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A Methodological Framework to Evaluate Environmental Vulnerabilities in Urban Areas: Two Case Studies in Italy

Paola Gallo, Silvia Vitale * and Giannantonio Di Tuoro

Department of Architecture (DiDA), University of Florence, 50121 Florence, Italy; paola.gallo@unifi.it (P.G.); giannantonio.dituoro@unifi.it (G.D.T.)

* Correspondence: silvia.vitale@unifi.it

Abstract

Climate change poses increasing threats to urban populations, with rising temperatures exacerbating heat-related health risks and reducing outdoor thermal comfort. Although cities occupy only a small fraction of the Earth's surface, they function as complex ecosystems where human transformations significantly influence environmental quality and public health. This research introduces a trans-scalar methodological framework to assess the impacts of climate change on human well-being in urban areas, integrating qualitative and quantitative approaches. The methodology combines direct field observations, instrumental surveys using infrared thermography, quantitative land cover analysis (Runoff and RIE indices), and predictive microclimatic simulations using ENVI-met 5.8. The framework is applied to two case studies in Italy, the municipalities of Bibbiena and Borgo San Lorenzo, focusing on pedestrian accessibility to community healthcare facilities, known as Community Houses. Results reveal critical environmental vulnerabilities, including surface temperatures reaching up to 60 °C on impervious materials, runoff coefficients exceeding 80%, and Physiological Equivalent Temperature (PET) values exceeding 56 °C during summer peak hours, indicating extreme heat stress conditions. The proposed framework enables the identification of priority intervention areas for climate adaptation strategies, supporting evidence-based urban design that prioritises public health and thermal comfort. The methodology offers replicability for other Mediterranean cities facing similar climate challenges, providing a decision-support tool for planners and public administrations.

Keywords: urban resilience; climate change adaptation; sustainable urban design; outdoor thermal comfort; user-centred design; Urban Heat Island; health-oriented design

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1. Introduction

The world has recently experienced rapid urbanisation and a substantial surge in urban population. Urbanisation is a global phenomenon that has accelerated rapidly during the 20th century [1] all over the world, but especially in Mediterranean regions [2]. The United Nations (UN) Population Division Department states that today 58% of the world's population lives in urban areas. This is expected to rise to 70% by 2050, when the world's urban population will exceed 6 billion [3]. The increase in population and, consequently, in housing, work and transport facilities, as well as the rapid expansion of urban areas, has therefore become an ever-growing phenomenon [4]. This process has involved the transformation of natural landscapes into densely populated areas, leading to a significant loss of ecosystems and soil functions, with consequences for biodiversity and local microclimate [5,6].

1.1. Problem Statement: Addressing Climate Vulnerability in Urban Spaces

The quality and composition of urban soils play an increasingly critical role in determining cities' vulnerability to climate-related risks. The loss of permeable surfaces represents a determining factor in modifying urban microclimates, contributing to rising surface and air temperatures, altering radiant surface balances, reducing air humidity, and disrupting atmospheric exchanges [7]. Soil-dependent ecological functions, including oxygen production, microclimate regulation, carbon storage, and biodiversity, are essential for both environmental quality and the performance of the built environment [8]. Continuous anthropogenic processes (excessive soil consumption, urbanisation, and soil sealing) simultaneously reduce naturalness within urban environments and diminish the health benefits that natural environments provide [9]. Concurrently, these processes transform cities into spaces where the absence of natural elements and permeable surfaces compromises evapotranspiration and natural ventilation, exacerbating the Urban Heat Island (UHI) effects and contributing to rising heat-related mortality rates alongside increasing temperatures [10]. Therefore, with accelerating urbanisation worldwide, understanding the linkages between urban environments, well-being, and health has become fundamental. Recent research has increasingly focused on applying the scientific method to urban design, known as Evidence-Based Design (EBD), which establishes connections between scientific evidence, design parameters, and user impacts [11].

Despite growing recognition of the linkages between urban climate and public health, three critical gaps remain in the literature. First, existing studies have largely focused on either microclimatic analysis or land cover assessment, with limited integration of these dimensions into a coherent methodological framework. Second, the specific vulnerability of pedestrian pathways to healthcare facilities, a dimension of climate justice and population health, has been largely overlooked. This research addresses these gaps by developing and testing a trans-scalar framework that integrates qualitative observations, instrumental measurements, and predictive simulations, with a specific focus on pedestrian accessibility to healthcare services in small municipalities. Therefore, recognising soil as an indirect indicator of the built environment's capacity to respond to climate change, the research focuses on developing a framework that, through land cover maps, assesses vegetation cover indices and thermo-physical performance of urban materials. The methodological approach adopts digital analysis and simulation tools to develop restorative design solutions that improve the social, environmental, and functional conditions of selected case studies. By analysing environmental data within urban fabrics and conducting on-site investigations in neighbourhoods most vulnerable to the UHI effect, the final aim of the research is to inform citizens and provide robust evidence to public administrations for creating healthy urban micro-areas that prioritise individual and collective needs.

The paper focuses on the methodology used to develop decision support tools for public administrations and planners aimed at creating resilient neighbourhoods that promote human well-being. The main research questions of this paper are:

- RQ1: How does microclimate affect accessibility to socio-health services?
- RQ2: How can spatial analysis support climate-adaptive urban planning in small municipalities?

The paper is structured into five main sections. Section 1 provides the introduction and literature review, establishing the scientific background on UHI effects, urban health, and the relationship between the built environment and human well-being. This section also presents the Tuscany Health Ecosystem (THE) research project and introduces the two case studies of Bibbiena and Borgo San Lorenzo. Section 2 describes the materials and methods, presenting the trans-scalar methodological framework and detailing each phase of the research, from qualitative field observations to quantitative environmental diagnosis and predictive microclimatic simulations. Section 3 presents the research results, including surface temperature measurements, land cover analysis, and ENVI-met simulation outputs for both case studies. Section 4 discusses the findings considering the existing literature, explores the health implications of the results, outlines implications for policy and practice, and acknowledges the limitations of the study. Finally, Section 5 presents the conclusions, highlighting the methodological contributions and outlining future research directions.

1.2. Scientific Foundations of the Urban Heat Island (UHI)

The Urban Heat Island (UHI) is one of the most widely studied and best-characterised local climate phenomena in the scientific literature. Since Howard's pioneering observations [12], research has consistently shown that urban environments can experience significant thermal increases relative to their surrounding rural areas, reflecting a distinctive thermal behaviour derived from the physical transformations associated with the urbanisation process. Contemporary urban climatology has confirmed that UHI is not merely a meteorological phenomenon, but rather the thermal expression of profound modifications of the Earth's surface that alter the urban energy balance and generate specific microclimates with persistently elevated temperatures [13–15]. Recent studies have expanded this understanding by showing that the magnitude of the phenomenon intensifies as urban densification and the fragmentation of green areas increase [16–20].

The literature identifies several urban factors that explain the formation and magnitude of UHI. First, soil sealing drastically reduces evapotranspiration, one of the most effective natural mechanisms for dissipating heat. The replacement of permeable surfaces with rigid pavements increases surface temperature and decreases relative humidity, intensifying thermal stress in densely built areas [12,21]. Second, the use of low-albedo materials, such as asphalt or concrete, entails high absorption of solar radiation, which increases the thermal load accumulated during the day and prolongs nocturnal warming. Research on the thermal properties of materials has shown that relatively small variations in albedo can produce significant decreases in surface temperature and improve buildings' energy efficiency [22–24]. A third key factor is the loss of urban vegetation, closely linked to reduced shade, reduced evapotranspiration, and greater direct exposure of surfaces to solar radiation. Different studies have shown that the absence of vegetative cover increases air and surface temperatures, especially in vulnerable neighbourhoods with lower availability of green infrastructure [25,26]. Comparative results in Mediterranean and Asian cities confirm that even small, vegetated areas can reduce local temperatures by 1–3 °C, underscoring their value as baseline climate infrastructure [27,28]. Fourth, dense urban morphology, characterised by narrow streets, tall buildings, and compact structures, hinders ventilation and thermal exchange with the external atmosphere, favouring heat trapping and the persistence of high night-time temperatures [29,30]. This morphological influence has been widely documented in studies analysing the relationship between urban geometry and ventilation flows, confirming its role as a structural modulator of urban thermal behaviour [31,32].

1.3. Theoretical Framework on Urban Health

It is a scientific fact that the built environment is a determinant of health [33] as it can influence people's behaviours and lifestyles, thereby contributing to the increase in chronic diseases and the reduction in community well-being [34,35]. In particular, the urban space where people habitually move and live is a silent promoter of health. Among the initiatives undertaken at the international level are the creation of the Healthy Cities network promoted by the World Health Organization (WHO), which emphasises how an environment-based approach to health is increasingly necessary today to achieve healthy and resilient cities, and the series of actions and research that have led to the development of an "urban health" approach as a first step toward integrating health within urban policies [36–39].

The Sustainable Development Goal (SDG) 11 of the 2030 Agenda [24] supports the need to make cities and living places inclusive, safe, resilient, and sustainable, highlighting, among other elements, the creation of public green spaces and better urban design through participatory and inclusive methodologies. Added to this is SDG 3, which aims for access to healthcare services for all and the promotion of mental health and well-being to reduce the mortality rate caused by chronic diseases. The attention of the WHO and the United Nations thus does not focus solely on innovative healthcare models but also on integrated spatial approaches to create health in neighbourhoods, connecting different actors and organising public space to meet the community needs. This concept is also reiterated in the New European Bauhaus programme promoted by the European Commission, which makes the neighbourhood and the small-scale project [40] its field of action to improve well-being and the sense of belonging for smaller communities through guiding tools and the involvement of stakeholders in the participation process [41].

Best Practices: Quartieri Sani Hub and U-CARE Project

Within the international context described above, where the built environment plays an important role in creating health and well-being for communities and individuals, the research project Quartieri Sani Hub aims to improve the public-use space of neighbourhoods and, consequently, the lives of their inhabitants: this goal can be achieved through the development of design scenarios and strategic factors that serve as guidelines for improving the physical-environmental conditions of public urban space within a vision of the healthy neighbourhood. Quartieri Sani Hub led to the definition of an interdisciplinary and cross-scalar conceptual model, in which the characteristics of the neighbourhood are synthesised and systematised into seven themes: Neighbourhood for All; Neighbourhood of Interactions; Active Neighbourhood; Neighbourhood of the Senses; Green Neighbourhood; Smart Neighbourhood; and 1500-Metre Neighbourhood. This model identifies, for each theme, a list of general and specific characteristics that define a healthy neighbourhood [42]: each specific characteristic of a theme corresponds to a set of qualitatively measurable variables applicable to the urban space through the analysis of the built environment [41].

Similarly, the research project U-CARE uses 226 ecosystem indicators to address the environmental risks that impact the health and well-being of citizens in urban areas. These qualitative and quantitative indicators provide fundamental data on environmental conditions, impacts on public health, and the effectiveness of urban design strategies. Organised into the following macro-categories: Pedestrian Accessibility, Water Infrastructure, Urban Microclimate, and Nature-based Solutions (NbS), these are evaluation tools that allow urban planners and designers to address the urban challenges of the contemporary world effectively. The U-CARE ecosystem indicators demonstrate how a good quality public space must be designed through a holistic approach that considers a wide range of indicators to identify the level of accessibility and inclusiveness of the urban space, observing the different types of users and the activities they carry out in the public space [43].

1.4. The Tuscany Health Ecosystem (THE) Project

This research is conducted within the framework of the Tuscany Health Ecosystem (THE), a research project promoted by the Tuscany Region and all Tuscan universities, including the University of Florence. THE is funded by the Italian Ministry of University and Research (MIUR) through the National Recovery and Resilience Plan (PNRR), financed by the European Union—Next Generation EU. The project is structured into ten macro-research themes, or "spokes," all addressing life sciences topics. Specifically, spoke 10, titled "Population Health," involves universities and public and private entities (Scuola Superiore Sant'Anna, University of Florence, University of Pisa, University of Siena, University for Foreigners of Siena, Dedalus spa) to integrate methods and tools to enhance the implementation of innovations in the Italian healthcare system, primarily through population and community engagement.

The primary aim of the research project is to investigate how climate change effects impact public spaces and to identify innovative solutions that can reverse adverse trends. Additionally, the study seeks to bridge the gap between research and practice by developing a methodological framework for practitioners (professionals, public administration technicians, etc.) that enables prediction and design of adaptive solutions for urban microclimates, with particular attention to user well-being.

Employing a system-thinking approach, the research project examines all relevant factors and their interrelationships, focusing primarily on the Tuscany Region. The investigation concentrates on proximity and interconnection space, including streets, courtyards, pedestrian and bicycle paths, undeveloped areas, and parking lots, surrounding community healthcare facilities (hospitals and Community Houses). These spaces represent ideal contexts for testing innovative approaches to built environment design, improving environmental conditions, and consequently enhancing the psycho-physical well-being of users.

1.5. Application to the Case Studies of Bibbiena and Borgo San Lorenzo

The study focuses on pedestrian accessibility around the Community Houses located in Bibbiena and Borgo San Lorenzo, considered central nodes in the territorial services network. The Community House is a primary healthcare structure that can serve as a focal point for a proximity network that extends beyond the traditional provision of health services, offering tailored social services, representing a driver for health promotion in the neighbourhood. This network can help foster social connections and promote community engagement, contributing to overall health and well-being at the neighbourhood level [42].

1.5.1. Bibbiena

The urban area of Bibbiena is organised around a compact historic core, accompanied by dispersed settlements and expansions developed primarily along major roadways. Green spaces are predominantly located at the urban periphery, while wooded areas and green zones intertwine with the built fabric within a morphological context characterised by sloping terrain. This configuration, typical of inner area centres, delineates an urban environment with both potential and structural constraints. Critical issues include accessibility and urban space usability: limited public transportation coverage, absence or inadequate dimensions of sidewalks compromising walkability, and lack of bicycle infrastructure reinforced by terrain too steep for functional cycling, resulting in car dependency. These factors, combined with an ageing population and limited gathering spaces, reduce social interaction opportunities and impact urban vitality.

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1.5.2. Borgo San Lorenzo

The urban area of Borgo San Lorenzo features good public service provision, compact urban structure, and significant green space presence, contributing to overall positive perceived urban quality. These conditions derive from a combination of central public spaces (squares, green areas, and riverfront paths), active social participation, and urban structure favouring pedestrian and bicycle mobility. However, this potential is partially limited by recurring criticalities including high car presence in main public spaces, absence of clear directional signage, and discontinuity in pedestrian and bicycle networks, which at several points appear fragmented or inadequately integrated.

Additionally, field investigations revealed criticalities represented by the peripheral and less functional location of the Community Houses in both municipalities, resulting in difficult accessibility by foot or by public transport, especially for vulnerable groups (the elderly, children, people with pre-existing health conditions), who constitute a substantial portion of healthcare facility users.

2. Materials and Methods

To study the impacts of the UHI effects and the loss of vegetation cover on human well-being, a trans-scalar working methodology (Figure 1) was developed, consisting of phases that are not directly sequential. This approach enabled the identification and mapping of environmental vulnerabilities within critical areas of the urban fabric where discomfort conditions occur.

- Phase 1: Qualitative and fact-finding survey, based on direct field observation supported by instrumental diagnosis, to better understand the state of the urban fabric in proximity to healthcare facilities (hospitals and Community Houses); followed by the identification of ecosystem indicators to support the subsequent phase;
- Phase 2: Quantitative urban environmental diagnosis, using simulation tools, during which data on the relationship between the physical environment and potential impacts on user well-being were collected, simulated, and interpreted.

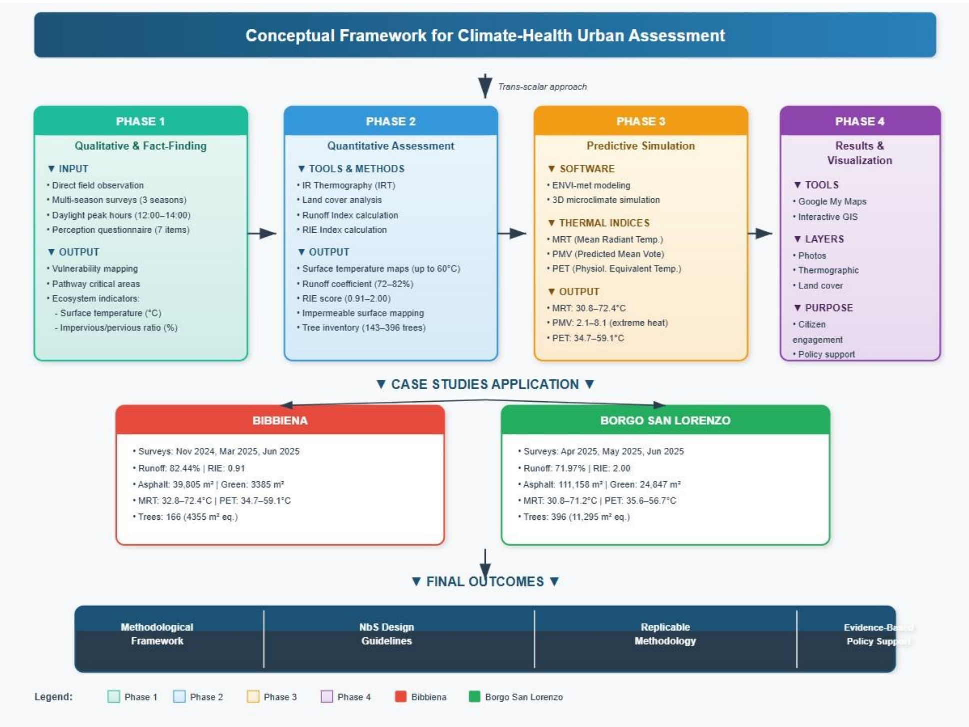

Figure 1. Conceptual framework for climate-health urban assessment. Source: Authors.

2.1. Phase 1—Qualitative and Fact-Finding Survey

In this phase, qualitative observations were carried out considering exclusively the pedestrian movements that people make daily, starting from the main urban aggregates within the municipalities of Bibbiena and Borgo San Lorenzo (Figure 2), and along the main approach routes to the respective healthcare facilities (Community Houses and the Mugello Hospital).

(**a**)

(**b**)

Figure 2. The location of healthcare service facilities (Casa della Salute and Ospedale del Mugello) in the municipalities of Bibbiena (**a**) and Borgo San Lorenzo (**b**). Source: Authors.

The first step involved direct observation of the phenomena through on-site surveys; this phase was necessary to gather detailed information to verify the current conditions of the pathways in relation to the UHI effects and the loss of vegetation cover, to monitor the negative impact on citizens' well-being.

The proposed method includes, first of all, the analysis of the territory to identify vulnerabilities of pathways and rest areas to and from healthcare facilities through the selection of strategic points considered most vulnerable to the UHI effects and the loss of vegetation cover.

Two main actions were undertaken to analyse the territory and identify vulnerabilities. First, we mapped the pedestrian pathways that people take daily, starting from urban areas with the highest concentration of residents and following the main easily walkable routes that branch out to reach local healthcare facilities, specifically the Community Houses and the Mugello Hospital. Second, we developed focus maps along these pathways (Figure 3) to analyse the two aspects under consideration, UHI effects and loss of vegetation cover, in those urban places that present environmental criticalities. These places included rest areas, small open spaces, squares, streets, parking lots, and urban voids characterised by lack of shading, high soil sealing, scarce vegetation, absence of natural elements, and lack of blue infrastructures.

In this analysis activity, surveys were conducted in different periods of the year (autumn, spring, and summer) to capture seasonal variations in comfort conditions and environmental vulnerability. All surveys were conducted between 12:00 and 14:00, during the time when solar radiation is at its maximum and the effects of the UHI are most perceptible. During each survey, attention was focused on: (1) identification of areas with greater environmental vulnerability and analysis of pedestrian pathways to healthcare facilities; and (2) identification of ecosystem indicators to monitor environmental quality and manage the impact on human activities.

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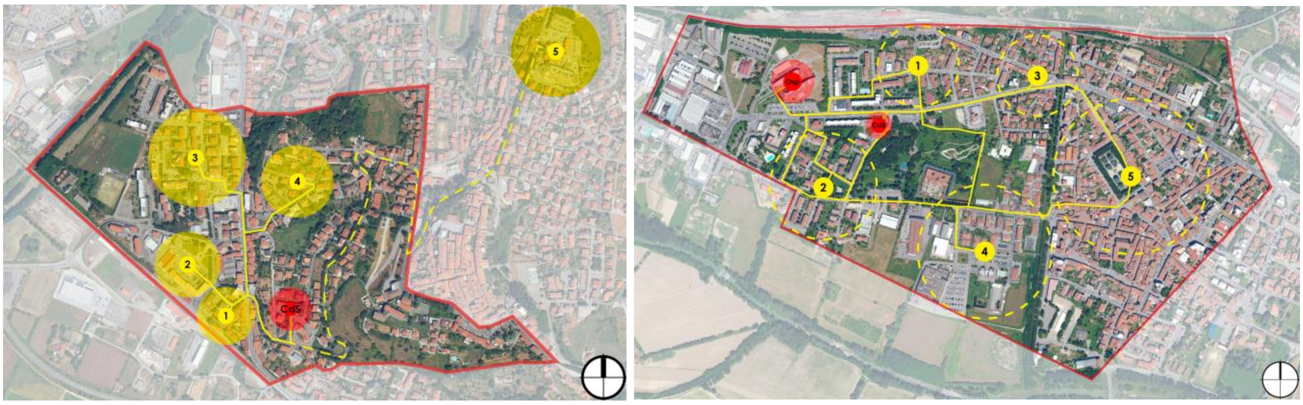


(**a**) (**b**)

Figure 3. Map of routes from the designated areas at healthcare service facilities of Bibbiena (**a**) and Borgo San Lorenzo (**b**). Source: Authors.

2.1.1. Identification of Vulnerable Areas

The areas most exposed to thermal discomfort, potentially subject to the UHI effects, were identified by assessing the absence of natural or artificial shading, the presence of permeable and impermeable surfaces, and the poor microclimatic quality of public spaces. Those routes commonly used by residents were observed, considering the presence or absence of mitigation elements (trees, porticoes, canopies, etc.), rest areas, crossings, and architectural barriers.

The environmentally most vulnerable urban areas identified, with reference to outdoor comfort conditions, were selected with the objective of analysing pedestrian flows converging toward healthcare facilities. They were identified according to the two fundamental criteria of environmental vulnerability and pedestrian flow intensity.

Each analysed pathway was graphically represented to highlight sidewalks, crossings, squares, parking lots, and public spaces within or adjacent to the urban environment. Critical areas were identified as sections or parts of the pathway characterised by unfavourable environmental conditions or recurring problems that exacerbate thermal discomfort, particularly during the middle of the day and in the warmer seasons. These critical areas typically exhibited one or more of the following characteristics: absence or scarcity of shading, whether natural (tree cover) or artificial (canopies, porticoes); widespread presence of asphalt surfaces or materials with high heat storage capacity; sealed soils completely exposed to sunlight, such as parking lots or squares without trees; and pedestrian areas lacking biodiversity, including vegetation, natural elements, and blue infrastructures.

For each pathway, a detailed information sheet was created (Figure 4): (1) a map of the pathway indicating the analysed sections and the localised critical areas; (2) a description of the pathway, indicating the type of space traversed; and (3) photographic documentation illustrating the actual conditions of the spaces, focusing on the critical points identified.

This phase enabled a shift from a general reading of the urban pedestrian network to a deep understanding of the environmental conditions experienced daily by citizens, highlighting where the greatest thermal and environmental discomfort is concentrated, what urban characteristics make a pathway more or less comfortable, and how materials, morphology, and the absence of vegetation contribute to heat accumulation or the lack of quality in public space. The comparison of data collected across different seasons (autumn, spring, and summer) made it possible to trace a dynamic picture of the seasonal evolution of environmental conditions along the observed pathways.

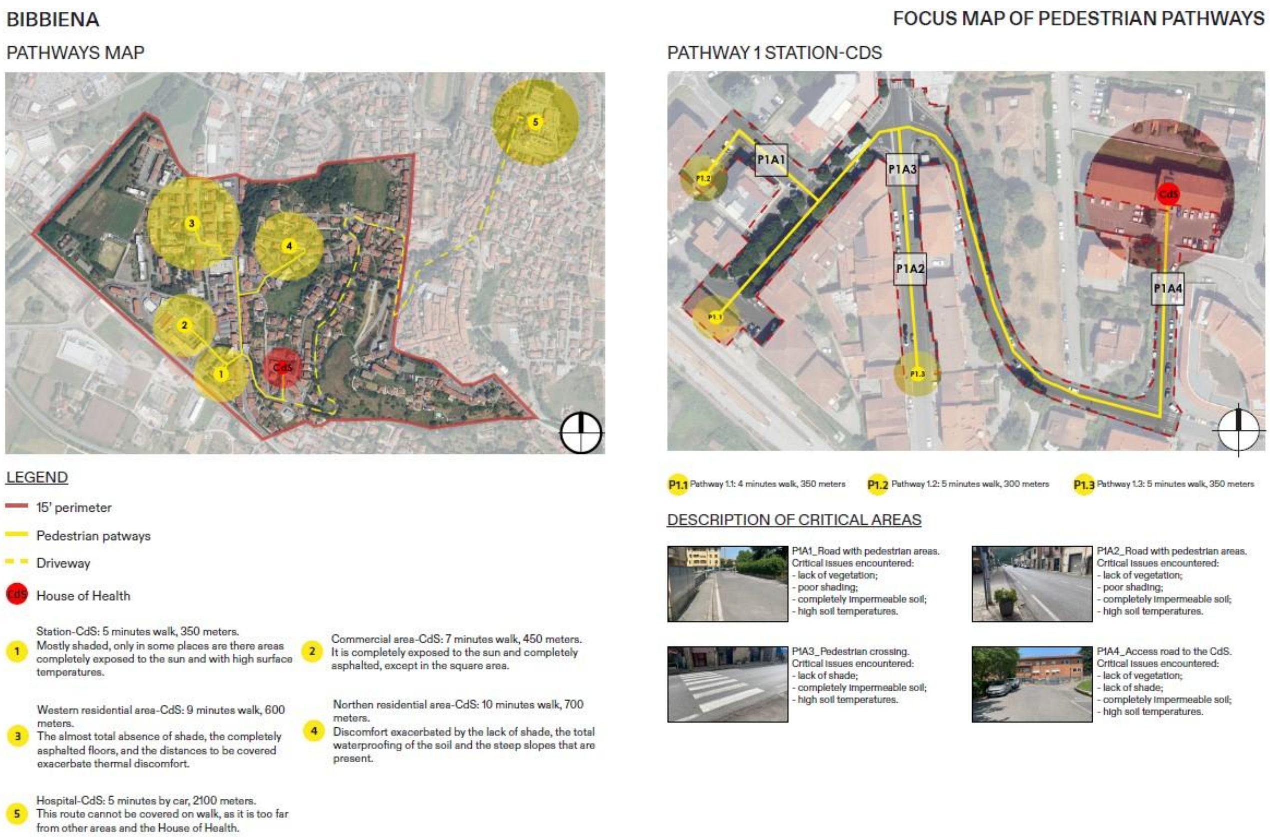


Figure 4. Sample worksheet on route analysis. Source: Authors.

2.1.2. Identification of Ecosystem Indicators

At the conclusion of the analysis phase of pedestrian pathways and critical areas in the contexts under examination, specific ecosystem indicators were identified, capable of capturing the environmental quality of the places to assess the impact on citizens' well-being and to guide any design proposals toward climate resilience. This phase required the analysis of the collected information to transform it into measurable and comparable parameters. The selected indicators served three primary purposes: evaluating the environmental conditions of pedestrian pathways to and from healthcare facilities, objectively measuring the degree of vulnerability of each area, and providing operational tools for monitoring and supporting design and planning decisions.

For this study, the analysis considered two of the main ecosystem indicators for assessing environmental quality. For the UHI effects, we used surface temperature (°C) as the primary indicator, as it is widely recognised in the literature as a reliable indicator for UHI intensity and potential thermal stress for the population. For the loss of vegetation cover, we used the percentage ratio of impervious surfaces to pervious surfaces (%), which serves as an indirect indicator of ecological permeability and the reduction in ecosystem services in urban areas.

2.2. Phase 2—Quantitative Urban Environmental Diagnosis

The second phase of the working methodology concerns the quantitative urban environmental diagnosis, conducted with digital tools. Unlike the previous phase, this phase employed tools and resources capable of transforming the considerations emerging from the first phase into objective data, enabling the study of the urban ecosystem of the sample area to better understand the relationships between the physical environment and the potential impacts on user well-being.

The actions of this phase encompassed three main activities. First, an instrumental measurement campaign was conducted to assess urban microclimate parameters, with particular attention to surface temperatures as an indicator of the UHI effects. Second, a quantitative assessment of land cover was performed using the Runoff Index and the Building Impact Reduction Index (RIE) to evaluate the hydrological performance and permeability of the study areas. Third, predictive modelling and simulation were carried out using the ENVI-met software to forecast microclimatic conditions under typical summer scenarios.

2.2.1. Surface Temperature Indicator

During the survey phase, instrumentation capable of acquiring surface temperatures of urban materials using IR thermography (InfraRed Thermography—IRT) was employed; this is a non-destructive investigation technique capable of visualising and measuring the thermal energy radiated by an object in order to determine its surface temperature and distribution, producing an image referenced to a thermal scale. The infrared camera detects not only the radiation caused by the object's temperature but also radiation originating from surrounding areas that is reflected by the object itself. Both types of radiation vary according to atmospheric absorption, and the measurement value can be strongly influenced by ambient temperature.

An instrumental measurement campaign of surface temperatures of urban materials was, therefore, conducted along the main pedestrian pathways connecting the identified areas to the Community House, with the aim of determining the surface temperatures of the several materials present along the routes (asphalt, stone, concrete, grass surfaces, etc.), in order to understand heat distribution at ground level and identify the surfaces most responsible for thermal accumulation in urban environments.

The infrared thermography measurements were conducted using a thermal camera with the following specifications: spectral range of 7.5–14 μm, detector resolution of 640 × 480 pixels, thermal sensitivity of <0.05 °C, and stated measurement accuracy of ±2 °C or ±2% of the reading. Emissivity values of 0.95 for asphalt, 0.92 for concrete, 0.90 for stone, and 0.98 for grass surfaces were applied according to the manufacturer's guidelines and established references [44]. The reflected apparent temperature was corrected using the camera's built-in atmospheric correction function. Measurements were taken at a distance of 1–5 m, with the camera positioned perpendicular to the target surface to minimise angular effects. Measurements were conducted between 12:00 and 14:00 under clear-sky conditions to ensure comparable solar radiation conditions, with wind speed < 3 m/s to minimise the influence of environmental factors on the readings.

For each pathway and each identified critical area, a comprehensive data sheet was developed to construct a detailed analytical framework of the microclimatic conditions (Figure 5). Each sheet included three components: (1) an excerpt of the site plan with identification of measurement points; (2) photographs of the locations to frame the urban context and the physical conditions of the pathway; and (3) corresponding thermographic images that graphically display the surface temperatures of pavements and adjacent surfaces.

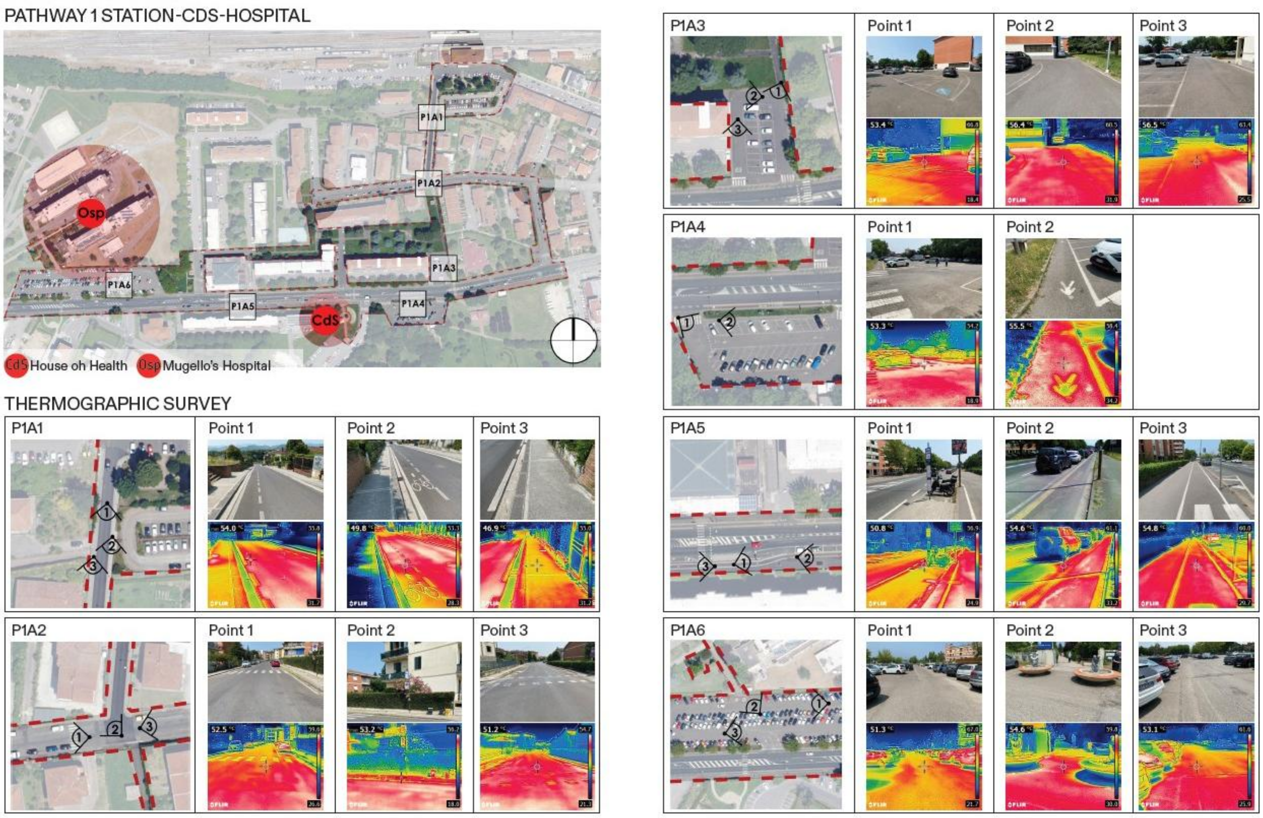


Figure 5. Standard data sheet for the instrumental measurement of urban microclimate parameters. Source: Authors.

2.2.2. Quantitative Assessment of Land Cover

The study of land cover is essential for understanding how human activities influence the hydrological and environmental characteristics of soil and how this impacts environmental behaviour, causing harm to human wellbeing.

For the quantitative assessment of the loss of vegetation cover, analyses were conducted considering two complementary indices: (1) the Runoff Index, that evaluates the percentage ratio between the annual volume of surface runoff and the annual volume of precipitation, providing a measure of the hydrological performance of the urban surface; and (2) the Building Impact Reduction Index (RIE), that analytically assesses the environmental quality of an area in terms of soil permeability and the presence of green areas, yielding a dimensionless qualitative value ranging from 0 to 10.

To determine the Runoff Index, the surfaces of public or publicly accessible portions, including sidewalks, roads, and green areas, that can be walked to reach healthcare facilities were considered. The square metres of surface area were extracted and then subdivided by percentage according to their degree of impermeability, based on a classification that distinguished impermeable public linear infrastructure (asphalted or paved), impermeable public spaces (asphalted and/or paved), public and publicly accessible green spaces, and semi-permeable public spaces such as parking lots or sidewalks with permeable paving.

To each of the above surfaces, based on the materials of which they are composed, we assigned a Runoff coefficient reflecting their hydrological performance. Impermeable spaces received a coefficient of 0.90, semi-permeable spaces received a coefficient of 0.70, and permeable green spaces received a coefficient of 0.15. From the sum of the percentage of surface area considered relative to the total surface area of the pathway, multiplied by the coefficients of the individual Runoff values of the materials of which it is composed, the total Runoff coefficient of the reference pathway was obtained.

The Runoff coefficients of 0.90 for impermeable spaces, 0.70 for semi-permeable spaces, and 0.15 for permeable green spaces were adopted based on established hydrological references for urban surfaces [45,46]. These values are consistent with the guidelines provided by the Italian National Institute for Environmental Protection (ISPRA) for urban hydrological assessment and are widely used in urban planning practice in Italy. The coefficients reflect the typical hydrological performance of the surface materials encountered in the study areas and account for factors such as surface roughness, slope, and drainage characteristics.

To define the Building Impact Reduction Index (RIE), the areas considered were only the public portions accessible to pedestrians, including sidewalks, roads, and green areas of all the pedestrian pathways under examination. For the calculation of the RIE, three main components were considered. The first component was the Equivalent Tree Surface Area (Se), which accounts for the contribution of trees to permeability through their root systems, which favour infiltration, and through their interception of precipitation. Two categories of trees were included based on height: those between 4 and 12 m and those between 12 and 18 m. The second component was the Treated Green Surfaces (Svi), which are specifically designed areas that maximise water infiltration; these green areas have a runoff coefficient (Ψi) of 0.1, meaning that only 10% of the water runs off while the remaining 90% infiltrates. The third component was the Non-Treated Green Surfaces (Sij), which include surfaces with varying permeability, from asphalt to permeable pavements, each contributing to surface runoff to varying degrees.

The RIE evaluation range is expressed on a scale where a value of 4.00 represents the minimum acceptable standard, 5.00 indicates improvement, and 6.00 represents excellence. Since the RIE value is a direct indicator of the area's hydrological performance, the higher this value, the greater the soil's capacity to manage stormwater through infiltration.

For each pathway, data sheets (Figure 6) were developed containing the results obtained from both the Runoff and RIE calculations, including the following information: (1) a map of the pathway with identification of the spatial areas used for calculating the two indices; (2) calculation tables containing the results of the land cover analyses; and (3) data regarding the runoff coefficients of the materials used for the calculations.

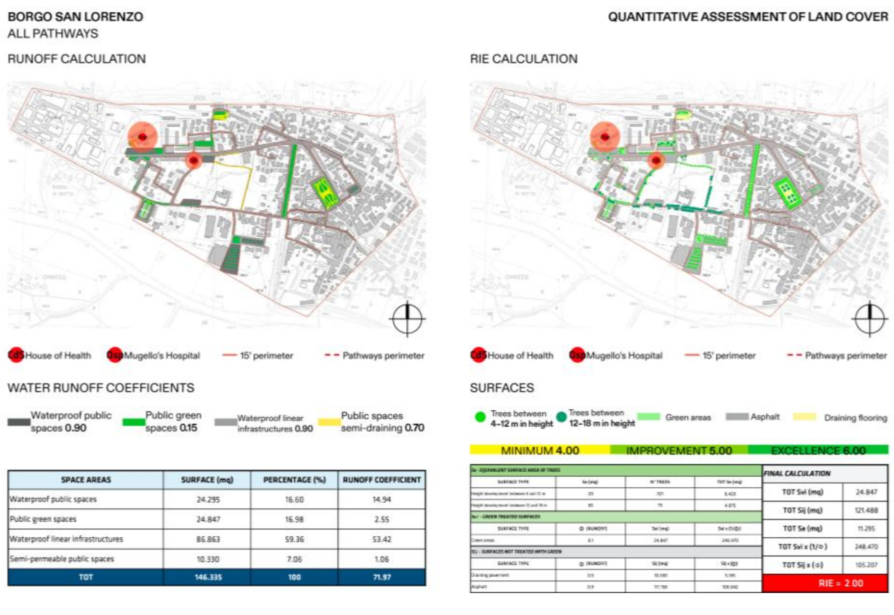


Figure 6. Standard form for the quantitative assessment phase of land cover. Source: Authors.

2.2.3. ENVI-Met Simulations

To assess outdoor thermal conditions in urban spaces, the software ENVI-met, a predictive model based on the fundamental laws of fluid dynamics and thermodynamics, was used to simulate key microclimatic indicators under typical warm-season conditions. The simulations were performed for a representative warm-season day (Table 1) to reflect typical conditions experienced by users.

Table 1. Representative climatic conditions for ENVI-met simulations.

Parameter	Bibbiena (11 August 2024)	Borgo San Lorenzo (15 July 2024)
Min Temperature (°C)	15.7	18.9
Max Temperature (°C)	29.0	35.3
Min Relative Humidity (%)	49	24
Max Relative Humidity (%)	100	82
Wind Speed (km/h)	4.2	5.5

The representative microclimatic scenario was evaluated using the representative day technique, which yields a characteristic summer meteorological scenario using actual data from days in the selected period. This consolidated method can extract statistical information about the "representative day" used to analyse the urban thermal fluid dynamics. This method uses a large data sample and traces both the day that best represents the hot scenario and the one that least describes it as an anomaly. The data sample analysed using the representative day method relates to the hot scenarios (days where the average daytime temperature exceeds 25 °C) over the last five years, with temperature as the dominant variable. In addition to temperature, data on humidity, wind speed, wind direction, and shortwave and longwave radiation over the twenty-four-hours of the "representative day" were entered into the system. Using the representative day method rather than the average day allows real scenarios to be used [47].

The ENVI-met software uses all this information combined with geometric-material information, providing the evaluation of the interrelation between buildings, vegetation, and various surface coverings. Satellite photos data were used to define the materials of the horizontal surfaces of outdoor spaces. Each material was identified by a specific colour, producing a vector diagram of the materials associated with each colour code (referring to the ENVI-met library). Existing buildings were modelled using a material prevalent throughout the entire envelope, ensuring the reliability of the results based on appropriate simplifications necessary for the use of the software employed. The modelling of existing vegetation was based on the use of geometric elements populated with various parameters relating to the classification of the size of tree and shrub species and linked to the flowering index of the different species, the type of leaves (evergreen or deciduous) and the LAD (Leaf Area Density) index, characterising the types of canopy according to the size and density of the foliage [48].

The simulations were scheduled and executed at three distinct times of the day to capture significant variations in environmental conditions and solar radiation. At 12:00, when solar radiation is typically at its peak and ambient temperatures can reach their highest values. At 14:00, when solar radiation remains very intense, and temperatures typically reach their daily maximum. At 16:00, when the sun's angle is different, temperatures may undergo significant variations compared to noon, while still maintaining a relevant thermal impact.

To assess the main microclimatic vulnerabilities along the pedestrian pathways, we calculated three thermal comfort indices using the ENVI-met software. The Mean Radiant Temperature (MRT) quantifies the effect of radiation, the radiant heat coming from all surrounding surfaces such as buildings, vegetation, pavements, and the sky, on a person's perception of heat. The Predicted Mean Vote (PMV) describes the average thermal sensation of a large group of people exposed to a given thermal environment on a seven-point scale ranging from −3 (cold) to +3 (hot), with 0 indicating thermal neutrality. This index considers both environmental factors—air temperature, humidity, air velocity, and radiant temperature—and personal factors—metabolic rate and clothing insulation—to predict thermal comfort. The Physiological Equivalent Temperature (PET) is particularly useful for assessing comfort in outdoor environments, as it considers the impact of all meteorological factors on the human body's thermal balance.

To assess the plausibility and consistency of the ENVI-met simulations, we conducted an indirect plausibility assessment of the model outputs against independent measurements. The results are described in detail in Section 3.5, where we compare simulated PET values with field measurements and established literature benchmarks. The indirect plausibility assessment confirms that the ENVI-met model captures the spatial and temporal patterns of the urban microclimate with acceptable accuracy for the purposes of this study.

For each pathway and critical area, a detailed data sheet was developed summarising the ENVI-met simulation results (Figure 7). Each sheet included: (1) a map of the pathway with identification of the critical areas; (2) screenshots showing the modelling of the area in ENVI-met, and (3) excerpts of the plan view of the critical areas for each thermal comfort index (MRT, PMV, PET), with simulation times for each critical area.

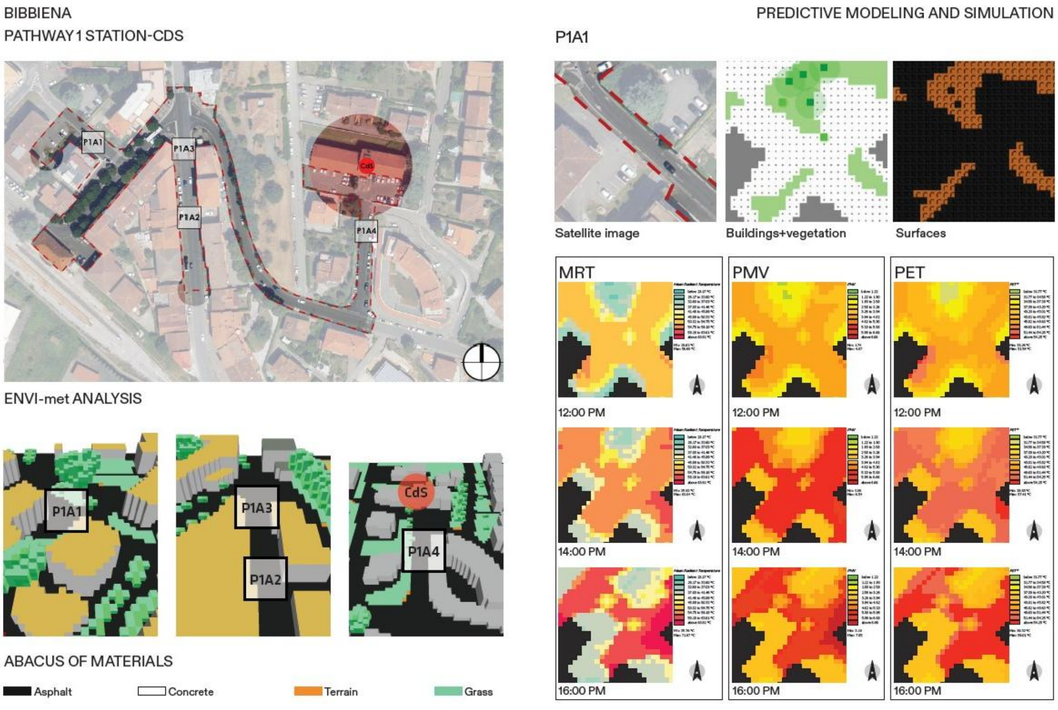
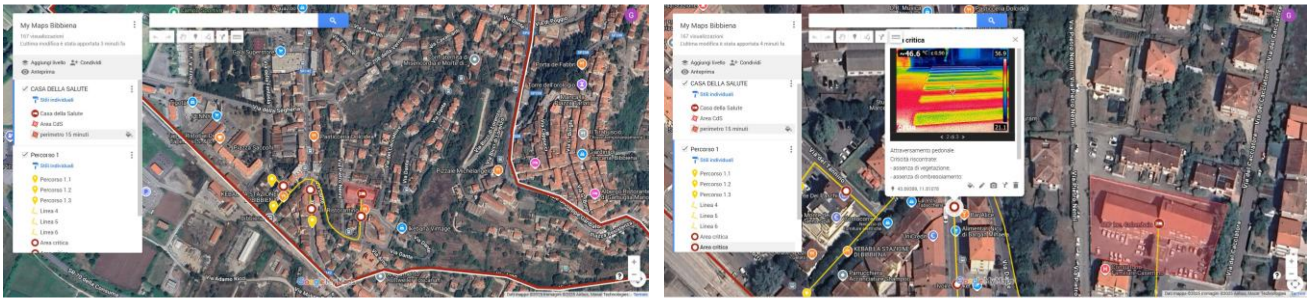


Figure 7. Standard form for the modelling and predictive simulation phase. Source: Authors.

The final phase focuses on presenting the results obtained from the analyses conducted along the routes from the identified urban areas to the healthcare facilities. To make the results accessible and usable by citizens, all the analyses conducted have been collected into an interactive map created with *Google My Maps* (Figure 8). The purpose of the interactive map is threefold: (1) to enable virtual exploration of the pedestrian pathways; (2) to visualise the critical issues identified along the routes; and (3) to offer an informative and immersive experience useful for both citizens and professionals.



(**a**) (**b**)

Figure 8. Photos showing the current state of the analysed point by *Google My Maps*. Source: Authors.

The map contains several georeferenced information layers, visible along the main routes that people take daily to reach healthcare facilities. The interactive map contains three main types of georeferenced information. The first layer consists of current state photographs, which are images taken on site showing the current condition of each route. The second layer comprises thermographic images, which are surveys conducted with an infrared camera that highlight the surface temperatures of urban materials in the areas most vulnerable from the perspective of outdoor comfort. The third layer consists of land cover images, which are elaborations that distinguish surfaces by land use to assess their permeability, shading potential, and surface heat absorption capacity.

3. Results

The intention to investigate the vulnerabilities of pedestrian pathways and the areas surrounding healthcare facilities is significant from the perspective of reducing the negative effects of climate change. The way we move within cities is fundamental not only for reducing emissions but also, and above all, for improving the quality of life of the people who live there.

3.1. Field Observation Results

Direct analysis confirms that, in terms of distance, all routes fall within the concept of the 15 min City [49]. The pedestrian pathways analysed, therefore, constitute the fundamental connection network between the population and healthcare services, and as such play a key role in the design of a more inclusive and sustainable city. However, the qualitative conditions of the pathways vary considerably and significantly influence users' perception of comfort.

The field observations revealed four key findings. First, asphalt surfaces lacking shading, particularly near intersections, along specific pedestrian sections, and in rest areas, registered extremely high temperature sensations across all field observations in different seasons. Second, some sections of the routes to healthcare facilities were found to be particularly exposed to solar radiation without adequate mitigation solutions such as trees or canopies. Third, green or shaded areas, where present, showed a clear reduction in surface temperatures and improved perceived comfort. Finally, the geometric and spatial urban configuration exhibited poor flow hierarchy, absence of rest areas, and disconnection at the intersections of vehicular and pedestrian flow nodes.

Therefore, the analysis of the pathways revealed several critical areas characterised by environmental vulnerabilities. In Bibbiena, the most critical pathways included the route from the commercial area to the Community House, which was completely exposed to sunlight and almost entirely asphalted, and the route from the northern residential area, which was characterised by steep slopes, absence of shading, and complete soil sealing. In Borgo San Lorenzo, the critical areas included the route from the train station to the

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healthcare facilities, which presented high traffic volumes and a lack of hierarchy between pedestrian and vehicular flows, and the route from the historic centre, which featured narrow streets with limited ventilation that trap heat during summer months.

3.2. Instrumental Measurements

3.2.1. Surface Temperatures by Material

The instrumental measurement campaign revealed significant variations in surface temperatures across different materials, seasons, and locations. Table 2 presents the surface temperature ranges observed for the main urban materials during the three seasonal survey periods.

Table 2. Detailed surface temperature by material.

Case Study	Season	Asphalt (°C)	Concrete (°C)	Stone (°C)	Grass (°C)
Bibbiena	Autumn (7 November)	30–35	25–30	22–28	15–18
	Spring (10 April)	35–40	28–32	25–30	16–20
	Summer (26 June)	55–60	45–50	40–45	25–30
Borgo San Lorenzo	Autumn (7 November)	30–35	25–28	22–25	14–17
	Spring (10 April)	30–35	26–30	23–27	15–18
	Summer (26 June)	55–60	42–48	38–43	22–28

The results reveal that asphalt surfaces consistently exhibited the highest temperatures across all seasons and case studies. During summer conditions, asphalt temperatures reached up to 60 °C, while concrete and stone surfaces ranged between 42 and 50 °C and 38–45 °C, respectively. In contrast, grass surfaces maintained significantly lower temperatures (22–30 °C), demonstrating the cooling effect of vegetated surfaces. The temperature difference between asphalt and grass surfaces exceeded 30 °C during peak summer conditions, highlighting the critical role of vegetation in mitigating surface heating. The seasonal comparison reveals a clear pattern of increasing surface temperatures from spring to summer, with the greatest temperature increases observed on asphalt surfaces. Specifically, in Bibbiena, asphalt temperatures increased from 30 to 35 °C in autumn to 55–60 °C in summer, representing a temperature increase of 20–25 °C.

3.2.2. Seasonal and Spatial Variations

The instrumental measurement campaign revealed that traditional urban materials, including asphalt, concrete, and stone, intensify the UHI effect, worsening perceived comfort and causing considerable harm to people's health. In contrast, urban greenery, reflective materials, and shaded areas offer effective heat mitigation, significantly improving both comfort conditions and liveability within cities.

In detail, the spatial analysis revealed that the highest surface temperatures were consistently recorded in areas with high asphalt coverage, limited vegetation, and absence of shading. These areas included large parking lots, wide roadways, and open squares without trees. In contrast, areas with high tree cover, such as the Parco della Misericordia in Borgo San Lorenzo, maintained significantly lower surface temperatures, creating local microclimates that offer relief from heat stress.

3.3. Land Cover Analysis

The land cover analysis reveals that both case studies exhibit critical environmental conditions during summer periods, with Borgo San Lorenzo showing marginally better performance due to higher tree cover and green area presence. However, both sites demonstrate conditions incompatible with safe pedestrian use during peak summer hours without adequate mitigation interventions.

As detailed in Table 3, the land cover analysis reveals that Borgo San Lorenzo, despite having a larger total area of impermeable surfaces (121,488 m^2 vs. 45,660 m^2), has proportionally more green areas (24,847 m^2 vs. 3385 m^2) and a substantially higher tree count (396 vs. 166 trees). This higher vegetation coverage contributes to the lower Runoff coefficient (71.97% vs. 82.44%) and higher RIE value (2.00 vs. 0.91) observed in Borgo San Lorenzo. Therefore, the presence of the Parco della Misericordia in Borgo San Lorenzo, a large urban park with extensive tree cover, fitness areas, and water features, contributes significantly to the improved environmental performance observed in this case study.

Table 3. Overall land cover analysis of case studies.

Indicator	Bibbiena	Borgo San Lorenzo
Total impermeable surfaces (m^2)	45.66	121.48
Total green areas (m^2)	3.38	24.84
Tree count (4–12 m)	143	321
Tree count (12–18 m)	23	75
Total equivalent tree surface (m^2)	4.35	11.29
Asphalt surface (m^2)	39.80	111.15
Permeable paving (m^2)	5.85	10.33
Overall Runoff (%)	**82.44**	**71.97**
Overall RIE	**0.91**	**2.00**

3.4. ENVI-Met Simulation Results

3.4.1. Thermal Comfort Indices

The ENVI-met simulations provided detailed information on the thermal conditions experienced by pedestrians along the pathways. Table 4 presents the summary results for the three thermal comfort indices calculated.

Table 4. Comparative analyses between case studies.

Indicator	Bibbiena (Min–Max)	Borgo San Lorenzo (Min–Max)	Health Significance
MRT (°C)	32.79–72.40	30.76–71.21	>60 °C indicates severe radiant stress
PMV *	2.12–8.09	2.41–7.97	>3 indicates extreme heat sensation
PET (°C)	34.68–59.11	35.64–56.69	>41 °C indicates extreme heat stress
Runoff (%)	82.44	71.97	>70% indicates critical impermeability
RIE (0–10)	0.91	2.00	<4.00 indicates inadequate permeability

* Note: Values > 3 are outside the standard ISO 7730 scale and indicate conditions beyond the “hot” category.

The results obtained from the simulations indicate that for MRT, during the time slots analysed, the values recorded fall within a range from a minimum of 30.76 °C to a maximum of 72.40 °C. The minimum value of 30.76 °C suggests moderate radiation conditions, found in shaded areas or areas with relatively cool surrounding surfaces, with a moderate radiant load. The maximum value of 72.40 °C indicates an extremely high radiant load, found in areas intensely exposed to the sun, where direct solar radiation and heat reemitted by dark surfaces (such as asphalt or building facades) significantly contribute to the perception of heat. This value represents a condition of severe thermal stress, which decisively contributes to the sensation of intense heat and can make the environment very uncomfortable for people staying outdoors.

The PMV values ranged from 2.12 to 8.09 on the extended scale. The minimum value of 2.12, which indicates strong perceived heat, is already at the upper limit of thermal comfort on the standard ISO 7730 scale. This suggests that even at the "coolest" point, the pedestrian pathway presents rather unfavourable thermal conditions for people. The maximum value of 8.09 is extremely high and lies well outside the standard PMV scale. This value, which indicates an exceptionally intense and severe perception of heat, suggests that in some areas and times, environmental conditions are so adverse as to generate an unbearable sensation of heat.

The PET values ranged from 34.68 °C to 59.11 °C. The minimum value of 34.68 °C falls into the category of "moderate heat stress" (29.1–35 °C), indicating that even in the "coolest" areas of the pathways, people may perceive some degree of thermal discomfort. The maximum value of 56.69 °C is exceptionally high and falls into the category of "extreme heat stress" in an amplified manner, far exceeding the standard threshold of 41 °C [50].

3.4.2. Spatial Distribution of Thermal Stress

The spatial analysis of the ENVI-met outputs revealed significant variations in thermal comfort within the study areas. In Bibbiena, the highest MRT and PET values were recorded in the commercial area and the northern residential area, where extensive asphalt surfaces, limited tree cover, and absence of shading create extreme thermal conditions. The lowest values were observed in shaded areas along the station route, where tree cover provides some relief. In Borgo San Lorenzo, the highest thermal stress was observed in the commercial area and the historic centre, where narrow streets limit ventilation and extensive asphalt surfaces trap heat. The lowest values were observed along the route through the Parco della Misericordia, where tree cover and water features contribute to localised cooling.

3.5. Consistency and Plausibility Assessment of ENVI-Met Simulation Results

To assess the plausibility and consistency of the ENVI-met simulation outputs, we compared our results with field measurements and established literature benchmarks. We acknowledge that this analysis does not constitute a formal model validation, as the measured and simulated variables represent different physical quantities, but rather serves as an indirect consistency check. A rigorous validation would require direct comparison of simulated air temperature with in situ measurements of the same variable at the same locations and times. This analysis is therefore intended to provide supporting evidence for the reliability of the simulation approach, while recognising its limitations.

3.5.1. Comparison with Field Measurements

To assess the consistency between the ENVI-met simulations and field observations, we compared measured surface temperatures with simulated PET values. We recognise that these variables represent different physical quantities: surface temperature characterises the thermal condition of a material, whereas PET is a composite outdoor thermal-comfort index derived from air temperature, mean radiant temperature, humidity, wind speed, clothing insulation, and metabolic activity [50]. Consequently, the numerical differences reported in Table 5 cannot be interpreted as model error or prediction accuracy. Rather, this comparison serves as an indirect plausibility check, supporting the qualitative consistency of the simulation outputs with field observations. The alignment of extreme values, measured surface temperatures up to 60 °C on asphalt and simulated PET values up to 59 °C, suggests that the ENVI-met model captures the magnitude of thermal stress conditions.

Table 5. Comparison between measured surface temperatures and simulated PET values.

Location	Measured Surface Temp (°C) (Min–Max)	Simulated PET (°C) (Min–Max)	Temperature Difference (°C) (Min–Max) *
Asphalt (sun-exposed)	55–60	52–59	3–5
Concrete (sun-exposed)	42–50	45–52	1–3
Stone (shaded)	38–43	35–40	3–5
Grass (shaded)	22–30	34–37	5–10

* Note: The values reported in this table represent temperature ranges observed across multiple measurement points. The "Temperature Difference" column indicates the range of differences between measured surface temperatures and simulated PET values for each material type. These values are intended to illustrate the general consistency between the two datasets and should not be interpreted as quantitative validation metrics. A formal validation would require direct comparison of equivalent variables (e.g., simulated vs. measured air temperature) at the same locations and times.

As detailed in Table 5, the comparison reveals that measured surface temperatures and simulated PET values are generally consistent, with differences ranging from 1 to 5 °C for most material types. The greatest discrepancy is observed for grass surfaces, where the difference between measured surface temperatures and simulated PET values ranges from 5 to 10 °C, reflecting the fact that grass surfaces are cooler than the surrounding air temperature due to evapotranspiration.

3.5.2. Comparison with Literature Benchmarks

To further assess the external plausibility of our simulation results, we compared the PET values obtained from our study (34.68–59.11 °C) with those reported in similar studies conducted in Mediterranean urban contexts. Núñez Peiró et al. [27] reported PET values ranging from 35 to 55 °C during summer heatwaves in Madrid, while Arellano Ramos and Roca Cladera [28] documented PET values up to 52 °C in Barcelona. We acknowledge that this comparison serves as an external plausibility check rather than a formal model validation, as the cited studies differ in climatic conditions, urban morphology, vegetation cover, model resolution, and simulation parameters. Nevertheless, the consistency between our findings and these established benchmarks provides supporting evidence for the reliability of our simulation approach. The slightly higher maximum values observed in our study (56–59 °C) can be attributed to the specific morphological characteristics of the study areas, including extensive asphalt surfaces and limited tree cover, which are comparable to conditions documented in other small Mediterranean municipalities.

3.5.3. Uncertainty and Limitations

We acknowledge that the ENVI-met simulations involve simplifications in geometry and material properties that may introduce systematic errors. The model assumes homogeneous building envelopes and does not account for variations in building materials, occupancy patterns, or transient shading effects. The infrared thermography measurements are also subject to several sources of uncertainty, including camera accuracy (±2 °C or ±2%), emissivity settings for different surface materials (asphalt: 0.95, concrete: 0.92, stone: 0.90, grass: 0.98), reflected temperature effects, measurement distance and angle, and atmospheric corrections [44].

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The consistency and plausibility assessment suggests that the ENVI-met model outputs are broadly consistent with field observations and literature benchmarks. However, in the absence of a formal validation based on direct comparison of equivalent variables, the results should be interpreted as indicative of relative thermal comfort conditions rather than accurate absolute predictions. The primary value of the simulation results lies in identifying relative differences in thermal comfort across different locations, surface materials, and times of day, rather than in providing precise absolute temperature values.

3.6. Health Risk Assessment

Based on the PET values obtained from the simulations, we assessed the health risks associated with the thermal conditions documented in the study areas. Table 6 presents the classification of heat stress levels and associated health risks.

Table 6. Heat stress classification and health risks.

PET Range (°C)	Heat Stress Category	Health Risk	Bibbiena	Borgo San Lorenzo
<29.1	No thermal stress	Low	-	-
29.1–35.0	Moderate heat stress	Mild	✓ (min)	✓ (min)
35.1–41.0	Strong heat stress	Moderate	✓	✓
>41.0	Extreme heat stress	High	✓ (max)	✓ (max)

The results indicate that both case study areas experience extreme heat stress conditions during summer months, with PET values exceeding 41 °C. These conditions are directly attributable to three factors: extensive impermeable surfaces (runoff coefficients 72–82%), insufficient tree canopy cover (RIE values 0.91–2.00 vs. minimum standard 4.00), and widespread use of high thermal mass materials, including asphalt and concrete, without adequate shading. For vulnerable populations, including the elderly, children, and people with pre-existing health conditions, exposure to PET values > 41 °C for prolonged periods increases risks of heat stroke, cardiovascular stress, and dehydration. The pathway conditions to healthcare facilities are particularly concerning, as individuals seeking medical care may already be in compromised health states.

3.7. Interactive Mapping Results

The interactive map created with *Google My Maps* provides a comprehensive visualisation of the results. The map contains three main layers: current state photographs, thermographic images, and land cover images. These layers allow users to explore the critical areas identified along the pathways, to visualise the surface temperatures of urban materials, and to assess the permeability and shading potential of different surfaces. The interactive format facilitates the communication of results to citizens and practitioners, supporting evidence-based urban planning decisions. The map reveals that the most critical areas in both case studies are characterised by a combination of high surface temperatures, extensive impermeable surfaces, and limited vegetation cover. These areas correspond to the critical areas identified in the field observations and land cover analysis, confirming the multi-method approach's effectiveness in identifying environmental vulnerabilities.

4. Discussion

The proposed methodological framework demonstrates the value of integrating multi-scale and multi-temporal analyses for understanding urban environmental vulnerabilities. The combination of qualitative observations, instrumental measurements, and predictive simulations provides a comprehensive understanding of factors contributing to thermal discomfort and potential health risks.

4.1. Interpretation of Key Findings

The results reveal critical environmental vulnerabilities in both case study areas, with conditions that pose significant risks to pedestrian comfort and public health. The MRT values, ranging from 30.76 °C to 72.40 °C, indicate that pedestrians in sun-exposed areas experience extreme radiant loads that can lead to severe thermal discomfort. The PET values exceeding 56 °C during summer peak hours represent a level of heat stress that exceeds the threshold for extreme heat stress (>41 °C), as defined by Matzarakis et al. [50]. These findings are particularly concerning given that the study areas are characterised by ageing populations, with over 25% of residents aged 65 years or older, who are especially vulnerable to heat-related health risks.

The Runoff coefficients (71.97–82.44%) and RIE values (0.91–2.00, well below the minimum standard of 4.00) indicate a high degree of soil sealing and inadequate permeability. These conditions not only contribute to the UHI effect by reducing evaporative cooling but also increase the risk of surface flooding during extreme precipitation events, a growing concern in Mediterranean regions experiencing more frequent and intense rainfall events.

The comparison between the two case studies reveals that Borgo San Lorenzo demonstrates marginally better environmental performance, with lower maximum PET values (56.69 °C vs. 59.11 °C) and Runoff coefficients (71.97% vs. 82.44%). This difference can be attributed primarily to Borgo San Lorenzo's higher tree cover (396 trees vs. 166 trees) and greater green area presence (24,847 m^2 vs. 3385 m^2). This finding underscores the critical role of urban greening in mitigating the UHI effect.

4.2. Comparison with Existing Literature

The findings align with previous studies demonstrating the effectiveness of ENVI-met for urban microclimate analysis and the critical role of vegetation and permeable surfaces in mitigating the UHI effects [47,48]. The PET values recorded in this study (up to 59.11 °C) are comparable to those documented in Mediterranean cities such as Barcelona and Madrid during heatwave conditions [27,28]. However, this study extends existing work by integrating the health services accessibility dimension, focusing specifically on pathways to healthcare facilities, a critical consideration for population health in the context of climate change.

Compared to other existing approaches, such as Quartieri Sani Hub [41,42] and U-CARE [43], the workflow proposed in this research offers several advantages: it enables a parametric investigation of interactions between different elements of the urban environment, quantifies the influence of built environment materials on urban comfort, and provides outputs that can be directly used in planning processes.

4.3. Health Implications

The thermal conditions documented in this study pose significant public health risks, particularly for vulnerable groups, including the elderly, children, and people with pre-existing health conditions, who constitute a substantial portion of healthcare facility users. Prolonged exposure to PET values > 41 °C increases risks of heatstroke, cardiovascular stress, and dehydration [50]. The pathway conditions to healthcare facilities are particularly concerning, as individuals seeking medical care may already be in compromised health states. For vulnerable groups, the combination of poor thermal comfort and limited mobility may serve as a barrier to healthcare access, potentially contributing to health inequities. Furthermore, the cumulative exposure to heat stress along daily pathways may have long-term health effects. Indeed, repeated exposure to extreme temperatures is associated with increased risk of cardiovascular and respiratory diseases [50]. Therefore, the presence of extensive asphalt surfaces and insufficient tree cover in both case studies contributes to prolonged heat exposure for residents making routine trips to healthcare facilities and other essential services.

4.4. Implications for Policy and Practice

The framework provides public administrations and practitioners with four operational tools. First, it enables the identification of priority intervention areas based on environmental vulnerability mapping. Second, it allows for the evaluation of proposed interventions through predictive simulation before implementation. Third, it facilitates monitoring of intervention effectiveness using quantitative indicators. Fourth, it supports citizen engagement through accessible visualisation tools, including interactive maps.

Public administrations can use the methodological framework to assess the environmental vulnerability of their city's neighbourhoods in terms of the built environment, i.e., public spaces and pathways. By identifying the presence or absence of spatial variables in the urban space, maps can be created to represent the neighbourhood's strengths and weaknesses. By processing these maps, it is possible to create an interactive map that can be used as a tool to raise awareness about outdoor comfort issues among citizens. In conclusion, the framework can aid city institutions responsible for health and care promotion by providing crucial guidance on emphasising wellbeing-promoting factors to encourage healthy lifestyles, behaviours, and a health-conscious approach to urban space use.

4.5. Limitations of the Study

The study has several limitations that should be acknowledged. First, the ENVI-met simulations involve simplifications in geometry and material properties that may affect accuracy. The model assumes homogeneous building envelopes and does not account for variations in building materials and occupancy patterns. Similarly, IRT measurements are influenced by environmental conditions, including humidity and wind, that can alter surface temperature readings. Second, measurements and simulations were conducted for representative summer days rather than across the entire summer season. The surveys were conducted only between 12:00 and 14:00, capturing peak solar radiation conditions but missing diurnal variations. Seasonal and interannual variability, including the impact of heatwave events of varying intensity and duration, requires further investigation. Third, the framework has been applied to only two case studies in Tuscany. Broader validation across different climatic and urban contexts, including larger cities, different climatic zones, and diverse socioeconomic conditions, is needed to establish the generalizability of the framework. Moreover, the focus on small municipalities limits the applicability of findings to larger urban contexts with different morphologies and population densities. Finally, the study does not include direct health outcome data (morbidity, mortality) or socioeconomic vulnerability indicators. While the relationship between heat stress and health outcomes is well-established in the literature [50], direct correlation with local health data would strengthen the health implications of the findings.

5. Conclusions

Public space today is the most sensitive element to record environmental and social changes, and the one where aggregative policy comes into play, representing the plurality of the concept of *polis*. Improving accessibility and quality of public space, in the sense of a public, proximate asset, especially where urban fabric is particularly dense, and improving microclimatic conditions is essential for the success of urban projects, in terms of vibrancy, integration of multiple uses, and inclusivity of different user profiles. The adoption of strategies that increase the presence of green spaces, with the introduction of resilient, native tree and shrub species with high environmental mitigation capacity, promotes reconnection with larger natural systems and the establishment of a widespread ecological network supporting the resilience of the entire urban system [51].

The adoption of design support tools capable of evaluating the effectiveness of policies and strategic actions has required a review of environmental indicators to ensure more careful evaluation and control [52].

5.1. Methodological Contributions

The methodological contributions of this study to the research field are many. First, it provides a replicable methodological framework integrating qualitative and quantitative analyses for urban climate vulnerability assessment. The framework combines direct field observations, infrared thermography, land cover analysis, and ENVI-met predictive simulations into a coherent workflow applicable across different urban contexts. Second, it quantifies critical environmental conditions in two Tuscan municipalities, documenting surface temperatures reaching up to 60 °C, runoff coefficients ranging from 72% to 82%, and PET values exceeding 56 °C during summer peak hours. These findings provide essential baseline data for intervention planning. Third, it demonstrates the value of combining instrumental measurements with predictive simulations for evidence-based design, showing how the integration of IRT measurements and ENVI-met simulations provides a comprehensive understanding of microclimatic conditions. Finally, it identifies specific indicators, including surface temperature, runoff coefficient, RIE, and PET, that are suitable for monitoring intervention effectiveness and can be used by practitioners and public administrations to evaluate the impact of implemented interventions.

5.2. Future Research Directions

Building on the limitations and findings of this study, several future research directions are identified. First, the framework should be extended to additional case studies in different European contexts to test its replicability and adaptability. Second, direct validation of ENVI-met simulations with extensive in situ measurements, including air temperature, wind speed, and humidity at multiple heights and locations, should be conducted to further validate the model outputs. Third, integration with health outcome data (hospital admissions, emergency calls, mortality) would strengthen the health implications of the findings. Finally, the methodological framework should include the formulation of a questionnaire on the perceived degree of outdoor comfort, through which citizen involvement makes it possible to identify perceived urban environmental issues and to understand levels of outdoor comfort satisfaction among those who walk and stop in the main approach areas to healthcare facilities in order to access the services offered during the most critical season, summer.

By providing a user-friendly decision-support tool for planners and public administrations, based on the proposed framework, this research contributes to the development of more resilient, equitable, and healthy proximity public spaces. The framework enables the identification of priority intervention areas and supports evidence-based urban planning decisions. However, the findings should be considered indicative and interpreted with caution, particularly in contexts different from those of the case studies.

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Abbreviations

The following abbreviations are used in this manuscript:

UN	United Nations
UHI	Urban Heat Island
EBD	Evidence-Based Design
WHO	World Health Organization
SDG	Sustainable Development Goal
NbS	Nature-based Solutions
THE	Tuscany Health Ecosystem
MIUR	Ministry of University and Research
PNRR	National Recovery and Resilience Plan
IRT	InfraRed Thermography
RIE	Building Impact Reduction Index
LAD	Leaf Area Density
MRT	Mean Radiant Temperature
PMV	Predicted Mean Vote
PET	Physiological Equivalent Temperature

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