Planning for Climate Proof Cities

Massimiliano Granceri Bradaschia
Filippo Magni
Francesco Musco *Editors*

Climate Change Adaptation, Flood Risk, and Beyond

State of Play in the Science-Policy-Action Nexus

Springer

Planning for Climate Proof Cities

Series Editor

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International commitments to design resilient and adaptive cities, as consequence of the Global Climate Change, can represent the most relevant issue (both political and scientific) of the twenty-first century, requiring an explicit revision of the processes of planning and managing cities.

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The series will be strongly interdisciplinary, connecting disciplines that can contribute to design and plan “climate proof cities” of the next decades.

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Editors

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Foreword

Adaptation to climate change is a societal and ecological challenge that must be responded to from a multi-lens point of view. The information and knowledge that we use to adapt to climate change will depend on what types of data we consider important and relevant and also what types of sources of data are considered. We live in a world of multiple knowledge and multiple stakes and failing to take this into account when preparing the ground to adapt will end in simplistic solutions and ways of doing that do not sufficiently reflect the needs and realities of societies and ecosystems. We have experienced almost three decades of science and policy development to prepare for the (now current and future) impacts of climate change, but still important challenges persist when it comes to understanding the challenges ahead. For one, when planning to adapt to climate change one must realise that it is not something that can be addressed in isolation. We live in a reality of compound crises and risks and climate change is just one of them. Assessments of risks and vulnerabilities are therefore required to adopt a complex and diverse understanding of needs, resources, and capacities. In the same way, for actions on the ground to be successful, they need to address not only climate change impacts but also existing and compounded ecological and societal structural vulnerabilities. However, for this to happen, the way we think of adaptation should also change. Processes of planning and decision-making should embrace more interdisciplinary and transdisciplinary approaches where scientific, policy and local expert knowledge can co-exist to provide the best available information to adapt to climate change impacts in context-specific settings. Finally, there is a need for society to understand that adaptation is not an end but a culture of doing and living in this world subject to changing climates and unstable socio-political systems. We must pursue approaches to policy and action that are grounded on the continuous re-evaluation of impacts and processes on the ground to learn and adapt to those changing socio-ecological conditions. This book delves into the different layers of complexity that characterise climate change adaptation from problem understanding to planning and action, demonstrating that it is not a wicked problem, but rather a challenge that requires a different set of socio-political and scientific skills and mindsets.

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The Editors confirm that the content of this book is the sole responsibility of its Authors and Editors and does not necessarily reflect the views of the EC.

Venice, Italy

Dr. Massimiliano Granceri Bradaschia
Dr. Filippo Magni
Prof. Francesco Musco

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About the Editors

Massimiliano Granceri Bradaschia is a post-doc researcher at IUAV University of Venice and an independent consultant with more than 10 years of work experience in Urban and Environmental Planning, Climate Change Adaptation, Monitoring and Evaluation, Public policy analysis. He is a professional with diverse and multicultural experiences as both scholar and practitioner in Brazil, France, Spain, Italy, and in the lusophone African countries. He holds a Ph.D. in Urban and Regional Development (2020) and a M.Sc. in Urban and Environmental Planning (2014).

He is officially chartered to the Italian Urban Planning National Register (2014) and to the Turin Architects and Urbanists register (2020).

He's been working at the services of: (i) governments, (ii) private companies and consortia, (iii) learning and research institutions, (iv) donors and funding organizations, supporting the improvement and update of their operative frameworks with the aim to mainstream Sustainability and Climate Change Adaptation.

Filippo Magni urban planner, holds a Ph.D. in planning and public policies for the territory at Università Iuav di Venezia, a master's degree in planning at Iuav with a double title from the International Master in Estudios Territorials i de la Poblaciò issued by the Universitat Autonoma de Barcelona (UAB). He is currently a researcher in urban and regional planning.

He has carried out research and teaching abroad at Universitat Autonoma de Barcelona, Universidad de Sevilla, and the Drexel University of Philadelphia, where, through a multidisciplinary approach, he focused on the need to redesign urban planning tools, recognised as the main vectors capable of increasing greater resilience to climate change.

He is the scientific co-coordinator of the Interreg ITA-CRO project "ADRIADAPT and of the project" Venice 2021-Line 5.3.1. He is the coordinator of the technical-scientific consultancy unit for the implementation of the climate strategies of the municipalities of the Lombardy region, activated by Iuav and Cariplo Foundation within the "F2C-Fondazione Cariplo per il clima" project. Previously he coordinated the technical support unit for the Interreg MED 2014-2020 projects "COEVOLVE and LIFE MASTER ADAPT".

Francesco Musco urban and environmental planner, Ph.D. in Analysis and Governance of Sustainable Development (Ca' Foscari, Venice), Full Professor in Urban and Environmental Planning at the Department of Architecture and Arts—University Iuav of Venice. Currently teaches "Environmental planning", "Spatial Planning for Climate Change", "Urban design".

Currently is Director of Research at Iuav (2021–2024) and Director of the MS in Urban Planning for Transition and professor of Ph.D. program in "Spatial planning and public policies for the territory" at Iuav.

Scientific coordinator of numerous EU-funded projects and research and he obtained more than 8 million euros of competitive research funds in the period 2011–20. Among his publications: with M. van Staden (2010), Local Government for Climate Change, Springer, NY; (2016); (ed) Counteracting Urban Heat Island Effects in a Global Climate Scenario, Springer NY.

Chapter 1
Introduction: How Climate Change Adaptation is Addressed Through Science-Policy-Action Nexus in This Book

Massimiliano Granceri Bradaschia and Filippo Magni

Abstract In a historical period characterised by the increasingly serious impacts of climate change, the need to develop adaptive strategies to address complex and interconnected challenges has become an imperative that can no longer be postponed. The need to address this phenomenon calls for the adoption of a comprehensive, multi-risk approach, requiring the integration of cutting-edge scientific knowledge and practical experience. This approach includes collaborative public policy formulation, leveraging collective stakeholder understanding and facilitating pervasive and strategic actions on the ground. Precisely the Science-Policy interface emerges as a crucial dimension in this scenario of change, requiring the transfer and co-production of knowledge between climate experts, spatial planners, and policy makers. Also, the Policy-Action interface is central, requiring a re-evaluation of spatial policy frameworks and the development of new operational tools and processes. Starting from these premises, the book emphasises the collaborative efforts of the main actors that characterise this triple science-policy-action relationship: scholars, policy makers, civil servants, and practitioners. This publication unfolds in three distinct sections, each meticulously addressing a critical dimension of the overall challenge. The narrative is structured to traverse the intricate landscape of scientific inquiry, policy formulation, and the imperative for transformative action. As this scientific exploration proceeds, the integration of different disciplines and the imperative for collaborative efforts underscore the need for a holistic approach in addressing the multiple impacts of climate change.

Keywords Science-policy · Policy-action · Holistic approach · Climate change adaptation

In a historical period characterised by the increasingly serious impacts of climate change, the need to develop adaptive strategies to address complex and interconnected

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challenges has become an imperative that can no longer be postponed. This volume aims to explore the intricate landscape of climate change adaptation processes, characterising it as a multi-disciplinary, multi-scalar and multi-actor challenge, requiring a holistic and proactive response.

The need to address this phenomenon calls for the adoption of a comprehensive, multi-risk approach, requiring the integration of cutting-edge scientific knowledge and practical experience. This approach includes collaborative public policy formulation, leveraging collective stakeholder understanding and facilitating pervasive and strategic actions on the ground. The imperative is underscored by the intricate nature of climate change impacts, which require a pervasive and adaptive strategy that considers multiple risks and integrates knowledge from multiple disciplines. Consequently, a robust response requires the synthesis of scientific expertise, social sharing in policy development, and sustained efforts by actors on the ground to effectively mitigate and adapt to the multifaceted challenges posed by climate change.

Precisely the Science-Policy interface emerges as a crucial dimension in this scenario of change, requiring the transfer and co-production of knowledge between climate experts, spatial planners, and policy makers. Within the framework presented, the analysis of ecosystem services takes on a new and increasingly central role as a key component in climate risk assessments. This analytical approach clarifies the intricate interdependencies between natural systems and human vulnerabilities, providing a broad understanding of ecosystem capacity to mitigate or exacerbate climate-related risks. The use of advanced methodologies in the analysis of ecosystem services enables a comprehensive assessment of the multiple contributions of ecosystems to human well-being, emphasising their role as critical components in climate adaptation and resilience strategies. This integrative assessment further emphasises the importance of recognizing and harnessing the ecosystem services provided by natural systems to inform evidence-based decision making in the face of complex climate challenges.

In the current scientific arena, extensive investigations have been conducted to clarify the cause-effect and effect-response relationships associated with climate change. However, there has been a significant shift in focus, bringing to the forefront the hitherto underestimated interface between policy dynamics and implementable strategies. This paradigmatic shift underscores the critical role of the policy dimension in contemporary climate adaptation processes. It underscores the imperative to transcend theoretical understanding and effectively translate climate knowledge into tangible actions. Today, the Policy-Action interface is central, requiring a re-evaluation of spatial policy frameworks and the development of new operational tools and processes. This reconceptualization accentuates the urgency of implementing policy measures oriented toward mitigation and adaptation to climate impacts, thus fostering a synergistic integration of scientific knowledge with site-specific and target-oriented policy initiatives.

Nevertheless, one key obstacle remains evident in the area of climate change adaptation: the absence of a well-defined and effective monitoring and evaluation (M&E) framework to assess this complex process. Despite the abundant availability of data on various climate phenomena such as floods, heat waves, and droughts, there is a lack of a comprehensive and unambiguous M&E system that facilitates the assessment of adaptation efforts and related spatial impacts. This deficiency in the M&E apparatus hinders processes for assessing the effectiveness of implemented adaptation strategies and inhibits the development of a holistic understanding of their spatial implications. A robust M&E framework is essential to promote scientific (and economic) evidence-based decision-making processes, enabling policymakers to assess the success of adaptation interventions, identify areas for improvement, and refine strategies in response to changing climate dynamics. Consequently, the development of an effective M&E system emerges as an imperative step to improve the effectiveness and resilience of climate adaptation initiatives.

Starting from these premises, the book emphasises the collaborative efforts of the main actors that characterise this triple science-policy-action relationship: scholars, policy makers, civil servants, and practitioners. Structured in three distinct parts, the text outlines the complexities of climate change adaptation.

This publication unfolds in **three distinct sections**, each meticulously addressing a critical dimension of the overall challenge. The narrative is structured to traverse the intricate landscape of scientific inquiry, policy formulation, and the imperative for transformative action. As this scientific exploration proceeds, the integration of different disciplines and the imperative for collaborative efforts underscore the need for a holistic approach in addressing the multiple impacts of climate change.

The first part of the volume delves into the interface between science and policy, focusing mainly on the Adriatic region. Here the emphasis is on the development and monitoring of multi-risk assessments. This scientific effort aims to serve as a conduit, effectively bridging the gap between the reservoir of scientific knowledge and the construction of public policy. The ultimate goal of this first part is to equip decision-making processes with a solid foundation, ensuring that policies are not only aware of scientific insights but are also adaptive to the dynamic challenges posed by climate change.

With a seamless transition, **the second part** focuses on the intricate interplay between policy and action. Within this segment, how theoretical frameworks are translated into practical tools is explored, touching on areas ranging from land-use planning to climate finance. The focus extends to the design of tailored operational plans for both coastal and river flooding, clarifying the complex issues involved in mitigating the impacts of climate change at the ground level. In addition, this section addresses the increasingly pressing challenge of M&E for flood-related projects, offering innovative methodologies to bridge the gap between policy intentions and tangible results achieved by these projects.

The third part of this scientific exploration, titled "From Action to Policy," shifts the focus within Brazil's experiential landscape. Here, the narrative is polarised toward water-sensitive and art-driven approaches, recounting ongoing experiences that redefine conventional perspectives on urban water and secondary river systems. Through an analytical lens, these experiences are presented as a model for both local communities and policymakers, highlighting the transformative potential of creativity and cultural elements in the field of climate change adaptation.

In this book, the multi-faceted trajectories of the several scientific explorations led to the statement of that necessary holistic condition recalled in the opening. Adaptation to climate change is presented no longer as a compartmentalised effort; instead, it becomes a dynamic and interconnected challenge to be responded to with collaboration and integrated methodologies.

By addressing existing gaps in monitoring and evaluation, ecosystem services analysis, and drawing inspiration from bottom-up experiences, this publication aims to establish a solid foundation for effective and sustainable adaptation to climate change. The collaborative engagement of key stakeholders and contributors along the science-policy-action nexus emerges as the force that can drive new land management and flood risk reduction processes, accompanying through the intricate complexities of climate change toward a future characterised by resilience and adaptability.

Part I
From Science to Policy

Chapter 2
Assessing Hydrogeological Vulnerability Within Northern Apennines: An Integrated Spatial Analysis in Emilia-Romagna Region (Italy)

Gianfranco Pozzer

Abstract The steady increase in climate change-related disaster phenomena in Italy forces territorial (and local) governments to meet a growing demand to revise mitigation and adaptation protocols. Housing solutions and models are called upon to update resilience strategies *vis-à-vis* phenomena such as the spatial convergence of various impacts and vulnerabilities. Complex vulnerability domains, often unpredictable, require new computational technologies and a clear definition of "spatial knowledge" according to critical issues, emerging challenges, and settlement perspectives. This paper provides an opportunity to test this hypothesis using spatial modelling and remote sensing techniques. The objective is to ease the identification of physical-environmental correlations/associations among endogenous and exogenous factors, namely between morphological states and climatic stressors "captured" through satellite images. The contribution is part of the European project AdriAdapt Interreg Italy-Croatia coordinated by CMCC (Euro-Mediterranean Center on Climate Change). It develops a test of spatial interaction between flooding, landslides, and drought. The test is conducted within the sample territory of Unione dei Comuni Valle del Savio (Emilia-Romagna Region), an area frequently affected by flooding events and hydrogeological instability. The results show a significant overlap between hydraulic performance and spatial texture, providing a new vulnerability vision in a multi-system perspective.

Keywords Climate proofing · Anthropogenic activity · Runoff modelling · Remote sensing · Multi-vulnerability · Spatial planning · Uncertainty

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2.1 Introduction[1]

The Italian peninsula is a territory at high hydraulic and hydrogeological risk due to morphological reasons, a fast and dense urbanization and inefficient land use.[2] According to estimates from the Institute for Environmental Protection and Research (ISPRA) for 2021 (Trigila et al., 2021), over 90% of Italian municipalities are affected by hydrogeological criticalities or coastal erosion phenomena. Additionally, about 7 million people live in areas with high flood risk. In this context, current climate anomalies will have a significant impact, posing new challenges to land planning, management, and regulation devices. According to the Intergovernmental Panel on Climate Change (IPCC) predictions, climate change-related phenomena will intensify in the coming decades, and extreme events will increasingly increase rise risk to environmental protection and territorial safety (Espon Climate, 2022; IPCC, 2018; Iturbide et al., 2021).

Recent flooding events (Spring of 2023) in various provinces of Emilia-Romagna are unquestionable evidence. They demonstrate how the presence of meteorological phenomena of particular intensity and duration, combined with morphological fragility, partly related to climate change and partly to anthropic factors,[3] can worsen territorial instability and environmental degradation (Raikes et al., 2019). These

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[1] This contribution provides a brief overview of the results of a scientific research project on climate change (2019–2021), initially conducted within the Planning and Climate Change Lab of the University Iuav of Venice (coordinated by the scientific supervisor Francesco Musco, with the technical and methodological support of Filippo Magni, Denis Maragno, Gianfranco Pozzer, and Giovanni Carraretto). The research results have recently been incorporated into IR.IDE (a platform for scientific innovation established as part of the Department of Excellence Iuav project, 2018–2022), thanks to the collaboration between the VAULT study centre of IR.IDE (Value Activators in Urban Landscape and Territory) and the Planning and Climate Change Lab of Iuav. The contribution presents the methodological results of the AdriAdapt project (experimental research funded under the European Interreg Italy-Croatia program). The contents partly refer to a previous paper presented at the XXIII National Conference of SIU—Italian Society of Urban Planners (Pozzer et al., 2021).

[2] For many years, Italy has been grappling with the consequences of climate change due to its unique combination of morpho-climatic, morphological, topographic, and geological characteristics. The storm "Ciaran" on November 2nd and 3rd, 2023, generated more than 73 extreme meteorological events (wind gusts and heavy rainfall), hitting many regions hard, with Lombardy and Tuscany being among the most affected, resulting in casualties, missing persons, and significant damage (source: Dire—National Press Agency, November 4, 2023). In Italy, flood risk management requires a high level of interaction between hydraulic engineering and territorial planning, and policies must now work synergistically and systemically more than ever to counter the increasing territorial vulnerabilities (Landauer et al., 2019). These policies should promote sustainable land use, infrastructure, and mobility models adapted to the changing climate, as Mims (2021) highlighted. Regarding the possibilities of reducing risk, the recommendations of the De Marchi Commission, proposed immediately after the floods of 1966, remain relevant. In addition to structural interventions, non-structural works should also be considered, enabling the prediction of when and with what intensity a flood event could occur. This can facilitate the creation of new communication channels for managing emergency phases, alerting the population and ensuring safety where needed.

[3] For instance, sea-level rise, drought, erosion, deforestation, intensive crop cultivation, soil consumption, etc.

phenomena generate violent and extensive flooding, often exacerbated by hydraulic inefficiencies in drainage systems (Galimberti & Balbo, 2023),[4] soil compaction processes, or a significant increase of sealed surfaces.[5]

In Emilia-Romagna, soil artificialization reduces the resilience of local ecosystems with adverse effects on vulnerability and risk components (Munafò, 2022). There is a noticeable reduction in the surface needed for natural rainwater infiltration, which flows into highly urbanized environments much more rapidly than in the past (Avand & Moradi, 2021). This process can be monitored through specific "inflow-outflow" dynamic simulation models with logical criteria on flooding based on a spatial association between land use, runoff and terrain morphologies (Pistocchi, 2018).

Such a simulation helps to draw potential risk scenarios, assessing the effectiveness of mitigation and adaptation actions during planning and programming activities (European Commission, 2021). In this perspective, the present work illustrates an experimental approach for assessing vulnerability to landslides and floods, focusing on hydraulic and hydrogeological features in spatial analysis. The European project AdriAdapt—Resilience information platform results for Adriatic cities and towns (PAP/RAC, 2021) are used here. They were developed at the Department of Culture of the Project at the Iuav University of Venice in collaboration with the CMCC (Euro-Mediterranean Center on Climate Change). The study area is located in the Valle Savio (Emilia-Romagna, Italy), and an analysis impacts model on flooding, drought, and landslides is applied.[6] The factors considered vary with data availability as parameters and physical properties are acquired through remote sensing. The simultaneous consideration of endogenous and exogenous factors facilitates the construction of an integrated geo-dataset capable of catching spatial correlations between phenomena considered by climate-proof planning tools (Magni, 2019). The result helps define a planning dimension capable of recognizing territorial vulnerability

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[4] In addition to these conditions, extensive storm surges may prevent the natural drainage of river waters into the sea due to the temporary rise in sea level.

[5] In many Italian territories, the causes contributing to soil consumption are partly attributed to the correlation between the building and construction cycle, infrastructural policies (Patassini & Pozzer, 2018), and the overall regional economic cycle, where the role of the financial component is much more prominent than in the past (Fregolent & Savino, 2014). The dynamics of soil sealing activate specific consumption levels related to settlement morphologies, construction processes, and coverage patterns. Settlement morphologies represent the model of urbanization as an organizational component aimed at forms of consumption uses, and functions. Generally, these phenomena interact, generating synergistic morpho-typological effects, compensatory or decidedly conflicting. The effects of consumption tend to change depending on settlement contexts and the planning cultures, giving rise to territorial fragilities and vulnerabilities that differ in intensity, territorial size, morphological composition, and settlement patterns. Changes in land use intensity can also be traced back to territorial dynamics already activated by administrative fragmentation, which, combined with other economic and demographic factors (demographic balances), tend to define forms of consumption with a contextual peculiarity (Patassini & Pozzer, 2018).

[6] Related impacts occur as first-order, overlapping or contiguous "joint evidence", while cumulative impacts result from additive or multiplicative effect interactions. Cumulative impact is also understood as "second-order evidence" with a nonlinear or complex effect (conversation with Patassini, 2023).

as an outcome of cumulative impacts generated (in part) by the effects of climate change (de Sherbinin et al., 2019; IPCC, 2022). The concept of spatial association (semantically contiguous to correlation but different in metric terms) emerges from structural and contextual informative layers (Fritzsche et al., 2014; O'Brien et al., 2007; Tapia et al., 2015).

In summary, the contribution demonstrates how processing new spatial information generated by modelling cumulative impacts combined with remote sensing analysis enriches understanding of spatial vulnerability assessment in a multi-systemic learning perspective (see, for example, Maragno et al., 2023).[7] The choice of study area enhances the convergence of these new data, comparing them with informative sources, theoretical aspects, and procedural elements validated by various scientific contributions (Kamel Boulos & Wilson, 2023; Maragno et al., 2021).

The article is divided into four parts. The first part (Sect. 2.2) presents the scope of work, research design, and the study area. The second part (Sect. 2.3) introduces an integrated modelling approach. Techniques and data analysis procedures for studying impacts illustrate the logic and operational steps, from constructing individual vulnerability indices to recognizing an aggregated mapping. The third part (Sect. 2.4) discusses the results of empirical research. They reflect the potential of a working methodology capable of recognizing the existing correlation between morphological states and incremental surface runoff. This involves estimating the ratio between impact indicator values and using topological overlapping.[8] The fourth and final part (Sect. 2.5) discusses the procedure's usefulness and the reliability of its results. The method demonstrates how land use and impacts are partly connected to the morphologies of the territory and, in part, directly comparable and assessable in a meta-evaluation process.

The article concludes with recommendations and suggestions for future practice and research.

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[7] Here, "systemic vulnerability" represents (and measures) an area's propensity to manifest multidimensional issues, considering the combined reading of three impact conditions: floods, droughts, and landslides. The systemic (or multi-systemic) approach favors integrated assessment cues, facilitating the process of selecting adaptation strategies (and priority areas for intervention) through Decision support systems (Dss) or multicriteria analysis techniques.

[8] It is important to remember that the resurgence of geological phenomena (such as landslides) is a very complex dynamic, where associations like drought landslide and runoff landslide require appropriate interpretative contextualization. This work assumes a strategic-knowledge connotation to support the definition of planning practices oriented towards climate-proofing.

2.2 Scope of Research: References, Design, and Case Study

2.2.1 Theoretical Background

This contribution is part of the European program AdriAdapt Interreg Italy-Croatia,[9] coordinated by the CMCC. Its main aim is to increase the capacity of the Upper Adriatic to adapt urban and coastal areas to climate change. The article focuses on the study's progress related to three particularly adverse classes of impact within the territories of Valle Savio[10]: flooding, landslides and drought.[11]

Innovative elements lead to spatial analyses that estimate the differential hydraulic risk linked to morphologies and land use changes (Ungaro et al., 2014). The work delves into a research field recognized at institutional,[12] academic, and operational levels in urban and territorial management practices (Musco, 2016; Pietrapertosa et al., 2019).[13] In territorial governance, assessing hydraulic danger (and flooding) is increasingly recognized with attention in mitigation and adaptation practices (Kourtis & Tsihrintzis, 2021; Wilby & Keenan, 2012). Adaptation is a complex[14] process that relies primarily on the geographic, geomorphological, and climatic specificities of the location (Wamsler et al., 2013), as well as on the "culture" of local communities (Patassini, 2022; Romero Lankao & Zwickel, 2015): it activates

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[9] The project analyses impact types that interact with the vulnerability dynamics of the following territories: the Municipality of Udine, the Municipality of Cervia (RA), the Unione Valle Savio, the Municipality of Vodice (Croatia), and the County of Šibenik (Croatia). The following impacts are recognized analytically and cartographically: Urban Heat Islands, Urban flooding, Wildfires, Drought, Landslides, Sea-level rise, and Salt intrusion. The project aims to provide local authorities with the territorial knowledge necessary to prepare procedures and planning models capable of interpreting and raising the resilience levels of settlement environments, preparing them to withstand the mechanical stresses induced by increasingly severe climate variations.

[10] The Union of Municipalities Valle del Savio includes the following territorial units: Bagno di Romagna, Cesena, Mercato Saraceno, Montiano, Sarsina, and Verghereto.

[11] Drought results from local transformations (agricultural changes, urbanization, hydraulic management, etc.) and general climatic variations.

[12] Please refer to Italian legal conditions concerning the imposition and management of hydrogeological constraints and the formation of hydrogeological planning plans (Italian acronym: PAI).

[13] In Italy, many investigations and research on Adaptation to climate change are commissioned and published by the *Fondazione per lo Sviluppo Sostenibile* (see www.fondazionesvilupposostenibile.org).

[14] Adaptation to climate variations has characterized human life and migrations from ancient times, as evidenced by some historical reconstructions. Forms of Adaptation had characterized periods when humans lived by hunting and gathering, when they began to develop agricultural and breeding technologies, with the foundation of the first cities and their subsequent transition in industrial and post-industrial revolutions, as well as in more recent analogue and digital phases. Adaptation is a "vital" practice that produces culture, and its exceptionality is generally experienced in actual or threatened catastrophes and transitional phases (conversation with Patassini, 2023).

economies, infrastructures, capacities, and flows, responding to how risk components arise (Füssel, 2010). When looking at the settlement environment, it is strategically relevant to recognize the domains of vulnerability (IPCC, 2014). This requires an in-depth analysis of morphological structures, physical-functional components, eco-systemic characteristics, and, more generally, dynamic equilibrium conditions (Bridle, 2022; Stewart et al., 2014). Such an operational need is partially met by the availability of new sources and actual interoperability of spatial information, which is assumed to be updatable based on multi-temporal and multi-scale devices.[15]

2.2.2 Research Design

The study addresses the spatial relationship between two constitutive components of hydraulic and hydrogeological systems: an endogenous and an exogenous component. The first component considers how land use and runoff coefficients contribute to altering the surface hydraulic regime of the territory, quantifying and spatializing the hydraulic impact at the scale of the hydrogeological basin (runoff or surface runoff). Hydraulic performance is estimated using a specific spatial simulation model that recognizes the correlation between territorial land use patterns, topography, and terrain morphologies (specifically, slopes, depressions, orientations, and valleys). The second component focuses on the dynamics of drought phenomenon linked to climatic-environmental effects studied with parameters and physical properties acquired through remote sensing.

Recognizing these two analytical dimensions allows a topological overlay between runoff, landslide phenomena, and drought environments.

The research follows an exploratory design (*impact analysis and modelling*) organized in two quantitative phases followed by a qualitative synthesis (Phase 3).

Phase 1: Remote Sensing Analysis. This phase identifies descriptors (variables) helpful for spatially detecting the consequences of climate change in terms of heat waves and drought. The drought study uses Landsat-8 satellite data, considering the impact of vegetation and thermal parameters capable of describing the structure of morphological spatial relationships and the varying degrees of vulnerability of anthropic and natural elements.

Phase 2: Morpho-Dynamic Analysis. The second phase develops a morpho-dynamic model of spatial association between runoff coefficients and a digital terrain model (Dtm). By applying direction and accumulation functions (GIS-based hydrologic modelling), it is possible to study the dynamic behaviour of surface runoff and quantify the impacts of land-use change on the evolution of flood vulnerability.

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[15] Spatial analysis and the latest approaches in quantitative geography highlight a semantic correlation, before a metric one, between space and time. The interpretation (represented or experienced) of space is spatialization, positioning in a space broader than the lines of time. Thus, space–time positioning becomes a provisional and oscillating pointer within spatial and temporal scales. This operation creates space and time (conversation with Patassini, 2023).

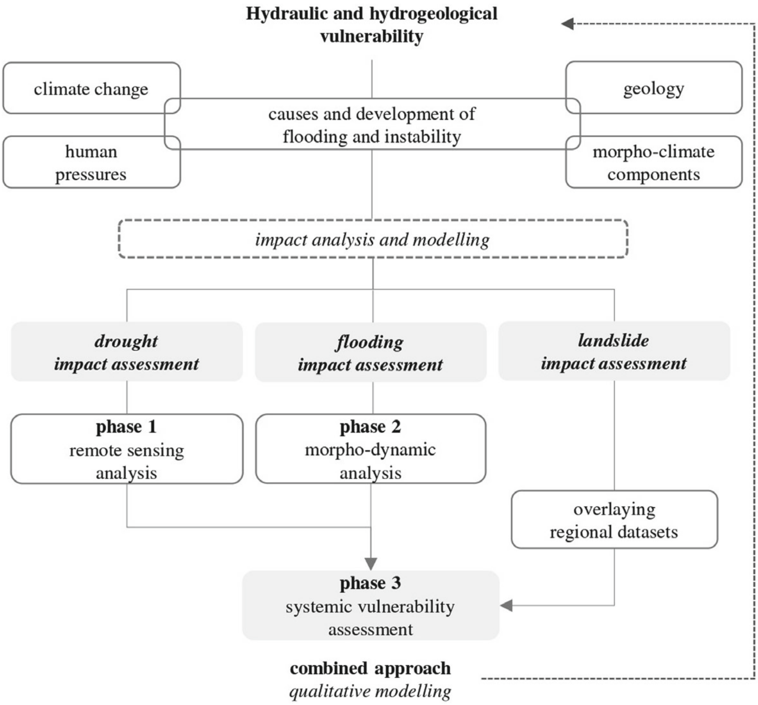

Fig. 2.1 Modelling systemic vulnerability: a logical path

Phase 3: Systemic Vulnerability Assessment. The third phase resumes the procedure for evaluating territorial vulnerability based on a combination of two environmental determinants: sensitivity and adaptive capacity.[16] It, therefore, proposes an evaluative overview based on a logical-spatial integration (at different scales) of ancillary and multi-spectral indices. This leads to recognising a systemic and integrated vulnerability model to landslides and floods (integrated reading of voluntary and mandatory information levels).

This phase generates a qualitative mapping of the most unstable areas and those susceptible to failure, aiming to highlight a potential spatial and morphological association between runoff and active landslides. This final step allows for an initial validation of the entire methodological framework.

The logical path of the research is outlined below (Fig. 2.1).

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[16] According to the IPCC approach, sensitivity represents the degree to which a given exposure negatively influences a system. It depends on the specific properties of the system under consideration. Adaptive capacity is the ability of a natural or built system to adapt to climate change in order to moderate potential impacts or damages.

2.2.3 Study Area Overview

The study area covers the Valle del Savio Municipal Union. It is a geographic-administrative area located along the Savio River, covering 810 km^2, almost entirely in the Province of Forlì-Cesena, with a very short stretch in the Provinces of Rimini and Ravenna. The Savio basin is between Valle del Bidente (Province of Forlì-Cesena) and Valle del Marenchia (Provinces of Arezzo, Pesaro-Urbino, and Rimini). The morphological profile of the area is characterized by an altitude ranging from 5 to 1520 m above sea level (mountain ranges of Tuscan-Romagnolo Apennines). The most common lithotypes from a pedological perspective are argillites, marly-sandstone, and alluvial deposits.[17] In terms of ecosystems, the Valley hosts multiple natural habitats and rich landscape biodiversity. Bio-climatically, the area is mainly belonging to the temperate region. Besides, the flat areas of the hinterland are moderately urbanized, while those near coastal shores are densely built-up (see, for evidence, urban areas of Cesena).

Only a portion of the Valle's territories falls under hydraulic constraint (Fig. 2.2).[18] In these areas, hydrogeological risk is widespread (Fig. 2.3), and it is primarily associated with slope instability or river courses due to specific environmental, meteorological, and climatic conditions. In addition, the combination of intense urbanization, the gradual abandonment of mountainous areas, and the increased frequency of extreme rainfall poses a severe environmental risk to settlements and human activities.

The analysis focuses on a sample area in the municipality of Bagno di Romagna (FC), providing a combined (correlated/associated) assessment of impacts.

The following factors justify the attention given to Valle Savio:

- presence of urban sprawl along the E45 European road, which at times runs parallel to the Savio River;

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[17] Source: Soil Cartography of the Emilia-Romagna Region.

[18] Focusing on the assessment framework of hazards and risks associated with floods—updated by the District Basin Authorities in December 2020 (see Article 6 of the European Floods Directive 2007/60/CE, second cycle of Management)—a context emerges in which Emilia-Romagna stands out as a region characterized by percentages of territory potentially subject to flooding significantly higher than the national average (Trigila et al., 2021). This situation increases the population's exposure to flood risk, considering three scenarios of hazard and probability (medium, low, high). As reported in the technical document by ISPRA (ibidem), the extensive extension of potentially floodable areas, especially starting from the medium hazard scenario in Emilia-Romagna, can be attributed to the complex and extensive network of drainage collectors and minor watercourses that develop over vast areas characterized by depressed morphology. These areas often host narrow riverbeds and raised embankments and are subject to a series of regulation and rectification interventions, especially in the plain regions. However, for events with return periods longer than those expected for a high-hazard scenario, it has emerged that the drainage system (mechanically or hybrid-managed) needs to be improved. This deficiency promotes widespread flooding over large portions of the regional territory, increasing flooding vulnerability. The provinces with the highest percentages of susceptible territory to floods are Ravenna and Ferrara, standing at 80% and almost 100%, respectively, considering a simulation related to a medium hazard scenario. The percentage of flood-prone areas in a medium-hazard scenario is approximately 18% for the Valle del Savio area.

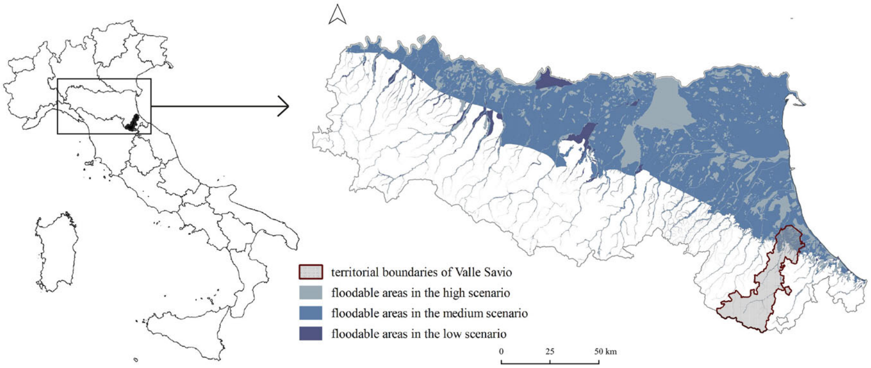

Fig. 2.2 Valle Savio in Emilia-Romagna Region. Floodable areas according to three different scenarios: high, medium, and low probability. *Source* Author's elaboration on the basis of vector maps of floodable created by ISPRA (database 2020)

- urban areas affected by periodic flooding;
- landslide movements related to slope instability, exacerbated by May 16 and 17, 2023 weather events.

2.3 Materials and Methodology

The research tests an exploratory model capable of analyzing geographic domains adversely influenced by a spatial convergence of impacts of different natures, namely drought, runoff, and landslides.

The approach can be considered experimental and involves:

- collection of data from interoperable sources (Sect. 3.1);
- application of algorithms for processing morphological information of impacts (Mapping: Sects. 3.2.1. and 3.2.2);
- cross-evaluation of impacts for a chromatic representation of vulnerability according to spatial coordinates (Modelling: Sect. 3.2.3).[19]

2.3.1 Data Acquisition

The study was conducted using various sources of information (Table 2.1). Some data refer to spatial and alphanumeric information already available at municipal levels (primary and general thematic maps); others come from diachronic readings or modelling states and dynamics through spatial analysis and remote sensing. The methodology also relies on a spatial correlation between satellite data from the

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[19] Landslide movements are incorporated into the assessment using the overlay technique.

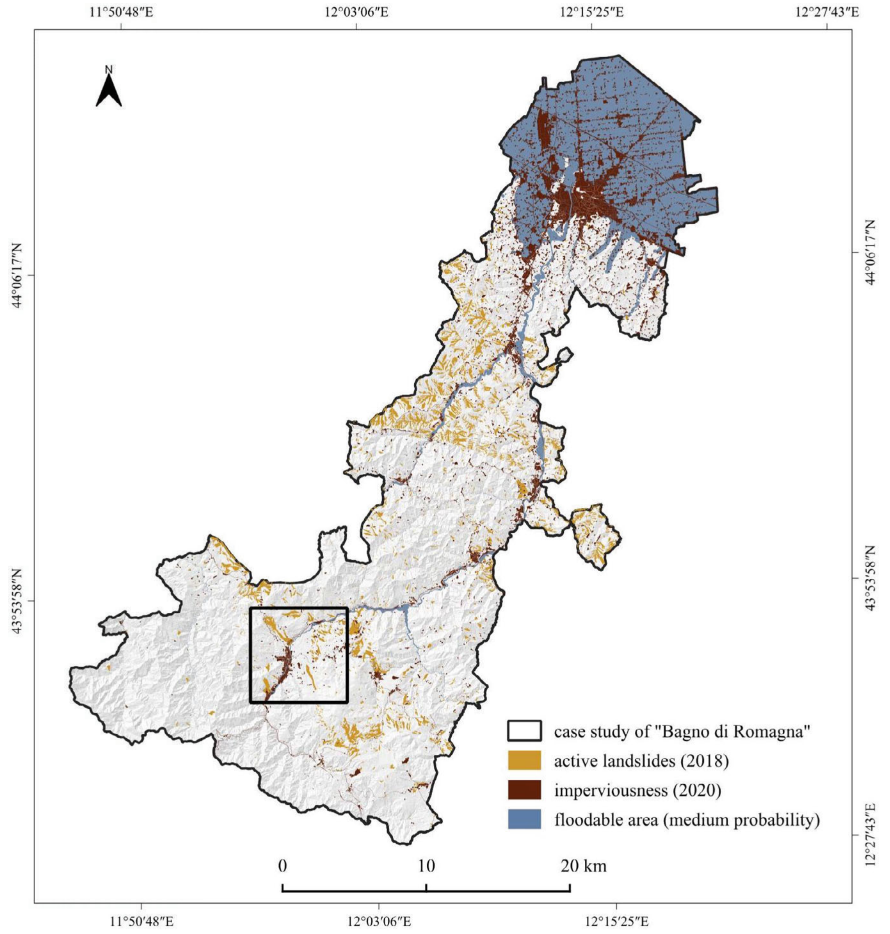

Fig. 2.3 Case study and hydrogeological risk profiles of Valle Savio. *Source* Author's elaboration based on vector maps of floodable areas and active landslide provided by ISPRA (database 2020) and Emilia Romagna Region (database 2018)

European Copernicus program and those recorded by national-scale monitoring and control systems (see, for example, ISPRA Institute).

Remote sensing and Geographic Information Systems (GIS) have been jointly utilized. Remote sensing analysis enables the estimated drought index linked to biophysical parameters derived from processing satellite images. The processing includes a hydro-morphological modelling algorithm for the dynamic simulation of

Table 2.1 Spatial information: category, layer, format and source

Category	Layer	Formats	Edition	Source
Themes of main geo-data	Hydrographic network of the Emilia-Romagna region	Vector	2020	Knowledge Framework of the Emilia-Romagna region
	Digital terrain model (Dtm) 5-m pitch of the Emilia-Romagna region	GeoTiff	2020	
Specific geo-data	Potentially floodable areas in the high, medium and low probability scenario—Emilia-Romagna region	Vector	2020	ISPRA
	Land use and land cover of the Emilia-Romagna region	Vector and raster	2020	Knowledge framework of the Emilia-Romagna region
	Emilia-Romagna Region landslide inventory map: active landslide deposition level[20]	Vector	2018	Geological databank of the Emilia-Romagna region
Remote sensing	LC08_L1TP_192029_ 20190820_20190903_01_T1	GeoTiff	2019	Landsat 8, USGS
	LC08_L1TP_192029_ 20181004_20181010_01_T1	GeoTiff	2018	
	LC08_L1TP_192029_ 20170729_20170811_01_T1	GeoTiff	2017	
	LC08_L1TP_192029_ 20160827_20170321_01_T1	GeoTiff	2016	
	LC08_L1TP_192029_ 20150708_20170407_01_T1	GeoTiff	2015	

surface runoff.[21] These techniques facilitate the definition of a guiding model for the multi-systemic and multi-dimensional assessment of hydrogeological vulnerability.

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[20] An active landslide refers to a deposit showing evidence of movement in the last seasonal cycle, regardless of the magnitude and speed (Source: Emilia-Romagna Region landslide inventory map).

[21] The algorithm developed is based on an adjustment of the method for hydraulic invariance by the Autorità dei Bacini regionali romagnoli (AdBRR—Emilia-Romagna, Italia). The operational concept of hydraulic invariance by AdBRR allows measuring the minimum reservoir volume to be allocated to areas transforming (land consumption, impermeabilization, urbanization) through the use of a planning index expressed in reservoir volume to associate with new impermeabilizations (Pistocchi, 2001). The criterion of hydraulic invariance is associated with the positive effects of urban drainage networks and the natural attenuation of floods due to the altimetric variations of the terrain (slopes and depressions).

2.3.2 *Mapping and Modelling*

2.3.2.1 Vegetation Health Index

The drought phenomenon is assessed through the Vegetation Health Index (Vhi).[22] This index sketches the intensity of drought and its spatial extent (Bento et al., 2018; Tripathi et al., 2013).[23] Landsat 8 satellite images are used to calculate the index. The estimation is indirect in that it is based on the forest and agricultural response of the vegetation. It captures thermal nature stresses or soil moisture changes.[24] Vhi is based on the ratio of two derived satellite indices: the Temperature Condition Index (Tci) and the Vegetation Condition Index (Vci). The Tci calculation uses thermal data obtained from Land Surface Temperature (Lst),[25] while Vci is based on vegetation data, Normalized Difference Vegetation Index (Ndvi),[26] capable of reflecting soil moisture conditions. Vci (2.1) is expressed with linearly standardized values (in %) that reflect vegetative stress associated with a low moisture rate (Kogan, 1995).

$$\mathrm{Vci} = (\mathrm{Ndvi}_{\mathrm{J}} - \mathrm{Ndvi}_{\mathrm{min)}}) / (\mathrm{Ndvi}_{\mathrm{max}} - \mathrm{Ndvi}_{\mathrm{min}}) * 100 \qquad (2.1)$$

TCI (2.2) is expressed with standardized values (in %) related to vegetative stress associated with high temperatures (Kogan, 1995).

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[22] The measurement of drought can be done according to different indices. Among the most widely used and internationally recognized ones is the Spi (Standardized Precipitation Index). This is a standardized indicator for detecting and assessing precipitation deficit (drought) at different time scales. The Spi index makes it possible to quantify the water surplus or deficit concerning the climatology of the area under consideration (see: https://www.isprambiente.gov.it/pre_meteo/siccitas/index.html). For a more in-depth discussion of the topic, see Vergni and Todisco (2010, 2011).

[23] The Vhi index can be associated with the strong inverse correlation between Ndvi and Lst under the hypothesis that a constant and intense increase in soil temperature negatively impacts vegetation vigour. This may contribute to the increased propensity of different tree species to be more or less easily attacked by fire. Against this background, the European Commission recently presented a draft regulation to track threats like fires fueled by climate change and illegal logging.

The data, produced mainly by satellite platforms, are already used at the European level and by member states to provide forest inventories continuously, identify land use (change) and monitor tree health. Information from satellite imagery will help identify illegal logging and mismanagement practices. The monitoring will allow shared forest data to be collected on the ground and via satellite. The goal is to have reliable data available to make faster and more timely decisions. These examples guide forest management in the digital age.

[24] To make the best use of Landsat-8 satellite imagery, choosing satellite data by concurrently evaluating temperatures during the hottest periods is essential. The selection of satellite images is based on four criteria: (i) acquisition year, (ii) acquisition month, (iii) daily average temperature, and (iv) absence of significant cloud cover. The selection considers orbital acquisition times with minimal atmospheric cloud presence.

[25] Lst is processed using a specific algorithm for extracting the land surface temperature based on the processing of thermal data acquired by Landsat 8 (Guha et al., 2018).

[26] Ndvi is calculated by measuring the spectral reflectance of vegetation, water, and bare soil in the visible, near-infrared, and red spectral bands (ibidem).

$$\mathrm{Tci} = (\mathrm{Lst}_{\max} - \mathrm{Lst}_{j)})/(\mathrm{Lst}_{\max} - \mathrm{Lst}_{\min}) * 100 \tag{2.2}$$

Vhi (2.3) is a proxy for the vegetation's health estimated based on a ratio between humidity values and more stressful thermal conditions (Kogan, 1995),

$$\mathrm{Vhi} = a * \mathrm{Vci} + b * \mathrm{Tci} \tag{2.3}$$

where "a" and "b" are coefficients quantifying the contribution of Vci and Tci to vegetation's response (with values ranging from 0 to 1). Low Vhi values identify areas more affected by drought.

Long-term Vhi analyses (conducted on various temporal scales) can represent geomorphologically, vegetation-wise, and climatically complex territorial realities. Notably, in conditions of intense and prolonged extreme events, Vci values can identify areas more affected by climatic phenomena during periods of drought (forest areas), average conditions, or in the presence of a rainfall surplus. The spatialization of Vhi can help identify different gradients of drought stress that, if adequately correlated with specific contextual information (endogenous and exogenous), can express the potential propensity of a specific forest or tree type to be affected by fires.[27]

2.3.2.2 Surface Runoff Estimation

The estimating hydraulic spatial performances is often entrusted to specific models simulating the "inflow-outflow" dynamics (Pistocchi, 2001, p. 5). The surface runoff is modelled based on a spatial association of land uses with terrain morphologies. An *ad-hoc* statistical model—developed in a GIS environment— clusters surface runoff dynamics into different land use categories (agricultural, urban, residential and industrial; woodland; wetland and semi-natural) using flow direction (FlowDir)[28] and accumulation (FlowAcc)[29] functions calculated at the basin scale.

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[27] Reading the Vhi satellite index in forestry can indicate moderate, severe or extreme water and heat stress conditions. Forests with low moisture levels can promote the rapid spread of fires, even on a large scale.

[28] The "Flow Direction" function processes a raster flow grid, assigning a numerical value (D8) to each pixel (spatial unit) based on the maximum slope. The D8 method recognizes eight possible drainage directions counterclockwise: 1—East; 2—Northeast; 4—North; 8—Northwest; 16—West; 32—Southeast; 64—South; 128—Southwest. The first pixel contains spatial information indicating towards which of the eight adjacent pixels the pixel itself is draining.

[29] The "Flow Accumulation" function makes preferential water flow paths visible. Where pixel values are very high, water converges massively (values will be higher closer to the valley). This results in a raster grid that assigns a numerical value to each cell, referring to the number of cells connected to that cell through the path of maximum slope. Cells corresponding to the watershed will have a value of 1, and the cell at the closing section will have a value equal to the sum of all cells in the basin. It should be noted that in Flow Accumulation, the actual water network does not emerge. It depends not only on topographic heights (Digital Elevation Model—Dem) but also on