their length within the overlap region are retained. If none of the candidates satisfy this threshold, the segment with the maximum overlap ratio is selected. A slightly relaxed threshold, compared to stricter values (e.g., 50%), is adopted to avoid excluding valid matches due

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to minor geometric misalignments while still ensuring that only representative segment overlaps are retained.

For short simulation network edges (<10 m), where geometric overlap may be less reliable, the segment with the smallest angular difference relative to the edge direction is selected.

This hierarchical filtering procedure produces a cleaned dataset in which each simulation edge is associated with the most appropriate segment or segments while minimizing false matches.

3.3.5. Ordering of Matched Traffic Segments

In some cases, a single edge remains associated with multiple segments after the spatial matching and filtering stages. For subsequent analyses, such as sequencing segments, aggregating speed or travel time information, or defining detector locations along the simulation network, it is necessary to establish an order among the matched segments.

To address this, a new integer ordering attribute is introduced. This attribute is assigned only to edges associated with more than one segment. The ordering is determined based on the distance between the start point of the edge and the midpoint of each corresponding segment. The segment whose midpoint is closest to the start of the edge is assigned an order value of 1, the next closest segment is assigned 2, and so on.

The midpoint of each segment is approximated using its centroid, while the reference position of the edge is defined by its start point. For each edge, the distances to all associated segment centroids are calculated and sorted in ascending order. The relative position of each distance in this ordered list defines the value of the ordering attribute.

This procedure is implemented in QGIS using aggregation functions within the Field Calculator, grouped by the simulation network edge identifier. For edges with only one matched segment, or with no associated segment, the ordering field remains NULL, as no ordering is required in these cases.

3.3.6. Attribute Join and Final Integrated Layer

The cleaned traffic dataset attributes are joined back to the original network GeoJSON layer using a Join by Attribute operation in QGIS with a one-to-many relationship. The edge identifier is used as the key field to associate the matched segment identifiers and their corresponding attributes from the buffer-based matching layer with the original network geometry.

After completing the attribute join, the resulting dataset is reprojected back to the WGS84 coordinate reference system (EPSG:4326) and exported in GeoJSON format. In the final integrated dataset, each edge is associated with the corresponding segment identifier(s) or remains NULL where no match is available.

This structure enables the subsequent integration of hourly traffic statistics, which can be linked to the network using the segment identifier as the key field.

3.4. Detector-Based Representation of Multiple Matches

In cases where a single simulation network edge is associated with multiple traffic segments, differences in segmentation between the simulation network and the traffic dataset lead to multiple traffic measurements (e.g., speed or travel time) corresponding to a single edge. To address this issue, a detector-based representation is introduced as part of the methodology. The objective is to preserve the segmentation of the traffic dataset while maintaining the simulation network's structure.

Lane area detectors (E2 detectors) available in the SUMO platform [25] are used to represent the spatial distribution of the matched traffic segments along each simulation edge. For edges associated with multiple segments, multiple detectors are placed along

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the edge according to the spatial ordering defined in Section 3.3.5, with each detector corresponding to one matched segment. Detector placement is implemented through a Python script that reads the matched dataset and automatically generates the detector configuration file.

This representation enables the extraction of simulation outputs (e.g., speed, flow, and occupancy) at locations consistent with the segmentation of the traffic dataset, allowing a more accurate comparison between simulated and observed traffic parameters. By integrating detector placement into the workflow, the framework preserves one-to-many relationships between simulation edges and traffic segments without modifying the network geometry, extending the matching process to a simulation-ready representation of traffic data.

4. Results and Discussion

The methodology described in Section 3 was applied to the study area presented in Section 2.3. The results of the spatial matching process are analyzed to evaluate the integration between the simulation network and the traffic dataset.

4.1. Matching Results and Dataset Structure

The final output of the proposed methodology is a GeoJSON layer representing the simulation network edges enriched with attributes derived from the traffic dataset. The resulting attribute table establishes a relationship between the network edges and the corresponding traffic segments. Each edge is associated with the identifier of the matched segment or remains NULL if no corresponding segment is found.

The attribute table of the integrated dataset includes several fields describing characteristics of both datasets. These include the simulation edge identifier, matched traffic segment identifier, and additional geometric and directional indicators used during the matching procedure. For each pair of matched segments, the dataset stores the edge length, segment length, azimuth angles of both geometries, angular difference, overlap length, overlap ratio, and the ordering attribute assigned when multiple segments correspond to a single edge. In addition, road attributes such as the speed limit from the simulation dataset (m/s) and the traffic dataset (km/h) are preserved.

Table 1 presents an example of several rows from the final dataset, illustrating the relationship between the edge identifiers and the matched segment identifiers, as well as selected geometric and directional attributes produced during the matching process.

Once the matching is completed, the id field of the traffic dataset allows the integration of traffic statistics with the simulation network. Using this identifier as a key field, hourly traffic information can be directly joined to the simulation network. As an example, the hourly dataset corresponding to the Autumn–Winter weekday period from September 2024 to March 2025 between 08:00 and 09:00, representing the morning peak hour, was joined to the integrated network. This operation enriches the simulation network with observed traffic indicators such as average travel time, median travel time, average speed, harmonic average speed, median speed, standard deviation of speed, and measurement counts.

The matching statistics for the study area indicate that the majority of edges are successfully associated with traffic segments. Out of 360 edges in the simulation network, 257 exhibit a one-to-one relationship with a single segment, while 40 edges are associated with multiple segments. Among these, 25 edges correspond to two segments, 7 to three segments, and 8 to four segments. In addition, 63 edges have no corresponding segment, indicating the absence of traffic data (Table 2). Overall, more than 80% of the network edges are successfully linked with traffic information, demonstrating the effectiveness of the proposed methodology.

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Table 1. Example rows of the integrated dataset.

Simulation Road Network Dataset				FCD Traffic Dataset								
OSM id	**Max Speed (m/s)**	**Length (m)**	**Angle**	**id**	**Segment id**	**Length (m)**	**Speed Limit (km/h)**	**Angle**	**Angular Difference**	**Overlap Length (m)**	**Overlap Ratio**	**Multiple Matches Order**
-1009845454	13.89	102.08	158.056	338	1166751986752520193	110.912	50	157.896	0.16	102.134	0.921	
-1078137846	27.78	39.04	274.434	317	1166751986720309249	11.712	30	270.687	3.747	8.165	0.697	1
-1078137846	27.78	39.04	274.434	315	1166751986720276481	39.182	30	275.569	1.135	31.118	0.794	2
-1078137847	13.89	47.19	155.012	364	1166751986776145921	58.261	50	154.425	0.587	47.232	0.811	
-163744716#0	13.89	135.69	68.188	354	1166751986775752705	18.148	50	65.291	2.897	10.44	0.575	1
-163744716#0	13.89	135.69	68.188	352	1166751986775719937	72.249	50	69.009	0.821	72.249	1	2
-163744716#0	13.89	135.69	68.188	350	1166751986775687169	22.161	50	67.021	1.167	22.161	1	3
-163744716#0	13.89	135.69	68.188	348	1166751986775654401	36.639	50	67.389	0.799	30.706	0.838	4
-199961727#0	13.89	687.96	187.04									
-199961727#1	13.89	30.62	241.465									

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Table 2. Distribution of the number of matched traffic segments associated with each simulation network edge in the study area.

Number of Matched Segments per Edge	Count	Percentage (%)
0	63	17.5
1	257	71.4
2	25	6.95
3	7	1.95
4	8	2.2

As a first assessment, the integrated dataset was visually inspected in QGIS. For most matched cases, the segments align well with the corresponding edges, confirming the effectiveness of the spatial, directional, and overlap-based filtering steps. However, some limitations were identified. Unmatched edges are often associated with residential or unclassified roads that are not included in the traffic dataset, resulting in missing traffic information.

Additional discrepancies occur in locations where geometric representations differ, particularly along curved roads or polylines with multiple vertices. In such cases, the computed angular difference may exceed the filtering threshold, preventing valid matches. An example of this situation is illustrated in Figure 5, where geometric curvature leads to directional inconsistency.

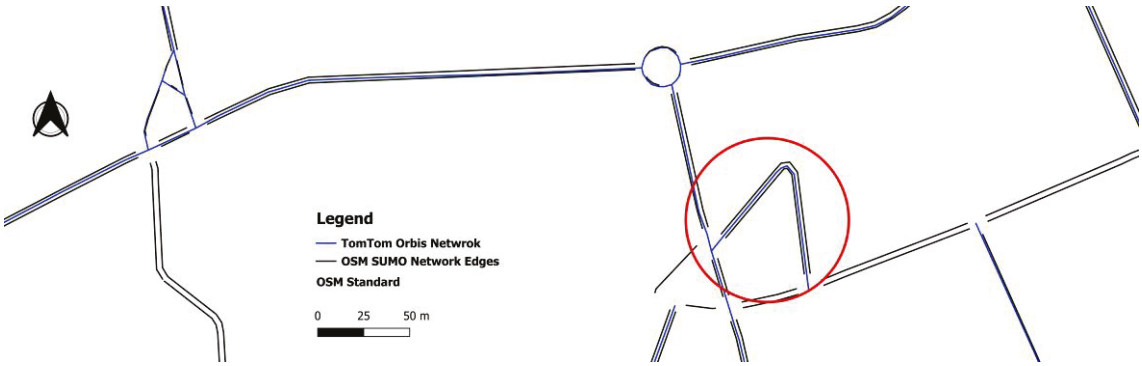


Figure 5. Example of geometric misalignment resulting in an unmatched edge due to directional filtering.

Further mismatches may occur near intersections or roundabouts, where the overlap-based filtering step may remove potential matches due to the relatively small overlap ratio between segments. Nevertheless, these cases typically occur on short or low-priority road segments and therefore have limited impact on the overall integration of the simulation network with traffic data.

Validation of Matching Results

To quantitatively assess the performance of the proposed methodology, a manual validation was conducted on all 360 simulation network edges. Each edge was evaluated by comparing the matched traffic segments with the true corresponding segments identified through visual inspection in QGIS. Validation was performed using the simulation network edges as the reference unit, as this represents the fixed structure required for simulation, while traffic data must be consistently integrated onto it.

For each edge, the numbers of true matches, detected matches, and correctly matched segments were recorded. Based on these values, performance metrics were computed, including precision and recall. Precision is defined as the ratio of correctly matched

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segments to the total number of detected matches, while recall represents the ratio of correctly matched segments to the total number of true segments.

The validation results indicate an overall precision of 97.8% and a recall of 96.2%, demonstrating that the proposed methodology achieves high accuracy in identifying relevant matches while maintaining a limited number of false and missing associations. In terms of edge-level accuracy, 346 out of 360 edges (96.1%) were correctly matched, while 3 edges (0.8%) were partially correct and 11 edges (3.1%) were incorrectly matched. These results confirm the robustness of the proposed approach.

A more detailed analysis shows that, out of 360 edges, 63 resulted in no match. Among these, 60 correspond to cases where no FCD data are available, while 2 are associated with directional filtering errors (Figure 5), in which valid segments were excluded due to angular differences greater than 45°. One additional case corresponds to a missing match in a roundabout due to offset-related geometric misalignment. Among the 257 one-to-one matches, 249 were correctly identified. The remaining cases include 2 false matches, where segments were incorrectly assigned despite low overlap but acceptable angular difference, and 6 missing matches, mainly occurring in roundabouts due to horizontal misalignment, lack of finer FCD segmentation, or offset-related discrepancies. For the 40 one-to-many matches, 37 were correctly identified. The remaining cases include 1 missing match, where one of the true segments was not captured due to geometric misalignment, and 2 cases affected by the overlap threshold, where valid segments were excluded because their overlap ratio was below the adopted threshold. Overall, 14 false matches were identified, including a small number of partially correct cases, while 8 edges showed inconsistencies between the number of detected and true matches.

The analysis of mismatches indicates that most errors are associated with missing matches rather than incorrect associations. These cases are primarily caused by geometric discrepancies between datasets, including horizontal misalignment, and, in a few cases, insufficient overlap or directional filtering effects. In particular, mismatches were observed near roundabouts and intersections, where differences in network representation and segmentation are more pronounced. Despite these localized issues, the high precision and recall values indicate that by the adopted thresholds and filtering criteria provide an acceptable matching performance for the integration of traffic data with the simulation network.

4.2. Application of Detector-Based Representation in Simulation

The detector-based representation introduced in Section 3.4 is applied to the integrated dataset to illustrate its use in handling multiple matches within the simulation environment. For simulation edges associated with multiple traffic segments, multiple detectors are placed along the same edge according to the spatial ordering defined during the matching process. This enables each segment to be represented individually within the simulation while preserving the original network structure.

This correspondence is illustrated in Figure 6, where multiple traffic segments mapped to a single edge are represented by multiple detectors, enabling segment-level comparison of traffic variables.

The same approach can also be extended to the entire network, enabling systematic monitoring of simulation outputs and facilitating direct comparison with observed traffic data. Additionally, detector-based measurements can be used as input for model calibration or traffic demand estimation, further enhancing the integration between simulation and observations.

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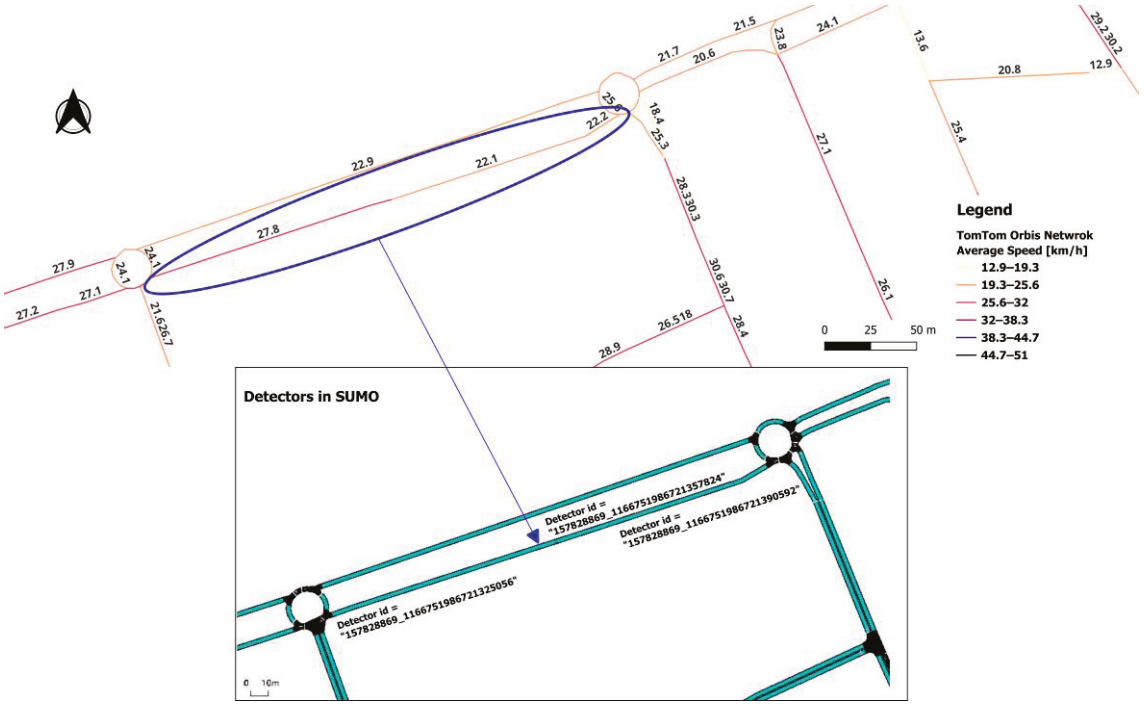


Figure 6. Example of multiple traffic segments corresponding to a single simulation edge and the associated placement of E2 detectors along the edge.

4.3. Transferability Analysis in an Additional Case Study

To further assess the transferability of the proposed methodology, an additional application was conducted in a different urban area located in the southwest of Turin, Italy, with a specific focus on the intersection of Corso Trapani and Corso Peschiera, including adjacent roads such as Via Frejus and Corso Racconigi (Figure 7). The traffic dataset was derived from the TomTom Traffic Stats platform [15], covering mainly primary roads and excluding minor and service roads, with the same structure described in Section 2.2. The objective of this additional application was to evaluate the applicability of the methodology across various locations.

As discussed in Sections 3.1 and 3.2, buffer and offset values can be adjusted depending on the geometric differences between datasets. Based on an initial visual inspection, the average lateral offset between networks was estimated, confirming that an offset value of 1.5 m is suitable for the traffic dataset in most cases. To increase the capture of candidate matches before the filtering stage, a buffer value of 6 m was applied to the simulation network edges.

The results show that, following the proposed methodology, the dataset was successfully integrated with the simulation network where traffic data were available, which in this case were limited to the main roads. As a result, out of 183 simulation edges from OSM, 135 simulation edges were not matched, while 48 edges were successfully associated with traffic segments. Among these, 28 correspond to one-to-one matches and 20 to one-to-many relationships, including cases with higher segmentation (up to six segments associated with a single simulation edge). These differences are primarily due to variations in data availability (as shown in Figure 7) and segmentation schemes between the traffic dataset and the simulation network. Despite these differences, the methodology consistently identified appropriate spatial correspondences between simulation network edges and traffic segments.

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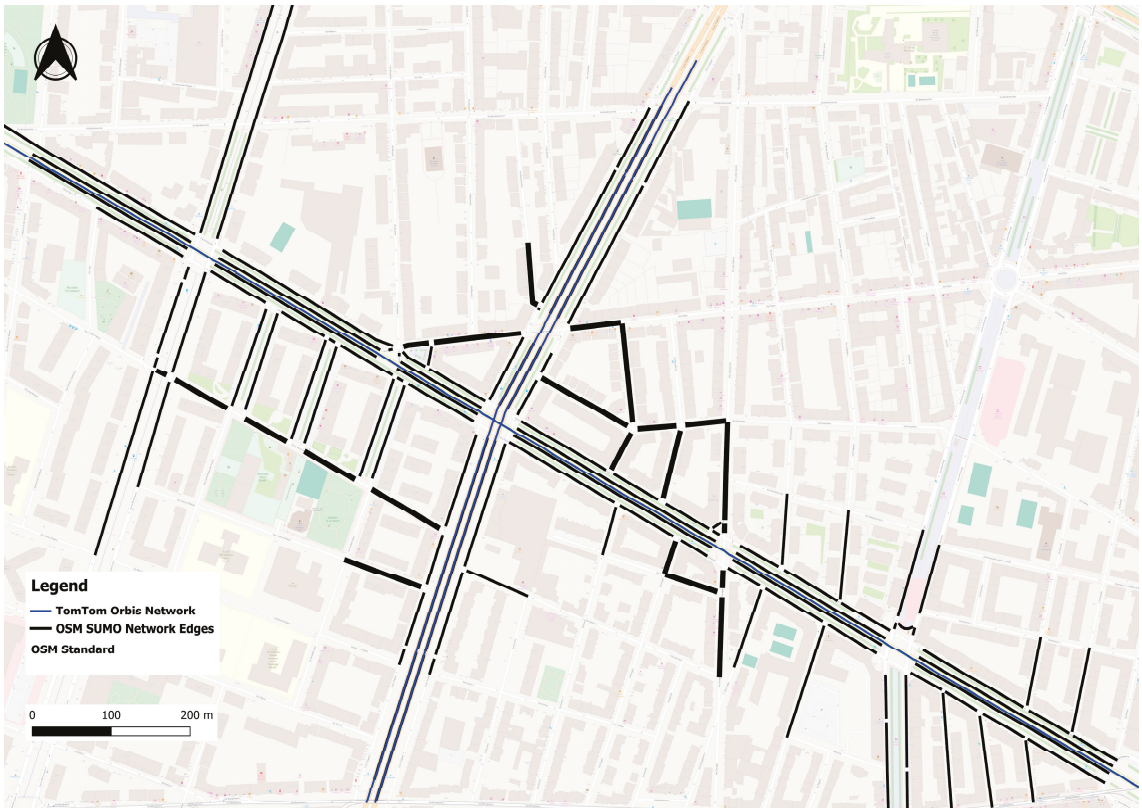


Figure 7. Overlay of simulation network edges and FCD traffic segments in the Turin case study.

Although this second case study is also based on an urban area, it presents a more complex network structure with dense intersections. The results demonstrate that the proposed framework can be applied across different locations. The methodology shows practical transferability, requiring only an initial approximation of buffer and offset parameters based on dataset characteristics, while maintaining robust matching performance.

4.4. Potential Applications

The integration of traffic information with the simulation network enables several practical applications for traffic modeling and simulation studies.

A first application is the correction and refinement of speed limits in the simulation network. Open-source data may contain inaccurate speed limit values that can affect simulation realism. For example, as shown in Table 1, an edge corresponding to OSM ID -1078137846 has a maximum speed of 27.78 m/s (100 km/h), which is unrealistic for a road located in the city center of Biella. However, the matched data indicate a speed limit of 30 km/h, derived from two associated segments. Updating these attributes with the integrated dataset can improve the network's accuracy before simulations.

Another application is the placement of traffic detectors in microscopic simulations. While Section 4.2 focuses on their role in representing multiple matched segments along a single edge, detectors can also be used more generally to monitor traffic conditions along network links [25]. These detectors function similarly to traffic monitoring devices, such as vehicle-tracking cameras, and measure indicators such as vehicle counts, speeds, queues, and congestion conditions. By using the matched segment information, detectors can be systematically placed along the simulation network's edges corresponding to traffic-monitoring locations. This enables the extraction of simulation outputs that are directly comparable with observed traffic data.

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Such integration also enables improved simulation validation procedures. In previous work, simulation validation was performed by manually selecting representative routes and comparing simulated average speeds with observed floating car data along those routes [6]. Although this approach provided useful insights into the overall simulation performance, the validation process remained limited to aggregated route-level comparisons and required manual selection of validation paths. However, with the integrated dataset produced by the proposed framework, validation can be performed systematically at the edge level, enabling comparison of simulated and observed traffic indicators such as speed and travel time for each matched segment and time interval. This increases the spatial resolution and robustness of the validation process.

Another potential application is the estimation and calibration of traffic demand. FCD datasets provide information on vehicle movements, speeds, and traffic density at a higher spatial resolution than traditional detector networks. As discussed by Veihelmann et al. [12], high-resolution probe counts can be integrated into microscopic traffic simulations by matching commercial traffic datasets with simulation networks and using the resulting traffic counts as constraints for demand generation and route sampling. In particular, segment-level traffic counts can support route sampling, O–D matrix calibration, and demand generation procedures, enabling the development of more realistic large-scale microscopic simulations.

Overall, the integration framework presented in this study provides a flexible basis for network calibration, detector placement, simulation validation, and traffic demand generation, facilitating the use of traffic data in simulation-based transport studies.

5. Conclusions

This study presented a GIS-based framework for integrating FCD traffic data with road networks used in traffic simulation models. The proposed methodology addresses a common challenge in transportation modeling: integrating heterogeneous datasets that represent the same road infrastructure using different segmentation schemes and without shared identifiers. By combining spatial analysis techniques within a GIS environment, the framework enables the association of traffic segments with a simulation network derived from open-source data.

The methodology consists of several sequential steps, including preprocessing of the simulation network and traffic data, spatial buffering, spatial joining, directional consistency filtering, overlap-based matching, and hierarchical cleaning of candidate matches. These procedures enable the identification of spatial relationships between the two datasets while minimizing false matches due to geometric differences or segmentation inconsistencies. The workflow is implemented using standard tools in QGIS, ensuring transparency, reproducibility, and applicability without requiring complex optimization or machine learning approaches.

The proposed framework was applied to a case study in the central area of Biella, Italy. Despite structural differences between the datasets, the matching process successfully associated more than 80% of the simulation network edges with corresponding FCD traffic segments. Most matches resulted in one-to-one relationships, while a smaller proportion reflected one-to-many associations due to finer segmentation in the traffic dataset. A quantitative validation conducted on all simulation network edges showed high matching accuracy, with overall precision and recall values of 97.8% and 96.2%, respectively. The analysis also showed that most mismatches were related to missing matches caused by geometric discrepancies near roundabouts, intersections, or curved road segments, rather than incorrect associations between unrelated segments.

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An additional case study conducted in a neighborhood in Turin further demonstrated the transferability of the proposed methodology across different study areas. Despite the more complex urban network structure, the methodology maintained robust matching performance, confirming that the directional and overlap-based filtering criteria are effective, while buffer and offset parameters can be adjusted according to dataset characteristics and geometric alignment conditions.

The resulting integrated dataset provides a structured link between edges modeled for simulation and traffic statistics. This enables the direct integration of hourly traffic indicators such as travel time, speed, traffic flow, and traffic variability into the simulation network. Such information can improve the reliability of traffic simulation models and support several practical applications. These include correcting network attributes such as speed limits, systematically placing traffic detectors within simulation environments, and validating simulation outputs against observed traffic data. Additionally, the framework facilitates the use of traffic observations as constraints for estimating and calibrating traffic demand in microscopic simulations.

Although the methodology demonstrated promising results, some limitations remain. Differences in network geometry, particularly near curved road segments or complex intersections, may lead to missing matches when directional thresholds or overlap criteria are applied. Furthermore, some roads in the simulation network may not be included in the traffic dataset, leading to unavoidable gaps in the integrated network. The adopted thresholds demonstrated robust performance in the presented applications; however, future research could further investigate adaptive or automated threshold selection procedures, additional geometric similarity indicators, or hybrid approaches combining GIS-based matching with machine learning techniques.

Overall, the study demonstrates that heterogeneous traffic datasets can be effectively integrated with simulation networks through a GIS-based workflow. The proposed framework offers a transferable approach for preparing enriched traffic simulation models by taking advantage of big-data traffic platforms. This can support transportation planning processes oriented toward sustainable mobility actions, which in some cases may generate side effects that should be predicted in advance to better manage the application of traffic control strategies and mobility management measures.

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References

1. Lopez, P.A.; Wiessner, E.; Behrisch, M.; Bieker-Walz, L.; Erdmann, J.; Flotterod, Y.-P.; Hilbrich, R.; Lucken, L.; Rummel, J.; Wagner, P. Microscopic Traffic Simulation Using SUMO. In *Proceedings of the 2018 21st International Conference on Intelligent Transportation Systems (ITSC), Maui, HI, USA, 4–7 November 2018*; IEEE: Piscataway, NJ, USA, 2018; pp. 2575–2582.
2. Sheng, W.; Liu, K.; Jia, D.; Zhou, J.; Wang, Z.; Wang, C.; Li, X.; Feng, Y. A Multi Scenario Simulation Study on the Systemic Benefits of Fleet Electrification for Urban Sustainability in Shanghai. *Sustainability* **2026**, *18*, 4077. [CrossRef]
3. Jo, H.; Kim, H. Developing a Traffic Model to Estimate Vehicle Emissions: An Application in Seoul, Korea. *Sustainability* **2021**, *13*, 9761. [CrossRef]
4. Rossi, R.; Ceccato, R.; Gastaldi, M. Effect of Road Traffic on Air Pollution. Experimental Evidence from COVID-19 Lockdown. *Sustainability* **2020**, *12*, 8984. [CrossRef]
5. Shahdani, F.J.; Santamaria-Ariza, M.; Sousa, H.S.; Coelho, M.; Matos, J.C. Assessing Flood Indirect Impacts on Road Transport Networks Applying Mesoscopic Traffic Modelling: The Case Study of Santarém, Portugal. *Appl. Sci.* **2022**, *12*, 3076. [CrossRef]
6. Charlang Bakhtyari, A.; Carboni, A.; Deflorio, F.; Ferraro, M.; Sica, L. Impact Assessment on Spatial Connectivity and Simulation of Traffic Flows under Flood-Related Road Network Disruptions. *Sustain. Cities Soc.* **2025**, *135*, 107003. [CrossRef]
7. Aghababaei, M.; Costello, S.B.; Ranjitkar, P. Transportation Impact Assessment Following a Potential Alpine Fault Earthquake in New Zealand. *Transp. Res. Part D Transp. Environ.* **2020**, *87*, 102511. [CrossRef]
8. Rapelli, M.; Casetti, C.; Gagliardi, G. Vehicular Traffic Simulation in the City of Turin From Raw Data. *IEEE Trans. Mob. Comput.* **2022**, *21*, 4656–4666. [CrossRef]
9. Wang, S.; Djahel, S.; McManis, J. An Adaptive and VANETs-Based Next Road Re-Routing System for Unexpected Urban Traffic Congestion Avoidance. In *Proceedings of the 2015 IEEE Vehicular Networking Conference (VNC), Kyoto, Japan, 16–18 December 2015*; IEEE: Piscataway, NJ, USA, 2015; pp. 196–203.
10. He, K.; Carhart, N.; Pregnolato, M.; De Risi, R. Flood-Induced Traffic Congestion and Accessibility Loss for Urban Road Networks Using Agent-Based Simulation: The Case Study of Bristol, UK. *Int. J. Disaster Risk Reduct.* **2026**, *136*, 106053. [CrossRef]
11. Rapelli, M.; Casetti, C.; Gagliardi, G. TuST: From Raw Data to Vehicular Traffic Simulation in Turin. In *Proceedings of the 2019 IEEE/ACM 23rd International Symposium on Distributed Simulation and Real Time Applications (DS-RT), Cosenza, Italy, 7–9 October 2019*; IEEE: Piscataway, NJ, USA, 2019; pp. 1–8.
12. Veihelmann, T.; Shatov, V.; Lübke, M.; Franchi, N. Using Probe Counts to Provide High-Resolution Detector Data for a Microscopic Traffic Simulation. *Vehicles* **2024**, *6*, 747–764. [CrossRef]
13. Dabbas, H.; Fourati, W.; Friedrich, B. Floating Car Data for Traffic Demand Estimation-Field and Simulation Studies. In *Proceedings of the 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC), Rhodes, Greece, 20–23 September 2020*; IEEE: Piscataway, NJ, USA, 2020; pp. 1–8.
14. Zhang, Y.; Zuo, X.; Zhang, L.; Chen, Z. Traffic Congestion Detection Based On GPS Floating-Car Data. *Procedia Eng.* **2011**, *15*, 5541–5546. [CrossRef]
15. Tom Tom MOVE. Available online: https://move.tomtom.com/ (accessed on 22 July 2025).
16. Salvo, G.; Karakikes, I.; Papaioannou, G.; Polydoropoulou, A.; Sanfilippo, L.; Brignone, A. Enhancing Urban Resilience: Managing Flood-Induced Disruptions in Road Networks. *Transp. Res. Interdiscip. Perspect.* **2025**, *31*, 101383. [CrossRef]
17. Kumar, K.D.; Anitha, M.L.; Veena, M.N. Real-Time Bengaluru City Traffic Congestion Prediction Using Deep Learning Models. *Int. J. Transp. Dev. Integr.* **2025**, *9*, 619–628. [CrossRef]
18. Guo, Q.; Xu, X.; Wang, Y.; Liu, J. Combined Matching Approach of Road Networks Under Different Scales Considering Constraints of Cartographic Generalization. *IEEE Access* **2020**, *8*, 944–956. [CrossRef]
19. Hacar, M.; Gökgöz, T. A New Approach for Matching Road Lines Using Efficiency Rates of Similarity Measures. *Int. J. Eng. Geosci.* **2021**, *6*, 146–156. [CrossRef]
20. Wu, H.; Xu, S.; Huang, S.; Wang, J.; Yang, X.; Liu, C.; Zhang, Y. Optimal Road Matching by Relaxation to Min-Cost Network Flow. *Int. J. Appl. Earth Obs. Geoinf.* **2022**, *114*, 103057. [CrossRef]
21. Zuo, Z.; Yang, L.; An, X.; Zhen, W.; Qian, H.; Dai, S. A Hierarchical Matching Method for Vectorial Road Networks Using Delaunay Triangulation. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 509. [CrossRef]
22. Hackeloeer, A.; Klasing, K.; Krisp, J.M.; Meng, L. Road Network Conflation: An Iterative Hierarchical Approach. In *Progress in Location-Based Services 2014*; Gartner, G., Huang, H., Eds.; Lecture Notes in Geoinformation and Cartography; Springer International Publishing: Cham, Switzerland, 2015; pp. 137–151. ISBN 978-3-319-11878-9.
23. Zhang, M.; Yao, W.; Meng, L. Automatic and Accurate Conflation of Different Road-Network Vector Data towards Multi-Modal Navigation. *ISPRS Int. J. Geo-Inf.* **2016**, *5*, 68. [CrossRef]

24. Hootenanny. Available online: https://github.com/ngageoint/hootenanny (accessed on 9 December 2025).
25. SUMO. Lanearea Detectors (E2). Available online: https://sumo.dlr.de/docs/Simulation/Output/Lanearea_Detectors_%28E2%29.html (accessed on 9 December 2025).

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Spatiotemporal Dynamics of Urban Expansion and the Thermal Environment: Implications for Sustainable Development in the Yellow River Basin

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Abstract

Rapid urbanization in the Yellow River Basin intensifies the conflict between urban expansion and the thermal environment, threatening ecological security and sustainable development. Utilizing multi-source data (2000–2023) including nighttime light (NTL) and land surface temperature (LST), this study applies spatial analysis and Geographically Weighted Regression (GWR) to explore the spatial associations between urban development and LST and its drivers across core cities. The results indicate significant spatiotemporal differentiation: mid-downstream cities exhibited contiguous urban expansion, whereas upstream growth remained constrained by local topography, with heat islands consistently concentrating in built-up areas. The warming rate decreased gradually from downstream (0.29–0.40 °C/year) to upstream (0.20–0.30 °C/year). The LST-NTL correlation strengthened notably in mid-downstream regions but remained moderate upstream. GWR analysis revealed that urban development intensity, represented by NTL, is the primary driver of LST increase downstream, while natural factors predominantly mitigate warming upstream. This long-term, multi-city comparison provides a scientific basis for precise urban heat island management and sustainable planning in the basin.

Keywords: Mann–Kendall non-parametric test; nighttime light; Sen's slope; spatial autocorrelation; land surface temperature; urban development

1. Introduction

Against the backdrop of the synergistic advancement of global sustainable development agendas and regional strategies, the implementation paths of UN SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action) [1], together with China's national strategy for ecological preservation and high-quality development in the Yellow River Basin [2], collectively impose urgent requirements for the regulation of urban thermal environments and the construction of ecological security patterns. The rapid pace of global urbanization has led to increased LST and heat island effects, which pose significant ecological challenges to regional sustainable development [3]. LST serves as a crucial indicator of the thermal environment, demonstrating spatiotemporal variations that are fundamentally associated with the intensity of urban development, land surface characteristics, and

natural conditions [4–6]. These variations significantly influence ecological functions [7,8], human comfort [9], and climate regulation [10,11]. Thus, revealing the spatial interaction mechanisms between LST and heat island effects has become a significant research focus in geography and urban ecology, offering a scientific foundation for urban development strategies that achieve the coexistence of human and natural systems.

International research commenced in the 19th century with the initial observation that metropolitan temperatures surpass those in suburban areas [12]. During the 20th century, it increasingly depended on Landsat satellite thermal infrared data for the quantitative inversion of LST [13,14]. Previous studies predominantly relied on single-dimensional metrics, such as developed land or impermeable surfaces, to quantify urban expansion [15–17]. However, the full impacts of urban development are not captured by this narrow perspective. Consequently, since the start of the twenty-first century, the utilization of NTL data has transcended these limitations. Because NTL data strongly correlates with human activity, it enables a multidimensional quantification of urbanization, encompassing economic, demographic [18–20], and land intensities [21–23]. Rather than merely tracking the physical footprint of built-up areas, this approach captures the true multifaceted essence of urban growth. In China, early thermal environment studies relied predominantly on isolated meteorological stations [24,25]. Since then, the discipline has broadened to encompass urban agglomeration scales by utilizing multi-source remote sensing data [26–28], incorporating methodologies such as GWR to clarify spatial heterogeneity [29–31]. Contemporary research now concentrates on examining the spatial response patterns and driving mechanisms of LST. Despite growing interest, the existing body of research on the core cities of the Yellow River Basin exhibits considerable limitations. Studies frequently focus exclusively on the immediate thermal conditions of specific cities in isolation [32] or merely treat LST as an auxiliary factor in ecological assessments [33,34]. To understand the full spatial dynamics of the region, these cities must be compared collectively. As the principal political and economic centers of the basin, they share common watershed ecological constraints and exhibit significant geographical and ecological interdependence along the river network. Furthermore, the national strategy for ecological preservation and high-quality development in the Yellow River Basin strongly emphasizes their coordinated governance and sustainable urban growth [3]. Comparing these primary administrative hubs along the basin gradient provides a necessary and unified scientific foundation for regional thermal environment management under these shared ecological and policy frameworks.

Urban development is fundamentally a multifaceted process encompassing population aggregation, economic concentration, and land transformation. Because a single metric cannot comprehensively capture these dynamic spatial changes, early research relying on singular indicators faced significant constraints: impervious surfaces only reflect physical land alteration, population statistics suffer from unit discrepancies, and economic data are difficult to spatialize. To overcome this, satellite-derived NTL data has emerged as a superior proxy, capable of comprehensively representing urban vitality at the grid scale [35,36]. Its pixel values have substantial connections with metrics like economic density, population density, and urban development levels [18,22]. While researchers have widely utilized NTL data to investigate urban development and LST correlations at various administrative levels, a critical gap remains. The existing literature has rarely examined the comparative heterogeneity of these connections across core cities in the upper, middle, and lower reaches of the Yellow River over an extended period from 2000 to 2023. Neglecting this watershed-scale gradient obscures the distinctive associative qualities of different river segments. Therefore, this study amalgamates NTL and land use data to quantify long-term urban development processes, establishing a robust platform for further LST correlation analysis and mechanism interpretation.

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The current study has established a core framework that includes data collection, indicator measurement, connection analysis, and mechanism interpretation to evaluate the interactions between urban development and Land Surface Temperature (LST) in the Yellow River Basin from 2000 to 2023. Within this framework, we utilized three primary methods: First, the Sen + Mann–Kendall (MK) test [31,37] identifies long-term temporal trends and critical shifts in the thermal environment. Second, the Standard Deviation Ellipse (SDE) [38] is applied to track the spatial dynamics of urban development and the thermal environment. By analyzing the distribution centers and dominant expansion directions of NTL and LST, this method visually demonstrates whether their spatial evolutions are synchronous and coordinated. Finally, a Geographically Weighted Regression (GWR) model [39] incorporates NTL and Digital Elevation Model (DEM) data to quantify the spatial heterogeneity and localized driving forces of LST. By seamlessly integrating these techniques, this approach offers robust support for tackling critical inquiries: "How does urban development affect LST? What are the distinguishing factors among different categories of core cities?" This methodology ensures the accuracy and methodical quality of the study findings.

To address the aforementioned limitations, this study selects the core cities of the Yellow River Basin as the research area. The specific research objectives are: (1) to clarify the spatiotemporal correlation characteristics between urban development and LST from 2000 to 2023; (2) to identify the spatial drivers of urban development and LST within the basin; and (3) to develop gradient-based optimization strategies for thermal environment management. By achieving these objectives, this study provides a vital scientific foundation for understanding urban–thermal environment interactions in temperate semi-arid and semi-humid watersheds. More importantly, it directly supports China's national strategy, the "Outline of Ecological Conservation and High-Quality Development in the Yellow River Basin" [40], by offering precise, watershed-specific guidance for reconciling rapid urban expansion with regional ecological security.

2. Materials and Methods

2.1. Introduction to the Study Area

The core cities of the Yellow River Basin consist of seven urban centers: Jinan in Shandong Province and Zhengzhou in Henan Province in the lower reaches; Taiyuan in Shanxi Province and Xi'an in Shaanxi Province in the middle reaches; and Lanzhou in Gansu Province, Yinchuan in Ningxia Hui Autonomous Region, and Xining in Qinghai Province in the upper reaches (Figure 1). Geographically, they are strategically distributed across all flow sections, perfectly capturing the complete spatial gradient and diverse topographical conditions of the entire watershed.

These seven cities were defined and selected as the core cities primarily due to their critical administrative levels, immense economic contributions, and substantial population sizes. As provincial or regional capitals, they function as the principal implementation areas for the national strategy of ecological conservation and high-quality development in the Yellow River Basin [40], serving as its absolute political, economic, and cultural centers. They act as crucial hubs linking industrial, demographic, and resource components throughout eastern, central, and western China. As of 2023, these cities collectively concentrate a permanent population of over 50.79 million and generate a total Gross Regional Product exceeding 5 trillion yuan, representing the most significant demographic and economic concentration within the basin.

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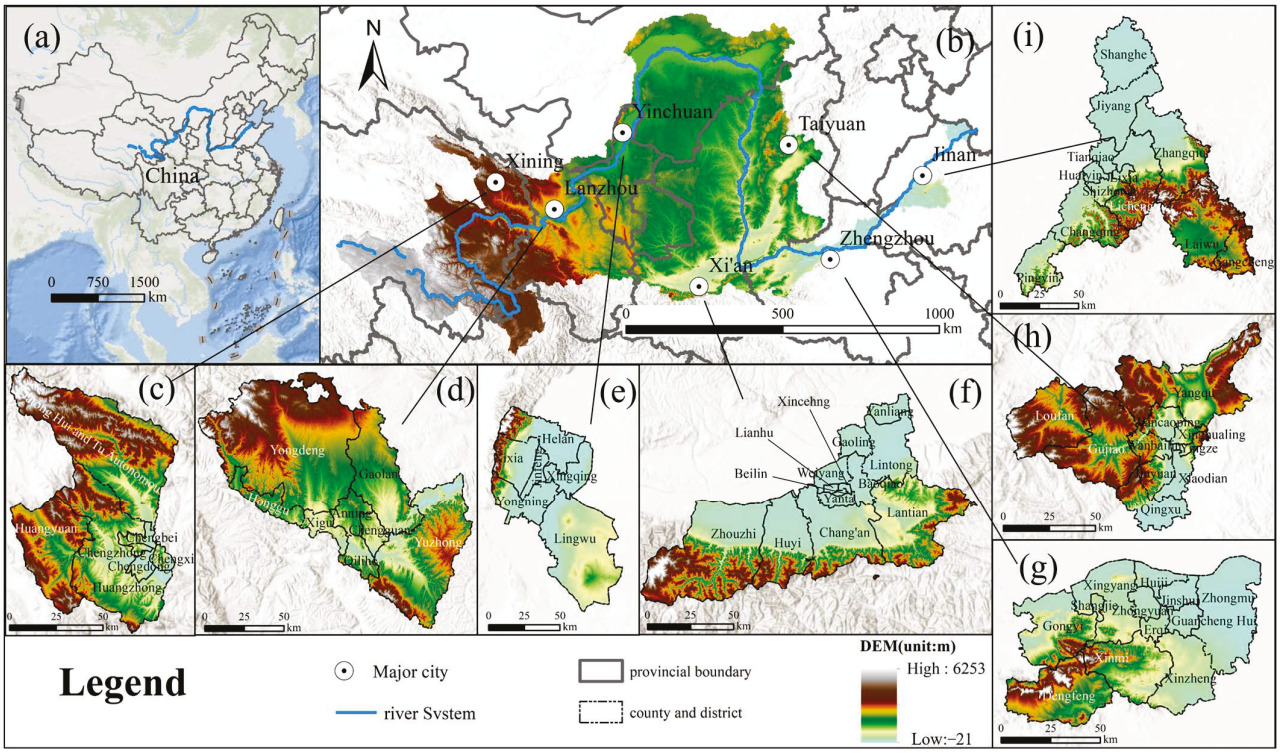


Figure 1. Overview of the study area (seven core cities in the Yellow River Basin). (**a**) location of the Yellow River Basin in China; (**b**) elevation of the Yellow River Basin; (**c**) Xining; (**d**) Lanzhou; (**e**) Yinchuan; (**f**) Xi'an; (**g**) Zhengzhou; (**h**) Taiyuan; (**i**) Jinan. Note: This map is drawn based on the standard map of the Map Technology Review Center of the Ministry of Natural Resources (Map Review No.: GS (2023)2767). The boundary of the base map remains unchanged, and the same applies hereinafter).

2.2. Data Sources

(1) For summer LST, the 8-day LST product (MOD11A2, Collection 6.1) from the MODIS sensor on the Terra satellite was selected. The research was conducted from 2000 to 2023 to ensure data stability, with summer defined as June to August. For the calculation of the summer mean LST, 11 to 12 eight-day composite images were integrated per year; specifically, 11 images were used for the year 2001, and 12 images for all other years. Data processing was performed on the Google Earth Engine (GEE) platform https://earthengine.google.com (accessed on 6 January 2026). To ensure high data quality, the Quality Control (QC) bands—namely, QC_Day and QC_Night—were strictly utilized. By extracting Bits 0–1, which serve as the Mandatory QA flags, pixels affected by cloud contamination or categorized as poor quality were masked out. Following this QA filtering, a valid physical threshold mask between −50 °C and 70 °C was applied to eliminate any remaining extreme outliers. Furthermore, to address data gaps often observed in glacial or persistent cloud-covered areas, a 3 × 3 pixel focal mean interpolation was implemented for spatial completion before computing the final summer average LST.

(2) Land use data were acquired from the 30 m spatial resolution dataset supplied by the Resource and Environment Science and Data Center of the Chinese Academy of Sciences. The national categorization framework's basic system was employed to classify land use types in the research region into cropland, woodland, grassland, water bodies, built-up land, and unused land.

(3) NTL statistics were obtained from the United States National Geophysical Data Center (NGDC) and the Earth Observation Group (EOG), spanning from 2000 to 2023. A

systematic preparation workflow was initially executed on the raw data. This entailed fusion-based denoising to eliminate artifacts from moonlight, cloud shadows, and incidental light sources; spatial clipping utilizing the study area's vector boundary; and radiometric correction to standardize the data. Integrating DMSP–OLS and NPP–VIIRS datasets presents two primary challenges: the intrinsic pixel saturation of DMSP-OLS in metropolitan centers, and the systematic scale gap between the dimensionless DMSP–OLS data and the radiometrically calibrated NPP–VIIRS data.

To address the first challenge, this study utilizes current research [41,42] and implements the Vegetation-Adjusted NTL Index (VANUI) to desaturate DMSP/OLS data from 2000 to 2013 for successful data integration. The particular formula is as follows:

$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}} \quad (1)$$

$$\text{VANUI} = 1 - \text{NDVI} \times \text{NTL}_{\text{Nor}} \quad (2)$$

In the formula, NDVI signifies the Normalized Difference Vegetation Index; NTL_{Nor} denotes the normalized DMSP/OLS NTL pixel values; and VANUI indicates the desaturated NTL index value.

Furthermore, to address the second challenge and achieve seamless longitudinal integration between the two different sensors, a rigorous cross-sensor calibration was conducted on the GEE platform. Concurrent observation samples were extracted across the study area by pairing the 2013 VANUI-corrected DMSP–OLS with the initial 2014 NPP–VIIRS data. A second-degree polynomial regression model was established (R^2 = 0.7086) to translate the NPP–VIIRS radiance values into the simulated DMSP–OLS scale. The derived calibration formula is expressed as:

$$DMSP_{simulated} = -0.000464 \times VIIRS^2 + 0.040489 \times VIIRS + 0.131988 \quad (3)$$

By applying this robust calibration model to the 2015 and 2023 NPP–VIIRS data, a highly consistent and comparable long-term NTL time-series dataset (2000–2023) was successfully synthesized. To ensure data continuity, temporal consistency tests were conducted across consecutive study periods. The correlation coefficients for the paired datasets all surpass 0.84, with each connection being statistically significant at the 0.01 level (Table 1). Furthermore, a first-order autoregressive (AR(1)) test confirmed the temporal stability of the integrated series, with lag-1 coefficients for all seven core cities ranging from 0.844 to 0.883 ($p < 0.01$). The aforementioned results demonstrate that the combined desaturation and cross-calibration processing successfully eradicated saturation bias and scale discrepancies, rendering the dataset appropriate for long-term time series research.

Table 1. Temporal consistency verification of NTL data across consecutive study nodes (2000–2023).

Compared Years	Data Type Compared	Correlation Coefficient (R)
2000, 2005	DMSP (VANUI)–DMSP (VANUI)	0.920091679422431 **
2005, 2010	DMSP (VANUI)–DMSP (VANUI)	0.919862933686646 **
2010, 2015	DMSP (VANUI)–NPP–VIIRS (Simulated)	0.847876885335112 **
2015, 2023	NPP–VIIRS (Simulated)–NPP–VIIRS (Simulated)	0.854683595140872 **

Note: ** indicates significance at the $p < 0.01$ level.

(4) Socio-economic data, including the permanent resident population, urbanization rate, and Gross Domestic Product (GDP) for the core cities in the Yellow River Basin, were employed in this study. All data were obtained from officially published local statistical yearbooks (e.g., Jinan Statistical Yearbook 2024, Xining Statistical Yearbook

2024, Gansu Statistical Yearbook 2024) compiled by the respective administrative units and released by China Statistics Press. These official statistics are characterized by high completeness and reliability. To quantitatively validate the effectiveness of NTL as a proxy for urban development intensity in this specific basin, a Pearson correlation analysis was conducted, and the highly significant positive correlations between total NTL and these socio-economic metrics are detailed in Appendix A (Table A1).

2.3. Research Methods

2.3.1. Data Preprocessing and Classification of Land Surface Temperature Levels

To address inconsistencies in spatial resolution and units across multi-source raster data and uphold the scientific rigor and consistency of subsequent spatial analyses, thorough preprocessing was conducted on the core data used in the study. Taking into account the size attributes of the Yellow River Basin and the study aim regarding urban–thermal environment interactions, a target resolution of 1 km × 1 km was established, ensuring a balance between data preservation and computing performance. All raster data were standardized with the resampling tool in ArcGIS 10.8 to achieve a consistent scale. Bilinear interpolation was utilized for upscaling NTL data to preserve the numerical continuity of NTL values and appropriately represent the gradual fluctuations in human activity intensity. The mean resampling approach was utilized for LST data to reduce the impact of individual outliers on regional temperature attributes. Mean resampling was utilized to downscale both digital elevation models and land use data. This method harmonized terrain detail with the retention of surface information while attaining congruence with the desired resolution. After resampling, spatial consistency tests were performed to ensure that the data accuracy satisfied the criteria for further analysis.

We adopted the "grid sampling–multi–value extraction" approach from previous studies to generate standardized spatial analysis units. Utilizing administrative boundary vector data from seven cities within the Yellow River watershed, we produced a 1 km × 1 km regular grid employing the grid generation feature of ArcGIS 10.8. The grid vertices were subsequently transformed into sample points. Thereafter, the pixel values of the resampled NTL, LST, DEM, and land use raster data were spatially linked to their corresponding grid sampling points, creating a one-to-one sample dataset. This offers a cohesive fundamental sample unit for future analysis, including Sen + MK trend tests, bivariate spatial autocorrelation, and GWR.

The substantial variations in core variable dimensions, together with inconsistencies from multi-source sensors and multi-phase climatic changes, diminish data comparability and undermine the credibility of multivariate modeling or spatiotemporal dynamic analyses.

$$v_{norm} = \frac{v - v_{min}}{v_{max} - v_{min}} \quad (4)$$

In the formula, v denotes any data point in the original dataset (radiation values for NTL or temperature values for LST); v_{min} signifies the minimum value in the original dataset; v_{max} indicates the maximum value in the original dataset; v_{norm} represents the normalized result, with a value range of [0, 1].

2.3.2. The Classification of Land Surface Temperature Levels

The research region was categorized into five thermal zones based on LST using the mean-standard deviation method [43]: high-temperature zone, sub-high-temperature zone, medium-temperature zone, sub-low-temperature zone, and low-temperature zone [37]. The high-temperature and sub-high-temperature areas were designated as heat island zones. Table 2 presents the specific categorization criteria.

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Table 2. LST classification criteria and value interval.

	Low Temperature Zone	Sub-Low Temperature Zone	Medium Temperature Zone	Sub-High Temperature Zone	High Temperature Zone
formula	$T < \mu - 1.5$ std	$\mu - 1.5$ std $\leq T < \mu - 0.5$ std	$\mu - 0.5$ std $\leq T < \mu + 0.5$ std	$\mu + 0.5$ std $\leq T < \mu + 1.5$ std	$T > \mu + 1.5$ std
summer	$T < 23.09$	$23.09 \leq T < 26.24$	$26.24 \leq T < 32.52$	$32.52 \leq T < 25.66$	$T > 35.66$

2.3.3. Theil–Sen Median Trend Analysis and Mann–Kendall Test

The Sen + MK trend test is a non-parametric statistical technique employed to identify trend alterations [44] in time series data. This work employs this approach to examine LST trends in the Yellow River watershed from 2000 to 2023, thereby enabling the detection of long-term alterations in urban development and LST.

Employing Sen's slope analysis to assess LST changes in the Yellow River watershed during the last twenty years:

$$\beta = \text{median}\left(\frac{x_j - x_i}{j - i}\right), \; j > i \tag{5}$$

In the formula, using LST as an example, x_i and x_i denote the sequence values for indices I and j, respectively, where $2000 \leq i < j \leq 2023$. A positive β signifies an elevation in LST, whereas a negative β denotes a reduction. This approach has benefits over parametric statistics since it accommodates missing values in time series data and does not necessitate adherence to any particular distribution. The Mann–Kendall (MK) test assesses the importance of trends in variation. The computation can be articulated as follows: For a series of numbers $x_i = (x_1, x_2, \ldots, x_n)$, the statistic S is computed as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i) \tag{6}$$

$$\text{sgn}(x_i - x_j) = \begin{cases} 1, \; x_j - x_i > 0 \\ 0, \; x_j - x_i = 0 \\ -1, \; x_j - x_i < 0 \end{cases} \tag{7}$$

In the formula, x_i and c represent the sequence values of I and j, respectively. When $n \geq 10$, the statistical value S approximates a normal distribution, and the Z-value can be used for trend testing:

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}, \; S > 0 \\ 0, \; S = 0 \\ \frac{S-1}{\sqrt{VAR(S)}}, \; S < 0 \end{cases} \tag{8}$$

$$VAR(S) = \frac{n(n-1)(2n+5)}{18} \tag{9}$$

In the formula, n denotes the quantity of data points in the series, whereas the statistical value Z varies from $(-\infty, +\infty)$. At a certain significance level α, when $|Z| > u_{1-\alpha/2}$, it signifies that the sequence demonstrates substantial variance at the α level. This study utilized $\alpha = 0.05$ and $\alpha = 0.01$. According to trend analysis and statistical test outcomes, the variations in each variable are categorized into three levels: (1) Significant Decrease (Slope < 0, $p < 0.05$); (2) Non-Significant Change (Slope < 0 and Slope > 0, $p > 0.05$); (3) Significant Increase (Slope > 0, $0.01 < p < 0.05$).

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2.3.4. Standard Deviation Ellipse

The standard deviation ellipse (SDE) is a technique employed to delineate geographical distribution patterns. Calculating parameters such as the ellipse's center, major axis, minor axis, and azimuth elucidates characteristics like the geographical distribution center, range, and directional trends of elements [37]. This study creates a two-dimensional scatter plot utilizing the grid pixels of NTL on the *x*-axis and LST on the *y*-axis. Employing standard deviation ellipses to delineate substantially grouped scatter zones, thoroughly elucidating the association between NTL and LST.

$$\mathrm{P} = \left(\sqrt{\frac{\sum_{\mathrm{i}=1}^{n} \mathrm{x}_{\mathrm{i}}'}{n}}, \sqrt{\frac{\sum_{\mathrm{i}=1}^{n} \mathrm{y}_{\mathrm{i}}'}{n}} \right) \tag{10}$$

$$\mathrm{R} = \arctan\left(\frac{\sum_{\mathrm{i}=1}^{n} \mathrm{x}_{\mathrm{i}}'^2 - \sum_{\mathrm{i}=1}^{n} \mathrm{y}_{\mathrm{i}}'^2 + \sqrt{\left(\sum_{\mathrm{i}=1}^{n} \mathrm{x}_{\mathrm{i}}'^2 - \sum_{\mathrm{i}=1}^{n} \mathrm{y}_{\mathrm{i}}'^2\right) + 4\left(\sum_{\mathrm{i}=1}^{n} \mathrm{x}_{\mathrm{i}}' \mathrm{y}_{\mathrm{i}}'\right)^2}}{2\sum_{\mathrm{i}=1}^{n} \mathrm{x}_{\mathrm{i}}' \mathrm{y}_{\mathrm{i}}'} \right) \times \pi \tag{11}$$

$$\mathrm{D} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{n} \left(\mathrm{x}_{\mathrm{i}}' \cos \mathrm{R} - \mathrm{y}_{\mathrm{i}}' \sin \mathrm{R}\right)^2}{\sum_{\mathrm{i}=1}^{n} \left(\mathrm{x}_{\mathrm{i}}' \sin \mathrm{R} - \mathrm{y}_{\mathrm{i}}' \cos \mathrm{R}\right)^2}} \tag{12}$$

$$\mathrm{S} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{n} \left(\mathrm{x}_{\mathrm{i}}' \cos \mathrm{R} - \mathrm{y}_{\mathrm{i}}' \sin \mathrm{R}\right)^2}{n}} \tag{13}$$

In the formula, P signifies the center coordinates of the standard deviation ellipse; x_{i}' and y_{i}' denote the coordinates of the NTL and LST two-dimensional scatter points I, respectively; n represents the total number of scatter points; R indicates the direction angle of the standard deviation ellipse, illustrating the predominant direction of the two-dimensional scatter distribution. The sensitivity of LST to NTL response is evident: a lower value corresponds to a steeper slope in the scatter distribution, signifying that a one-unit increase in NTL leads to a more substantial rise in LST. D serves as the indicator of directionality; a greater value signifies a more pronounced directionality in the distribution of the scatter plot. S serves as the dispersion indicator; a larger value signifies an increased degree of dispersion in the scatter plot.

2.3.5. Bivariate Spatial Autocorrelation

Bivariate spatial autocorrelation analyzes geographical correlations between two variables, including both global and local spatial autocorrelation [45]. The global bivariate Moran's I index evaluates the spatial correlation between two variables over the whole research region. The Local Index of Spatial Autocorrelation (LISA) identifies spatial connection patterns between two variables in localized areas, including high–high clustering, low–low clustering, high–low clustering, and low–high clustering. This work utilizes GeoDa (version 1.22.0.21) to compute the bivariate spatial autocorrelation indices between urban development and LST in the Yellow River Basin, with the objective of examining their geographical correlation features.

$$I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(y_i - \overline{y})}{S^2 \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}} \tag{14}$$

In the formula, I signifies the bivariate global spatial autocorrelation index, indicating the overall spatial correlation between variables x and y; n represents the total number of spatial units; W_{ij} is the spatial weight matrix formulated via the K-nearest neighbor

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method; x_i and y_i denote the observed values of the independent and dependent variables in spatial units I and j, respectively; S^2 is the variance of all samples.

The calculation method for the Bivariate Local Moran's I is as follows:

$$I_i = z_i \sum_{j=1}^{n} w_{ij} z_j \quad (15)$$

In the formula, I_i denotes the local spatial connection between the independent and dependent variables in spatial unit i; z_i and z_j indicate the variance-standardized values of the observed data in spatial units i and j, respectively. Four clustering patterns may be inferred from I_i. The LISA (Local Indications of Spatial Association) distribution map graphically represents the clustering and differentiation characteristics of independent and dependent variables in localized regions. Clustering patterns can be classified into four categories: HH (High–High) clustering, where spatial unit i displays a high value of the independent variable and neighboring unit j shows a high value of the dependent variable; LL (Low–Low) clustering, where spatial unit i exhibits a low value of the independent variable and neighboring unit j also exhibits a low value of the dependent variable; LH (Low–High) clustering, where spatial unit i has a low value of the independent variable while neighboring unit j has a high value of the dependent variable; and HL (High–Low) clustering, where spatial unit i possesses a high value of the independent variable while neighboring unit j has a low value of the dependent variable.

2.3.6. Geographically Weighted Regression Model

Geographically Weighted Regression (GWR) is a localized spatial analytic technique aimed at accurately identifying diverse attributes within spatial data connections [46]. GWR enhances conventional global regression methods by including geographic location data into the regression framework, yielding localized parameter estimates for specific spatial units. The formula for calculation is as follows:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{n} \beta_k(u_i, v_i) x_{ik} + \varepsilon_i \quad (16)$$

In the formula, u_i represents the longitude of the sample point, v_i signifies the latitude of the sample point, x_{ik} indicates the kth independent variable at (u_i, v_i) among n independent variables; $\beta_0(u_i, v_i)$ and $\beta_k(u_i, v_i)$ represent the intercept term and the regression coefficient of x_{ik}, respectively; y_i and ε_i denote the observed value and the random error term at (u_i, v_i), respectively. A GIS-based spatial regression analysis addressing geographical heterogeneity was employed, utilizing the GWR model with a fixed kernel function and AICc-optimized bandwidth.

Nighttime light, Digital Elevation Model, and Slope were selected as explanatory variables to capture the interaction between anthropogenic drivers and natural constraints. Nighttime light quantifies socioeconomic intensity and human-induced heat emissions [47]. Digital Elevation Model and Slope represent fundamental topographical constraints that govern local atmospheric diffusion and dictate urban expansion patterns [48].

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3. Results

3.1. Analysis of the Spatiotemporal Characteristics of Urban Development and Land Surface Temperature

3.1.1. Spatial and Temporal Distribution Patterns of Urban Development and Thermal Environment

Between 2000 and 2023, high-NTL-value zones in the Yellow River Basin experienced significant expansion, accompanied by remarkable urban development (Figure 2). The high-NTL-value zones in the middle and lower reaches progressively transformed from isolated patches into continuous expanses, demonstrating substantial expansion. At the higher elevations, Lanzhou's NTL created a slender, elongated corridor along the river valley. The NTL expansion in Yinchuan was constrained, but Xining's NTL saw growth, albeit in a rather scattered manner. This illustrates the geographical variation in urban development along the high, middle, and lower segments of the Yellow River Basin.

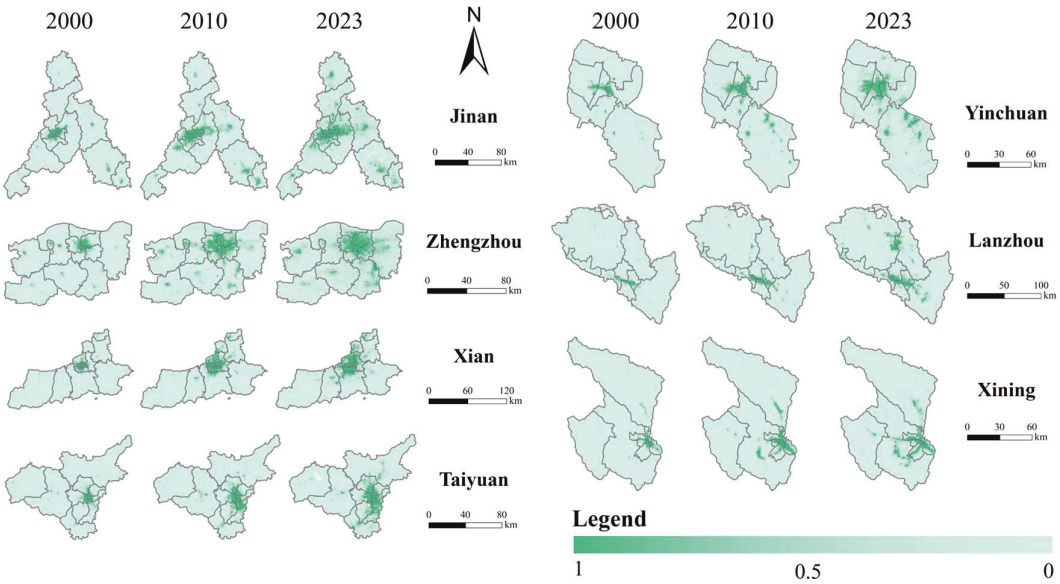


Figure 2. NTL maps of the seven core cities in the Yellow River Basin (2000–2023).

From 2000 to 2023, the urban heat island zones of core cities in the Yellow River Basin transitioned from exposed surfaces to urban areas, a spatiotemporal pattern reflected by the thermal level distribution of LST (Figure 3) and supported by the land use classification map (Figure 4). Detailed five-year-interval classification maps are provided in Appendix A. Between 2000 and 2005, urban development was minimal, leading to a diminished urban heat island impact. High-temperature areas were mostly located in agricultural or uncultivated regions. The exposed surface caused these places to heat quickly under solar radiation, resulting in elevated LST readings. Between 2010 and 2023, the expansion of metropolitan areas exacerbated the urban–rural differential in LST, with heat island zones encroaching toward urban peripheries. In contrast, extensive continuous regions of agricultural land and green spaces, despite increasing LST values, demonstrated a reduction in thermal intensity, shifting to moderate-temperature or sub-high-temperature zones. This phenomenon is especially evident in Zhengzhou. In 2000, elevated temperature zones were dispersed over agricultural land. By 2023, these zones increasingly overlapped with built areas, whereas the thermal intensity of adjacent farms fell markedly. Lanzhou's built-up land is arranged in an east–west strip centered on the Yellow River valley; nevertheless, the urban heat island effect transcends the limits of these developed regions, creating a high-temperature zone throughout the region, with the river valley at its nucleus. Between 2000 and 2023, the expansion of new development land along river valleys and adjacent

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regions exacerbated heat buildup. High-temperature zones persisted in their intensification, with heat intensity becoming increasingly noticeable relative to other cities.

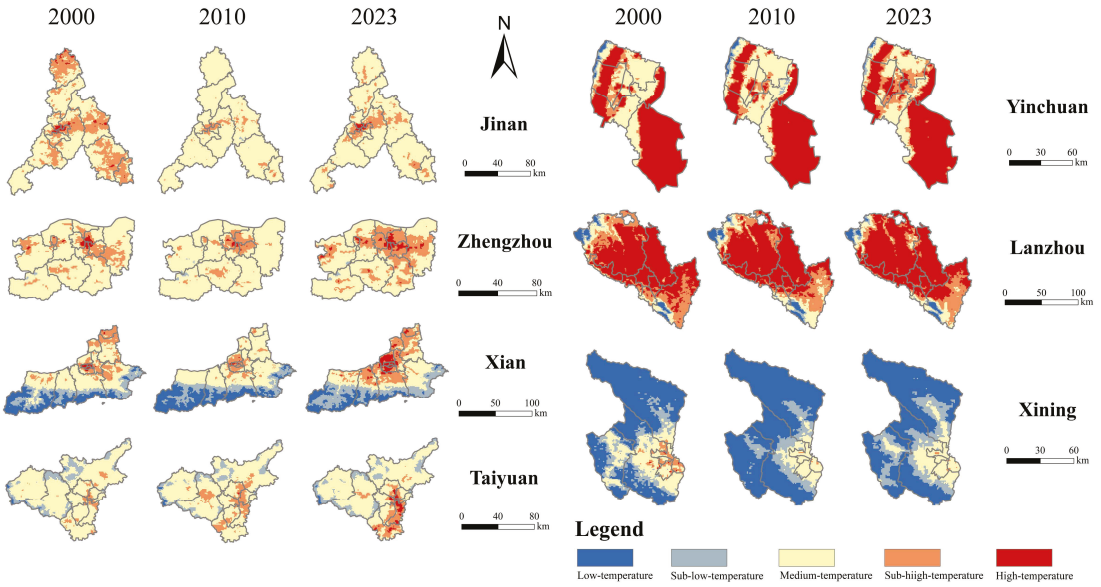


Figure 3. Distribution maps of thermal levels in the seven core cities of the Yellow River Basin (2000–2023).

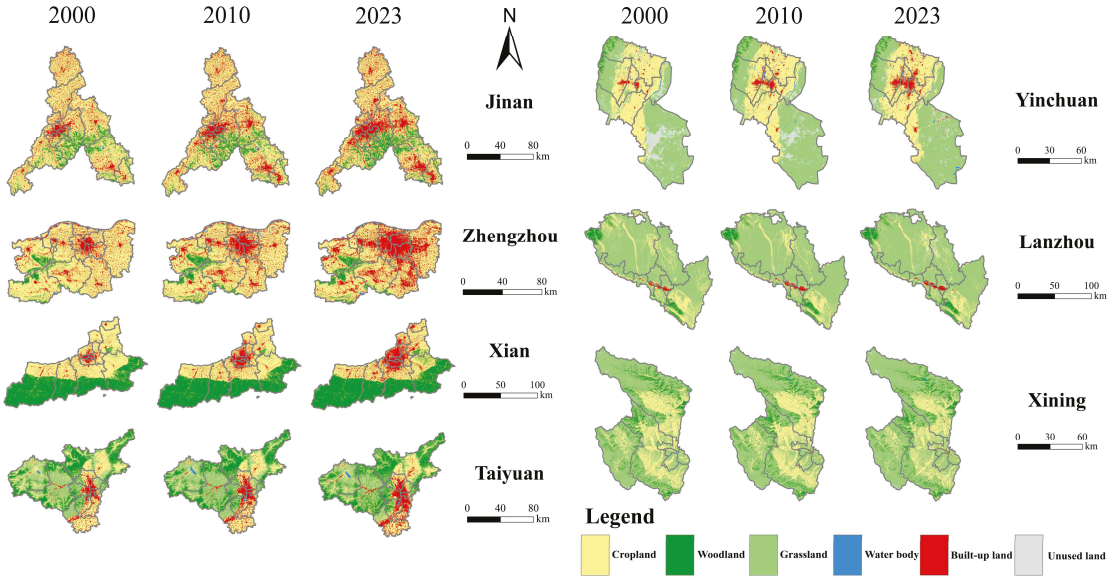


Figure 4. Land use classification of the seven core cities in the Yellow River Basin (2000–2023).

Considering the diverse topography of the Yellow River Basin and the correlations between LST distribution, urban development patterns, and terrain, Jinan and Zhengzhou are situated in the lower reaches on plains with extensive landscapes that facilitate large-scale urban development. Taiyuan is situated in the river valley zone of the Loess Plateau's middle reaches, where urban areas emerge along the valley. Xi'an is situated in a plain area that offers sufficient potential for urban expansion. Lanzhou is confined by the northern and southern mountains bordering the Yellow River Basin, leading to a compact, linear urban layout. Yinchuan is surrounded by vast deserts, while Xining is situated in a river valley on a plateau. Topographical variances result in unique urban development patterns, thereby affecting LST distribution. Urban development occurs rapidly in plains and river valleys, where human activity is concentrated. Impervious surfaces replace natural surfaces,

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thereby leading to strong heat emission and retention effects that drive the increase in LST. Conversely, urban expansion is limited in mountainous and desert peripheries, where LST is more profoundly affected by natural surfaces, and the influence of urban areas on LST is comparatively diminished.

3.1.2. Time Series Analysis of Land Surface Temperature

Analysis of summer LST trends in the core cities of the Yellow River Basin from 2000 to 2023 indicates, based on MK test results (Figure 5), that notable temperature increases are concentrated in the primary urban areas of each city. Urban centers typically demonstrated either extremely significant or significant warming, directly associated with concentrated human-generated heat emissions stemming from land use expansion, population growth, and industrial clustering during urban development. The more pronounced warming signals in the middle-lower reaches (Jinan, Zhengzhou) relative to the upper-middle reaches indicate a correlation between the intensity of urban development and the increase in LST.

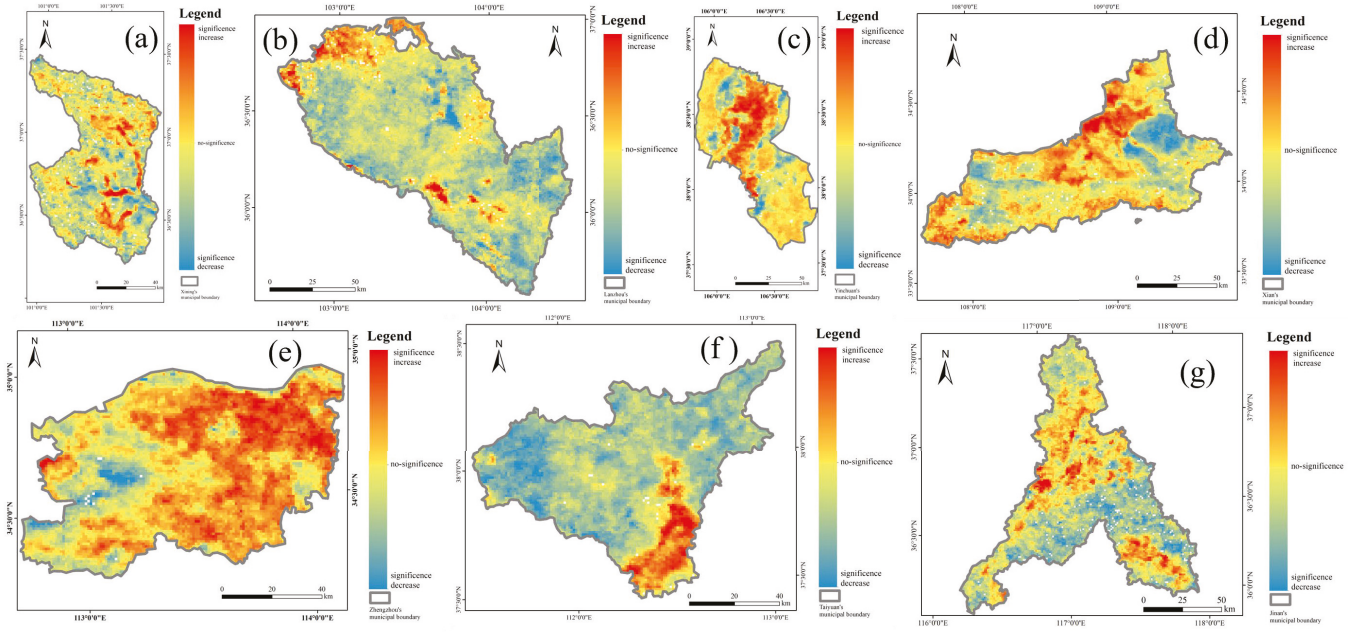


Figure 5. LST M-K non-parametric test for summer (2000–2023): (**a**) Xining; (**b**) Lanzhou; (**c**) Yinchuan; (**d**) Xi'an; (**e**) Zhengzhou; (**f**) Taiyuan; (**g**) Jinan.

Conversely, regions adjacent to the urban centers of the seven cities, primarily consisting of agricultural land and natural surfaces, demonstrated no notable LST signals owing to the diminished impact of urban development activities. This pattern creates a thermal environment marked by significant warming in urban centers and stable conditions in adjacent natural areas.

Sen's slope study results (Figure 6) reveal increased warming rates in core urban areas, with the urban districts of Zhengzhou and Jinan displaying slopes of 0.29–0.4 °C/year. Xi'an and Taiyuan see temperature increases of 0.35–0.38 °C/year, attributed to continuous urban expansion that facilitates heat storage. Lanzhou and Xining demonstrate temperature increases of 0.2–0.3 °C/year, attributed to slower urbanization and less growth intensity, leading to a more gradual pace of change. Yinchuan exhibits localized warming exclusively inside its built metropolitan center. Regions characterized by natural surfaces, including uncultivated terrain and agricultural fields, have slopes nearing zero, with certain areas reflecting marginally negative values.

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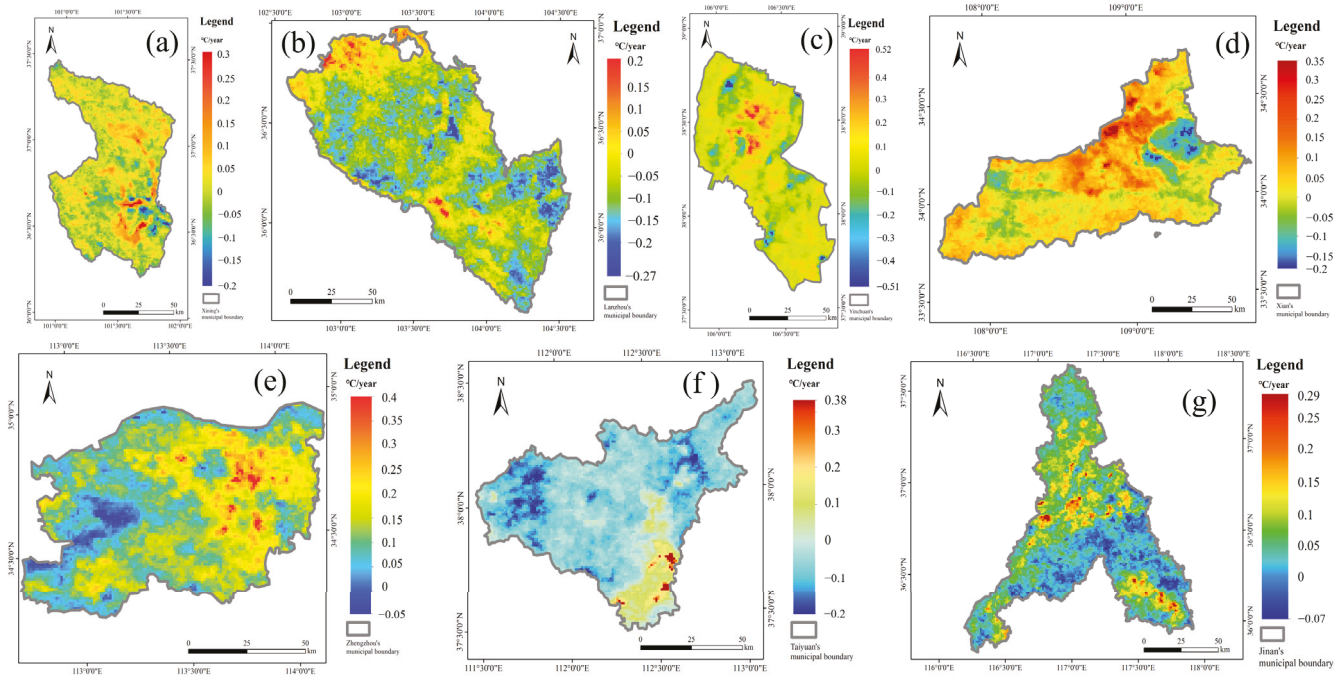


Figure 6. Summer LST slope trend (2003—2020)**:** (**a**) Xining; (**b**) Lanzhou; (**c**) Yinchuan; (**d**) Xi'an; (**e**) Zhengzhou; (**f**) Taiyuan; (**g**) Jinan.

Overall, LST alterations in core cities are intricately associated with urban development; major urban regions characterized by concentrated development demonstrate elevated Sen slopes and strong upward trends in Mann–Kendall tests. Peripheral natural areas, less affected by development, demonstrate slopes toward zero, with certain locations displaying marginal cooling tendencies, indicating the impact of urban development intensity on LST. The prominent patterns in MK tests predominantly correspond with the extent of Sen slope variations.

3.2. The Influence Mechanism of Urban Development on Land Surface Temperature

3.2.1. The Correlation Between Urban Development and Land Surface Temperature

The correlation coefficient between NTL and LST and the spatial characteristics of the two-dimensional scatter plot were obtained through analysis (Figure 7, Table 3). The analysis is as follows:

Between 2000 and 2023, the association between NTL and LST in the Yellow River Basin demonstrated notable geographical gradient variations throughout its upper, middle, and lower reaches: The middle and lower reaches exhibited a robust positive association between NTL and LST, with the correlation strength progressively intensifying. Conversely, the higher reaches had very weak connections, with Lanzhou and Yinchuan showing moderate negative correlations and exceedingly low positive correlations. This illustrates the basin-specific differential pattern between levels of urban development and thermal environments. From a watershed-scale temporal perspective, the correlation coefficients between NTL and LST in the downstream cities of Jinan and Zhengzhou, as well as the midstream cities of Taiyuan and Xi'an, demonstrate a significant upward tendency. This illustrates the more robust beneficial influence of urban expansion on LST over time. Although the correlation coefficient in upstream Xining exhibits an increase, its magnitude remains constrained. Conversely, Lanzhou and Yinchuan have highly stable correlation features, with their coefficients continually remaining at low levels.

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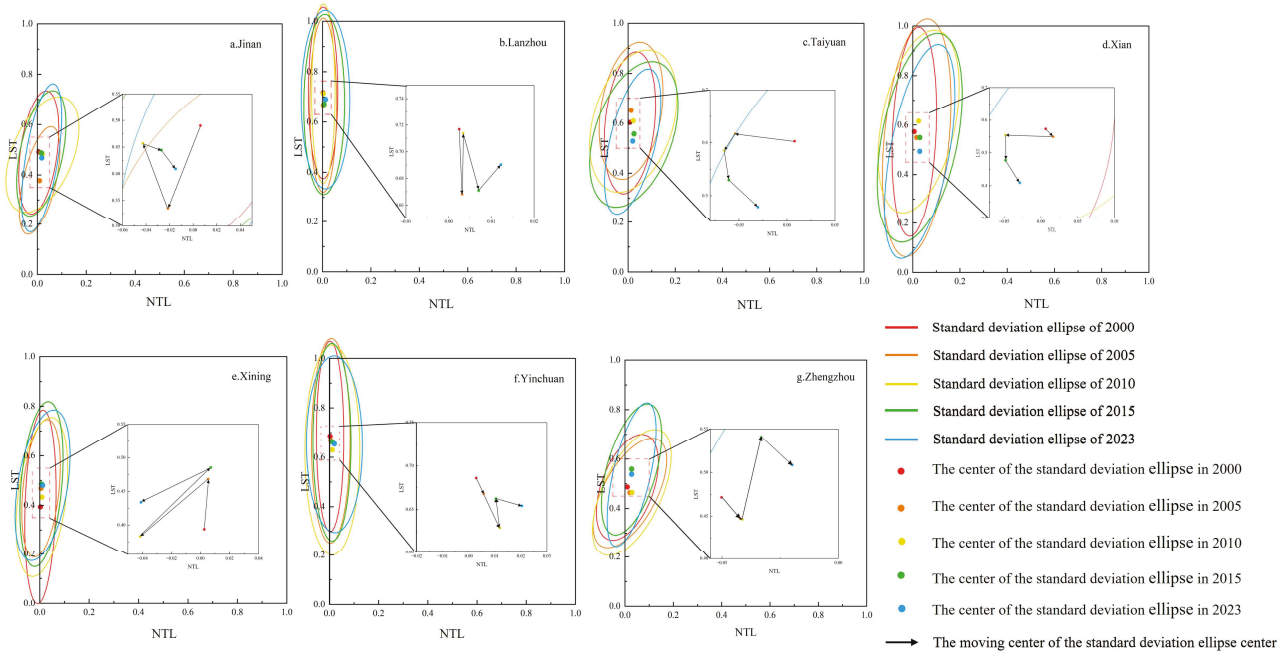


Figure 7. Spatial characteristics of standard deviational ellipses for NTL and LST in the seven core cities of the Yellow River Basin (2003–2020).

Geometrically, the SDE parameters provide an intuitive measure of the spatial coupling between NTL and LST. The Azimuth (R) indicates the primary trajectory of warming relative to urban growth. Directionality (D) reflects the dominance of this linear trend. Crucially, Dispersion (S) measures the degree of data scattering; a lower S value signifies a tighter, more synchronous coupling between urbanization and temperature increases, with fewer spatial deviations. Applying these metrics reveals distinct watershed-level patterns directly associated with the phases of urban development. In the downstream cities of Jinan and Zhengzhou, D progressively intensifies while S diminishes, with R converging to the 76–81° range. This indicates that continuous urban expansion, population and industrial clustering, and the proliferation of impervious surfaces drive a highly synchronous, positive increase in LST. Similarly, the midstream cities of Taiyuan and Xi'an show rising D and dropping S, with azimuths converging between 75° and 79°. Here, rapid urban development and the incremental amalgamation of metropolitan areas reinforce a strong, linear NTL-LST relationship.

Conversely, upstream cities exhibit weaker and more constrained coupling. Xining shows reduced D and rising S, reflecting a growing but scattered thermal response to expedited late-stage urbanization. Meanwhile, Lanzhou and Yinchuan display low D, considerable S, and stable azimuths near 90°. Their scatter plots lack a discernible linear trend because their urban thermal responses are largely constrained by natural factors, specifically the river valley topography in Lanzhou and desert surface characteristics in Yinchuan. This clear watershed-level distinction offers a scientific foundation for the tailored management of urban thermal environments in the Yellow River Basin.

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Table 3. Relevant parameters of NTL and LST in the seven core cities of the Yellow River Basin (2003–2020).

Area	Year	Correlation Coefficient	Standard Deviational Ellipse			
			Central Coordinates (NTL, LST)	Directionality (D)	Discreteness (S)	Azimuth R (°)
Jinan	2000	0.376 ***	(0.006, 0.489)	0.124	0.038	82.123
	2005	0.566 ***	(0.009, 0.376)	0.111	0.033	76.467
	2010	0.459 ***	(0.021, 0.481)	0.122	0.062	67.103
	2015	0.469 ***	(0.016, 0.485)	0.127	0.044	77.85
	2023	0.570 ***	(0.018, 0.466)	0.15	0.033	80.612
Lanzhou	2000	0.004 ***	(0.002, 0.715)	0.17	0.03	89.96
	2005	0.009 ***	(0.003, 0.666)	0.173	0.028	89.918
	2010	0.005 ***	(0.003, 0.712)	0.178	0.024	89.961
	2015	0.029 ***	(0.007, 0.669)	0.179	0.042	89.588
	2023	−0.004 ***	(0.012, 0.689)	0.177	0.05	90.066
Taiyuan	2000	0.251 ***	(0.008, 0.601)	0.143	0.052	83.671
	2005	0.276 ***	(0.013, 0.649)	0.139	0.064	80.123
	2010	0.335 ***	(0.022, 0.608)	0.148	0.084	71.563
	2015	0.404 ***	(0.025, 0.555)	0.153	0.082	69.323
	2023	0.559 ***	(0.020, 0.526)	0.15	0.048	75.599
Xi'an	2000	0.204 ***	(0.006, 0.571)	0.212	0.046	87.275
	2005	0.313 ***	(0.017, 0.546)	0.242	0.069	84.154
	2010	0.388 ***	(0.025, 0.614)	0.188	0.078	77.643
	2015	0.419 ***	(0.030, 0.547)	0.216	0.08	78.276
	2023	0.527 ***	(0.029, 0.491)	0.221	0.062	78.855
Xining	2000	0.178 ***	(0.003, 0.392)	0.197	0.031	88.31
	2005	0.338 ***	(0.005, 0.467)	0.14	0.037	84.215
	2010	0.356 ***	(0.009, 0.431)	0.163	0.049	82.786
	2015	0.315 ***	(0.007, 0.484)	0.168	0.041	84.999
	2023	0.404 ***	(0.011, 0.479)	0.155	0.05	80.658
Yinchuan	2000	−0.006 ***	(0.003, 0.684)	0.192	0.028	90.052
	2005	0.027 ***	(0.006, 0.666)	0.207	0.039	89.701
	2010	0.004 ***	(0.012, 0.627)	0.213	0.056	89.929
	2015	−0.010 ***	(0.010, 0.660)	0.2	0.039	90.12
	2023	−0.013 ***	(0.020, 0.652)	0.179	0.057	90.265
Zhengzhou	2000	0.470 ***	(0.010, 0.485)	0.113	0.054	69.392
	2005	0.602 ***	(0.020, 0.463)	0.123	0.055	61.263
	2010	0.588 ***	(0.028, 0.463)	0.139	0.061	64.313
	2015	0.530 ***	(0.027, 0.558)	0.137	0.051	73.7
	2023	0.624 ***	(0.027, 0.537)	0.149	0.039	76.852

Note: *** indicates $p < 0.001$. While extremely low correlation coefficients such as the near-zero values observed in Lanzhou and Yinchuan appear statistically significant due to the massive sample size, their actual effect size is functionally zero.

3.2.2. Global Spatial Association Between Urban Development and Land Surface Temperature

We employed the GeoDa (version 1.22.0.21) to compute the bivariate global Moran's I for LST and NTL in the core cities of the Yellow River Basin. The results (Table 4) indicate substantial positive geographical correlations between LST and NTL in the majority of cities, but weaker connections are seen in few instances. Jinan, Taiyuan, Xi'an, Xining, and Zhengzhou regularly demonstrate positive Moran's I value over all years, with *p*-values under 0.001 and typically elevated Z-values, signifying robust geographic correlations

between LST and NTL in these urban areas. Elevated NTL in specific places results in increased LST in adjacent regions. This occurs due to thermal exchange between regions with varying LST levels: an increase in NTL in a localized area initially elevates LST within that region, and the heat is subsequently disseminated to adjacent areas via atmospheric circulation and other mechanisms, ultimately resulting in a rise in LST in those surrounding areas as well. Between 2000 and 2023, the bivariate Moran's I value for these substantially associated cities exhibited a generally increasing trend, signifying a persistent enhancement of NTL's favorable impact on adjacent LST values.

Table 4. Bivariate Moran's I statistical values of LST and NTL in the seven core cities of the Yellow River Basin (2003–2020).

Area	2000	2005	2010	2015	2023
Jinan	0.3659 (38.6222) ***	0.5416 (56.4701) ***	0.4718 (54.3962) ***	0.4505 (47.7029) ***	0.5439 (56.7126) ***
Lanzhou	−0.0016 (−0.166)	0.0094 (1.0933)	0.0032 (0.3537)	0.03 (3.5422) ***	−0.0019 (−0.2373)
Taiyuan	0.259 (21.7172) ***	0.2817 (25.6107) ***	0.343 (30.7573) ***	0.3993 (34.046) ***	0.5463 (45.9199) ***
Xi'an	0.2048 (20.9258) ***	0.3109 (31.6861) ***	0.3907 (40.0767) ***	0.4157 (40.2347) ***	0.5207 (51.6933) ***
Xining	0.178 (16.2869) ***	0.3248 (28.5195) ***	0.3479 (29.1621) ***	0.3171 (28.4069) ***	0.3931 (34.8881) ***
Yinchuan	−0.0153 (−1.2619)	0.0194 (1.71)	−0.0027 (−0.2615)	−0.0153 (−1.389)	−0.0155 (−1.3138)
Zhengzhou	0.4369 (40.6205) ***	0.5693 (51.5682) ***	0.5715 (52.7212) ***	0.513 (48.241) ***	0.6042 (53.7389) ***

Note: Values in parentheses are Z-test values; *** indicates $p < 0.001$.

In the case of Taiyuan, the Moran's I index was 0.259 in 2000 and increased to 0.5463 in 2023, indicating a substantial rise. Zhengzhou has constantly achieved a high level, increasing from 0.4369 in 2000 to 0.6042 in 2023, firmly securing the top position among the seven cities. This is due to the ongoing expansion of urban size during the urbanization process, where spatial distribution has progressively transitioned from dispersed to continuous and concentrated. As a result, the urban heat island effect in these cities has strengthened, having a more significant warming impact on the surrounding environment. Furthermore, the growth and densification of urban built environments have intensified the localized effects of urban development on LST, hence accentuating the "spillover effect" of urban regions on adjacent thermal environments [49]. This has resulted in a progressively robust regional link between LST and NTL. The dual-variable Moran's I and its variant exhibit substantial differences among the seven cities. Zhengzhou and Jinan consistently exhibited elevated levels, with Moran's I attaining 0.6042 and 0.5439, respectively, in 2023; Taiyuan and Xi'an closely trailed, recording values of 0.5463 and 0.5207, respectively, demonstrating significant growth; Xining, despite commencing from a low baseline of 0.178 in 2000, progressively rose to 0.3931 by 2023.

The fundamental cause is that the disparities in spatial association between LST and NTL are intricately associated with urban development patterns and natural geographical characteristics. From 2000 to 2023, core cities in the Yellow River Basin demonstrated substantial disparities in their urban development paradigms. Throughout the urbanization process in the middle and upper parts of the Yellow River Basin, urban development was centered on adjacent regions, resulting in the swift and ongoing growth of built-up land.

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Zhengzhou and Xi'an had gains in building land of 86.57% and 127.14%, respectively, but Taiyuan and Jinan recorded rises of 61.41% and 50.92%. The urban heat island effect has a clear "agglomeration–diffusion" process spatially. The spatial distribution of NTL closely correlates with variations in LST, resulting in a consistent rise in Moran's I. Taking into account urban development characteristics, the thermal environmental effects of urban expansion in these cities demonstrate distinct spatial transmissibility, whereby localized urban sprawl significantly influences adjacent LST alterations. Conversely, Lanzhou's positioning in the Yellow River valley, flanked by mountains to the north and south, restricts lateral urban development. The metropolis displays a constricted, elongated distribution with inadequate spatial continuity, obstructing the development of concentrated heat transfer "spillover effects." As a result, the geographic connection between NTL and LST is minimal. Despite Yinchuan's comparatively elevated urbanization rate, its urban development is marked by challenges like fragmented industrial configurations and the conflation of built environments with natural zones. As a result, the geographical distribution of NTL exhibits a weak correlation with the heat island effect, leading to LST consistently demonstrating little effects from NTL. The regional disparities in urban development resulted in notable divergence in the dual-variable Moran's I values for LST and NTL across the seven cities.

3.2.3. Local Correlation Between Urban Development and Land Surface Temperature

Bivariate local spatial autocorrelation and GWR analyses were performed on NTL and LST in the core cities of the Yellow River Basin, producing LISA cluster maps (Figure 8), local explanatory power maps derived from the GWR model (Figure 9) and spatial heterogeneity maps of influencing variables (Figure 10), respectively. Owing to disparities in natural circumstances and urban development patterns, their geographic distributions exhibit significant variability while adhering to some fundamental principles. The bivariate LISA analysis revealed distinct spatiotemporal evolutionary patterns for the four types of local spatial clusters across the basin gradient. H-H clusters, predominantly located in continuous built-up areas, exhibited an outward expansion, particularly in midstream and downstream plains. In contrast, L-L clusters maintained long-term spatial stability within upstream natural ecological zones. L-H clusters consistently characterized the urban-rural transition zones at administrative boundaries, while H-L clusters, initially scattered around urban green spaces and water bodies, significantly shrank over the study period. These spatiotemporal dynamics and inter-city differences are deeply intertwined with local physical drivers, as further elucidated by the GWR analysis below.

The GWR study indicates that the substantial quantity of zero values in the NTL dataset, which pertains to underdeveloped or places with less human activity, may result in distortions during model fitting. Consequently, this segment of the data was omitted to preserve the scientific integrity of the research. Multicollinearity assessments indicated that the variance inflation factors (VIF) for all independent variables varied from 1.6 to 3.2, with an average of 2.3, significantly within the conventional threshold of 10. The conditional indices varied from 8.5 to 21.7, with an average of 14.8, far below the conventional criterion of 30. The model satisfies the modeling criteria, and the outcomes are dependable. To further evaluate the localized performance and explanatory power of the GWR model, the spatial distribution of the Local R^2 values for the core cities was mapped (Figure 9). The Local R^2 values demonstrate the robust explanatory power of the model, particularly in contiguous urban expansion areas. By 2023, the Local R^2 values in the built-up areas of downstream and midstream cities exceeded 0.6, confirming that the selected variables (NTL, DEM, and SLOPE) effectively capture the localized driving mechanisms of the urban thermal environment. Building on this robust model performance, the subsequent interpretation of LISA cluster features is derived from the local heterogeneity maps of

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impact factors for the years 2000 and 2023 (Figure 10). For the spatial visualization of these GWR results, the local coefficients were strictly partitioned by a zero-value boundary to accurately distinguish between positive and negative localized impacts, followed by a sub-classification utilizing the Natural Breaks (Jenks) optimization method.

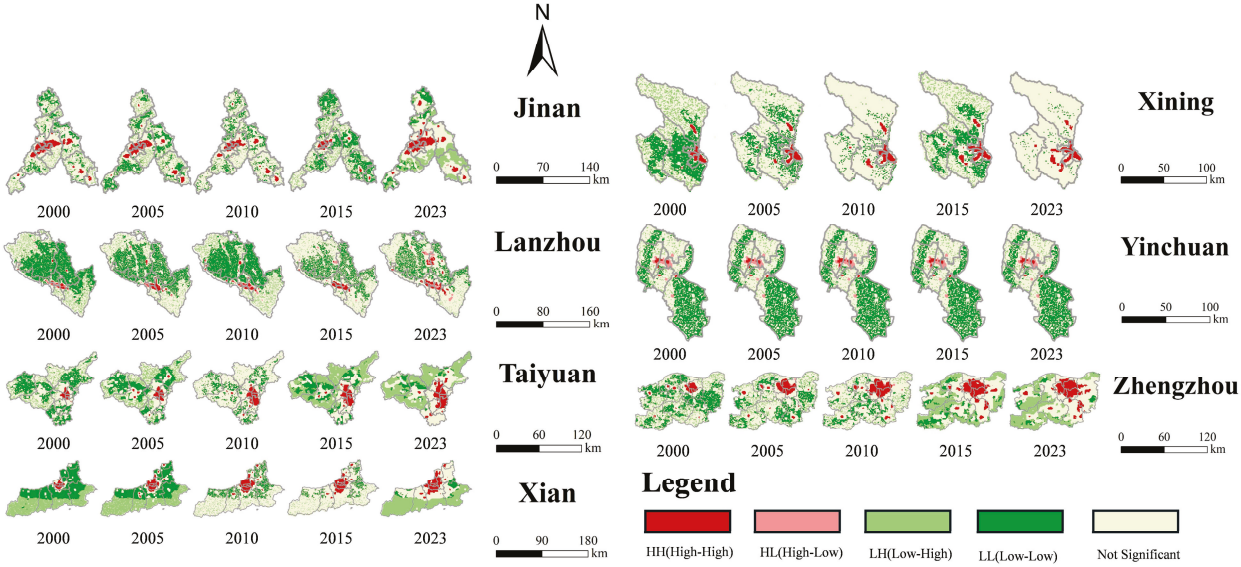


Figure 8. Distribution maps of bivariate LISA for LST and NTL in the seven core cities of the Yellow River Basin (2003—2020).

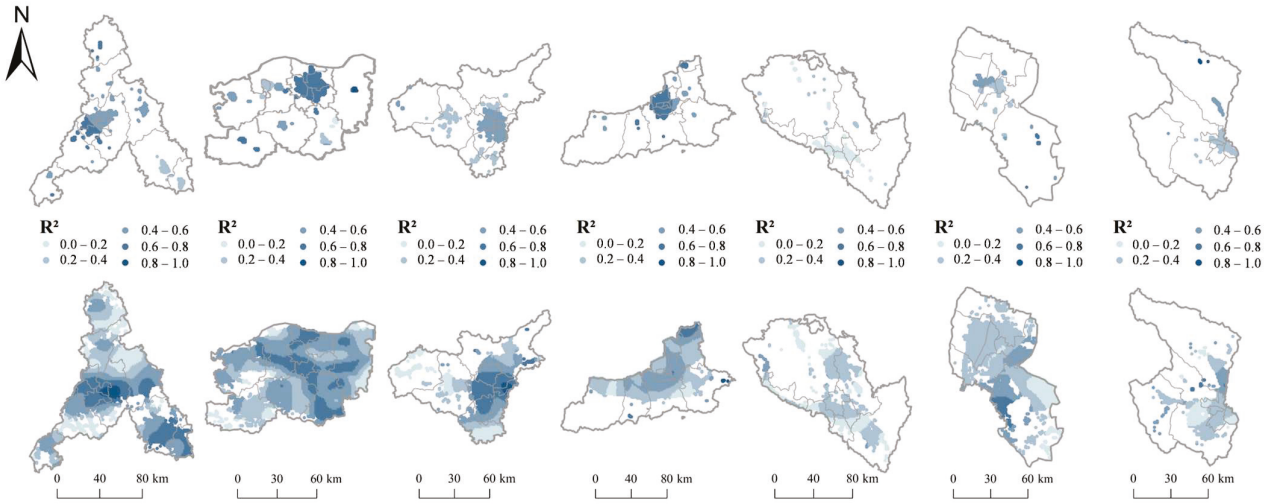


Figure 9. Spatial distribution of Local values derived from the GWR model (2000 and 2023). Note: Darker shades indicate higher local explanatory power of the variables for Land Surface Temperature (LST).

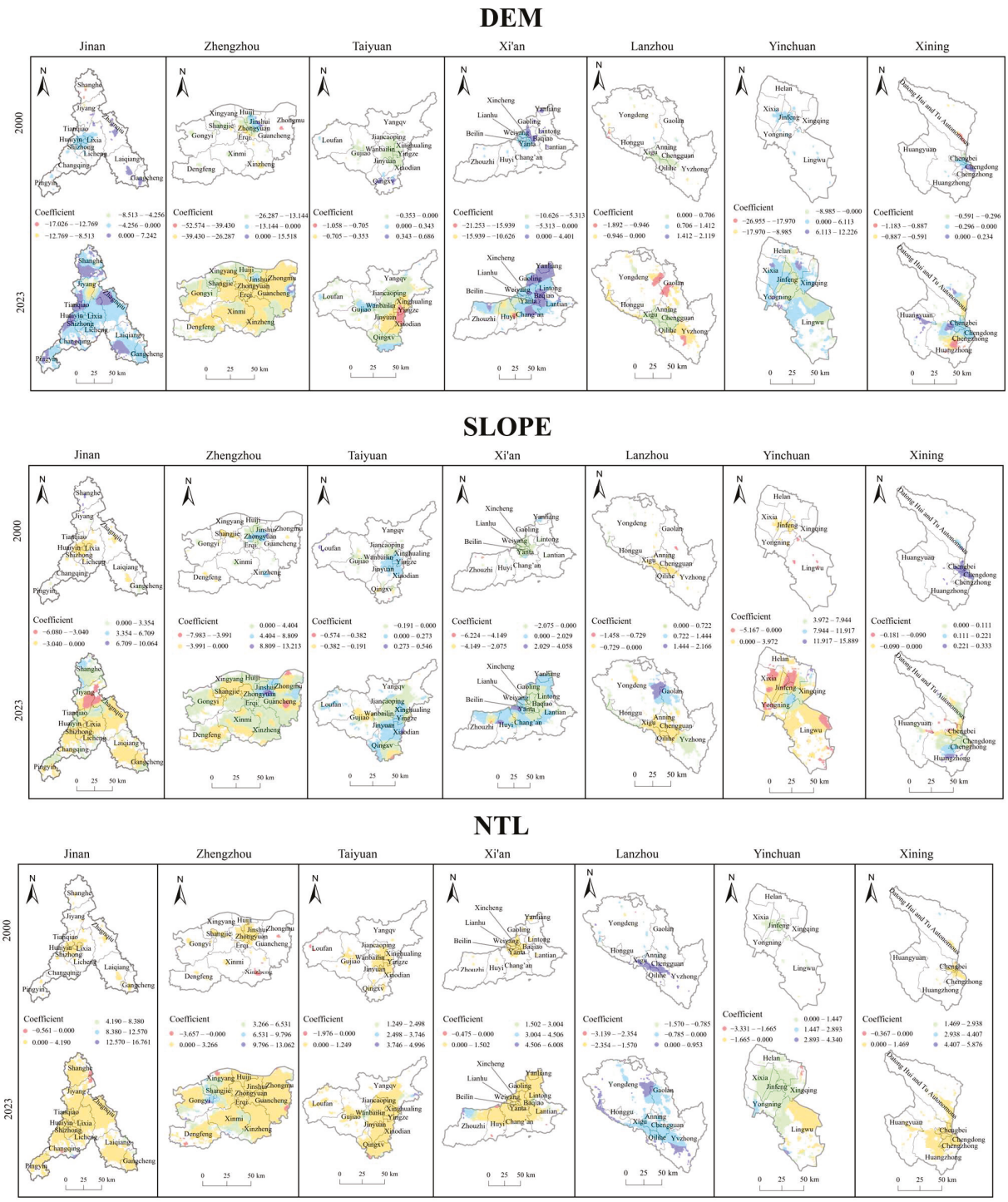


Figure 10. Spatial distribution of Geographically Weighted Regression (GWR) local coefficients in the core cities of the Yellow River Basin (2000 and 2023).

Between 2000 and 2023, the NTL coefficient in upstream cities consistently exhibited low values with very slight increases. The terrain limitations indicated by the DEM and SLOPE coefficients were consistent and significant. The H-H agglomeration area grew gradually due to its low NTL coefficient and considerable topographical limitations, in conjunction with ecological protection policy regulations. L-L clusters, situated within natural functioning zones, demonstrate little human involvement. They exhibit significant spatial uniformity between low NTL and low LST, with no spatiotemporal fluctuation. L-H clusters were prevalent in transition zones of administrative boundaries, where localized variations in DEM and SLOPE coefficients indicated intricate surface conditions. Their low NTL coefficients demonstrated a geographic discrepancy with elevated LST in bare land and dryland agriculture. H-L clusters are intermittently located around natural cold islands such as river valley wetlands. The DEM and SLOPE coefficients offered topographic reinforcement for the persistence of cold islands, maintaining their cooling impact and averting total extinction.

As early as 2000, the NTL coefficient in midstream cities had attained a notably elevated level. In regions with mild topography such as Xi'an and Taiyuan, the topographical limitations indicated by the DEM and SLOPE coefficients were comparatively minimal, and H-H clusters had started to display first continuous traits. Between 2000 and 2023, the NTL coefficient had markedly risen, while terrain limitations, as seen by the DEM and SLOPE coefficients, had further diminished. Urbanization propelled the extension of urban development peripheries, and H-H clusters had a significant tendency for ongoing contiguous expansion. L-L clusters demonstrated significant magnitude in 2000. In 2023, urban development intensified, evidenced by a consistent increase in the NTL ratio concurrent with the growth of building land. The underlying surface type changed from agricultural and green areas to developed land, resulting in substantial modifications to the DEM and SLOPE coefficients. As a result, L-L clusters consistently diminished and were supplanted by H-H clusters. L-H clusters are consistently dispersed throughout overlapping zones of administrative boundaries. Local differences in DEM and SLOPE coefficients created urban-rural transition zones, preserving consistent low NTL and elevated LST attributes. These locations exhibited no substantial difference from H-H clusters. H-L clusters represented a minor overall share. In 2000, they were dispersed sporadically in urban green spaces and around water bodies. By 2023, the increased NTL coefficient induced urban heat island spillover effects, resulting in a significant contraction of H-L clusters.

By 2000, the NTL coefficient in downstream cities had attained a significant level over the whole basin. The DEM and SLOPE coefficients demonstrated mild topography, promoting urban development, whereas H-H clusters are swiftly proliferating. By 2023, the NTL coefficient had risen markedly, with H-H clusters demonstrating very continuous distribution patterns. The period from 2000 to 2023 saw L-L clusters, once extensive in suburban ecological areas, completely give way to H-H clusters following substantial built-up expansion and changes in NTL and terrain coefficients. In contrast, L-H clusters exhibited stability, maintaining a consistent presence at administrative boundaries. L-H clusters demonstrated a temporal pattern oscillating between distinct patches and connected clusters, since these borders frequently exist across urban-rural transition zones or ecological–urban interstices. DEM and SLOPE coefficients provide topographic limitations via isolated undulations, with minimal human interference. Subsurface attributes sustain heightened LST, exemplifying a quintessential spatial discrepancy. H-L clusters, limited in 2000 to areas near artificial water bodies and urban greenspaces, were nearly eradicated by 2023 under combined NTL increases and heat island expansion.

In summary, from 2000 to 2023, the upper, middle, and lower sections of the Yellow River demonstrated patterns of H-H cluster growth and an enhanced beneficial effect of

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NTL on LST. In the upstream region, multiple restrictions from biological and topographical considerations provide long-term stability in L-L agglomeration. The H-H agglomeration is confined to specific topographical contours, whereas NTL has a minimal impact on LST. In the midstream transitional zone between mountains and plains, intricate terrain leads to concurrent fluctuations in H-H and L-H agglomerations with urban development, resulting in spatially varied NTL effects. Downstream plains facilitate developmental opportunities via topographical characteristics, resulting in continuous human habitation agglomerations where non-tariff barriers exert significant dominance.

4. Discussion and Conclusions

4.1. Discussion

This study examines the geographical correlation between nocturnal illumination and land surface temperature, elucidating distinct link mechanisms between urban development and the thermal environment across the Yellow River Basin. The downstream cities of Jinan and Zhengzhou demonstrate improved positive correlations, whereas the midstream cities of Taiyuan and Xi'an display variable increases. The upstream cities of Lanzhou and Yinchuan show minor relationships. The driving mechanism demonstrates a clear basin gradient pattern. Downstream areas are primarily driven by urban development intensity as quantified by NTL, midstream regions display terrain driven synergies, and upstream zones experience natural regulation. Prior research has established that geography influences the spread of urban heat islands [48,50]. Downstream plain cities exhibit heat island impacts owing to continuous growth, corroborating the conclusion that urban agglomeration intensity positively correlates with heat island extent [51,52].

To explain the enhanced correlation in the middle and lower reaches, we hypothesize a synergistic mechanism where unconstrained topography facilitates contiguous urban expansion, thereby intensifying thermal spillover effects. The unconstrained plains in the downstream and broad valleys in the midstream facilitated a transition of urban development from dispersed patches to contiguous expanses. This shift is quantitatively reflected by gains in building land, including 86.57% and 127.14% increases in Zhengzhou and Xi'an, respectively. This continuous proliferation of impervious surfaces limits localized thermal diffusion and triggers thermal spillover effects [47,53]. Our bivariate spatial autocorrelation results support this macroscopic pattern, where the Moran's I index for Zhengzhou increased from 0.4369 in 2000 to 0.6042 in 2023 alongside the formation of continuous clustering patterns. Consequently, land surface temperatures become sensitive to incremental increases in urban intensity, leading to the enhancement of their linear correlation. Conversely, to examine the natural background dilution effect observed in upstream cities, we hypothesize that this regulation is context specific. While our spatial models quantified topographical constraints, distinct local natural factors likely further regulate these thermal environments; for instance, the combination of high altitude topography and sparse vegetation evapotranspiration restricts thermal accumulation in Xining [54]. In Lanzhou, strict valley topography tightly constrains the urban configuration and fundamentally alters local atmospheric diffusion conditions [55]. Furthermore, surface albedo and minimal soil moisture from surrounding arid deserts influence Yinchuan [56]. These unquantified natural backdrops and topographical constraints force a fragmented urban configuration that fundamentally dilutes localized anthropogenic heat.

This study quantifies the geographical variability of urban development and land surface temperature at the watershed scale, offering an analytical foundation for analogous research in temperate semi-arid and semi-humid watersheds. Furthermore, it facilitates the execution of ecological conservation policies in the Yellow River Basin by providing clear direction for thermal environment management. A collaborative thermal environment

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management system based on watershed gradient zoning should be implemented. Instead of a uniform approach, interventions must be context-specific for local urban planners. For the downstream plain cities of Zhengzhou and Jinan, policies should limit horizontal urban sprawl by promoting vertical development and mandating green infrastructure such as green roofs and cool pavements in new developments. In the midstream cities of Xi'an and Taiyuan, terrain-adaptive planning should be prioritized. This involves preserving ecological ventilation corridors along river valleys and mountain passes to prevent dense building clusters from blocking natural wind paths. For the upstream regions of Xining, Lanzhou, and Yinchuan, spatial planning should focus on ecological boundaries and maintaining natural land cover ratios such as regional wetlands and sparse vegetation to sustain their natural background dilution capacities against anthropogenic heat [57]. This framework provides spatial planning guidelines for thermal environment management across the basin.

Nonetheless, this study presents several limitations that warrant further investigation. First, the study relies on nighttime light as a holistic proxy for urban development. While effective macroscopically, it lacks direct physical indices such as the Normalized Difference Vegetation Index for green space ratios or building indices for building density. Second, the temporal scope is limited to summer land surface temperature. Thermal environment drivers exhibit significant seasonal variations since winter patterns are heavily influenced by anthropogenic heating demands and snow albedo effects. Therefore, our NTL-derived findings are constrained to the summer urban heat island effect. Third, despite rigorous cross-sensor calibration using the Vegetation-Adjusted Nighttime Light Index, residual uncertainties may remain when fusing different satellite datasets. Especially in upstream cities with weaker initial lighting signals, this could introduce biases into long-term trend analyses. Future research must address these gaps by incorporating seasonal comparative analyses and multi-source high resolution physical datasets to refine urban thermal environmental models.

4.2. Conclusions

This study systematically quantifies the spatiotemporal correlation between urban development and land surface temperature across the core cities of the Yellow River Basin from 2000 to 2023. Our primary finding reveals a significant downstream to upstream gradient in both warming rates and the spatial correlation between nighttime light and land surface temperature. This gradient is fundamentally driven by contiguous urban expansion downstream, terrain and urban synergies midstream, and strong natural background regulation upstream.

These findings are significant because they shift the research paradigm from isolated and single-city thermal assessments to a holistic watershed-scale perspective. By explicitly demonstrating how varied topographical and ecological constraints interact with urbanization, this research provides vital scientific support and actionable spatial planning strategies. It helps regional planners to balance rapid urban growth with critical ecological conservation under national watershed strategies.

Finally, while this study provides robust insights, it shares certain weak points. It is primarily limited by its exclusive focus on summer land surface temperature, the absence of direct micro-physical land cover indices like the Normalized Difference Vegetation Index or three-dimensional building density in the spatial regression models, and minor residual uncertainties from the cross-sensor calibration of long-term nighttime light data. Future research must address these limitations by integrating seasonal comparative analyses, particularly winter heating effects, and high-resolution physical drivers to further advance the accurate modeling and management of urban thermal environments.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study were obtained from third-party sources. The MODIS MOD11A2 Land Surface Temperature data were obtained from the Google Earth Engine (GEE) platform and are available at https://earthengine.google.com (accessed on 6 January 2026). The 30 m land use data were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences and are available at https://www.resdc.cn (accessed on 4 January 2026). The DMSP–OLS and NPP–VIIRS nighttime light data were obtained from the U.S. National Geophysical Data Center (NGDC) and are available at https://www.ngdc.noaa.gov/eog (accessed on 9 January 2026). The socio-economic data (population, urbanization rate, and GDP) were obtained from officially published local statistical yearbooks (e.g., Jinan Statistical Yearbook, Gansu Statistical Yearbook) released by China Statistics Press.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

LST	Land Surface Temperature
NTL	Nighttime Light
GWR	Geographically Weighted Regression
SDE	Standard Deviation Ellipse
LISA	Local Index of Spatial Autocorrelation

Appendix A

Table A1. Pearson correlation coefficients between total Nighttime Light (NTL) and socio-economic indicators in the seven core cities (2000–2023).

City	Correlation with GDP (R)	Correlation with Population (R)
Jinan	0.972 **	0.920 **
Zhengzhou	0.943 **	0.968 **
Taiyuan	0.954 **	0.964 **
Xi'an	0.959 **	0.944 **
Lanzhou	0.951 **	0.863 **
Yinchuan	0.929 **	0.974 **
Xining	0.933 **	0.921 **

Note: ** indicates significance at the $p < 0.01$ level.

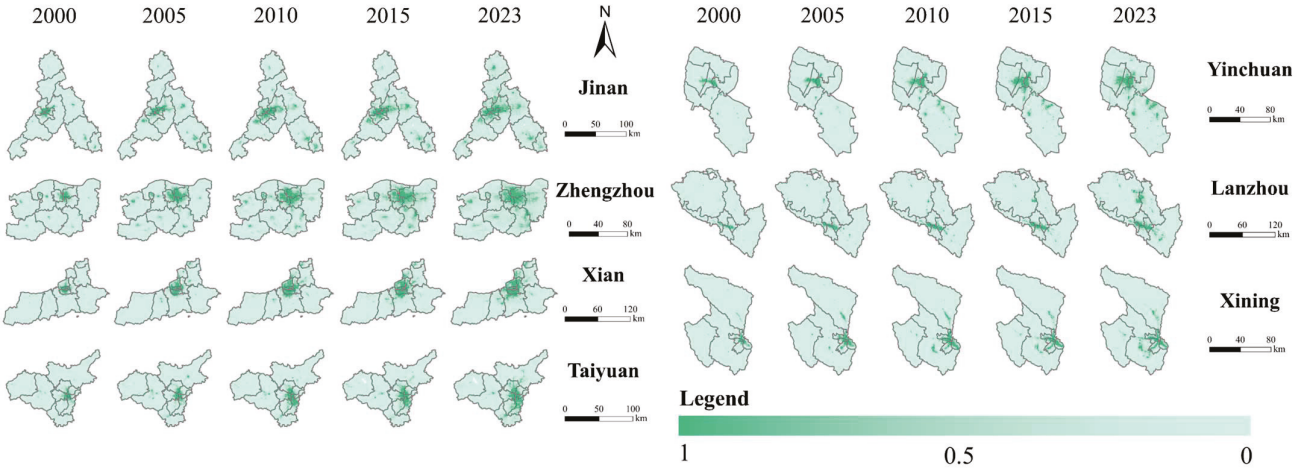


Figure A1. Detailed five-year-interval Nighttime Light (NTL) classification maps of the seven core cities in the Yellow River Basin.

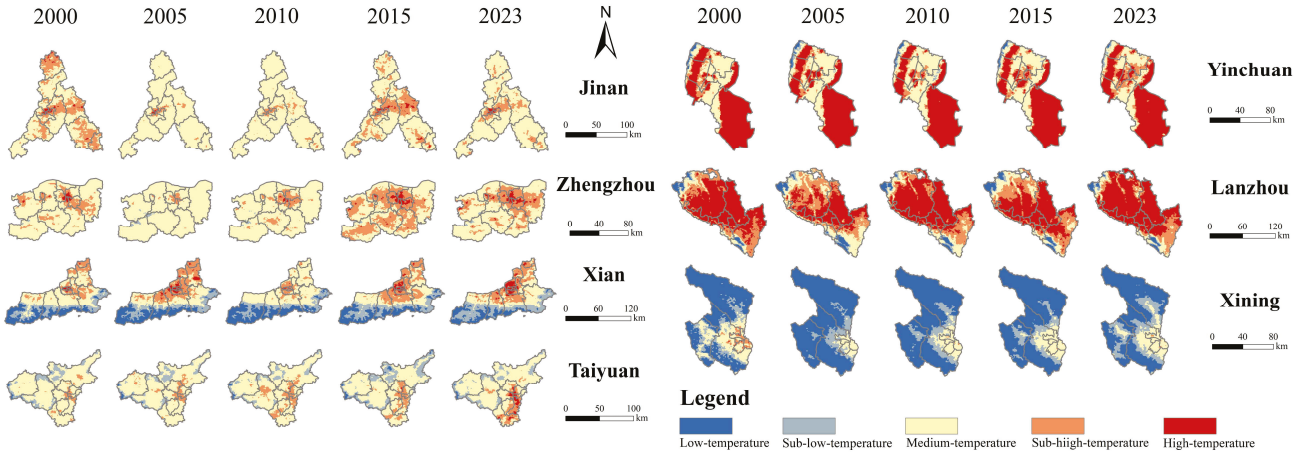


Figure A2. Detailed five-year-interval distribution maps of thermal levels in the seven core cities of the Yellow River Basin.

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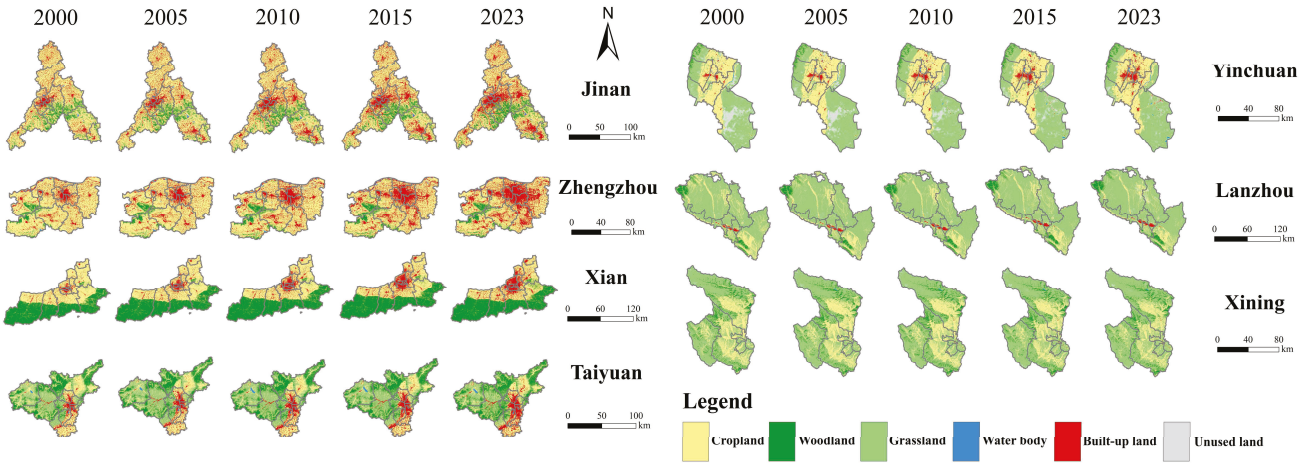


Figure A3. Detailed five-year-interval land use classification maps of the seven core cities in the Yellow River Basin.

References

1. Pradhan, P.; Costa, L.; Rybski, D.; Lucht, W.; Kropp, J.P. A Systematic Study of Sustainable Development Goal (SDG) Interactions. *Earths Future* **2017**, *5*, 1169–1179. [CrossRef]
2. Xu, H.; Shi, N.; Wu, L.; Zhang, D. High-Quality Development Level and Its Spatiotemporal Changes in the Yellow River Basin. *Resour. Sci.* **2020**, *42*, 115–126. [CrossRef]
3. Zhang, L.; Fang, C.; Zhu, C. Coupling Coordination and Decoupling Effects: Measuring the Interaction between Urban Agglomeration Ecosystems and Urbanization. *Cities* **2026**, *171*, 106788. [CrossRef]
4. Shen, Z.; Zhao, Y. Effect of Spatial Morphology on Land Surface Temperature and Their Interaction:A Case Study of Main Urban Area of Jinan City. *J. Arid Land Resour. Environ.* **2024**, *38*, 65–74. [CrossRef]
5. Tian, H.; Liu, L.; Zhang, Z.; Chen, H.; Zhang, X.; Wang, T.; Kang, Z. Spatiotemporal Diversity and Attribution Analysis of Land Surface Temperature in China from 2001 to 2020. *Acta Geogr. Sin.* **2022**, *77*, 1713–1729. [CrossRef]
6. Zhang, Y.; Wang, X.; Feng, Z.; Yuan, J.; Yu, M. Spatiotemporal Pattern and Influencing Factors of Thermal Environment Based on SEM Model: A Case Study in Xi'an Metropolitan Area. *Environ. Sci.* **2024**, *45*, 3734–3745.
7. Yan, D.; Zhang, Y.; Song, P.; Zhang, X.; Wang, Y.; Zhu, W.; Du, Q. Integrating Spatial Autocorrelation and Greenest Images for Dynamic Analysis Urban Heat Islands Based on Google Earth Engine. *Sustainability* **2025**, *17*, 7155. [CrossRef]
8. Li, L.; Zhan, W.; Hu, L.; Chakraborty, T.C.; Wang, Z.; Fu, P.; Wang, D.; Liao, W.; Huang, F.; Fu, H. Divergent Urbanization-Induced Impacts on Global Surface Urban Heat Island Trends since 1980s. *Remote Sens. Environ.* **2023**, *295*, 113650. [CrossRef]
9. Lehnert, M.; Savic, S.; Milosevic, D.; Dunjic, J.; Geletic, J. Mapping Local Climate Zones and Their Applications in European Urban Environments: A Systematic Literature Review and Future Development Trends. *Isprs Int. J. Geo-Inf.* **2021**, *10*, 260. [CrossRef]
10. Zimmermann, B.; Kruber, S.; Nendel, C.; Munack, H.; Hildmann, C. Assessing the Cooling Potential of Climate Change Adaptation Measures in Rural Areas. *J. Environ. Manag.* **2024**, *366*, 121595. [CrossRef]
11. Wang, Z.; Peng, Y.; Li, Y.; Zhou, X.; Xie, Y. Exploration of Influencing Factors of Land Surface Temperature in Cities Within the Beijing–Tianjin–Hebei Region Based on Local Climate Zone Scheme. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2024**, *17*, 9728–9744. [CrossRef]
12. Howard, L. *The Climate of London: Deduced from Meteorological Observations*; Cambridge University Press: Cambridge, UK, 2013.
13. Wan, Z.; Dozier, J. A Generalized Split-Window Algorithm for Retrieving Land-Surface Temperature from Space. *IEEE Trans. Geosci. Remote Sens.* **1996**, *34*, 892–905. [CrossRef]
14. Wan, Z.; Li, Z.-L. A Physics-Based Algorithm for Retrieving Land-Surface Emissivity and Temperature from EOS/MODIS Data. *IEEE Trans. Geosci. Remote Sens.* **1997**, *35*, 980–996. [CrossRef]
15. Ramyar, R.; Ramyar, A.; Kialashaki, Y.; Bryant, M.; Ramyar, H. Exploring reconfiguration scenarios of high-density urban neighborhoods on urban temperature-The case of Tehran (Iran). *Urban For. Urban Green.* **2019**, *44*, 126398. [CrossRef]
16. Shao, Z.; Ahmad, M.N.; Javed, A.; Islam, F.; Jahangir, Z.; Ahmad, I. Expansion of Urban Impervious Surfaces in Lahore (1993–2022) Based on GEE and Remote Sensing Data. *Photogramm. Eng. Remote Sens.* **2023**, *89*, 479–486. [CrossRef]
17. Seto, K.C.; Güneralp, B.; Hutyra, L.R. Global Forecasts of Urban Expansion to 2030 and Direct Impacts on Biodiversity and Carbon Pools. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 16083–16088. [CrossRef]

18. Bi, Y.; Zheng, L.; Wang, Y.; Li, J.; Yang, H.; Zhang, B. Coupling Relationship between Urbanization and Water-Related Ecosystem Services in China's Yangtze River Economic Belt and Its Socio-Ecological Driving Forces: A County-Level Perspective. *Ecol. Indic.* **2023**, *146*, 109871. [CrossRef]
19. Yang, C.; Yu, B.; Chen, Z.; Song, W.; Zhou, Y.; Li, X.; Wu, J. A Spatial-Socioeconomic Urban Development Status Curve from NPP-VIIRS Nighttime Light Data. *Remote Sens.* **2019**, *11*, 2398. [CrossRef]
20. Yang, Z.; Chen, Y.; Guo, G.; Zheng, Z.; Wu, Z. Using Nighttime Light Data to Identify the Structure of Polycentric Cities and Evaluate Urban Centers. *Sci. Total Environ.* **2021**, *780*, 146586. [CrossRef]
21. Yang, J.; Wang, Y.; Xiu, C.; Xiao, X.; Xia, J.; Jin, C. Optimizing Local Climate Zones to Mitigate Urban Heat Island Effect in Human Settlements. *J. Clean. Prod.* **2020**, *275*, 123767. [CrossRef]
22. Zheng, Y.; He, Y.; Zhou, Q.; Wang, H. Quantitative Evaluation of Urban Expansion Using NPP-VIIRS Nighttime Light and Landsat Spectral Data. *Sustain. Cities Soc.* **2022**, *76*, 103338. [CrossRef]
23. Zhu, E.; Qi, Q.; Chen, L.; Wu, X. The Spatial-Temporal Patterns and Multiple Driving Mechanisms of Carbon Emissions in the Process of Urbanization: A Case Study in Zhejiang, China. *J. Clean. Prod.* **2022**, *358*, 131954. [CrossRef]
24. Liu, X.D.; Chen, B.D. Climatic Warming in the Tibetan Plateau during Recent Decades. *Int. J. Climatol.* **2000**, *20*, 1729–1742. [CrossRef]
25. Yin, Z.Y.; Lin, Z.Y.; Zhao, X.Y. Temperature Anomalies in Central and Eastern Tibetan Plateau in Relation to General Circulation Patterns during 1951–1993. *Int. J. Climatol.* **2000**, *20*, 1431–1449. [CrossRef]
26. Peng, J.; Liu, Q.; Xu, Z.; Lyu, D.; Du, Y.; Qiao, R.; Wu, J. How to Effectively Mitigate Urban Heat Island Effect? A Perspective of Waterbody Patch Size Threshold. *Landsc. Urban Plan.* **2020**, *202*, 103873. [CrossRef]
27. Peng, J.; Ma, J.; Liu, Q.; Liu, Y.; Hu, Y.; Li, Y.; Yue, Y. Spatial-Temporal Change of Land Surface Temperature across 285 Cities in China: An Urban-Rural Contrast Perspective. *Sci. Total Environ.* **2018**, *635*, 487–497. [CrossRef] [PubMed]
28. Qin, M.; Ouyang, H.; Jiang, H.; Luo, T.; Zhou, Y.; Liu, Y. Spatiotemporal Evolution Characteristics and Driving Factors of Heat Island Effect Based on Territorial Perspective: A Case Study of Beibu Gulf Urban Agglomeration, China. *Ecol. Indic.* **2024**, *166*, 112197. [CrossRef]
29. Wang, J.; Qian, Y.-G.; Han, L.-J.; Zhou, W.-Q. Relationship between Land Surface Temperature and Land Cover Types Based on GWR Model: A Case of Beijing-Tianjin-Tangshan Urban Agglomeration, China. *Yingyong Shengtai Xuebao* **2016**, *27*, 2128–2136. [CrossRef]
30. Yu, C.; Xu, D.; Peng, Y.; Zhou, S.; Lu, D. Analysis of Land Surface Temperature Drivers and Marginal Effect on the Yangtze River Delta Urban Agglomeration. *Ecol. Indic.* **2025**, *178*, 114123. [CrossRef]
31. Alimujiang, K.; Zhang, X.; Liang, H. The Spatial Relationship between Seasonal Surface Temperature and Landscape Pattern of the Urban Agglomeration on the Northern Slope of the Tianshan Mountains. *Geogr. Res.* **2024**, *43*, 1267–1287. [CrossRef]
32. Dong, L.; Pan, J.; Wang, W.; Feng, Y. Spatiotemporal Pattern of Summer Thermal Field and Its Relationship with Land Cover in Lanzhou Based on RS and GWR. *Soils* **2018**, *50*, 404–413. [CrossRef]
33. Airiken, M.; Zhang, F.; Chan, N.W.; Kung, H.-T. Assessment of Spatial and Temporal Ecological Environment Quality under Land Use Change of Urban Agglomeration in the North Slope of Tianshan, China. *Environ. Sci. Pollut. Res.* **2022**, *29*, 12282–12299. [CrossRef] [PubMed]
34. Wang, X.; Meng, Q.; Zhang, L.; Hu, D. Evaluation of Urban Green Space in Terms of Thermal Environmental Benefits Using Geographical Detector Analysis. *Int. J. Appl. Earth Obs. Geoinf.* **2021**, *105*, 102610. [CrossRef]
35. Cong, K.; Dong, C.; Bo, X.; Han, J. Evolution Analysis of Urban Spatio-Temporal Pattern in Shandong Province by Nighttime Light Remote Sensing. *J. Geomat.* **2021**, *46*, 78–82. [CrossRef]
36. Chen, Y.; Zheng, Z.; Wu, Z.; Qian, Q. Review and Prospect of Application of Nighttime Light Remote Sensing Data. *Prog. Geogr.* **2019**, *38*, 205–223. [CrossRef]
37. Shen, Z.; Zeng, J. Spatial Relationship of Urban Development to Land Surface Temperature in Three Cities of Southern Fujian. *Acta Geogr. Sin.* **2021**, *76*, 566–583. [CrossRef]
38. Halefom, A.; He, Y.; Nemoto, T.; Feng, L.; Li, R.; Raghavan, V.; Jing, G.; Song, X.; Duan, Z. The Impact of Urbanization-Induced Land Use Change on Land Surface Temperature. *Remote Sens.* **2024**, *16*, 4502. [CrossRef]
39. Sulekan, A.; Syed Jamaludin, S.S. Review on Geographically Weighted Regression (GWR) Approach in Spatial Analysis. *Malays. J. Fundam. Appl. Sci.* **2020**, *16*, 173–177. [CrossRef]
40. The Central Committee of the Communist Party of China and the State Council. *Outline of Ecological Conservation and High-Quality Development in the Yellow River Basin*; The State Council of the People's Republic of China: Beijing, China, 2021.
41. Chen, S.; Hu, D.; Wong, M.S.; Ren, H.; Cao, S.; Yu, C.; Ho, H.C. Characterizing Spatiotemporal Dynamics of Anthropogenic Heat Fluxes: A 20-Year Case Study in Beijing–Tianjin–Hebei Region in China. *Environ. Pollut.* **2019**, *249*, 923–931. [CrossRef]
42. Zhang, Y.; Luo, F. How Are Green Spaces Associated with Chronic Disease Incidence in Australia? Direct Health Benefits and Interactive Effects with Socioeconomic Status Based on Multiple Green Space Indicators. *Sustain. Cities Soc.* **2025**, *121*, 106229. [CrossRef]

43. Han, B.; Luo, Z.; Liu, Y.; Zhang, T.; Yang, L. Using Local Climate Zones to Investigate Spatio-Temporal Evolution of Thermal Environment at the Urban Regional Level: A Case Study in Xi'an, China. *Sustain. Cities Soc.* **2022**, *76*, 103495. [CrossRef]
44. Li, K.; Li, C.; Hu, Y.; Xiong, Z.; Wang, Y. Quantitative Estimation of the PM2.5 Removal Capacity and Influencing Factors of Urban Green Infrastructure. *Sci. Total Environ.* **2023**, *867*, 161476. [CrossRef]
45. Wang, Y.X.; Li, X.S.; Zhang, C.; He, W.K. Influence of Spatiotemporal Changes of Impervious Surface on the Urban Thermal Environment: A Case of Huai'an Central Urban Area. *Sustain. Cities Soc.* **2022**, *79*, 103710. [CrossRef]
46. Luo, F.; Zhang, Y.; Kong, Z.; Dai, Y. Which Green Is More Equitable? A Multi-Indicator Urban Green Space Assessment across Vulnerable Population Groups from an Environmental Justice Perspective. *Ecol. Indic.* **2025**, *178*, 113948. [CrossRef]
47. Wang, X.; Zhang, Y.; Yu, D. Exploring the Relationships between Land Surface Temperature and Its Influencing Factors Using Multisource Spatial Big Data: A Case Study in Beijing, China. *Remote Sens.* **2023**, *15*, 1783. [CrossRef]
48. Dong, C.; Shi, H.; Gao, Y.; Zheng, C.; Wu, Y.; Zhang, Y. The Buffering Effect of Topography Induced Microhabitat on Regional Temperature Change. *Acta Ecol. Sin.* **2023**, *43*, 5137–5149. [CrossRef]
49. Lin, Y.; Jim, C.Y.; Deng, J.; Wang, Z. Urbanization Effect on Spatiotemporal Thermal Patterns and Changes in Hangzhou (China). *Build. Environ.* **2018**, *145*, 166–176. [CrossRef]
50. Jia, Y.; Hao, C.; Niu, C.; Qiu, Y.; Du, J.; Xu, F.; Liu, H. Spatio-Temporal Variations of Precipitation and Runoff and Analyses of Water-Heat-Human-Land Matching Characteristics in Typical Mountainous Areas of China. *Acta Geogr. Sin.* **2019**, *74*, 2288–2302. [CrossRef]
51. Kim, Y.; Yu, S.; Li, D.; Gatson, S.N.; Brown, R.D. Linking Landscape Spatial Heterogeneity to Urban Heat Island and Outdoor Human Thermal Comfort in Tokyo: Application of the Outdoor Thermal Comfort Index. *Sustain. Cities Soc.* **2022**, *87*, 104262. [CrossRef]
52. Wang, C.; Li, Y.; Myint, S.; Zhao, Q.; Wentz, E. Impacts of Spatial Clustering of Urban Land Cover on Land Surface Temperature across Köppen Climate Zones in the Contiguous United States. *Landsc. Urban Plan.* **2019**, *192*, 103668. [CrossRef]
53. Liu, M.; Ma, H.; Bai, Y. Understanding the Drivers of Land Surface Temperature Based on Multisource Data: A Spatial Econometric Perspective. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2021**, *14*, 12263–12272. [CrossRef]
54. Chen, G.; Lu, X.; Li, Q.; Zhang, S.; Tysa, S.K. Divergent Urban Canopy Heat Island Responses to Heatwave Type over the Tibetan Plateau: A Case Study of Xining. *Land* **2025**, *14*, 2033. [CrossRef]
55. Chai, J.; Zhang, Z.; Chen, L.; Ma, X.; Wu, Z. Analysis of the Spatial and Temporal Evolution Characteristics and Driving Forces of the Surface Thermal Environment in Lanzhou City. *Sustainability* **2023**, *15*, 7700. [CrossRef]
56. Wang, J.; Lu, L.; Zhou, X.; Huang, G.; Chen, Z. Spatio-Temporal Patterns and Drivers of the Urban Heat Island Effect in Arid and Semi-Arid Regions of Northern China. *Remote Sens.* **2025**, *17*, 1339. [CrossRef]
57. Zhang, L.; Fang, C.; Zhu, C.; Gao, Q. Ecosystem Service Trade-Offs and Identification of Eco-Optimal Regions in Urban Agglomerations in Arid Regions of China. *J. Clean. Prod.* **2022**, *373*, 133823. [CrossRef]

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Urban Design and Resilient Cities: Simulating Crowd Behavior to Reduce Urban Risk

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Abstract

The growing incidence of natural and man-made disasters, exacerbated by climate change, has highlighted the role of urban planning and design in reducing the impact of the risks they pose. This refers to pre-disaster recovery planning (PDRP), an innovative practice that aims to improve the response of urban contexts affected by a disaster, with urban planning actions implemented in peacetime, i.e., before the disaster occurs. This paper presents a methodology that integrates agent-based simulation and safety-based urban design within a sustainability-oriented urban planning framework. The methodology aims to support the design of safer and more resilient public spaces, focusing on open areas within heritage districts and operating within a sustainability-oriented urban planning framework. The proposed approach integrates simulation and design to evaluate the performance of existing spatial layouts under stress conditions and explore alternative configurations that optimize evacuation dynamics and minimize risks. The result of applying the simulation to the current urban context therefore allows for the identification of appropriate urban design techniques and practices aimed at defining alternative spatial scenarios and improving the urban form in terms of its evacuation performance.

Keywords: urban design; urban safety; evacuation planning; resilient public spaces; sustainability-oriented

1. Introduction

The increase in the incidence of natural disasters due to climate change and urban dynamics that continue to consume land puts the role of urban planning and design at the center as a tool for reducing risk to humans. So-called Pre-Disaster Recovery Planning (PDRP), an emerging practice that pursues prevention objectives through pre-disaster preparedness, mitigation, and response capacity building, takes on a very important role. It includes how to keep urban management and essential services functioning, where to locate temporary housing, how and where to rebuild, how to reestablish essential economic activities, etc. Communities can and must take measures before they are hit by a disaster to ensure that the consequences of the disaster do not themselves become a disastrous and chaotic situation [1–3]. In this perspective, pre-disaster planning can be interpreted as a crucial component of sustainable urban development. Anticipating risk and integrating safety into spatial transformation processes contributes to the long-term sustainability of cities, reducing both environmental exposure and social vulnerability.

This article describes the results of research in the field of PDRP, which aims to use software to simulate crowd behavior during evacuation due to a disaster, to evaluate the performance of the settlement (the system of open public spaces) and implement urban design actions and interventions aimed at improving its urban form. This reduces urban risk and consequently increases safety and resilience [4,5]. The research described in this article therefore contributes to filling a significant gap in the scientific literature in the field of prevention, namely that of Safety-Based Urban Design (UDS-b). In fact, there is very little scientific research addressing the issue of urban design techniques for urban risk reduction using simulation tools, i.e., how to modify and adapt the urban form to make a neighborhood or city affected by natural or anthropogenic risks as safe as possible [6,7].

The research methodology can be summarized in six phases that are developed in the context of an Urban Digital Twin (UDT): (1) the construction of the simulation tool; (2) the identification of case studies on which to apply the tool from phase 1; (3) application of the simulator; (4) definition of UDS-b techniques; (5) construction of alternative urban scenarios aimed at risk reduction by applying the techniques from phase 4; (6) feedback from the simulation to verify the improvement in urban performance in terms of risk.

At the heart of this methodology is a simulation environment developed using the GAMA platform [8,9], which supports agent-based modeling of crowd behavior during emergencies. The platform allows for detailed representations of the built environment, crowd dynamics, and individual decision-making processes, making it particularly suitable for simulating evacuation scenarios triggered by catastrophic events such as earthquakes [10]. This simulation tool is integrated into a UDT that is being developed as part of a broader research project and incorporates an in-depth knowledge system that uses static and dynamic data (statistical and geographical data) with simulation tools (to verify urban performance) and representation tools (scenarios/dashboards) [11]. From a sustainability standpoint, the simulation-based approach supports the transition from reactive emergency management to proactive and adaptive spatial governance. By combining digital modelling, behavioural analysis, and design experimentation, the research provides a decision-support tool for managing environmental hazards within a framework of sustainable urban resilience.

This article is organized as follows. Section 2 reviews the relevant literature; Section 3 presents the materials and methods; Section 4 details the crowd-behavior simulator; Section 5 describes the Atri historic-centre case study and data preparation; Section 6 reports and discusses the results for Scenario 0 and Scenario 1; Section 7 concludes with implications and avenues for future research.

2. Literature Review

The field of research that characterizes the study presented in this article draws on two major themes: (i) models and methods for simulating crowd behavior in the event of evacuation; (ii) urban design techniques aimed at reducing the risk of evacuation and consequently increasing urban safety and resilience.

In the first field, scientific literature highlights numerous experiences concerning the study of models and algorithms, highly differentiated on collective human dynamics [12–14] and very often concerning seismic hazards or fires. These studies use approaches based on multi-agent models [10,15–18], in some cases using libraries for the construction of the network model and the implementation of algorithms with databases to store spatial data and map viewers to represent the simulation results [19,20]. There are also experiences that implement simulation platforms. Alternatively, there is research that implements and builds interdisciplinary simulation platforms that can be used in very different contexts, not only for evacuation analysis and planning [9,21].

Analysis of the scientific literature shows that simulation tools are developed mainly for simulations inside buildings [22,23] and much less for open urban spaces [24–26]. These tools are very often based on artificial intelligence applications [27].

Some studies focus on analyzing the risk of the road network by considering the flow of people in ordinary and evacuation situations [28], analyzing, for example, the connectivity of the network to identify the best routes in the event of a disaster [29,30] and the performance of emergency areas during evacuation, shelters, or strategic facilities for disaster response [31,32].

Other studies focus on data sources for modeling crowds, such as cell phones [23,33], or explore crowd behavior models to be applied to simulation, such as panic, highlighting the existence of a large body of research on this topic [17,24,25,34,35].

In the second field, urban design techniques aimed at risk reduction, scientific literature highlights few research experiences that link risk assessment, including evacuation through simulation tools, to the study of urban form performance. For example, there is research that evaluates this performance in relation to the location of shelters using Geographic Information Systems (GIS) and agent-based computer models [6], or that introduces new approaches to crowd management in relation to the contribution of urban design [36] or to actively guide crowds [37]. Specific research topics use simulation results to reorganize mobility infrastructure for evacuation [38,39]. Others attempt to identify urban design techniques for risk reduction and flexible planning and management of urban spaces, without evaluating the performance of urban form [7]. The research described in this article refers precisely to this specific topic, i.e., the use of tools for evaluating the performance of urban form aimed at risk reduction. In particular, the research focuses on evaluating the performance of open public spaces as nodes in the evacuation and emergency management network. A review of the scientific literature shows that there is a lack of scientific research in this field, which our work aims to fill by studying a tool for simulating crowd behavior whose application to an urban context allows us to assess its performance in terms of evacuation risk following a disastrous event.

3. Methodology

As mentioned in the previous paragraphs, the objective of the research described in this article is to define and apply a methodology aimed at applying a tool for simulating crowd behavior during an evacuation due to a disastrous event to urban contexts of various types and forms in various urban contexts, and consequently to apply urban design techniques to the settlement structure based on safety and aimed at improving urban performance for evacuation and thus increasing urban resilience. This work proposes a general simulation-informed design procedure for outdoor public spaces, organized as a simulate $\rightarrow$ design $\rightarrow$ re-simulate cycle. Spatial modifications are implemented as parametric operators (opening/resizing of access points, removal of obstacles, reallocation and sizing of assembly areas, wayfinding measures) and tested across multi-scale scenarios with capacity constraints at the destinations. Performance is assessed with replicable metrics (time to safety, cumulative share of people safe, density and bottlenecks), and the marginal effect of each operator is estimated through replications and sensitivity analysis, yielding quantitative feedback directly usable in design. Moreover, the procedure acts as an evidence-based validator of civil-protection emergency plans by stress-testing key parameters—such as assembly-area capacity and placement, and the effectiveness of wayfinding—against simulated demand and pedestrian behavior. This represents a scientific and methodological advance, since emergency planning is typically decoupled from urban planning and the provision/configuration of public space often follows ad hoc, preference-driven choices; our approach anchors those decisions in reproducible,

model-based evidence. The method's structure is independent of the case study and is transferable to different contexts given the same basic inputs (walkable network, population, assembly areas).

The methodology is divided into the following phases, which are developed in the context of a UDT:

(1) The design and implementation of the software for the simulation tool.
(2) The identification and characterization of case studies to which the tool from phase 1 can be applied.
(3) The application of the simulator to the case studies to obtain the pre-project Scenario 0.
(4) The definition of UDS-b techniques for risk reduction.
(5) The assessment of urban risk and the construction of alternative urban scenarios (post-project Scenario 1) aimed at risk reduction by applying the techniques of phase 4.
(6) Feedback from the simulation to verify the improvement in urban performance in terms of risk.

The first phase concerns the development of the modeling environment. The open-source GAMA platform was used, which supports spatially explicit agent-based simulations with customizable behavioral parameters [8,9]. Each agent within the model represents a single actor with specific attributes, such as movement speed and decision-making patterns, and can react dynamically to environmental stimuli and the behavior of surrounding agents. Simulation scenarios are evaluated using a set of performance indicators commonly adopted in evacuation studies. These include total evacuation time, average and maximum crowd density in critical areas, and the percentage of agents reaching safety within a defined time threshold. These indicators allow for quantitative comparison between baseline and optimized scenarios and provide empirical evidence to guide land-use planning decisions [30]. To ensure the robustness of the model, validation procedures include internal consistency checks, sensitivity analyses, and consultations with industry experts. The second phase (Phase 2) involves identifying case studies and developing GIS vector bases to be imported into the simulator (Phase 1) in QGIS open-source software version 3.34, which models all urban elements, and particularly the system of open public spaces useful for defining the evacuation network. The spatial model is constructed using a combination of institutional and open access datasets. These include orthophotos and topographic maps for reconstructing the morphology of the site, vector data on buildings and routes, and population estimates derived from institutional records and statistical sources. This provides the basis for the pre-project Scenario 0. In Phase 3, the results of the Scenario 0 simulation provide a diagnostic assessment of the site's critical issues, highlighting problem areas in terms of crowd congestion, insufficient capacity of emergency gathering points (waiting or safety areas), or delays in individuals reaching safe areas. The behavioral logic implemented in the model is based on established principles in evacuation science, with particular attention to the influence of spatial constraints on pedestrian movement, as explored in works such as Shiwakoti and Sarvi [35] and Wang et al. [17].

Based on the diagnostic results, Phase 4 involves the formulation of spatial interventions, derived from UDS-b techniques, aimed at improving the evacuation performance of the system. These interventions, designed within an integrated GIS and simulation environment, may involve the repositioning or expansion of emergency areas, the modification of pedestrian circulation routes, or the removal of spatial barriers that hinder exit. UDS-b is linked to the identification of the urban risk that generates it and which is reflected in the evacuation risk. In Phase 5, the post-project scenario is constructed by applying the UDS-b to the existing urban structure with the aim of reducing both the evacuation risk and the urban risk. The latter is an intrinsic characteristic of the urban organism and derives from the combination of urban hazard with vulnerability and exposure. Once implemented, the

new post-project scenario (Phase 5) is subjected to a second simulation (Phase 6), which allows for a comparative assessment with respect to the baseline condition and thus provides feedback information. This cyclical process, based on successive iterations of simulation and redesign, allows for the progressive refinement of spatial solutions and the validation of design choices through measurable indicators. Such a feedback cycle [4,24,40] is essential for the transition from static, rule-based planning approaches to adaptive, performance-oriented spatial design. In short, the methodology employs an agent-based evacuation model. The environment is built from GIS layers: buildings as obstacles, a derived walkable network, designated safe areas with capacity (m^2/person), and diffuse obstacles (e.g., parked cars) that reduce effective width and free-flow speed. Agents (pedestrians) are initialized from population/address points with heterogeneous speed, reaction time, and route preferences. They navigate the pedestrian graph toward the nearest available safe area; capacities are monitored, and agents dynamically reroute when an area saturates, or local congestion emerges. Model outputs include (i) time series of safe-area occupancy and saturation/clearance times and (ii) a georeferenced "crowdness" map highlighting highly traversed segments and critical choke points. These outputs support comparative testing of the current state (Scenario 0) versus design alternatives, enabling iterative, safety-oriented adjustments to public-space configuration and safe-area provision.

4. The Crowd Behavior Simulator

The simulator is an agent-based environment implemented in GAMA and organized around a compact set of species that encode the urban context and evacuation dynamics in a spatially explicit way (georeferenced inputs, continuous space, discrete time). The design follows established practice in evacuation ABMs—behavioral heterogeneity, congestion effects, reproducible scenario management—and leverages GAMA's GIS-native modelling and scheduling [8,9]. Each pedestrian is an autonomous agent with a bounded-rational perceive–evaluate–act loop. Attributes include preferred speed, acceleration bounds, perception radius, compliance, and noise terms. Route choice balances shortest-path tendencies with density-aware re-routing and obstacle avoidance; social influence (herding/following) is parameterized rather than hard-coded to allow sensitivity tests against behavioral assumptions reported in evacuation literature [12,41,42]. Motion controllers enforce collision avoidance and density-dependent speed adaptation to reproduce bottleneck saturation and flow nonlinearities [17]. Buildings are polygonal, non-walkable obstacles that structure the urban fabric and constrain both visibility and movement. Scenario rules may attach attributes (e.g., height/frontage) and debris buffers to reflect event-induced hindrances that slow or divert flows, consistent with city-scale evacuation modelling that explicitly treats open-space accessibility and barrier states [10]. The obstacle species covers permanent impediments (fences, walls, closed gates) and temporary ones (narrowings, works, debris). A light typology scheme governs whether an obstacle is hard (impassable) or soft (speed penalty). Among soft obstacles, parked vehicles can be optionally ingested via a shallow deep-learning detection on aerial/satellite imagery [43]; detected footprints are vectorized and used to reduce effective corridor width along walkable surfaces, leaving the behavioral engine unchanged [6]. Walkability is encoded as a pedestrian graph derived from tessellated walkable polygons and centroid connections, supplemented by local permeability rules. Agents move in continuous space but query this graph to compute least-cost targets and trigger re-routing when link costs change (capacity usage, temporary closures). Assembly areas (waiting/safety spaces) are target nodes with capacity constraints and occupancy tracking for performance assessment [4]. A central scheduler advances environment fields and agent steps; stochastic elements (departure delays, tiebreakers, perception noise) are controlled by seeded streams to enable ensemble reproducibility and

sensitivity analysis [42]. The simulator returns scalar metrics (total evacuation time, share reaching safety at fixed horizons, peak/mean densities), time series (occupancy/evacuation curves), and georeferenced raster/vector of cumulative footfall and congestion for before/after comparison in design iterations [4,8]. Bounded rationality is represented by finite perception, decision tolerances, and network-constrained route choice. Multiple parameters about agents' behavior are defined. Agents perceive obstacles and peers within fixed radii (P_obstacle_consideration_distance = 3.0 m, P_pedestrian_consideration_distance = 3.0 m), accept small target deviations (P_tolerance_target = 0.8), and may attempt a detour with probability P_proba_detour = 0.5. Movement follows the Social Force Model (SFM) provided by GAMA with the parameter sets declared in the code: simple (P_A_pedestrian_SFM_simple = 4.5, P_relaxion_SFM_simple = 0.54, P_gama_SFM_simple = 0.35, P_lambda_SFM_simple = 2.0, P_n_prime_SFM_simple = 3.0, P_n_SFM_simple = 2.0). Desired speed is sampled from a truncated normal distribution (gauss (3.6, 1.8) km/h, clipped to 3–4 km/h). Route choice targets the nearest safe area along the pedestrian network, subject to capacity limits read from the shapefile attributes (max_capacity).

These values are empirically grounded by accepted ranges in the pedestrian-dynamics literature but are not fitted to site-specific trajectories. Accordingly, the model is used to compare design operators and capacity configurations rather than to predict individual routes. Validation is performed at the outcome level: (i) capacity consistency at assembly areas (occupied slots vs. max_capacity exported in goals.csv), and (ii) plausibility of spatio-temporal crowding patterns derived from the instant/history heatmaps.

5. Case Study

The case study focuses on the historic center of Atri (Abruzzo, Italy), a hilltop settlement characterized by compact medieval fabric, narrow streets with variable cross-sections and sharp curvature (Figure 1). This morphology, together with the prevalence of masonry buildings and tightly interlocked fronts, creates a highly constrained pedestrian network where small variations in effective width or continuity can trigger disproportionate congestion during emergency egress. The presence of a limited number of open public spaces of adequate size—potential waiting or safety areas—further concentrates evacuation demand along a few critical corridors, heightening sensitivity to local bottlenecks and temporary impediments.

These spatial properties align with issues repeatedly documented in city-scale evacuation studies, in which accessibility of open spaces and barrier states condition time-to-safety outcomes. The knowledge base integrates institutional vector datasets (building footprints, public space polygons, street fabric) with orthophotos and derived layers used to operationalize evacuation modelling. Buildings are represented as polygons with attributes required by the simulator (e.g., height or frontage where available), while candidate emergency safe areas are digitized and parameterized with conservative capacity assumptions. Safe areas come from the Civil Protection Emergency Plan for the Municipality of Atri. A conservative capacity was assigned to each designated waiting area by dividing its net usable surface by 2.5 m^2 per person (as a precaution for the possibility that the crowd might stay for a long time). This threshold, already adopted in previous assessments on size and site selection of emergency assembly points [44], balances the need to prevent excessive crowding with the operational requirement to accommodate short-to-medium stays during post-event coordination (e.g., triage, information, redistribution). In the simulator, this value becomes a hard capacity constraint: once instantaneous occupancy approaches the computed limit, incoming agents are re-routed to alternative areas, and the resulting occupancy trajectories are recorded for performance assessment. Table 1 shows safe area surface and capacity calculated according to these parameters.

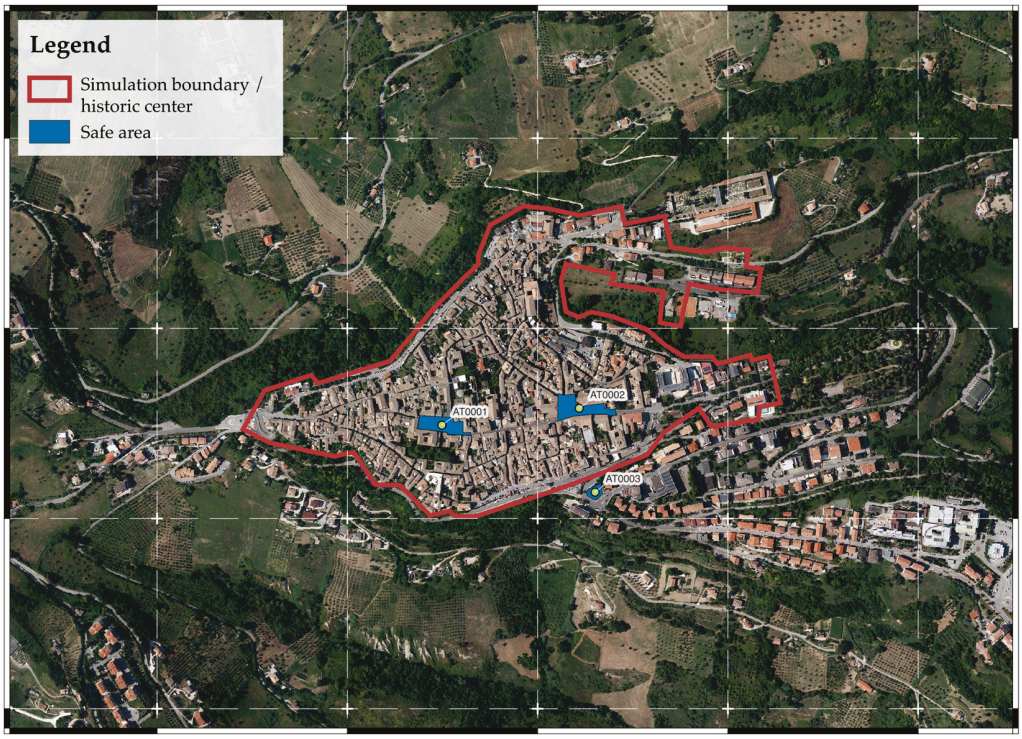


Figure 1. Aerial view of the area.

Table 1. Safe area dimension and capacity.

Safe Area Id	Surface (m^2)	Maximum Capacity (People)
AT0001	1984	794
AT0002	2177	871
AT0003	449	180
Total	4610	1845

Population proxies are associated with address points to define origins and initial agent allocations. Number of residents for each address points were provided by the local municipality in an excel table containing addresses and residents (e.g., "Street name and house number, number of residents"). The table was imported in QGIS and geocoded using MMQGIS plugin in order to generate georeferenced points in the case-study environment. Walkability is encoded by deriving a pedestrian graph from the polygonal street fabric via regular tessellation and centroid connectivity, preserving local permeability and enabling shortest-path queries and dynamic re-routing during the simulation. Assembly areas are treated as target nodes with capacity and occupancy tracking, while buildings function as non-walkable obstacles that also shape visibility fields along the network. To reflect Atri's historically constrained cross-sections, a layer of soft obstacles is introduced, accounting for localized reductions in effective width along key corridors. Among these, parked vehicles are detected from recent aerial/satellite imagery through a lightweight deep-learning workflow; detections are vectorized and used to apply segment-level width penalties without altering the behavioral engine.

6. Results

The simulation framework is based on a set of general parameters that are consistent across all case studies. These include: the total number of people evacuating from each building and traveling to designated emergency assembly areas via the shortest available route; the time taken to reach these areas; and the progressive occupancy rate of each emergency zone over time. The simulation results are organized into two scenarios: the

first (Scenario 0) corresponds to the current spatial configuration of each campus, while the second (Scenario 1) reflects an optimized layout developed through the application of UDS-b strategies. The simulation code was custom developed by the authors and calibrated to ensure effective integration between the modeling environment and pre-processed geospatial data in a GIS environment. These spatial data form the foundation of the modeling process. At the end of each simulation, a georeferenced raster output is generated that represents the level of crowding along the pedestrian routes used during the evacuation. This output can be directly overlaid on the original spatial data to allow for comparative and visual analysis.

6.1. Scenario 0—Initial Conditions for Urban Performance

In the baseline configuration, as mentioned before, the historic center of Atri is modelled with three designated waiting areas (AT0001, AT0002, AT0003). The spatial layer visualizes and enforces both permanent barriers (building fronts, walls, fenced perimeters) and soft impediments along corridors (local narrowings, curvature-induced pinch points, and parked vehicles vectorized from aerial/satellite imagery via a lightweight deep-learning workflow), as recommended for credible city-scale evacuation assessment in heritage fabrics (Figure 2).



Figure 2. Scenario 0: The results of applying the initial conditions (pre-project) of the simulation.

These impediments are treated as non-walkable (hard) or penalized (soft) obstacles and are rendered on the georeferenced outputs to make critical path constraints explicit during analysis [5,10]. The occupancy trajectories of the three safe areas (Figure 3) show differentiated uptake dynamics. AT0001 exhibits the fastest growth and reaches saturation at approximately 4.38 min, after an inflection between 3–4 min; this rapid filling suggests a favorable catchment and short access paths, but also signals a potential under sizing relative to its demand basin. AT0002 follows a steadier trajectory, surpassing 60% around 3 min, approaching ~98–100% by ≈5.45 min, which indicates balanced accessibility with residual tail effects likely linked to downstream corridor capacity. AT0003 displays a delayed onset (near zero until roughly 2 min), a mid-course acceleration between 3–5 min, and completes at about 5.83 min; the late start and long tail are consistent with longer approach routes and sensitivity to localized narrowings highlighted in the obstacle layer.

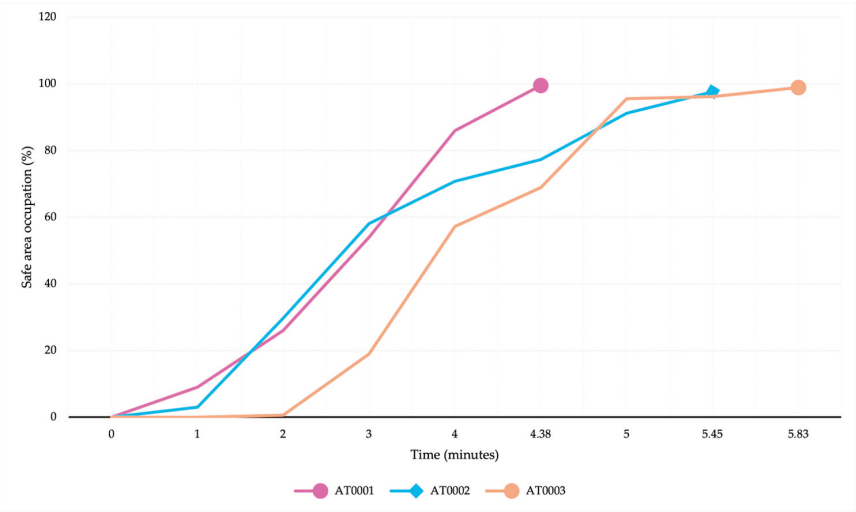


Figure 3. Scenario 0: safe area occupation over time.

These patterns—early saturation in proximal areas, steady but extended filling for centrally located spaces, and delayed convergence for peripheral or poorly connected spaces—mirror established findings on the interplay between open-space accessibility, corridor capacity, and temporary impediments in evacuation performance. Overall, Scenario 0 reveals (i) a high dependency on a limited set of feeder corridors, where mapped obstacles concentrate congestion, and (ii) asymmetric demand among the three waiting areas, with AT0001 absorbing arrivals quickly and AT0003 underperforming until impediments clear. For Scenario 0, from a total of 2831 people, 986 can't reach safe areas due to not sufficient capacity. These diagnostics provide the evidence base for UDS-b adjustments in Scenario 1, targeting corridor regularization, selective capacity rebalancing across the three areas, and the mitigation of soft obstacles to shorten tails in the occupancy curves.

6.2. Scenario 1—Optimized Urban Performance Conditions

The simulation applied to Scenario 0 made it possible to identify critical issues for evacuation and, consequently, critical issues in the structure and urban form that increase risk. The aim of the research is therefore to precisely define the urban elements that determine these critical issues and to intervene on their form to reduce the risk. This intervention takes the form of applying UDS-b techniques to urban contexts in Scenario 0 [45]. These interventions aim to reconfigure and reorganize the system of open public urban spaces, considered emergency areas, i.e., waiting or safety areas. This is done with the aim of reducing the risk of evacuation and, consequently, the time required for it, and eliminating the spatial obstacles that affect and make pedestrian flow critical.

6.2.1. UDS-b Techniques and Their Application

Simulation of Scenario 0 allows us to identify critical issues for evacuation during a specific disaster event. In our research, the simulation concerns a seismic event, but other hazards such as floods or landslides are also being studied. It is important to note that the GIS model of Scenario 0 is not only a representation of the current state of an urban structure, but also includes obstacles to evacuation identified in a specific urban risk study in two areas: (1) obstacles identified in an assessment of impediments caused by urban elements (specific shapes, street furniture, etc.); (2) obstacles derived from an analysis of the vulnerability of the built heritage, through which the possible damage to this heritage is identified and, therefore, the obstacles caused by the probable fall of debris or the opening of cracks. Debris are static and are generated from the buildings with the highest vulnerability index. This data comes from the Municipality's emergency plan that, according to the Italian regulations on these topics, contains insights and evaluations on built environment vulnerability. Obstacles identified with satellite images deep-learning analysis are static as well. In this article, the measures envisaged for risk reduction (UDS-b) refer only to the first field of study, obstacles. The table below (Table 2) is the result of a collection of studies that consider both above fields and do not only provide a classification of obstacles to evacuation but a complete collection of all factors that prevent evacuation.

Table 2. Risk factors for evacuation (revised from [45]).

Risk Factors for Evacuation	References
1. Presence of direct or indirect obstacles	
Stairs; Steep areas; Damaged pavement; Low grip paving; Curbs/absence of sidewalk ramps; Ditches; Bumps; Unsafe or unstable retaining walls; Road embankment with a slope > 2/3 (34°), unstable or looming; Bulky street furniture; Fences, closed gates	[45–50]
Cul de sac	[46,48]
Collapses	[45,51–53]
Railroad crossings; Interfering building aggregates	[45,46,49]
2. Emergency elements shape factor	
Excessive curvature; Excessive number of turns/redundant grids; Exceeding escape route capacity; Exceeding emergency area/open space/shelter/safe place capacity	[7,44,45,48,51–62]
3. Accessibility/Connection to emergency shelter	
Exceeding critical isochrones; Connectivity factor	[63]
4. Inefficiency of technological and road networks	
Road works at risk (tunnels, bridges, overpasses, etc.)	[30]
Path of technological networks unknown; Incomplete; technological networks (e.g., lack of telecommunications networks); Occluded technological networks	[52,53,60]

The risk factors for evacuation (Table 2) represent the structural elements and conditions of a neighborhood or urban district (but also of the entire city) that prevent or slow down evacuation during a disaster. It is these factors that UDS-b techniques act upon, with the aim of reducing urban risk as defined at the beginning of Section 6.2.1 to acceptable levels as much as possible. These techniques, which are currently in the classification and exemplification phase, aim to reduce or eliminate the effect of direct and indirect obstacles (category 1 in Table 2), improve the accessibility and design of emergency shelters (categories 2 and 3 in Table 2), and increase the efficiency of technological and road networks (category 4 in Table 2). Scenario 1 described in the following section derives from the application of these techniques.

6.2.2. Safety-Based Redesign with Distributed Micro Safe Areas

Scenario 1 operationalizes a UDS-b technique that introduces a distributed system of micro safe areas uniformly embedded within the historic fabric. Each new area is parameterized with conservative capacity (net area/2.5 m^2 per person) and mapped to the pedestrian graph as a target node, thereby shortening access distances and diversifying feasible destinations for simulated residents. The obstacle layer remains active (permanent barriers and soft impediments), but local routing pressure is rebalanced by increasing the density of admissible refuge points across the center. The occupancy trajectories (Figure 4) evidence a marked temporal dispersion of arrivals across nine safe areas (AT0001–AT0009), with several micro areas saturating very rapidly (e.g., AT0006 ≈ 1.4 min; AT0009 ≈ 2.5 min; AT0007 ≈ 4 min), while others stabilize at partial loads (AT0003 ≈ 33%; AT0004 ≈ 45%) and only a few carries a longer tail (e.g., AT0005 approaching 100% near ≈18 min). Compared to Scenario 0—where three areas absorbed demand with early saturation and long residual queues—the peak loads are redistributed, early local saturations occur closer to origins, and plateau effects in mid-size areas indicate relief of corridor bottlenecks rather than overflow. These dynamics are consistent with the expected benefits of increasing refuge granularity in constrained fabrics: shorter egress paths, more balanced catchments, and reduced competition on the same feeder links [64].

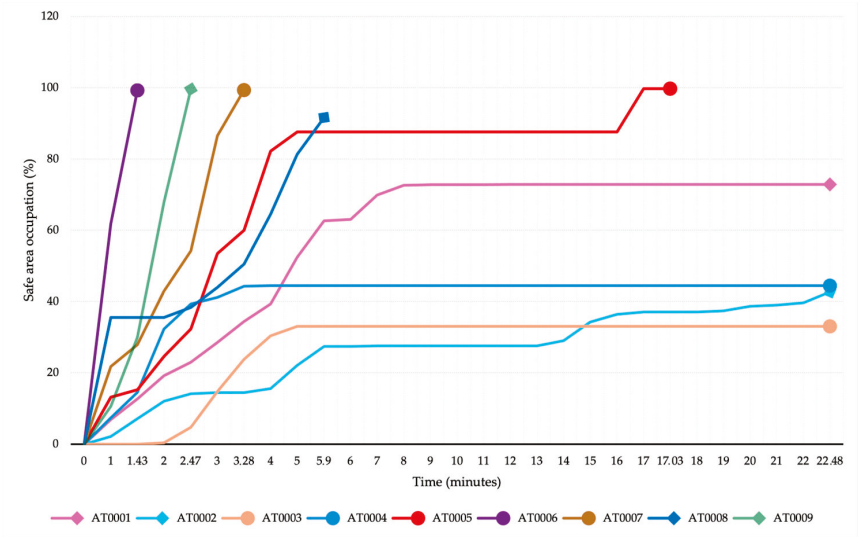


Figure 4. Scenario 1: safe area occupation over time.

The georeferenced "crowdness" maps for Scenario 1 (Figure 5) show attenuated hot spots along the primary east–west spine and at previously critical junctions (Zooms 1–3). By creating additional target nodes within one or two turns of most origins, the redesign breaks up long, curvature-constrained corridors typical of the medieval network and limits the build-up of density at choke points identified in Scenario 0. This spatial smoothing reflects the coupling of behavioral re-routing with increased destination availability, a pattern also emphasized in evacuation literature when open-space accessibility is improved [10]. Relative to Scenario 0, the micro-area strategy:

(1) Reduces average time-to-safety for residents closest to the added refuges (early, steep occupancy curves).
(2) Lowers maximum corridor densities by distributing flows onto multiple short approach paths.
(3) Limits tail behavior to a small subset of areas influenced by terrain or residual soft obstacles.
(4) Allows all citizens to reach safe areas.



Figure 5. Scenario 1: Simulation results when applying post-project conditions.

These improvements substantiate the efficacy of UDS-b as a simulation-informed intervention: modest, spatially even additions to the refuge system yield disproportionate gains in evacuation performance (Table 3) without altering the behavioral engine or relaxing obstacle constraints (Figure 6).

Table 3. Scenario 1 safe area dimension and capacity.

Safe Area Id	Surface (m^2)	Maximum Capacity (People)
AT0001	2,480,124	992
AT0002	2,903,903	1162
AT0003	642,807	257
AT0004	1,997,805	799
AT0005	967,085	387
AT0006	346,816	139
AT0007	780,474	312
AT0008	268,536	107
AT0009	566,321	227



Figure 6. Scenario 0 and 1 zoom comparison.

7. Conclusions

This study presented a simulation-driven approach to UDS-b, coupling an agent-based evacuation model with a geospatial representation of the historic centre of Atri in Italy. By translating morphological constraints and soft impediments into operational inputs, the framework quantified how modest spatial interventions—specifically, the introduction of uniformly distributed micro safe areas—can rebalance routing pressure, shorten effective egress distances, and dampen corridor bottlenecks. Methodologically, the contribution lies in the tight integration of GIS-backed urban form, behaviorally plausible agents, and design feedback cycles that convert performance diagnostics into spatial decisions. Substantively, the results support the use of evacuation performance as a measurable criterion for PDRP and the configuration of public space networks in heritage fabrics. The implementation is intentionally minimal and comparative. Behavioral parameters are range-grounded rather than site-fitted: desired speeds are sampled from a truncated normal, perception radii are fixed, and movement follows GAMA's SFM with the declared simple/advanced parameter sets. "Herding" is not an explicit imitation term; it emerges from local interactions and congestion within SFM and the network constraints. Decision-making is bounded via tolerances and simple heuristics: agents target the nearest assembly area on the pedestrian network, accept small target deviations, and may attempt detours with a fixed probability. The model does not represent heterogeneity in compliance, learning, or information broadcasting (e.g., dynamic guidance), and signage is not modelled as a dynamic stimulus. Capacity at destinations is enforced through the max_capacity attribute read from shapefiles, and occupancy is recorded. However, door/queue mechanics at exits are not explicitly modelled and moving obstacles or vehicles are not active in the experiments. The environment is static; hazards are not explicitly simulated. Validation is conducted at the outcome level (capacity consistency at assembly areas; plausibility of instant/history heatmaps) rather than through trajectory-level calibration, due to the unavailability of micro-data. For these reasons, the model is intended for relative appraisal of design opera-

tors and capacity configurations—i.e., to rank interventions and stress-test civil-protection parameters—rather than to produce absolute, site-calibrated evacuation-time predictions.

With this case study, a safety-based urban design strategy that removes on-street parking within the historic core to restore effective pedestrian width and reduce conflict points during evacuations was explored. While this is framed as a "what-if" scenario—since it presupposes the creation of peripheral public parking areas and associated access management—it illustrates how strategic, network-scale interventions can measurably improve responsiveness and resilience under natural-hazard conditions. By clearing stationary vehicles, the public-space system becomes more legible and permeable, lowering congestion risk, shortening clearance times, and increasing the robustness of route alternatives when localized bottlenecks occur. This approach is inherently strategic rather than purely tactical: it requires coordinated land-use decisions for replacement parking, staged implementation, and operational protocols for emergency alerts (e.g., temporary parking bans during forecast windows). It also yields important co-benefits beyond emergencies—enhanced walkability, improved public-realm quality, and reduced visual clutter—supporting the everyday functioning and heritage value of historic centers. Our results should be read as comparative evidence: the simulation indicates performance gains under specified assumptions, but feasibility, equity implications, and stakeholder acceptance must be verified through design development, mobility planning, and participatory processes. In this sense, the Atri scenario serves as a transferable template for coupling evacuation performance analysis with strategic public-space reallocation in historic urban fabrics. At this stage the evacuation model is hazard-agnostic and represents the post-warning movement of pedestrians to designated safe areas. A specific earthquake (magnitude, intensity, duration) is not simulated nor simulate endogenous damage, debris, or link failures. Debris, as explained, is a static obstacle defined according to the elements contained in Emergency Plan of the local municipality. Results should therefore be read as comparative evidence of how spatial configurations influence evacuation performance, not as event-specific impact forecasts.

Future work will deepen behavioral realism and broaden operational scope along four lines.

(i) Agent typologies and inclusivity: we will extend the population model to incorporate distinct "types" of evacuees—e.g., persons with mobility, visual, or auditory impairments; children; older adults—assigning differentiated speeds, perception, assistance needs, and decision heuristics. This will enable equity-aware evaluation of design options and sensitivity tests on inclusive routing and refuge provision.

(ii) Real-time data and validation: building on the UDT architecture, we will integrate near-real-time data streams (e.g., sensors, mobile telemetry, operational reports) to inform boundary conditions, calibrate key parameters, and conduct progressive validation under controlled drills or routine crowd conditions—addressing known gaps in empirical grounding for evacuation ABMs.

(iii) Scalability and transferability: the pipeline will be applied to larger, denser contexts—multi-district cores and metropolitan sub-systems—to test computational scalability, robustness of behavioral modules under high loads, and portability of design heuristics across varying urban morphologies and risk profiles.

(iv) Coupling the model with seismic fragility and ground-motion scenarios to represent blockage, capacity loss, and time-varying pre-movement under shaking and aftershocks.

These extensions will advance the framework from a decision-support prototype to an operational toolchain for emergency planning and everyday urban design: capable of accommodating heterogeneous populations, leveraging live data for model credibility, and informing policy at scales ranging from historic districts to populous cities.

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References

1. FEMA. Pre-Disaster Recovery Planning Guide for Local Governments. FEMA Publication FD 008-03. 2017. Available online: https://www.fema.gov/sites/default/files/2020-07/pre-disaster-recovery-planning-guide-local-governments.pdf (accessed on 2 February 2024).
2. Otsuyama, K.; Maki, N. A Comparative Analysis and Identification of Issues on Legislative Systems for Pre-Disaster Recovery Planning in Japan and U.S. *J. City Plan. Inst. Jpn.* **2018**, *53*, 132–143. (In Japanese) [CrossRef]
3. IRP-UNISDR. Guidance Note on Recovery. Pre-Disaster Recovery Planning. International Recovery Platform and United Nations Office for Disaster Risk Reduction. 2012. Available online: https://www.preventionweb.net/files/31963_predisasterrecoveryweb.pdf (accessed on 2 June 2024).
4. Di Ludovico, D.; Eugeni, F.; Zanfardino, G.; Di Marco, A. Simulating crowd behaviour to implement safety-based urban design techniques aimed at optimizing evacuation. *J. Urban Des.* **2025**, *30*, 401–422. [CrossRef]
5. Eugeni, F.; Zanfardino, G.; Di Ludovico, D. A crowd simulation-based tool for environmentally hazard-conscious urban design. *BDC-Boll. Del Cent. Calza Bini* **2024**, *24*, 147–162.
6. León, J.; March, A. An urban form response to disaster vulnerability: Improving tsunami evacuation in Iquique, Chile. *Environ. Plan. B Plan. Des.* **2016**, *43*, 826–847. [CrossRef]
7. Fallah, M.; Masoud, M.; Navaie, A. Role of resilient and flexible urban space in disaster Management. *Bull. Environ. Pharmacol. Life Sci.* **2014**, *3*, 01–06.
8. Taillandier, P.; Gaudou, B.; Grignard, A.; Huynh, Q.-N.; Marilleau, N.; Caillou, P.; Philippon, D.; Drogoul, A. Building, Composing and Experimenting Complex Spatial Models with the GAMA Platform. *Geoinformatica* **2018**, *23*, 299–322. [CrossRef]
9. Taillandier, P.; Vo, D.A.; Amouroux, E.; Drogoul, A. GAMA: Bringing GIS and Multi-Level Capabilities to Multi-Agent Simulation. In Proceedings of the 8th European Workshop on Multi-Agent Systems, Paris, France, 16–17 December 2010.
10. Iskandar, R.; Allaw, K.; Dugdale, J.; Beck, E.; Adjizian-Gérard, J.; Cornou, C.; Harb, J.; Lacroix, P.; Badaro-Saliba, N.; Cartier, S.; et al. Agent-based simulation of pedestrians' earthquake evacuation; application to Beirut, Lebanon. *arXiv* **2023**, arXiv:2309.02812. [CrossRef]

11. Sara, S.; Eugeni, F.; Di Ludovico, D. Urban and Spatial Planning Through the Support Tool of the Regional Digital Twin. In Proceedings of the Innovation in Urban and Regional Planning, Input 2023, L'Aquila, Italy, 6–8 September 2023; Marucci, A., Zullo, F., Fiorini, L., Saganeiti, L., Eds.; Lecture Notes in Civil Engineering. Springer: Berlin/Heidelberg, Germany, 2024; pp. 221–229, ISBN 9783031541179, ISSN 2366–2557. [CrossRef]
12. Yang, S.; Li, T.; Gong, X.; Peng, B.; Hu, J. A review on crowd simulation and modelling. *Graph. Models* **2020**, *111*, 101081. [CrossRef]
13. Haghani, M.; Sarvi, M. Crowd behaviour and motion: Empirical methods. *Transp. Res. Part B* **2018**, *107*, 253–294. [CrossRef]
14. Moghaddam, M.T.; Muccini, H.; Dugdale, J.; Kjagaard, M.B. Designing Internet of Behaviors Systems. In Proceedings of the 2022 IEEE 19th International Conference on Software Architecture (ICSA), Honolulu, HI, USA, 12–15 March 2022; pp. 124–134. [CrossRef]
15. Jobert, O.; Predhumeau, M.; Dugdale, J. Modelling and simulating age-dependent pedestrian behaviour with an autonomous vehicle. In Proceedings of the 37th ECMS International Conference on Modelling and Simulation ECMS 2023, Florence, Italy, 20–23 June 2023. [CrossRef]
16. Li, C.; Hou, J.; Cheng, W.; Gai, W. A multiagent-based modeling approach for emergency evacuation plan optimization during toxic gas releases within chemical plants. *Process Saf. Environ. Prot.* **2022**, *163*, 543–557. [CrossRef]
17. Wang, G.-N.; Chen, T.; Chen, J.-W.; Deng, K.; Wang, R.-D. Simulation of crowd dynamics in pedestrian evacuation concerning panic contagion: A cellular automaton approach. *Chin. Phys. B* **2022**, *31*, 060402. [CrossRef]
18. Almeida, J.E.; Rosseti, R.J.F.; Coelho, A.L. Crowd Simulation Modeling Applied to Emergency and Evacuation Simulations using Multi-Agent Systems. *arXiv* **2013**, arXiv:1303.4692. [CrossRef]
19. Chondrogiannis, T.; Bouros, P.; Emser, W. Simulation-based Evacuation Planning for Urban Areas. In Proceedings of the 29th International Conference on Advances in Geographic Information Systems (SIGSPATIAL '21), Beijing, China, 2–5 November 2021; ACM: New York, NY, USA, 2021; 4p. [CrossRef]
20. Chooramun, N.; Lawrence, P.; Galea, E. Urban scale evacuation simulation using buildingEXODUS. In Proceedings of the 14th Interflam 2016 Conference Proceedings, London, UK, 4–6 July 2016; p. 2. Available online: http://www.intersciencecomms.co.uk/html/conferences/Interflam/If16/if16.htm (accessed on 14 May 2025).
21. Kleinmeier, B.; Zönnchen, B.; Gödel, M.; Köster, G. Vadere: An Open-Source Simulation Framework to Promote Interdisciplinary Understanding. *Collect. Dyn.* **2019**, *4*, 1–34. [CrossRef]
22. Pluchino, A.; Garofalo, C.; Inturri, G.; Rapisarda, A.; Ignaccolo, M. Agent-Based Simulation of Pedestrian Behaviour in Closed Spaces: A Museum Case Study. *J. Artif. Soc. Soc. Simul.* **2014**, *17*, 16. [CrossRef]
23. Yoshimura, Y.; Sobolevsky, S.; Ratti, C.; Girardin, F.; Carrascal, J.P.; Blat, J.; Sinatra, R. An Analysis of Visitors' Behavior in the Louvre Museum: A Study Using Bluetooth Data. *Environ. Plan. B Plan. Des.* **2014**, *41*, 1113–1131. [CrossRef]
24. Liu, Y.; Lyu, L. Diversified Crowd Evacuation Method in Large Public Places. *IEEE Access* **2019**, *7*, 144874–144884. [CrossRef]
25. Simonov, A.; Lebin, A.; Shcherbak, B.; Zagarskikh, A.; Karsakov, A. Multi-agent crowd simulation on large areas with utility-based behavior models: Sochi Olympic Park Station use case. *Procedia Comput. Sci.* **2018**, *136*, 453–462. [CrossRef]
26. Mahmood, I.; Haris, M.; Sarjoughian, H. Analyzing Emergency Evacuation Strategies for Mass Gatherings using Crowd Simulation And Analysis framework: Hajj Scenario. In Proceedings of the SIGSIM-PADS '17: 2017 ACM SIGSIM Conference on Principles of Advanced Discrete Simulation, Singapore, 24–26 May 2017; pp. 231–240. [CrossRef]
27. Sidiropoulos, G.; Kiourt, C.; Moussiades, L. Crowd simulation for crisis management: The outcomes of the last decade. *Mach. Learn. Appl.* **2020**, *2*, 100009. [CrossRef]
28. Sasabe, M.; Fujii, K.; Kasahara, S. Road network risk analysis considering people flow under ordinary and evacuation situations. *Environ. Plan. B Urban Anal. City Sci.* **2020**, *47*, 759–774. [CrossRef]
29. Kim, J.; Park, J.; Kim, K.; Kim, M. RnR-SMART: Resilient smart city evacuation plan based on road network reconfiguration in outbreak response. *Sustain. Cities Soc.* **2021**, *75*, 103386. [CrossRef]
30. Bretschneider, S.; Kimms, A. Pattern-based evacuation planning for urban areas. *Eur. J. Oper. Res.* **2012**, *216*, 57–69. [CrossRef]
31. Howard, E.; Pasquini, L.; Arbib, C.; Di Marco, A.; Clementini, E. Definition of an Enriched GIS Network for Evacuation Planning. In Proceedings of the 7th International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM2021), Virtual Event, 23–25 April 2021; pp. 241–252. [CrossRef]
32. Yang, M.; Kumar, S.; Wang, X.; Fry, M.J. Scenario-robust pre-disaster planning for multiple relief items. *Ann. Oper. Res.* **2021**, *335*, 1241–1266. [CrossRef] [PubMed]
33. Yin, L.; Chen, J.; Zhang, H.; Yang, Z.; Wan, Q.; Ning, L.; Hu, J.; Yu, Q. Improving emergency evacuation planning with mobile phone location data. *Environ. Plan. B Urban Anal. City Sci.* **2020**, *47*, 964–980. [CrossRef]
34. Wachtel, G.; Schmöcker, J.-D.; Hadas, Y.; Gao, Y.; Nahum, O.E.; Ben-Moshe, B.P. Planning for tourist urban evacuation routes: A framework for improving the data collection and evacuation processes. *Environ. Plan. B Urban Anal. City Sci.* **2021**, *48*, 1108–1125. [CrossRef]

35. Shiwakoti, N.; Sarvi, M. Understanding pedestrian crowd panic: A review on model organisms approach. *J. Transp. Geogr.* **2013**, *26*, 12–17. [CrossRef]
36. Al-Kodmany, K. Crowd management and urban design: New scientific approaches. *Urban Des. Int.* **2013**, *18*, 282–295. [CrossRef]
37. Han, T.; Zhao, J.; Li, W. Smart-Guided Pedestrian Emergency Evacuation in Slender-Shape Infrastructure with Digital Twin Simulations. *Sustainability* **2020**, *12*, 9701. [CrossRef]
38. Kim, S.; Shekhar, S.; Min, M. Contraflow Transportation Network Reconfiguration for Evacuation Route Planning. *IEEE Trans. Knowl. Data Eng.* **2008**, *20*, 1115–1129. [CrossRef]
39. Kumar, K.; Romanski, J.; Van Hentenryck, P. Optimizing Infrastructure Enhancements for Evacuation Planning. In Proceedings of the Thirtieth AAAI Conference on Artificial Intelligence, Phoenix, AZ, USA, 12–17 February 2016; Volume 30. [CrossRef]
40. Radianti, J.; Granmo, O.C.; Bouhmala, N.; Sarshar, P.; Yazidi, A.; Gonzalez, J. Crowd Models for Emergency Evacuation: A Review Targeting Human-Centered Sensing. In Proceedings of the 46th Hawaii International Conference on System Sciences, Wailea, HI, USA, 7–10 January 2013; pp. 156–165. [CrossRef]
41. Karamouzas, I.; Sohre, N.; Narain, R.; Guy, S.J. Implicit Crowds: Optimization Integrator for Robust Crowd Simulation. *ACM Trans. Graph.* **2017**, *36*, 1–13. [CrossRef]
42. Wang, J.; Zhang, L.; Shi, Q.; Yang, P.; Hu, X. Modeling and simulating for congestion pedestrian evacuation with panic. *Phys. A Stat. Mech. Its Appl.* **2015**, *428*, 396–409. [CrossRef]
43. Aszkowski, P. Deepness: Deep neural remote sensing plugin for QGIS. *SoftwareX* **2023**, *23*, 101495. [CrossRef]
44. Şenik, B.; Uzun, O. An assessment on size and site selection of emergency assembly points and temporary shelter areas in Düzce. *Nat. Hazards* **2021**, *105*, 1587–1602. [CrossRef]
45. Bramerini, F.; Castenetto, S. (Eds.) *Manuale per l'Analisi della Condizione Limite per l'Emergenza (CLE) dell'Insediamento Urbano*; Commissione Tecnica per la Microzonazione Sismica, Dipartimento della Protezione Civile: Roma, Italy, 2016. Available online: https://www.protezionecivile.gov.it/static/5e8b2e1be3692d4ba5682907650bd518/CLE2.pdf (accessed on 11 August 2025).
46. Alkassabany, N.; Abouelfadl, H.; Alkassabany, Y. Enhancing pedestrian safety to improve urban health. *BAU J. Health Wellbeing* **2018**, *1*, 22.
47. Cai, K.; Wang, J. Urban design based on public safety—Discussion on safety-based urban design. *Front. Archit. Civ. Eng. China* **2009**, *3*, 219–227. [CrossRef]
48. EC-DGJFS. Pianificazione, Disegno Urbano, Gestione degli Spazi per la Sicurezza. Manuale. Politecnico di Milano–DIAP, IAU île-de-France, Regione Emilia-Romagna. 2007. Available online: http://www.costtu1203.eu/wp-content/uploads/2014/10/Manuale-Italiano.pdf (accessed on 11 August 2025).
49. Murao, O. Case study of architecture and urban design on the disaster life cycle in Japan. In Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China, 12–17 October 2008. Available online: https://www.iitk.ac.in/nicee/wcee/article/14_S08-032.PDF (accessed on 20 May 2024).
50. Bernardini, G.; Romano, G.; Soldini, L.; Quagliarini, E. How urban layout and pedestrian evacuation behaviours can influence flood risk assessment in riverine historic built environments. *Sustain. Cities Soc.* **2021**, *70*, 102876. [CrossRef]
51. Santibáñez, L.R. Urban Evacuation Tsunamis: Guidelines for Urban Design. *J. Eng. Archit.* **2016**, *4*, 117–132. [CrossRef]
52. Hosseini, K.A.; Jafari, M.K.; Hosseini, M.; Mansouri, B.; Hosseinioon, S. Development of urban planning guidelines for improving emergency response capacities in seismic areas of Iran. *Disasters* **2009**, *33*, 645–664. [CrossRef]
53. WHO-ROE. *Urban Planning, Design and Management Approaches to Building Resilience—An Evidence Review: First Report on Protecting Environments and Health by Building Urban Resilience*; WHO Regional Office for Europe: Copenhagen, NY, USA, 2022. Available online: https://www.who.int/europe/publications/i/item/WHO-10665-355761 (accessed on 11 August 2025).
54. March, A.; León, J. Urban Design: An Underutilized Tool for Disaster Risk Reduction? In Proceedings of the 7th State of Australian Cities Conference, Gold Coast, Australia, 9–11 December 2015. Available online: https://apo.org.au/node/63341 (accessed on 11 August 2025).
55. Fei, W.; Lu, D.; Li, Z. Research on the layout of urban disaster-prevention and risk-avoidance green space under the improvement of supply and demand match: The case study of the main urban area of Nanjing, China. *Ecol. Indic.* **2023**, *154*, 110657. [CrossRef]
56. Yang, J. Safety Urban Planning and Design Based on Disaster Prevention, Crime Prevention and Psychological Safety. *Open House Int.* **2019**, *44*, 84–87. [CrossRef]
57. Wei, Y.; Jin, L.; Xu, M.; Pan, S.; Xu, Y.; Zhang, Y. Instructions for planning emergency shelters and open spaces in China: Lessons from global experiences and expertise. *Int. J. Disaster Risk Reduct.* **2020**, *51*, 101813. [CrossRef]
58. Jayakody, R.R.J.C.; Amaratunga, D.; Haigh, R. Plan and design public open spaces incorporating disaster management strategies with sustainable development strategies: A literature synthesis. *MATEC Web Conf.* **2018**, *229*, 04001. [CrossRef]
59. Montejano-Castillo, M.; Moreno-Villanueva, M. The adaptability of public space in Mexico City after an earthquake: A preliminary classification. *Int. J. Saf. Secur. Eng.* **2016**, *6*, 104–113. [CrossRef]
60. Liu, L.; Lin, Y.; Wang, S. Urban design for post-earthquake reconstruction: A case study of Wenchuan County, China. *Habitat Int.* **2014**, *41*, 290–299. [CrossRef]

61. Zhu, W.; Xing, H.; Kang, W. Spatial Layout Planning of Urban Emergency Shelter Based on Sustainable Disaster Reduction. *Int. J. Environ. Res. Public Health* **2023**, *20*, 2127. [CrossRef]
62. Coutinho-Rodrigues, J.; Sousa, N.; Natividade-Jesus, E. Design of evacuation plans for densely urbanised city centres. *Munic. Eng.* **2016**, *169*, 160–172. [CrossRef]
63. Tsai, M.-T.; Chang, H.-W. Contribution of Accessibility to Urban Resilience and Evacuation Planning Using Spatial Analysis. *Int. J. Environ. Res. Public Health* **2023**, *20*, 2913. [CrossRef]
64. Wang, J.; Li, J.; Li, J.; Feng, J.; Xu, S.; Liu, J.; Wang, Y. Performance optimization of the obstacle to corner bottleneck under emergency evacuation. *J. Build. Eng.* **2022**, *45*, 103658. [CrossRef]

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Article

Deep Dive into the Recovery Fund: A (Real) Chance for Inner Areas? The Abruzzo Region Study Case, Italy

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Abstract

The National Recovery and Resilience Plan (NRRP) represents a transformative opportunity to reduce territorial, gender and generational disparities in Italy. It plays an even more important role for inner areas, which make up about three-fifths of the entire national territory and require structural investment to improve infrastructure, social services and access to healthcare services. This study aims to analyse the distribution of funds by project type, and to develop a geostatistical analysis-based methodology to critically evaluate two key aspects: the ability of small municipalities to access resources, and the effectiveness of the funding programme in meeting the specific needs of inner areas. The developed methodology consists of several steps aimed at collecting, standardising, geo-spatialising and analysing data relating to NRRP funds. This methodology is then applied to a case study of the Abruzzo region (Italy), which is considered particularly interesting due to its physical, historical and socio-economic characteristics that make it particularly vulnerable to natural disasters. The developed methodology consists of several steps aimed at collecting, standardising, geo-spatialising and analysing data relating to NRRP funds. The results of the spatial autocorrelation and cluster analyses were then overlapped and compared with the internal areas defined by the National Strategy for Inner Areas (NSIA). The outcomes reveal how investments interact with existing spatial planning instruments and development strategies, underscoring the critical role of accessibility, infrastructure, and public services in fostering equitable and sustainable regional development. The analysis offers insights into addressing structural disparities and enhancing territorial cohesion, with implications for policy alignment across multiple levels of governance.

Keywords: territorial transformations; National Recovery and Resilience Plan (NRRP); inner areas; cohesion strategies; spatial statistics; cluster analysis

1. Introduction

The National Recovery and Resilience Plan (NRRP) has been, and continues to be, an opportunity to address macroeconomic imbalances and reduce gender, territorial and generational disparities that hinder economic growth [1]. It supports the National Reform Plan (NRP) and is consistent with European economic governance, introducing a new economic framework built around three strategic axes: digital transition and innovation, ecological transition and social inclusion with territorial rebalancing. In line with the six pillars of the Next Generation EU, the measures defined in the six missions of the

NRRP correspond to these three strategic axes. The NRRP forms part of a wider European initiative aimed at driving post-pandemic recovery while tackling persistent structural imbalances, such as regional disparities and sustainability challenges [2].

This investment and reform framework aims to trigger transformative processes that will reshape the current development model. These processes will encompass various aspects of social, productive and territorial structures [3]. These transformations are intended to foster resilience and innovation, and address Italy's uneven regional development. This has historically impacted southern regions and inner areas the most [4].

Comprehensive assessment within the framework of spatial planning tools is required for physical interventions such as upgrading public facilities, enhancing territorial healthcare services, developing infrastructure for sustainable mobility, implementing land protection measures and strengthening territorial cohesion. The National Primary Healthcare System, for example, requires greater integration of digital technologies and improved communication between hospitals and community healthcare providers [5]. There is also a growing need to restructure the healthcare service network by enhancing accessibility to public health services, particularly in marginal [6] and underserved [7,8] areas and by strengthening outreach services.

The set of planned measures promotes a comprehensive reshaping of territorial systems. This is expected to have an impact on accessibility to services and infrastructure, demographic trends, the evolution of settlement patterns and synergies with ongoing development strategies and programmes. This multidimensional approach is consistent with the Organisation for Economic Co-operation and Development's (OECD) goals of sustainable regional development, which emphasise the integration of social, economic and environmental considerations [9]. Their effectiveness will be measurable over the long term [10] and proportional to the expected impacts on economic growth, environmental sustainability, and social cohesion [11].

The territorial transformations resulting from these investments should thus serve as an opportunity to improve socio-economic and environmental conditions, particularly in regions most affected by depopulation, socio-economic marginality and environmental fragility [12].

Referring to these areas as regions that, in recent decades, have been disconnected from urban-centred development models and are now experiencing marginalisation and depopulation [13], the relevant Italian reference legislative framework is the National Strategy for Inner Areas (NSIA). It stands as one of the most compelling examples of the EU's territorial cohesion goals [14]. Similarly to other European countries [15,16], the ultimate goal of the NSIA is to guide development that minimises spatial imbalances and fosters the effectiveness of policies and investments, tailored to the specific characteristics of different territorial systems [17].

It is clear that the substantial funding provided by the NRRP is being directed towards areas that are already highly complex and have had different policies in place for several years. In some cases, these strategies have been prompted by emergency events, such as major earthquakes, landslides and floods, as well as by disadvantaged socio-demographic conditions.

This research critically explores the intersection between space and policies in the implementation of Italy's NRRP. It aims to address a relevant, emerging research question:

To what extent does the NRRP identify and address the needs of municipalities, paying particular attention to those in the inner areas as defined by the NSIA?

In order to answer this question, two fundamental aspects must be critically assessed.

The first issue concerns the criteria and mechanisms for fund allocation, which directly determine the capacity of municipalities to access and manage these financial re-

sources. Unequal or overly complex allocation processes may risk excluding smaller or less well-resourced municipalities, reinforcing existing territorial disparities. Conversely, a transparent and equitable distribution system can strengthen local governments' ability to invest in strategic projects, promote balanced territorial development and ensure that the benefits of recovery and transition policies reach communities across the country.

The second issue relates to the extent to which the funding programme effectively addresses the specific needs of inner areas. If the measures are not sufficiently tailored to the structural challenges of these territories—such as demographic decline, limited infrastructure and restricted access to essential services—there is a risk that resources will fail to generate meaningful impact. On the other hand, a targeted approach that recognises the unique socio-economic conditions of inner areas can enhance their resilience, foster local development, and contribute to reducing long-standing territorial imbalances.

The spatialization of the projects envisaged by the NRRP represents a crucial first step in establishing a comprehensive assessment framework [18]. It enables the in-depth analysis necessary to evaluate consistency not only with the NSIA but also with other spatial governance instruments adopted at various scales to address broader objectives—such as national strategies for sustainable development [19] and climate change adaptation. In this context, this article focuses on the case study of the Abruzzo region, analysing the distribution of the funding allocated to each municipality within the different NRRP missions.

Cluster analysis was used to analyse the data and identify patterns of similarity and difference in the distribution of projects and funding. These results were then overlaid with the boundaries of inner areas. A comparison with the NSIA classification of municipalities provided further insights.

The study analysed the territorial distribution of funds in the Abruzzo region to investigate how territorial cohesion policies reflect—and sometimes reproduce—spatialised forms of power and unequal development strategies.

2. The Case Study

Abruzzo is a region in central Italy characterised by a complex polycentric structure, including urban poles and rural areas, industrial districts, a touristic coastline characterised by phenomena of territorial coalescence and mountain environments markedly affected by depopulation [20]. Covering a wide range of physical, historical and socio-economic environments, it is overall a region that is highly vulnerable and exposed to natural disasters [21], socio-economically vulnerable and poor in infrastructural endowments [22].

Two disruptive earthquakes (in 2009 and 2016) worsened the already stagnating economic performance, and the pre-existing conditions of marginalisation posed a significant challenge to the reconstruction process. However, the large amount of funds that came in during the post-earthquake phase constituted an uncommon opportunity to establish transformative patterns of development, cooperation and innovation [23]. Of the funds allocated for reconstruction, 68 municipalities in the region received investment during the two earthquake events. As is the case for much of the national territory, the regional territory is characterised by small municipalities that make up the inner areas, for which particular recovery and regeneration strategies are being implemented. In fact, the Abruzzo region has seven inner areas covering 139 municipalities, accounting for almost 46% of the total (Figure 1).

According to the 2023 Annual Report of the Italian National Statistics Institute (ISTAT) [24], Abruzzo region experienced a 3% population decline between 2011 and 2022, with an ageing population and a sharp drop in birth rates, especially in the inner

areas. In these regions, people aged over 65 make up more than 25% of the population, with some small towns reaching up to 30%.

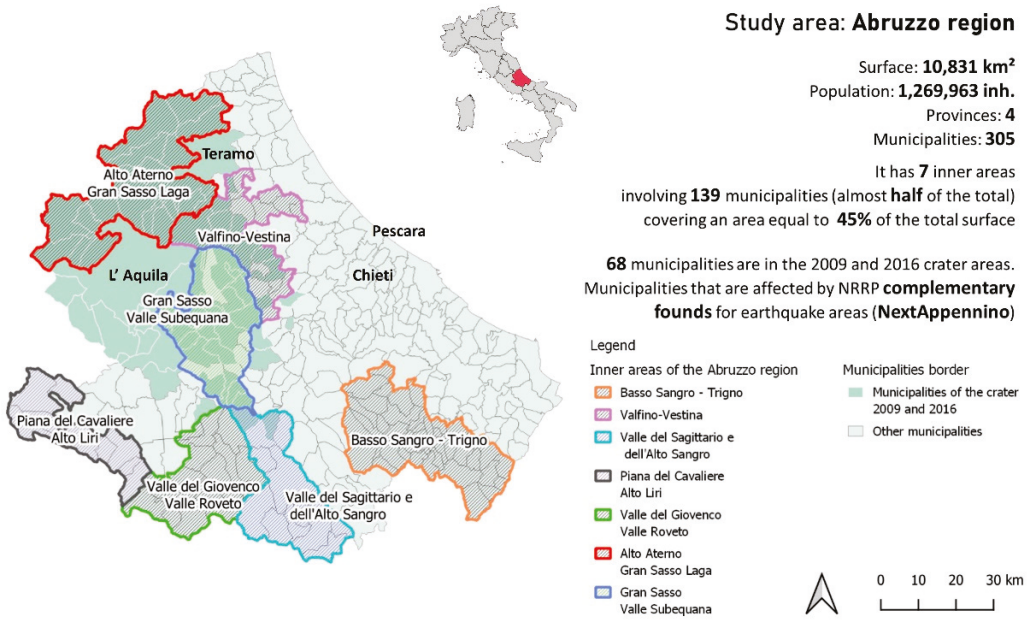


Figure 1. Study area with the identification of the seven inner areas and the municipalities of the 2009 and 2016 crater areas.

The situation is being exacerbated by the negative migration balance, which is mainly due to the outmigration of young people to cities or other Italian regions.

Socio-economically, coastal and urban areas such as the cities of Pescara, Chieti, and Teramo exhibit greater dynamism thanks to the boost from sectors such as tourism, services and industry. In contrast, the inner areas continue to suffer from chronic economic stagnation, linked to traditional sectors such as agriculture and crafts, which have been hit hard by competition and a lack of modern infrastructure [25]. According to ISTAT data, the unemployment rate in the inner areas is higher than the regional average, with youth unemployment exceeding 30%. The NSIA aims to reverse the socio-economic decline in Italy's inner areas by improving access to services, promoting local economic development, and fostering social cohesion. However, the 2023 Annual Report reveals that these policies have achieved only limited success to date. The future impact of the NSIA will depend largely on the capacity of these inner areas to attract investment and develop infrastructure that fosters innovation and growth, which are critical for long-term socio-economic revitalization.

The NSIA plays a crucial role in regions such as Abruzzo, where the pronounced territorial disparities between coastal and inner areas have had a negative impact on the social and economic fabric. The inner areas of the Abruzzo region have historically experienced de-population, geographical isolation and limited economic opportunities. The NSIA aims to address these issues through a comprehensive multi-sector approach. Its significance lies in fostering balanced and inclusive territorial development, not merely through the financing of individual projects, but by advancing a broader strategic vision designed to reduce inequalities and create long-term cohesion across regions. The NSIA aims to create better living conditions for those residing in these areas by improving access to essential services (healthcare, education, transportation) and fostering new economic opportunities based on innovation and the utilisation of local resources. This will help to curb depopulation and reverse socio-economic decline.

In Abruzzo's inner areas, the actions of the NSIA address specific issues such as limited access to public services, an ageing population, and structural difficulties in attracting investment. The strategy aims to revitalise these areas, not only economically, but also in terms of improving the quality of life, strengthening social cohesion and promoting territorial resilience. Interventions such as strengthening digital and transport infrastructure are essential for reducing the gap with more dynamic urban areas, while supporting local entrepreneurship can create new jobs in traditional sectors such as agriculture and sustainable tourism.

For the NSIA in Abruzzo to be successful, it must be able to coordinate interventions at local, regional and national levels, involving both public and private actors. As highlighted in the 2023 ISTAT Annual Report, the effectiveness of territorial cohesion policies will depend largely on these areas' ability to attract resources and capital, and on the active participation of local communities in decision-making.

The NSIA represents an essential tool for the revitalization of Abruzzo's inner areas. It is a sustainable development perspective that addresses the root causes of socio-economic problems, seeking to create a more inclusive and prosperous future for these communities. In this context, the challenge launched by the NRRP could represent a paradigm shift in the management of these areas and how their strategies are defined.

3. Materials and Methods

The applied methodology comprises three main steps:

- Dataset building concerning the distribution of NRRP projects in the Abruzzo region among its 305 municipalities, which constitute our sample;
- An autocorrelation analysis was carried out to verify whether the amounts financed for each mission aggregate spatially;
- A cluster analysis was performed to investigate whether contiguous areas within the sample of municipalities pursued the same investment strategy.

Figure 2 shows a methodological scheme that summarises the entire process.

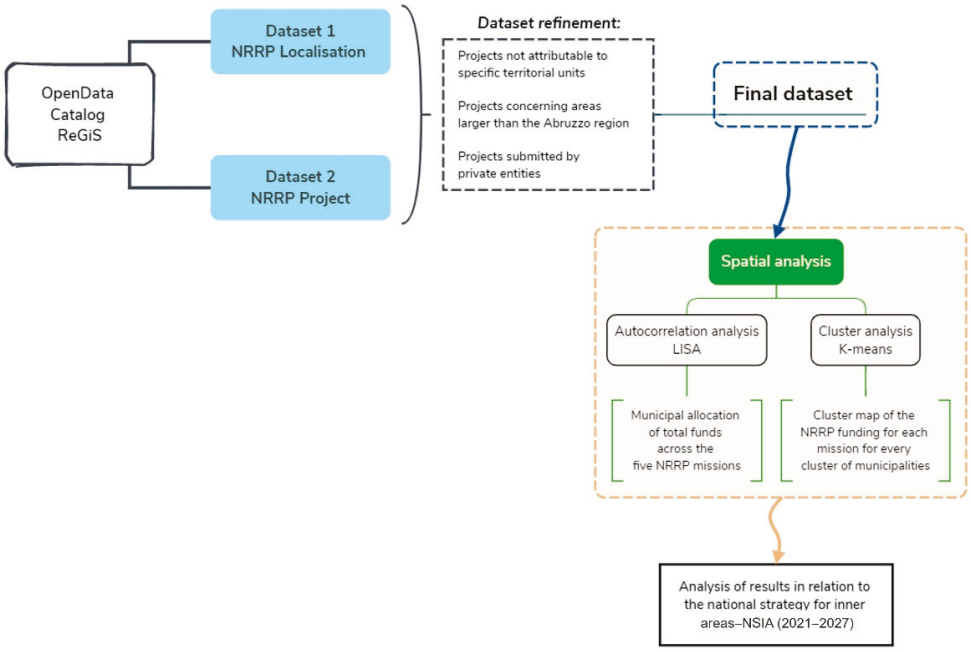


Figure 2. Methodological framework.

3.1. Dataset Building

The dataset is derived from the Open Data Catalogue, which is updated monthly in ReGiS [26], the information system developed by the Italian Ministry of Economy and Finance to ensure compliance with public works monitoring requirements. In particular, it includes the entire structure of the NRRP, enabling the precise display of measures, responsible parties and financial resources, as well as the monitoring of progress on each project in relation to national and European milestones and targets, and the characteristics of individual measures (e.g., climate and digital tags).

As part of this work, the data included in datasets 1 and 2 (NRRP Localisation and NRRP Project, respectively) were analysed and spatialized. Dataset 1 contains the following information for each project: the unique submission code, the project code (CUP), the local project code, the reference municipality with the province and address indicated and the date on which the data was last updated. Dataset 2, on the other hand, contains the following information for each project: the unique submission code, the CUP, the local project code, the NRRP Mission (hereafter referred to as "M"), the specific mission component (hereafter referred to as "C") and the total amount of funding. Furthermore, dataset 1 encompasses a greater number of projects than dataset 2, as a single project may span multiple locations (municipalities, provinces, regions or territorial areas).

For example, if a project with a unique CUP has been developed in four municipalities, dataset 1 will contain four rows, one for each municipality, with the CUP and local project code repeated. Dataset 2, on the other hand, will contain only one row with the CUP and the total funding provided by the project (as well as other information).

The two datasets contain different information and combining them makes it possible to link the funding of each project to its respective municipality, thus enabling the data to be visualised spatially. In fact, dataset 2 contains no information about the spatial extent of the project (municipality, region, province or other extent), whereas dataset 1 does. To achieve this, a biunivocal correspondence (one-to-many) was established between the CUP and the local project code. This double condition was necessary because the database contains multiple CUPs for different municipalities. Merging the two datasets returns a third dataset in which several critical conditions occur that will be resolved as follows:

- The total project amounts are repeated with the CUPs for the several different municipalities included in each project. To overcome this limitation of the union and avoid overestimating total project funding, it was assumed that the amount would be divided equally by the number of municipalities involved in the project in all cases where reference to the municipalities was explicit.
- For projects referencing a province but indicating all municipalities, funding was divided among all the municipalities belonging to the relevant province.
- In cases where the project does not appear to have an impact on specific municipalities, it has been eliminated entirely as it cannot be associated with a spatial dimension. One example is the project concerning the establishment of additional scholarships for the general medicine course.
- Projects referring to spatial extensions covering the whole nation, ministries, regions (without referring to municipalities), provinces and sub-territorial areas were eliminated and not considered in the database for analysis.
- All projects related to M3 (Infrastructure for Sustainable Mobility) were excluded from the analysis because they are nationally important projects relating to the modernisation and safety of rail and road networks (e.g., High Speed Rome—Pescara, Speeding up Pescara—Foggia—Brindisi, interventions along the A24–A25).

The analysis reveals the building of a dataset which, for each municipality in the case study, systematically organises information on the number of projects funded and the

corresponding NRRP funds received, broken down according to the different missions and specific components.

3.2. Autocorrelation Analysis

Spatial autocorrelation is a geostatistical technique used to analyse the spatial distribution of a variable across contiguous geographical areas and to evaluate local effects and clusters [27].

Based on the idea that data can be affected in terms of both geographical shape and spatial proximity and the values attributed to the same units, Tobler developed this method of jointly analysing the spatial behaviour of the analysed variable and what happens in its proximity [28].

In particular, it is useful to detect hotspots, i.e., high values accumulation areas, as well as cold spots, i.e., low values accumulation areas [29], assuming that space is homogeneous [30].

Since spatial autocorrelation analysis helps to understand whether spatial units have similar properties, this paper applied the Local Indicators of Spatial Association (LISAs), to measure local spatial autocorrelation among the municipalities of the Abruzzo region. The variable used was the total amount of money allocated to each of the five missions of the NRRP.

The LISAs index is calculated as follows:

$$I_i = \frac{(x_i - \underline{x})}{s_x^2} \sum_{j=1}^{N} \left(w_{ij} \left(X_j - \underline{X} \right) \right) \quad (1)$$

where represents the number of statistical units (i.e., the 305 municipalities of the Abruzzo region), x_i is the analysed variable in region i (i.e., the total amount of money for each mission), X represents the sample average, $S^2{}_x$ is the standard deviation and represents the weight matrix.

When running LISAs, the GeoDA (ver. 1.22.04) software also enables several specifications to be selected, including distance options, number of permutations and significance values [31].

Performing this analysis in the GIS environment allows us to take advantage of a spatially explicit decision support tool [32–34] showing the interrelationships between municipalities focusing on their applications for each NRRP mission. In particular, it is possible to detect five different situations:

- The hotspots (High-High), when high amounts of money and high levels of similarity with the nearby municipalities are observed;
- The cold spots (Low-Low), when low amounts of money and low levels of similarity with the nearby municipalities are observed;
- High-Low cluster, when high amounts of money occur with low levels of similarity with the nearby municipalities;
- Low-High cluster, when low amounts of money correspond to high levels of similarity with nearby municipalities;
- The municipalities not belonging to any of the above clusters do not show significant values of spatial autocorrelation.

3.3. Cluster Analysis

A cluster analysis was performed on the same dataset within the sample of the 305 municipalities of the Abruzzo region to verify whether similar strategies were pursued for project funding by the NRRP in different areas.

In particular, a cluster analysis was conducted by means of k-means [35], an unsupervised algorithm aimed at dividing a data sample into k clusters in such a way that within each cluster, the maximum degree of similarity is obtained and, at the same time, the maximum degree of dissimilarity between elements belonging to different clusters is obtained [34,36]. The algorithm, run over a configurable number of iterations, begins by randomly selecting k centroids and then assigns each element in the sample to the nearest centroid based on a Euclidean distance criterion [37]. At the end of each iteration, the average of the points assigned to the specific cluster is taken as the new centroid; the process then continues by convergence of the centroids.

A key element in executing the analysis is choosing the number of clusters, which is usually proportional to the size of the population in the original dataset. For the purposes of this study, it has been arbitrarily set at seven, which strikes a balance between minimising the overall variance and representing the spatial distribution of the obtained clusters.

4. Results

The project dataset update period for the Abruzzo region varies between 24 October and 11 November 2023. The dataset consists of 6537 projects distributed among all the missions for a total funding amount of EUR 1922 million.

As can be seen from Figure 3a, most of the projects concern interventions aimed at the digitalisation of Public Administrations (PAs) (M1C1: 2240 projects) through the strengthening of the adoption of the PagoPA platform services and the IO application, the enhancement of the adoption of the national digital identity platforms and the National Registry and the adoption of the Digital Civil Service and cloud enablement.

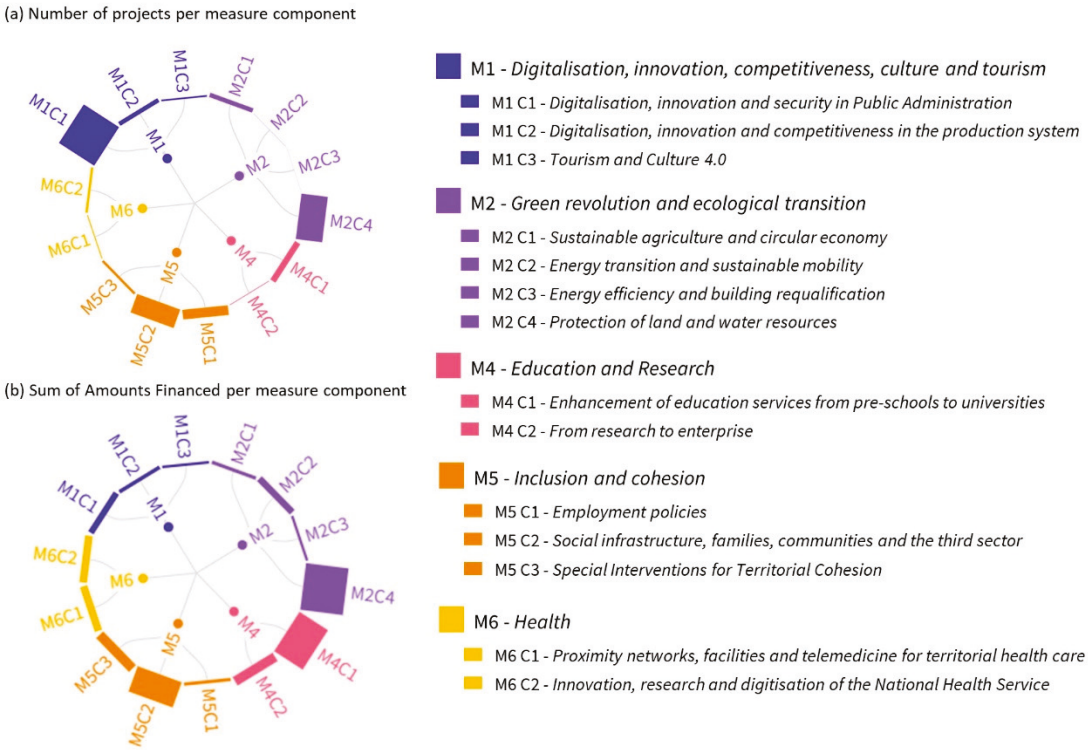


Figure 3. Overview of the (**a**) number of projects funded in the Abruzzo region and (**b**) allocation of funded amounts, by missions (Ms) and components (Cs).

In terms of funding, however, the M2C4 projects are the most substantial, with a total budget of EUR 491 million (Figure 3b) for 1424 projects. In fact, they are projects that require large investments because they involve protecting portions of the territory with

respect to water resources. Most of them concern investments in water infrastructure and the irrigated agro-system, with the aim of achieving sustainable management of water resources. Other projects focus on measures for flood risk management and reducing hydrogeological risks.

Of particular interest are the 202 projects and the total funding of EUR 175 million for mission M6, which focuses on health. This includes the construction of proximity facilities and telemedicine networks for territorial healthcare, as well as innovation, research and digitization of the National Health Service.

Of the collected dataset, 246 projects were not taken into account for the following reasons: they were not directly attributable to specific territorial units, they concerned areas larger than the Abruzzo region, the financing requested by private activities (hotels or B&Bs) was small, as well as other reasons. These projects cover a total of EUR 766 million in financing.

The first step of the applied methodology involves allocating the funding amounts for each NRRP mission to municipalities. As the aim of this paper is to interpret this data in the context of the NSIA, the initial analysis focused on understanding the distribution of these amounts among the seven inner areas planned for the 2021–2027 programming period.

As can be seen from Figure 4, all inner areas have invested mainly in M2, with values reaching EUR 23 million in 'Gran Sasso Valle Subequana', almost EUR 29 million in 'Valfino Vestina' and over EUR 35 million in 'Basso Sangro Trigno'.

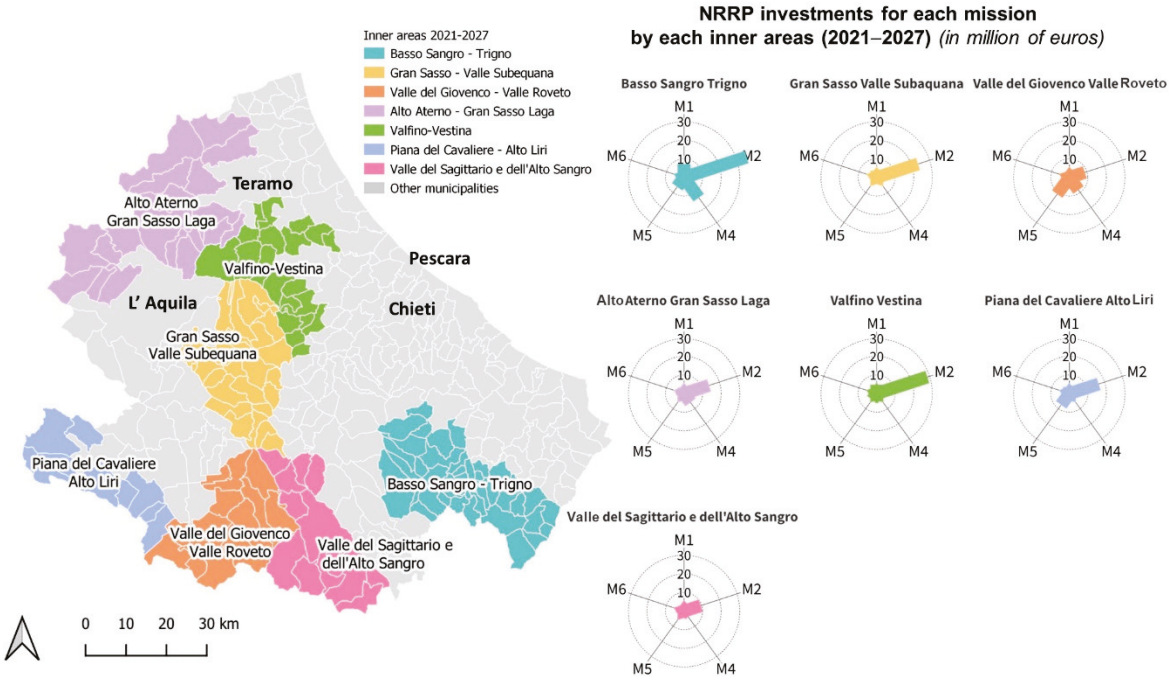


Figure 4. Overview of the spatialisation of NRRP funds by mission considering inner areas planned by the NSIA for the 2021–2027 programming period.

The 'Valle del Giovenco Valle Roveto' area has a budget for expenditure that is evenly distributed between M2, M4 and M5.

Almost all inner areas spent on all missions. The only exception is the 'Valle del Sagittario e dell'Alto Sangro' area, where the number of projects (and consequently the amount allocated) on Mission 6 is zero.

The results of the autocorrelation analysis, carried out to verify whether the amounts financed for each mission aggregate spatially, and of the cluster analysis, performed to

investigate whether contiguous areas pursued the same investment strategy for project funding by the NRRP, are set out below, according to the methodology set out in Section 3.

The autocorrelation analysis (Figure 5) highlights the dichotomy between the cost areas and the municipalities in the hinterland of the province of L'Aquila. In fact, there is an area centred around the provincial capitals of Pescara and Chieti, including smaller municipalities, which emerges as a high-high cluster with respect to all NRRP missions. Conversely, it is clear that the inner municipalities are having difficulty applying for projects and making use of the resources offered by the NRRP. The municipality of L'Aquila is also included in the high-low cluster for three out of five missions, meaning it has invested much more than the surrounding municipalities.

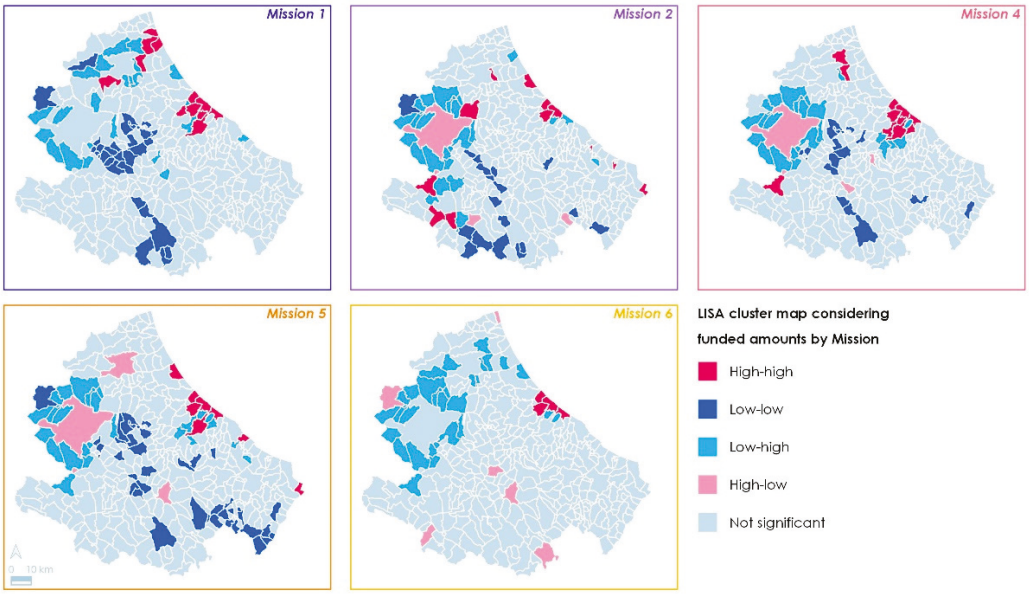


Figure 5. LISAs cluster map obtained considering the overall amounts related to each mission.

Figure 6 shows the result of the cluster analysis carried out on the basis of the investments for each NRRP mission. The first cluster, the largest, includes 270 municipalities whose investments exceed EUR 1 million only for Mission 2, with an average investment of approximately EUR half a million.

The second cluster includes 20 municipalities that invested between EUR 1.6 and 4.7 million on all five missions, with a preference for M4.

Cluster 3 invested more than EUR 17 million in Mission 5, around EUR 3.7 million in Missions 2 and 4 and around EUR 1.3 million in Missions M1 and M6.

The fourth cluster is characterised by spending ranging from EUR 2 million for M1 to EUR 22.8 million for M2, with an average value of around EUR 10 million. It comprises four municipalities, three of which are along the coastal strip, with only one in the hinterland.

Cluster 5 is made up of the two provincial capitals Teramo and Pescara, which invested over EUR 10 million in each mission, with a maximum of about EUR 31 million in M5.

Cluster 6 is the regional capital (L'Aquila), which has invested about EUR 91 million in M4, EUR 53 million in M2, EUR 45 million in M5, about EUR 33 million in M6 and only EUR 5 million in M1. Its average investment is more than EUR 45 million.

Finally, the last cluster (Cluster 7) is made up of the city of Chieti alone, which invested mainly in Missions 4 (more than EUR 47 million) and 5 (around EUR 39 million), with a minimum of EUR 2.5 million for M1.

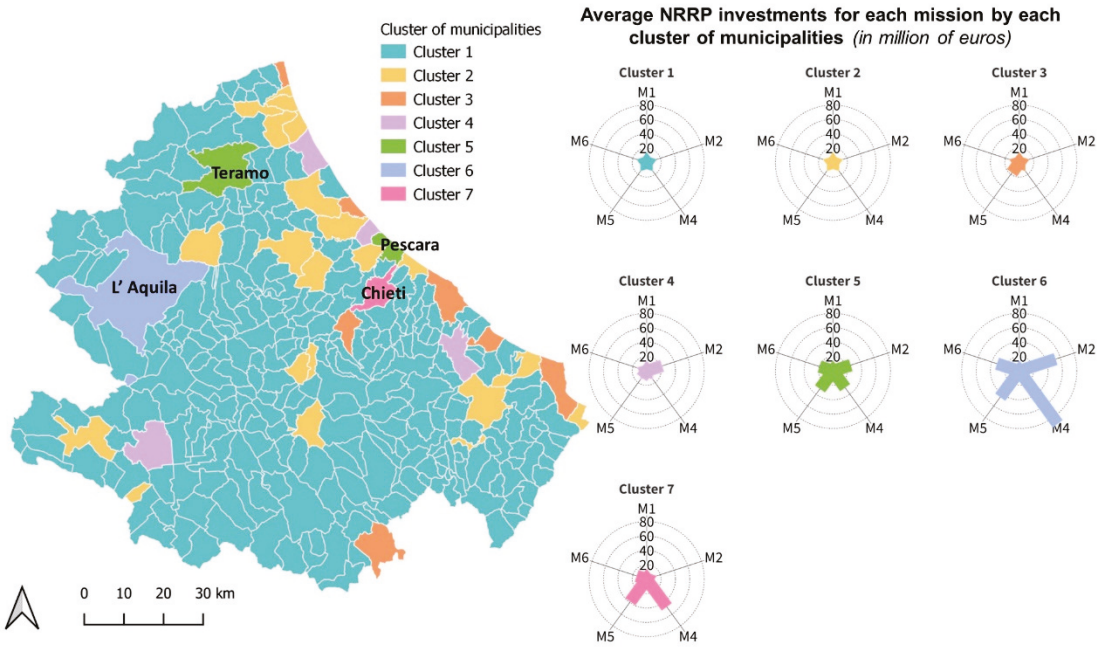


Figure 6. Overview of cluster analysis results. Radar charts represent the amounts of funding for each mission for every cluster of municipalities.

5. Discussion

The developed methodology and the related findings allow us to draw discussions and implications concerning two main points related to structural funding programmes.

Firstly, the relevant role of the criteria and methods used to allocate funding emerges.

Overly complex or unequal processes risk excluding smaller municipalities and deepening territorial disparities. Our findings in fact confirm what was recently highlighted by the European Investment Bank [38], the fact that smaller municipalities—especially those in less-developed marginal areas—face persistent and multi-faceted barriers in accessing public funding. The scientific literature also outlines that a significant number of local governments report that a lack of funding and complex regulatory procedures significantly hinder their capacity to invest in critical infrastructure, including climate actions. Shortages of technical and environmental expertise [39] further compound this problem. Additionally, smaller municipalities frequently lack the administrative capacity and in-house expertise necessary to manage funding applications, a barrier highlighted by the OECD as detrimental to smaller public entities undertaking EU-funded projects [38]. Bachtler et al. (2014) [40] reinforce these findings, showing that capacity gaps in small and rural municipalities also risk amplifying regional disparities by concentrating resources in larger urban centres better equipped to navigate funding systems. Another concern deals with citizens' engagement, with a general lack of municipal attention to civic participation, and warns that large-scale, multi-level funds may risk undermining social equity [41].

While rapid decision-making is recognised as synonymous with efficiency, Raco et al. (2018) [42] call for the need to have "slow cities" in order to better respond to funding opportunities with processes oriented to more sustainable and long-term perspectives.

In other words, evidence suggests that the good intentions for rethinking social protection and fostering innovation of funding programmes are not enough. Their success hinges critically on how funds are managed at the local level, how projects are implemented and the ability of local authorities to access funding and convert it into benefits for communities [43].

Notable examples of successful outcomes include the Bando Borghi initiative launched by the Italian Ministry of Cultural Heritage and Activities' (MiBACT), which channelled NGEU resources towards the sustainable recovery of mountain villages and inner areas [44]. Also, in Greece, the Recovery and Resilience Facility (RRF) funding was the main driver to reform urban policy and introduce Local Urban Plans and Special Urban Plans, aimed at tackling traffic congestion, environmental degradation and loss of green spaces, while promoting sustainable mobility and climate resilience [45].

Conversely, in Germany, even with equal funding, disparities emerged in the implementation of local climate policies, stemming from differences between the local administrations tasked with managing the resources [46].

The findings of this study corroborate a trend of pronounced heterogeneity in the allocation of NRRP funds among municipalities in the Abruzzo region. The territorial distribution of projects across different NRRP measures appears to be shaped less by the substantive needs of local contexts—such as infrastructure provision, service availability and risk mitigation—than by the administrative capacity to access funding and formulate project proposals.

The second issue concerns whether the funding programme adequately addresses the specific needs of inner areas. In this context, we consider the Italian NRRP, which is closely aligned with the 2021–2027 Cohesion policy framework. The NRRP represents an unprecedented opportunity to strengthen the capacity of the Italian public administration [47], bring about significant changes to development dynamics [48] and lay the foundations for building resilience, especially in fragile territories [49]. However, the effectiveness of these investments in inner areas must be considered in the context of a polycentric spatial organisation in need of widespread intervention. This context is characterised by significant structural fragility [20]. Moreover, these areas are affected by long-term depopulation, an ageing population, weak institutions and a lack of capital. This unfavourable concomitance of factors also negatively affects resilience to sudden shocks [50], as regretfully proven during the 2016 earthquake.

The many specific characteristics of inner areas outlined above mean that the effectiveness of investments in responding to specific needs must be evaluated in a spatially explicit way. As pointed out by [51], this becomes even more relevant when measuring the changes financed against the pursuit of sustainable goals. Currently, however, it is difficult to spatialise the data made available on the e-gov website. This is because it is challenging to disaggregate investments [52] and in trace them back to where they will result in change [53].

From the perspective of the NRRP's expected impacts, the results offer several points for discussion. Although the NRRP recognises the importance of the expected impact on social, economic and territorial cohesion, it pays little attention to the effects on citizens' well-being compared to economic growth [11]. However, there is a high risk that structural limitations, related to reform capacity and resource absorption, will prevail. In addition, the new highly centralised governance structure could cause implementation problems, as sub-national actors have been marginalised, contradicting European indications [54].

The announced paradigm shifts to opportunities for inner areas under the NRRP have not yet occurred and apparently will not take place. In fact, the clusters overlapping the seven inner areas of Abruzzo demonstrate that little investment has been made in projects, almost nullifying the chances of revitalisation. Another relevant factor is that the percentage of the population over 65 living in inner areas is generally higher than the national and regional average [55,56].

In these areas, therefore, there should be a strong interest in expanding care facilities for the elderly and dedicated medical services [57], i.e., everything summarised in

M6 of the NRRP, which is designed to reform the healthcare system by redesigning its territorial network [58].

In contrast, very few projects concerning M6 were submitted by municipalities in the inner areas: only 11 out of 139 municipalities did so. This often reflects a lack of the resources and skills needed to participate in complex calls for proposals, resulting in a 'windfall effect' that favours a few municipalities with the necessary expertise. This situation highlights the lack of an efficient territorialization of the NRRP, both at national level, with clear differences between north and south [51], and inside individual regions [59]. The capacity to calibrate interventions on the basis of the social and physical characteristics and specific needs of territories, or "territorialisation", appears to be lacking. Not all contexts require the same priorities, such as digitalisation or widespread healthcare, nor do they have the same capacity to reap long-term benefits from investments. Without long-term benefits, an intervention is inevitably in danger of failing. Failures can also be generated by the sheer complexity of the NRRP measures and by the extremely long timeframes for implementing the interventions [49], which risk misrepresenting their real function. For example, the NRRP has incorporated other already active programmes such as those on the quality of living (National Innovative Programme for the Quality of Living—PinQua) whose principles and objectives do not exactly reflect what is contained in the various measures. Regarding the Abruzzo region, the impact of the 2009–2016 Earthquake Areas Supplementary Fund under Macro measure B 'Economic and Social Revival' of the National Plan for Complementary Investments to the NRRP is significant. While complementary funds play a fundamental role, when they are incorporated into NRRP measures, they risk losing their original purpose of reconstruction. This also denaturalises the recovery and resilience interventions envisaged by the various NRRP measures. Consequently, while the NRRP enabled funding to be increased for existing programmes and plans, it also distorted its original objectives.

Another mismatch between demand for investment and requirements relates to the protection of land against hydrogeological risks. This is one of the key interventions under the mission on the Green Revolution and Ecological Transition (Mission 2 Component 4), which receives the largest share of funding from the NRRP at the national level—approximately EUR 69 billion [60].

Although inner areas constitute fragile territories [61] characterised by a high-level hydrogeological risk [62], not all inner areas of the Abruzzo region benefit from substantial investment in this funding line.

6. Conclusions

The novelty of this research lies in its spatial interpretation of the findings derived from a critical analysis of fund distribution in inner areas. As with most spatial analyses, it is inevitably affected by the edge effect, since the influence of neighbouring territories cannot be entirely accounted for during the clustering process. This limitation could be addressed in future studies by either broadening the spatial scope to include adjacent regions or employing interscalar approaches that consider cross-border interactions.

The analysis highlights the complex relationship between national programming and local development strategies, underscoring the political implications of how public resources are territorialized. It also raises critical questions about the transformative potential of infrastructure policies in promoting territorial cohesion and addressing structural imbalances. Although GDP or other direct economic indicators were not explicitly included, the study engaged with the economic dimension by examining inner areas, which are structurally disadvantaged in terms of accessibility, demographic trends and economic vitality. NRRP investments in these territories are therefore intrinsically linked to their

potential for socioeconomic development. A recent JRC study [63] confirms the systemic impact of these instruments, estimating that the RRF mobilises around 4% of European GDP and generates direct and indirect effects in all Member States, with Italy among the main beneficiaries thanks to investments in the green and digital transition. In this context, the results of the analysis suggest that the distribution of NRRP resources should not be considered simply as a financial allocation, but as part of a broader framework where spatial, economic and political dimensions intersect to shape patterns of territorial marginality and development opportunities.

The NRRP, in its original conception, does not seem to fully address the real challenge: ensuring compatibility between economic development, employment, welfare and environmental sustainability [64]. Simply stimulating GDP growth without introducing radical innovations in production technologies and consumption models risks exacerbating territorial inequalities and environmental vulnerability, without ensuring an equitable distribution of benefits. A territorial approach, on the other hand, makes it possible to assess whether investments are targeted at those sectors and supply chains capable of generating quality employment and local resilience.

In particular, the results obtained for the Abruzzo region indicate that the effectiveness of the allocated NRRP investments may be compromised, especially in the long term, by the way in which these resources have actually been implemented. This finding reinforces the observation of [65], according to which local capacity building and support for policy makers are priority areas for the allocation of funds, constituting a necessary step to enable local administrators to invest in a targeted manner, responding to the specific needs and characteristics of their territories. In this framework, the methodology proposed in the study is designed as a decision support tool, providing detailed geospatial information useful for the construction of territorial planning and governance strategies, helping to guide investment policies in a way that is more in line with local characteristics and needs. Future developments in the research aim to deepen the analysis beyond the distribution and territorial allocation of funds to explore the extent to which the NRRP is effectively integrated with the Sustainable Development Goals (SDGs). In particular, an important step will be to map investments across the different dimensions of the SDGs—such as clean energy, resilient infrastructure and sustainable communities—and to assess their effectiveness through targeted indicators, including their ability to contribute to reducing regional disparities. More detailed data at the municipal level and cross-cutting approaches that simultaneously consider economic, social and environmental variables will be essential to carry out these analyses.

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References

1. Sciortino, A. L'impatto del Pnrr Sulle Diseguaglianze Territoriali: Note Introduttive. *Riv. Assoc. Ital. Dei Cost.* **2022**, *3*, 2039–8298.
2. European Commission. Recovery Plan for Europe—European Commission. Available online: https://commission.europa.eu/strategy-and-policy/recovery-plan-europe_en#documents (accessed on 11 December 2024).
3. Crupi, F. Programmazione Economica e Organizzazione Territoriale. PNRR, Nuove Strategie e Strumenti per Città Inclusive, Sostenibili e Resilienti. In *Urbanistica Informazioni*; INU edizioni: Roma, Italy, 2023; pp. 190–192.
4. Viesti, G. *Riusciraà Il PNRR a Rilanciare l'Italia?* Donzelli Editore: Roma, Italy, 2023; p. 131.
5. Sheehan, J.; Laver, K.; Bhopti, A.; Rahja, M.; Usherwood, T.; Clemson, L.; Lannin, N.A. Methods and Effectiveness of Communication Between Hospital Allied Health and Primary Care Practitioners: A Systematic Narrative Review. *J. Multidiscip. Heal.* **2021**, *14*, 493–511. [CrossRef] [PubMed]
6. Filippini, T.; Vinceti, S.R. Italian National Recovery and Resilience Plan: A Healthcare Renaissance after the COVID-19 Crisis? *Acta Bio Medica Atenei Parm.* **2021**, *92*, 2021463. [CrossRef]
7. Parjanen, S.; Hyypiä, M. Innovation Platforms as a Solution to the Proximity Paradox. *Eur. Plan. Stud.* **2018**, *26*, 1312–1329. [CrossRef]
8. Solá, A.G.; Vilhelmson, B. Negotiating Proximity in Sustainable Urban Planning: A Swedish Case. *Sustainability* **2018**, *11*, 31. [CrossRef]
9. OECD. *A Territorial Approach to the Sustainable Development Goals: Synthesis Report*; OECD Urban Policy Reviews; OECD Publishing: Paris, France, 2020.
10. Tocci, G. Enhancement of Italian Small Towns and the National Recovery and Resilience Plan: The Experience of Smart Villages. In *Eastern Europe and the Mediterranean Basin "Come Back Home"-Abstracts Book*; IARC-ETQA Publishers: Lyon, France, 2023; p. 52.
11. Pilati, M. *National Recovery and Resilience Plans: Empowering the Green and Digital Transitions?* European Policy Centre EPC: Brussels, Belgium, 2021.
12. Bonavero, F.; Cassatella, C.; D'Errico, L. La Sfida Della Compatibilità Ambientale: Piani, Strategie e Strumenti per Attuare La Sostenibilità e La Resilienza in Città Metropolitana Di Torino. *Urban. Inf.* **2023**, *306 s.i.*, 53–54.
13. Rossitti, M.; Dell'ovo, M.; Oppio, A.; Torrieri, F. The Italian National Strategy for Inner Areas (SNAI): A Critical Analysis of the Indicator Grid. *Sustainability* **2021**, *13*, 6927. [CrossRef]
14. Cotella, G.; Vitale Brovarone, E. The Italian National Strategy for Inner Areas: A Place-Based Approach to Regional Development. In *Dilemmas of Regional and Local Development*; Routledge: London, UK, 2020; pp. 50–71. [CrossRef]
15. Medeiros, E. European Union Cohesion Policy and Spain: A Territorial Impact Assessment. *Reg. Stud.* **2017**, *51*, 1259–1269. [CrossRef]
16. Rosik, P.; Stepniak, M.; Komornicki, T. The Decade of the Big Push to Roads in Poland: Impact on Improvement in Accessibility and Territorial Cohesion from a Policy Perspective. *Transp. Policy* **2015**, *37*, 134–146. [CrossRef]
17. Asprogerakas, E.; Zachari, V. The EU Territorial Cohesion Discourse and the Spatial Planning System in Greece. *Eur. Plan. Stud.* **2020**, *28*, 583–603. [CrossRef]
18. Marchigiani, E. Regenerating Cities through Spatialized Social and Health Welfare. Learning from Microareas in Trieste. *Territorio: 97* **2021**, *2*, 31–41. [CrossRef]
19. Cowell, R.; Owens, S. Governing Space: Planning Reform and the Politics of Sustainability. *Environ. Plan. C Gov. Policy* **2006**, *24*, 403–421. [CrossRef]
20. Compagnucci, F.; Morettini, G. Improving Resilience at the Local Level: The Location of Essential Services within Inner Areas. Three Case Studies in the Italian Marche Region. *Reg. Sci. Policy Pract.* **2020**, *12*, 767–793. [CrossRef]
21. Marin, G.; Modica, M.; Paleari, S.; Zoboli, R. Assessing Disaster Risk by Integrating Natural and Socio-Economic Dimensions: A Decision-Support Tool. *Socio-Econ. Plan. Sci.* **2021**, *77*, 101032. [CrossRef]
22. Bonfiglio, A.; Coderoni, S.; Esposti, R.; Baldoni, E. The Role of Rurality in Determining the Economy-Wide Impacts of a Natural Disaster. *Econ. Syst. Res.* **2021**, *33*, 446–469. [CrossRef]
23. Di Giovanni, G. Post-Earthquake Recovery in Peripheral Areas: The Paradox of Small Municipalities' Reconstruction Process in Abruzzo (Italy). *Ital. J. Plan. Pract.* **2016**, *6*, 110–139.

24. ISTAT. *Rapporto Annuale 2023, La Situazione Del Paese*; Istituto Nazionale di Statistica: Roma, Italy, 2023.
25. Porta, A.; Segre, G.; Arauzo-Carod, J.M. The Italian National Strategy for Inner Areas: First Insights from Regions' Specialization in Cultural and Creative Industries. In *Clusters in Times of Uncertainty*; Edward Elgar Publishing: Cheltenham, UK, 2024; pp. 240–261. [CrossRef]
26. Localizzazione Dei Progetti Del PNRR. Available online: https://www.italiadomani.gov.it/content/sogei-ng/it/it/catalogo-open-data/localizzazione-dei-progetti-del-pnrr.html (accessed on 11 October 2024).
27. Sui, D.Z. Tobler's First Law of Geography: A Big Idea for a Small World? *Ann. Assoc. Am. Geogr.* **2004**, *94*, 269–277. [CrossRef]
28. Tobler, W.R. A Computer Movie Simulating Urban Growth in the Detroit Region. *Econ. Geogr.* **1970**, *46*, 234. [CrossRef]
29. Lin, Q.; Zhang, L.; Qiu, B.; Zhao, Y.; Wei, C. Spatiotemporal Analysis of Land Use Patterns on Carbon Emissions in China. *Land* **2021**, *10*, 141. [CrossRef]
30. Tang, X.; Li, C.Z.; Jiang, L.; Lai, X.; Zhang, L. A Spatial Autocorrelation Analysis for Land Use Change in the Guangdong-Hong Kong-Macao Greater Bay Area. In *International Symposium on Advancement of Construction Management and Real Estate*; Springer Nature: Singapore, 2022; pp. 847–858. [CrossRef]
31. Hughey, S.M.; Kaczynski, A.T.; Porter, D.E.; Hibbert, J.; Turner-McGrievy, G.; Liu, J. Spatial Clustering Patterns of Child Weight Status in a Southeastern US County. *Appl. Geogr.* **2018**, *99*, 12–21. [CrossRef] [PubMed]
32. Sung, C.H.; Liaw, S.C. A GIS Approach to Analyzing the Spatial Pattern of Baseline Resilience Indicators for Community (BRIC). *Water* **2020**, *12*, 1401. [CrossRef]
33. Vigani, M.; Khafagy, A.; Berry, R. Public Spending for Agricultural Risk Management: Land Use, Regional Welfare and Intra-Subsidy Substitution. *Food Policy* **2024**, *123*, 102603. [CrossRef]
34. Wang, Y.; Yang, Z.; Yu, M.; Lin, R.; Zhu, L.; Bai, F. Integrating Ecosystem Health and Services for Assessing Ecological Risk and Its Response to Typical Land-Use Patterns in the Eco-Fragile Region, North China. *Environ. Manag.* **2023**, *71*, 867–884. [CrossRef]
35. Hartigan, J.A. *Clustering Algorithms*; John Wiley & Sons Inc.: Hoboken, NJ, USA, 1975; ISBN 047135645X.
36. Wu, Y.-F.; Fa-you, A.; Yang, C.; Yan, S.; Kang, X. Accuracy Improvement of Different Landslide Susceptibility Evaluation Models through K-Means Clustering: A Case Study on China's Funing County. *Math. Probl. Eng.* **2023**, *2023*, 2913890. [CrossRef]
37. Arthur, D.; Vassilvitskii, S. K-Means++: The Advantages of Careful Seeding. In Proceedings of the Annual ACM-SIAM Symposium on Discrete Algorithms, New Orleans, LA, USA, 7–9 January 2007; pp. 1027–1035.
38. European Investment Bank. *The State of Local Infrastructure Investment in Europenull*; European Investment Bank: Beograd, Serbia, 2021.
39. Pasquini, L.; Shearing, C. Municipalities, Politics, and Climate Change: An Example of the Process of Institutionalizing an Environmental Agenda Within Local Government. *J. Environ. Dev.* **2014**, *23*, 271–296. [CrossRef]
40. Bachtler, J.; Mendez, C.; Oraže, H. From Conditionality to Europeanization in Central and Eastern Europe: Administrative Performance and Capacity in Cohesion Policy. *Eur. Plan. Stud.* **2014**, *22*, 735–757. [CrossRef]
41. Neidig, J.; Anguelovski, I.; Albaina, A.; Pascual, U. Multi-Level Finance Impacts on Participation, Inclusion, and Equity: Bricolage and Fuzziness in NextGenerationEU-Funded Renaturing Projects. *Environ. Sci. Policy* **2024**, *156*, 103753. [CrossRef]
42. Raco, M.; Durrant, D.; Livingstone, N. Slow Cities, Urban Politics and the Temporalities of Planning: Lessons from London. *Environment and Planning C: Politics and Space* **2018**, *36*, 1176–1194. [CrossRef]
43. Petmesidou, M.; Branco, R.; Pavolini, E.; González Begega, S.; Guillén, A.M. The EPSR and the Next Generation EU: Heralding a Reconfiguration of Social Protection in South Europe? *Soc. Policy Adm.* **2023**, *57*, 497–512. [CrossRef]
44. Bigiotti, S.; Costantino, C.; Marucci, A. DECISION-MAKING TOOLS FOR SUSTAINABLE RECOVERY OF RURAL VILLAGES: PLANNING POLICIES AND IMPLEMENTATION STRATEGIES FOR VALORISING SMALL COMMUNITIES IN INNER AREAS UNDER THE NEXT GENERATION EU PROGRAMME. *WIT Trans. Ecol. Environ.* **2024**, *262*, 479–494. [CrossRef]
45. Vassi, A.; Siountri, K.; Papadaki, K.; Iliadi, A.; Ypsilanti, A.; Bakogiannis, E. The Greek Urban Policy Reform through the Local Urban Plans (LUPs) and the Special Urban Plans (SUPs), Funded by Recovery and Resilience Facility (RRF). *Land* **2022**, *11*, 1231. [CrossRef]
46. Kammerer, M.; Zeigermann, U. Managing Climate Impacts—An Analysis of Adaptation Funding in German Cities and Districts. *npj Clim. Action* **2025**, *4*, 76. [CrossRef]
47. Polverari, L.; Piattoni, S. The Italian National Recovery and Resilience Plan and Administrative Capacity: A Real Game Changer? *Riv. Ital. Di Politiche Pubbliche* **2022**, *XVII*, 169–189. [CrossRef]
48. Ottone, V.; Barbieri, M. Research & Innovation Policy in the Italian NRRP: An Evalutation of Emerging Challenges for Multi-Level Governance. *Contemp. Ital. Politics* **2022**, *14*, 409–423. [CrossRef]
49. Urso, G.; Modica, M.; Faggian, A. Resilience and Sectoral Composition Change of Italian Inner Areas in Response to the Great Recession. *Sustainability* **2019**, *11*, 2679. [CrossRef]
50. Pendall, R.; Foster, K.A.; Cowell, M. Resilience and Regions: Building Understanding of the Metaphor. *Camb. J. Reg. Econ. Soc.* **2010**, *3*, 71–84. [CrossRef]

51. D'Adamo, I.; Rossi, E.N. Impact of Regional Investment on the Sustainable Development Goals: A Group Analysis of Economic and Territorial Development. *Sustain. Dev.* **2025**, *33*, 1816–1834. [CrossRef]
52. D'Andrea, S.; Silvia, D.; Di Bartolomeo, G.; D'Imperio, P.; Giancarlo, I.; Mara, M. Structural Reforms in the Italian National Recovery and Resilience Plan A Macroeconomic Assessment of Their Potential Effects. Government of the Italian Republic (Italy), Ministry of Economy and Finance, Department of the Treasury Working Paper No. 2. Available online: https://ssrn.com/abstract=4546997 (accessed on 11 September 2025).
53. Di Bartolomeo, G.; D'Imperio, P.; A Macroeconomic Assessment of the Italian National Recovery and Resilience Plan. Department of the Treasury Working Paper No. 2, March 2022. Available online: https://ssrn.com/abstract=4405861 (accessed on 11 September 2025).
54. Domorenok, E.; Guardiancich, I. The Italian National Recovery and Resilience Plan: Coordination and Conditionality. *Contemp. Ital. Politics* **2022**, *14*, 191–206. [CrossRef]
55. Dastoli, P.S.; Pontrandolfi, P. Methods and Tools for a Participatory Local Development Strategy. *Lect. Notes Netw. Syst.* **2022**, *482*, 2112–2121. [CrossRef]
56. Lanza, G.; Pucci, P.; Carboni, L.; Vendemmia, B. Impacts of the COVID-19 Pandemic in Inner Areas. *TeMA—J. Land Use Mobil. Environ.* **2022**, *2*, 73–89. [CrossRef]
57. Musso, F.; Angioni, M. Quale Modello Di Senior Cohousing per La Popolazione Delle Aree Interne. *AEA Inf.* **2022**, *2022*, 11–39.
58. Iodice, M.; Carini, E.; Scotellaro, M.; Martini, L.; Cosentino, M.; Roscio, G.; Borghini, A.; Mantoan, D. Territorial Coordination Centres and Telenursing: Innovation and Digitalisation of Home Care in Italy. *Eur. J. Public Health* **2023**, *33*, ckad160-1214. [CrossRef]
59. Fregolent, L.; Savino, M.; Beria, P.; Pucci, P.; Cellamare, C.; Franco, E.; Tamini, L. PNRR e La Grande Trasformazione Del Paese/PNRR in Materia Di Infrastrutture e Mobilità: Tra Investimenti e Riforme/PNRR: Rigenerazione Urbana e Housing/Il PNRR Nella Dimensione Della Prossimità: Questioni Problematiche e Scenari Di Opportunità. *Arch. Studi Urbani E Reg.* **2023**, *53*, 161–165. [CrossRef]
60. Fabbrini, F. Italy's National Recovery and Resilience Plan: Context, Content and Challenges. *J. Mod. Ital. Stud.* **2022**, *27*, 658–676. [CrossRef]
61. Ajo, G. Strategies for Preventive Protection of Historical Settlements against Seismic Events in Inner Areas. Security and Identity. *Il Capitale Cult. Stud. Value Cult. Herit.* **2019**, *2019*, 255–280. [CrossRef]
62. Chioni, C.; Pezzica, C.; Favargiotti, S. Territorial Digital Twins: A Key for Increasing the Community Resilience of Fragile Mountain Inner Territories? *Sustain. Dev.* **2024**, *32*, 1548–1563. [CrossRef]
63. EU's Recovery and Resilience Facility Impact Set to Reach EUR 891.7 Billion—European Commission. Available online: https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/eus-recovery-and-resilience-facility-impact-set-reach-eur-8917-billion-2025-05-21_en?utm_source=chatgpt.com (accessed on 11 September 2025).
64. Maranzano, P.; Noera, M.; Romano, R. The European Industrial Challenge and the Italian NRRP. *PSL Q. Rev.* **2021**, *74*, 207–218. [CrossRef]
65. Cassalia, G.; Calabrò, F. The Valuation of Unused Public Buildings in Support of Culture-Led Inner Areas' Small Villages NRRP Strategies: An Application Model in Southern Italy. *Lect. Notes Netw. Syst.* **2022**, *482*, 3–15. [CrossRef]

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