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Verona Adapt. Modelling as a Planning Instrument: Applying a Climate-Responsive Approach in Verona, Italy

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Abstract: In response to the global challenges brought on by climate change, cities around the world are adapting, innovating through nature-based strategies for sustainable development. Climate adaptation requires new interdisciplinary approaches in which different disciplines as well as research and practice proactively co-create and collaborate on adaptation to reduce the ongoing effects of anthropogenic climate change. Although awareness on climate adaptation is on the rise, new approaches for urban development are still in development. Moreover, existing approaches mainly focus on local-scale levels or lack a crossover with urban and landscape planning. The present contribution offers an example of an integrated approach bridging urban climatology, landscape planning, and governance to assess and develop climate adaptation solutions linking city and district levels. The city of Verona was taken as a case study to test this approach and its implications for the development of a green and blue infrastructure with a climate-responsive master plan for the district of Verona South. Through critical reflection on the application of the approach to the case study, we aimed to identify its potentials and barriers. Based on this reflection, we provide herein recommendations on how climate modelling can be integrated into planning, as well as on how urban planners and urban climatologists can support each other in making credible and salient climate adaptation solutions.

Keywords: urban climate adaptation; multifunctional landscape design; urban climatology; nature-based solutions; blue and green infrastructure; ecosystem services; meteorological modelling; interdisciplinarity

1. Introduction

The growing interest in climate change and its consequences on human well-being is fostering the inclusion of climate in planning activities in addition to economic, social, and environmental issues [1]. The link between urban development and climate change action is highlighted in the Paris Agreement (2015). The European Green Deal [2] further outlines a set of policy initiatives and funding opportunities to invest in making Europe climate neutral in 2050 by promoting circular economy and nature-based solutions (NBS). With these documents, the European Union recognized the importance of implementing the 2030 Sustainable Development Goals (SDGs) and contributed to integrating cities-related challenges through strong collaboration with local municipalities and inhabitants [3,4].

Cities' and communities' adaptation to climate change is outlined as one of the most emergent and urgent challenges in the near future [1,5,6]. Cities heavily affect climatic conditions, influencing both energy and water balances [7] and, at the same time, host more than half of the world population [8]. The clearest phenomenon of climate change in urban environments is the urban heat island (UHI) effect [7]. The UHI effect is caused mainly

by replacement of natural surfaces, such as grasslands, by unnatural and hard surfaces, such as pavements. Such materials absorb a great amount of heat and release it over a long time, especially during nighttime. Furthermore, the city morphology traps heat into urban canyons, blocks ventilation, and hampers radiative heat exchange with the sky [7]. The increased temperature leads to an increase in the use of energy due to air conditioning systems [9]. This further contributes to global climate change and to the local UHI effect.

A serious consequence of the UHI effect is the increased health risk for citizens. In particular, during so-called "heat waves", morbidity and deaths rise, especially among weaker people, because of the reduction of thermal comfort [10,11]. Several studies demonstrate the correlation between the increase in temperature and mortality: for example, Legambiente reports that in Rome, due to the heatwaves in 2003 and 2015, the mortality rose by 32.7% and 34%, respectively [10]. Making cities more adaptable to future changes provides therefore the necessary opportunities to rethink urban space and improve living conditions [9].

According to the EU, a key role in the implementation of climate adaptation strategies in cities is played by the principle of mainstreaming, which encourages the integration of adaptation policies and approaches into ongoing planning processes [12]. Mainstreaming requires interdisciplinary approaches where disciplines proactively co-create and collaborate on adaptation to reduce the ongoing effects of anthropogenic climate change [4–6]. Yet, this might also require new climate adaptation approaches for urban development in which different fields of knowledge and research come together, but these are still in development [13].

In response to the challenges brought on by climate change, the number of cities that are adapting through nature-based strategies for sustainable development is increasing [14–18]. In 2012, the city of Bologna launched the BLUE AP project, which published several reports and guidelines and served as a model for other medium-sized Italian cities [19]. The resulting climate adaptation plan was followed by the analysis of territorial vulnerabilities, performed with modelling tools. The obtained results will contribute to the development of a new city plan in line with the regional urban planning law [20]. Bologna is an exceptional case study since it was the first Italian city to adopt climate adaptation in such a solid way. However, Nikologianni et al. found limited evidence of the development of new ideas, approaches, and policies to deal with the climate crisis [15]. The procurement processes, policies, and regulations in relation to the climate strategies often follow "conventional frameworks" that do not allow for new approaches to arise and be embedded in planning and governance strategies [15,21] or are not specific or detailed enough [6].

The potential of nature-based solutions and urban green infrastructures (UGI) in relation to climate mitigation and adaptation have been considered in the planning of urban environments for decades [22,23]. With the emergence of global climate change, climate considerations in urban and open space planning have been on the rise. Moreover, new modelling methods and techniques are being developed to better measure and predict climate change and urban climate conditions. Incorporating climate modelling into urban and open space planning brings also the possibility to test different green climate adaptation measures, as is demonstrated in several studies (e.g., [24,25]). Yet, many studies are conducted at the microscale with ENVI-Met (e.g., [26–28]), while studies at the mesoscale often do not deliver the detailed information necessary for urban planning (for example, the CLARITY CSIS platform [29]).

This contribution offers an example of a climate-responsive approach in which we describe a multidisciplinary and interscalar design process combining fields of knowledge bridging urban climatology, landscape planning, and governance. This approach allowed us to develop and assess climate adaptation solutions with support from state-of-the-art meteorological simulations. The city of Verona was taken as a case study to test this approach and its implications for the development of a master plan on a mesoscale with a green and blue infrastructure. Testing the approach on a case study allowed us to adjust the proposal to an existing city form and to highlight the advantages and face the limits

that occur in a real-life situation [30]. The approach included subsequent steps for analysis and design phases to investigate, synthesize, and assess issues related to climate on two scale levels through modelling and mapping methods. Herein, aspects in relation to the urban environment, liveability, and development potentials are addressed. For every step of the process, we explain the contribution of the meteorological mesoscale models. In the end, the proposed climate-responsive approach is discussed from various perspectives. In particular, the collaborative exchange among fields of knowledge is critically evaluated in the light of potentials, barriers, and further opportunities.

2. Blue and Green Infrastructure as Climate Adaptation Strategy

NBS and UGI have been identified as suitable strategies to promote a more resilient and climate-responsive city [1,13,31]. Nature-based solutions have been defined as measures "inspired by, supported by or copied from nature" [18] (p. 4),that aim to meet various environmental, societal and economic benefits, while maintaining and enhancing natural capital [32,33]. The concept of UGI is related but differs from NBS due to its stronger link with strategic green space planning [34]. UGI is defined as an interconnected network of green spaces that provides a wide array of ecosystem benefits and integrates protection and enhancement of natural processes into spatial planning and territorial development [35–38].

Both NBS and UGI aim to contribute positively to climate adaptation and mitigation by ensuring and increasing the presence of green and blue areas, such as green roofs and walls, parks, urban forests, and rivers [7,35]. The green fraction in the city is effective for reducing heat absorption, air temperature, and exposure to solar radiation and wind [13]. Yet, the benefits of NBS and UGI go beyond mitigating the UHI effect. They provide different services related to energy saving, environmental quality, biodiversity, water management, and liveability [7,35,39]. For instance, natural drainage systems (the so-called "SuDS"— sustainable urban drainage systems) permit to intercept rainwater fallen on roofs and streets, to infiltrate it into the ground, or to be collected for future reuse [40]. In addition, the sociocultural role of UGI should be acknowledged. Accessibility to green areas has a great impact on public health and provides psychological and physical benefits. Green areas offer space for sports and recreation; connected they can improve slow mobility; and they can contribute to community identity [31]. During the hottest periods, they provide so-called "cool spots", which is particularly crucial for more vulnerable citizens, such as the elderly [41,42].

To make use of the full potential of NBS and UGI, they need to be considered on different scale levels. On a neighbourhood and city scale, natural ventilation corridors need to be planned in such a way that they link the so-called "cool spots" of the city and provide better comfort conditions in open spaces during heatwaves. At the same time, weather conditions need to be considered so as to not create discomfort in large open spaces due to cold winds [23]. Among the more interesting experiences involving these adaptation strategies, the effort by the city of Stuttgart deserves mentioning [43]. On the street scale, the ratio between the buildings' height and the width of the street greatly affects the ventilation in the urban outdoor space. If the ratio is high (i.e., buildings are much taller than the street's width), the natural ventilation is impeded, and good air exchange is not possible. In contrast, larger urban canyons demand shading devices (possibly trees) to improve pedestrians' comfort [44]. This aspect contributes also to the UHI effect: a more shaded canyon can be pleasant during the day, but it obstructs the releasing of heat trapped within it, increasing the time required to cool down the temperature during nighttime.

The envelope of NBS and UGI can be extended to vertical and horizontal built surfaces through the installation of green walls and green roofs. Green roofs can reduce the energy needed for air conditioning systems up to 50% as well as improve local climate conditions and retain rainwater to a higher or lesser degree dependent on the substrate's depth, climate, and meteorological conditions [35]. In addition, green roofs can support biodiversity by providing habitats for different species [45] and can extend green space for recreation in the form of real roof-top gardens [46].

This catalogue of strategies presented highlights the benefit achievable when NBS and UGI are installed in a city.

3. A Climate-Responsive Approach: Case, Methods, and Materials

The case of Verona was chosen due to its urgency to tackle urban heat stress as a health risk for its relative elderly population. Moreover, the city's ongoing and future plans for urban transformation were considered as an opportunity to mainstream climate adaptation into the city's policy- and decision-making. The climatic approach was developed independently from the municipality yet collaboration with the municipality ensured data availability and insights on ongoing planning procedures.

3.1. Verona as a Case Study

Verona is a medium-sized city with around 260,000 inhabitants (updated to 2019 [47]) located along the Adige River on the Po Plain, in northern Italy (Figure 1). Its humid subtropical climate (according to the Köppen and Geiger classification [48]), i.e., temperate without dry season, is influenced by the Alps to the north and by the proximity of lake Garda to the west [49]. On average (period: 1987–2016), Verona has four hot summer days (Tmax > 35 °C) per year; the combination of summer days (Tmax > 30 °C) and tropical nights (Tmax > 20 °C) is equal to 24. Verona has 327 45 cooling degree days per year [50]; this indicator is used to calculate the energy demand needed to cool a building and it is defined relative to the outside temperature, determining a threshold above which it is assumed a building needs cooling [51]. Compared to other urban audit cities in the EEA, Verona is largely above the average regarding the number of cooling degree days per year. In addition, as Verona positions in the top 5% of European cities with inhabitants of 75 years or older, it is clear that the adoption of a climate adaptation strategy is urgent to protect this risk group [50].

Due to its strategic position at the intersection of two transport routes in east–west and north–south directions, Verona has been an important infrastructural hub since Roman times. This role had a great impact on the urban form, since these routes were expanded into infrastructural corridors with highways, railways, and an airport. This massive presence of infrastructure affects, in particular, the southern area of the city: besides the discomfort generated by the traffic, the infrastructures represent physical barriers between the city and the surroundings.

3.2. An Approach across Scales Linking Climate Modelling and Open Space Planning

The climate approach describes a procedure on how climate modelling and open space planning can be combined to identify the potentials for urban climate adaptation across city and district scales. The procedure combines climate modelling methods with mapping, while addressing both analytic and design phases (Figure 2). At the city scale, an analysis with climate modelling methods, as well as the mapping of vulnerabilities, determines the most vulnerable districts for urban heat stress, which are, therefore, the most relevant for climate adaptation. At the district level, the vulnerabilities and potentials of the selected district are further analysed through climate modelling and mapping. The mapping includes parameters in relation to climate conditions as well as in relation to the urban structure, open spaces, planning opportunities, and liveability. The outcomes of the analysis phase feed into a design phase in which the main objectives for climate adaptation are developed into strategic guidelines. These guidelines provide a program for the design of a climate responsive master plan for the district. A research-by-designing process [52] intertwines the analysis and design phases and allows for the optimisation of the master plan by validating the effectiveness of its measures on climate conditions by means of simulations with a meteorological model.
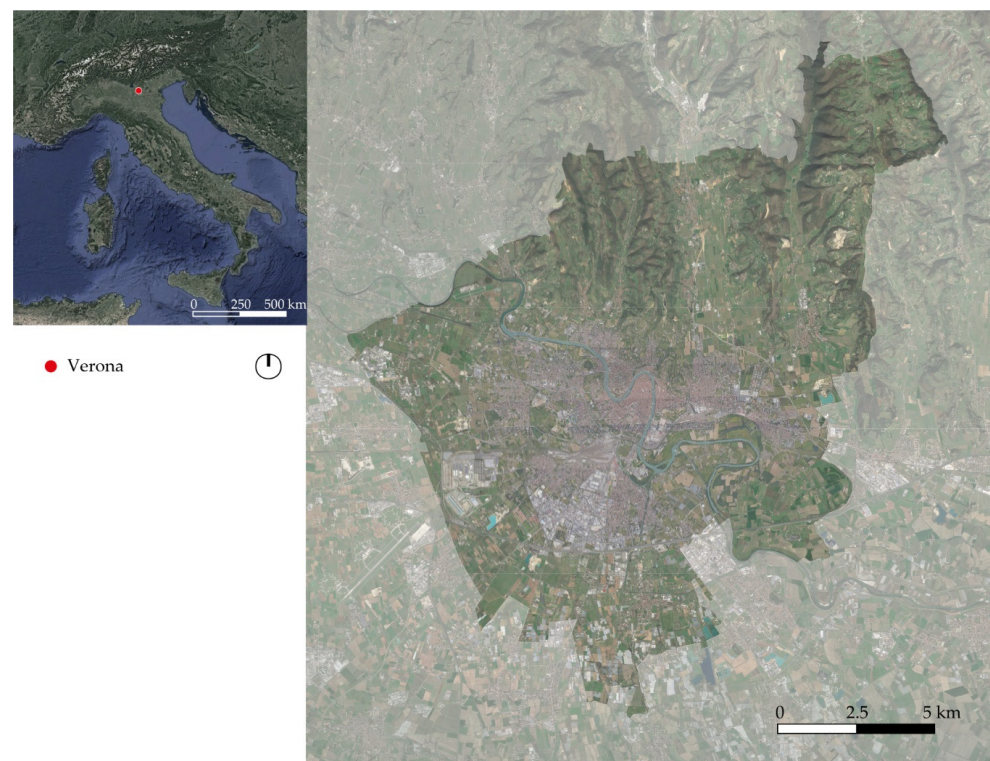
Figure 1. Aerial image of the city of Verona with an indication of its position (source: Google Earth).

3.3. City Scale Assessment

To acquire climate-relevant data on the physical geography of the test case, we classified the urban area according to the World Urban Database and Portal Tool (WUDAPT) protocol (available online: http://www.wudapt.org; accessed on 15 September 2020), adopting the Local Climate Zones (LCZ) framework [53], with a horizontal resolution of 30 m. This framework defines ten different urban classes based on specific values of urban fraction, buildings compactness, and height and thermal properties of building materials. This allowed us to classify Verona in homogeneous areas, which are expected to present different local climatic conditions. The outcome from using WUDAPT provided suitable information about urban morphology to the mesoscale meteorological model, which is fundamental for an accurate simulation of the climatic alterations induced by urban areas [54,55].

For the mesoscale meteorological model, we used the Weather Research and Forecasting (WRF) [56] model. This model was adopted to evaluate the modifications induced by the urban area of Verona on local climatic conditions. WRF is widely used for simulating urban climatic conditions in both operational and research applications [57,58]. To evaluate the effects of nature-based solutions in conditions characterized by a high thermal stress for the urban population, a 5-day period in 2017 was selected for the simulations as representative of a summer heat wave with a well-developed UHI. The simulations started at 1800 UTC (LST = UTC + 1 h) 31 July 2017 and ended at 0600 UTC 6 August 2017. The results of the first 6 h, being spuriously affected by the initialization, were not considered for the analysis. Four domains with increasing spatial resolution were adopted, with grid spacings of 9, 3, 1, and 0.33 km, respectively. The large-scale meteorological forcing was supplied by the 6-hourly NCEP Final Operational Global Analysis data on a 0.25-degree grid. The present simulations were run using the BEP-BEM urban parameterization schemes [59,60], which simulate heat, mass, and momentum exchange between the buildings and the environment, and allows for the estimation of the energy consumption by air conditioning systems. Gridded information on the urban morphology was directly used as input for the BEP scheme in order to provide an accurate representation of the city structure and of the urban and vegetation fractions. Detailed information about buildings' area and height, as well as vegetation and water bodies,

was provided by the Municipality of Verona and inserted in a geographic information system (GIS) in order to compute the suitable input parameters for the model. Once the city area was divided into a grid of 100×100 m^2 cells, the percentage of paved surfaces was calculated for each cell; with regards the built environment, the indicators computed and needed as input by the meteorological model were the mean height, the area occupied by the buildings, and their surface (walls + roof). The areas not covered by the municipal database were described based on the LCZ classification. The adoption of a meteorological model allows for the obtaining of the spatial distribution of the meteorological variables, such as air temperature and wind speed and direction. The WRF outcomes were split into two scenarios: daytime (0900–1500 LST) and nighttime (2000–0200 LST). In particular, the outcomes for the nighttime were considered, due to the fact that the UHI is stronger during this part of the day [55].
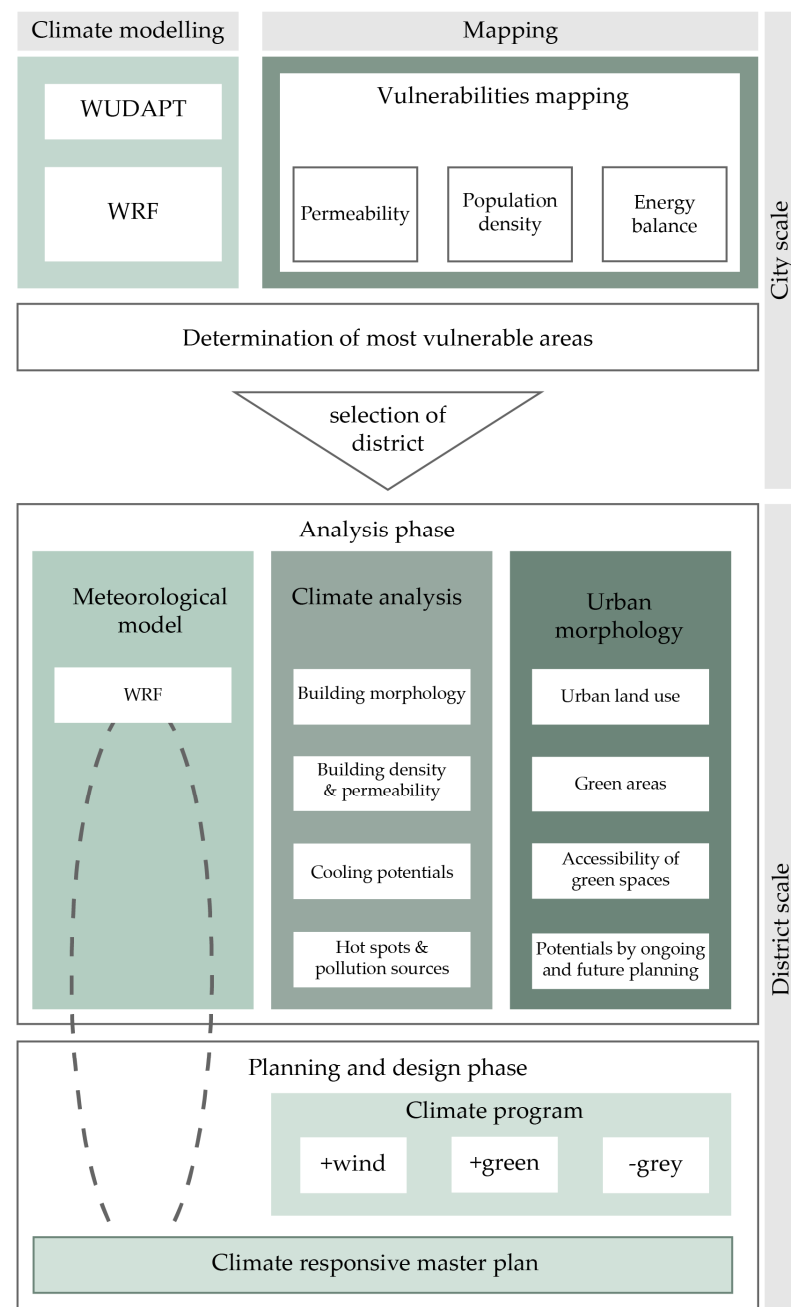

Figure 2. Diagram of the procedure of the climatic approach.

To relate the climatic conditions to the morphology and the concerned citizens, four additional aspects were investigated: the green and blue structures, population density, and energy consumption. These aspects are each standing in relation to the establishment of the heat wave risk. As described in the previous section, the green and blue infrastructures have a positive role in improving human well-being and urban climate [35,39]. Insights on population density allows for the highlighting of vulnerable areas. The more people live in a neighbourhood, the more likely green public areas and mitigation strategies will be needed. The energy consumption reflects the most active parts of the city, where anthropogenic heat highly contributes to the UHI [7], in particular during heat wave periods, when the cooling systems' demand increases [9]. Data on the green–blue structure was provided by the Municipality of Verona, data on population density, clustered in neighbourhoods, was downloaded from the public administration web portal [47], while data about energy consumption was extracted from an annual municipality report [61]. The recorded usage was categorized based on energy source and sector of use, which allowed us to distinguish between industrial and residential/commercial energy use.

To enhance comparability between heterogeneous data on the four aspects, homogeneous results were produced by shaping the data elaboration based on a grid structure. The value of each cell in the grid corresponded to the sum of the objects within the specific space. The green–blue structure was measured in terms of "fraction", i.e., the ratio between pervious surface and the total area. The population density was proportionally distributed based on the residential building volumes. For the energy consumption, data on energy use was categorized according to the building use between industrial and residential/commercial and further distributed based on building volumes. Based on the results of the WRF model and the vulnerabilities mapping, the areas with the strongest UHI effect, lack of vegetation, highest population density, and energy consumption could be identified as the most vulnerable areas regarding heat stress and human well-being. The superimposition of these analyses allowed us to detect the most vulnerable district of the test case and to proceed with the second step of the approach.

3.4. District Scale Assessment

The district level is assessed taking into account climate conditions, open space structure, and open space planning policies. The outcomes of the analysis phase feed into the design phase. The analysis at the district level started from the data used at the city scale. Yet, instead of working with indicators on a gridded structure, this time the actual urban layout was investigated. The database components were stored in the GIS environment: this procedure permitted the overlaying of several features and, afterward, relating these topics to create new remarks.

The analysis of the microclimatic characteristics of the district, inspired by Lenzholzer et al. [62], considered climatic conditions as well as urban features affecting the climate conditions. The outcome of the mesoscale meteorological model for the nighttime was adapted for the scale of the selected district. The analysis of the buildings' morphology was built upon the WUDAPT results. Residential districts were divided into three categories: open low-rise, open mid-rise, and linear mid-rise. The industrial areas were categorised in manufacturing and commercial buildings as well as industrial factories; the peculiar category of "large buildings" was added to describe exceptionally large structures, regardless of their urban function. It should be noted that the latter classification reflected mainly the plot layout, overcoming the LCZ scheme in favour of a more detailed description. This project allowed for field excursions, which proved to be a valuable instrument to improve the context analysis. Alternatively, the urban morphology could be further explored through the observation of satellite images as well. This step permits moving from a mesoscale satellite image-based procedure to a more specific analysis at the district scale.

In a subsequent analysis, building density and permeability were studied. Impermeable and semi-permeable surfaces were distinguished, assuming that vegetation was hardly present in the industrial area, while the private gardens were contributing to the permeability of the neighbourhoods. At the same time, the settlements were investigated for their level of openness, referring to the density of buildings: the residential areas were assumed to be more dense than the industrial ones, characterized by large spaces between buildings, mostly for logistic reasons. These assumptions were confirmed via field excursions.

The main potentials and barriers regarding climate conditions were schematized in the "cooling potential" and "heat and pollutant sources" maps. For the cooling potential, green and blue structures, which have the ability to cool down the surroundings and maintain more pleasant conditions in the areas, were mapped. The mapping was based on the air temperature map, the level of surface permeability, and the presence of green or blue structures; obstacles to natural ventilation, such as built-up structures acting as barriers against the prevailing wind direction, were also highlighted. These considerations represent the synthesis of the previous investigations. Regarding the heat and pollutant sources, the main traffic roads likely affect the well-being of residents as well as contribute to increased temperatures and air pollution. In addition, areas with the hottest temperature simulated in WRF were marked as "hot spots", indicating the necessity to propose modifications on those sites. The accumulation of these analyses provided an overview of the weaknesses and weak spots in regard to climate adaptation.

In contrast, the next set of analyses intended to provide an overview of the potentials in the district regarding climate adaptation. Illustrating the urban land use is the first step to assess the environment. To distinguish the residential districts from the industrial/commercial zones was important not only from a morphological point of view, but it also reflected the division of daytime and nighttime activities. Besides, the analysis of the land use allowed is to also determine non-built areas because they constitute a valuable capital for adaptation, especially public areas. In the second analysis, this was taken a step further by identifying green and blue areas. Green areas were further distinguished based on the type and height of the vegetation, i.e., parks, soccer fields, and cultivated fields. The metadata on the use of green spaces were obtained from the municipality's database. Further information was downloaded from the public administration's web portal [63] and added into the GIS database. The infrastructural network was mapped due to its dominant role in cities. Roads are sources of pollutants, heat, and noise, but also important for accessibility by connecting or separating areas, depending on factors like width, traffic, and vegetation.

Based on the guidelines of the WHO [64], the accessibility of public green areas at the district level was quantified. For each park with a surface greater than 0.5 ha (5000 m^2), a radius of 300 m was traced, representing a rough approximation of a 15-minute-long walk by an elderly person. In this way, the plots with poor accessibility became evident.

To build a more comprehensive picture of the opportunities for development within the district, the report "Verona Sud ATO 4" published in 2011 by the Municipality of Verona, in collaboration with the studio Federico Oliva Associati, was used [65]. The aim of this master plan was to bridge two planning instruments: one with a strategic value (Plan for the Asset of the Territory—PAT) and one with an operative value (Intervention Plan—PI) [66]. Within the framework of this project, the identification of unused, degraded, abandoned areas, transformation areas, planned removals, and inactive legislative constraints was conducted. Due to their status, these areas are more likely to be subjected to land use change and therefore have potential for positive transformative change. In addition, future projects were included in the framework: the new electric public system [67] and the transformation of the ex-freight terminal.

3.5. Design Phases

The district scale assessment provided a comprehensive overview of the opportunities and the weaknesses in the urban district regarding both climate and open spaces. Based on this assessment, a climatic program was developed with the main spatial guidelines for climate adaptation. These spatial guidelines aimed to connect the spatial features with potential for climate adaptation, as identified in the assessment. In this case, we selected the following three guidelines: improvement of natural ventilation, creation of an extensive green network, and reduction of impervious surfaces. For each of these guidelines, spatial configurations at the district scale were developed. These spatial configurations indicated the main spatial ideas behind the guidelines. Within the process of developing the guidelines, we already tried to consider constraints like the legislative framework, private properties, and stakeholders' interests.

The guidelines form a framework for a climate-responsive master plan, which was optimised through a research-by-design process. Within this process, the spatial configurations of the guidelines needed to be translated into concrete nature-based solutions and other spatial measures within a time horizon of twenty years. We started from the available areas detected in the district scale assessment to then find physical connections among these areas to create a green infrastructure while including existing valuable features in the new network. The master plan focused on the transformation of open space and minimal change of the urban layout or the activities within the district. The final proposal constituted a new vision for the district in which the green infrastructure formed the backbone for the climate adaptation process.

The mesoscale meteorological model allowed for the validation and assessment of the master plan by inserting the final layout of the master plan into the WRF model and simulating the effects of the employed nature-based solutions and other spatial measures. After a pre-processing phase, in which urban parameters were modified based on the proposal, the model was run with the same meteorological conditions as in the simulation of the current situation. The effectiveness was measured evaluating the difference between air temperature and wind speed in the current and future scenarios. This permitted the test of the master plan's effectiveness, verifying how nature-based solutions, and in particular climate adaptation strategies, could improve the microclimatic conditions within the urban environment. In addition, we simulated a scenario with the aim of evaluating the effectiveness of green roof technology by assuming different percentages and typologies of greening. The scenario we tested assigned green roofs in the industrial area, supplying a meaningful plot in which factories and warehouses host nature-based solutions to reduce their impact on the UHI.

4. Results

4.1. City Scale Assessment—Investigating the UHI Effect in Verona through WUDAPT Classification, WRF Model, and Vulnerability Maps

The results of the WUDAPT classification (Figure 3) indicate that "open low-rise", representing buildings one-to-three storeys tall sparsely placed, is the most common class in the urban area. On the other hand, in the city centre buildings are on average taller (3–10 storeys). In particular, in the southern part of Verona, some industrial clusters (LCZ 8, "large low-rise") can be identified, separate from the residential neighbourhoods.

The results of the WRF model were compared with observations from a weather station located close to the city centre to evaluate the ability of the numerical simulations to capture the peculiar climatic conditions characterizing the urban area. Figure 4 shows the comparison between simulations and observations for air temperature and wind speed. It can be seen that the model is able to simulate reasonably well air temperature in the urban area, with a slight overestimation during nighttime. In addition, wind speed is generally well predicted by the model, with occasional overestimations, especially during the last day of simulation.
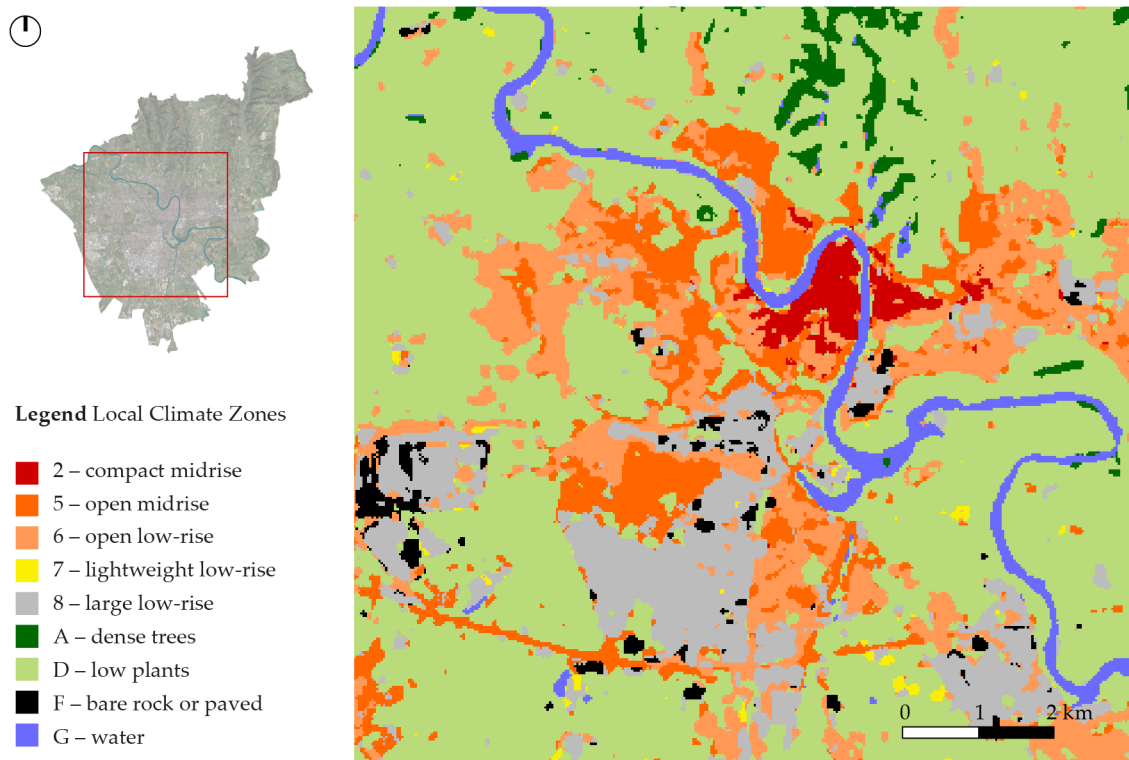
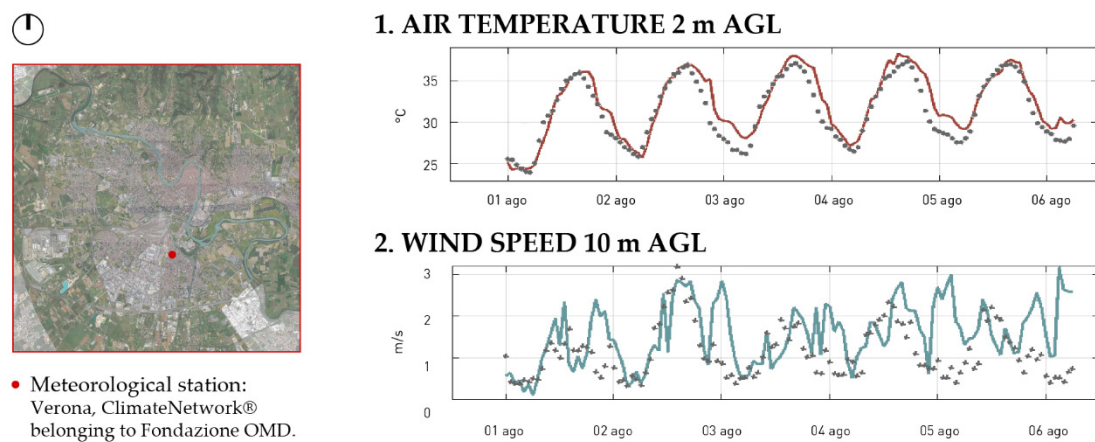**Figure 3.** LCZ classification of Verona (zoom to the city).

Figure 4. Comparison between data simulated by the WRF model and observed by the meteorological station in Verona (temperature and wind data refer to the meteorological station in Verona from the ClimateNetwork® belonging to Fondazione OMD). The continuous line represents the measurements from the WRF model, while the individual measurements of the weather station are indicated in dots and crosses.

Figure 5 shows a map of air temperature for the nighttime hours (2000–0200 LST) at 2 m above ground level (AGL) and of the wind field at 10 m AGL averaged over the five simulated days. The outcome of the model highlighted the areas most affected by the UHI effect. The UHI effect was clearly noticeable: air temperature in the city of Verona was 3–4 °C higher than in the surrounding rural areas. Moreover, the surrounding minor towns were distinguishable and characterized by higher temperatures. As previously hypothesised, the hottest area was the historical centre, characterized by compact buildings of at least three storeys (LCZ 2, "compact mid-rise") and an almost complete absence of vegetation. Another hot cluster could be found in correspondence with the southern area. This confirmed our previous analysis of the urban morphology of the industrial agricultural zone (zona agricola industriale—ZAI): this result is mostly due to the scarcity

of permeable surfaces and vegetation. Regarding ventilation, a northerly wind is present in the northern part of the city, closer to the pre-alpine foothills, while an easterly wind is present in the central and southern parts of the urban area. The former is related to typical mountain–plain circulations developing at night [68], while the latter is probably linked to large-scale circulations. In contrast, the model output showed that the UHI effect is less significant during daytime (see Figure A1): between 0900 and 1500 LST the difference between urban and rural air temperature was ~1–2 °C. An important result was the detection of cooler areas in correspondence of the Adige River and other minor water basins. The outcome of the model highlighted the areas most affected by the UHI effect.
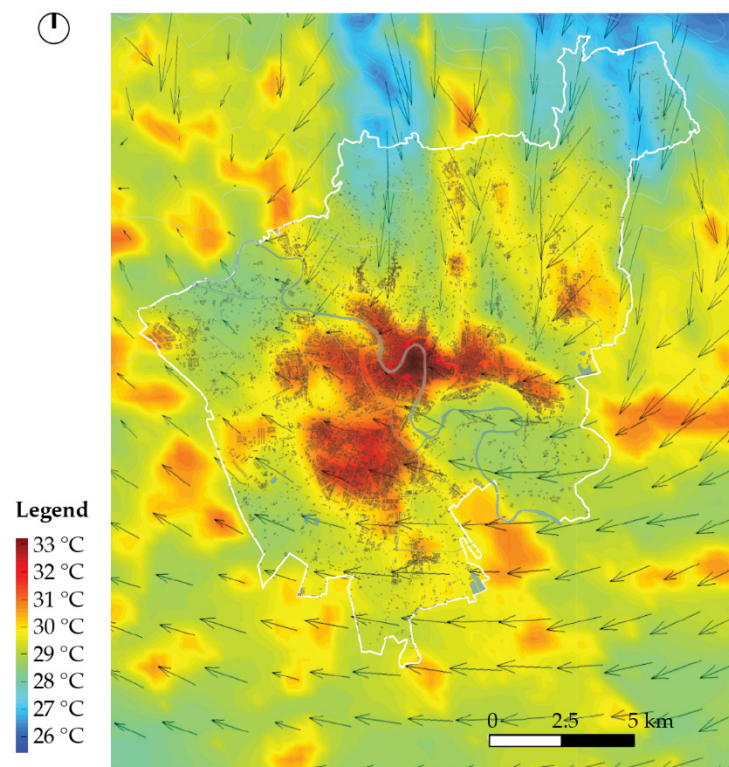

Figure 5. Air temperature at 2 m AGL and wind at 10 m AGL averaged over the 5 days simulated for the nighttime hours (2000–0200 LST).

The vulnerability analyses (Figure 6) show voids in the green fraction around the city centre, the southern area of Verona, and the large distribution centre west of Verona. The blue fraction shows the Adige River with its artificial channels and some small water bodies in the rural surroundings. Peak values for the energy consumption can be found in and around the city centre, as well as in the southern district of Verona. The residential density finds a marked separation in correspondence with the previously cited area with large low-rise structures (LCZ 8).

Based on the analyses, two areas stood out for climate adaptation: the city centre and the southern district of Verona. We selected for the present study the southern district of Verona because it was subject to an important transformation process; this constituted a valuable opportunity to implement climate adaptation strategies compared to the more well-assessed and less adaptable city centre.
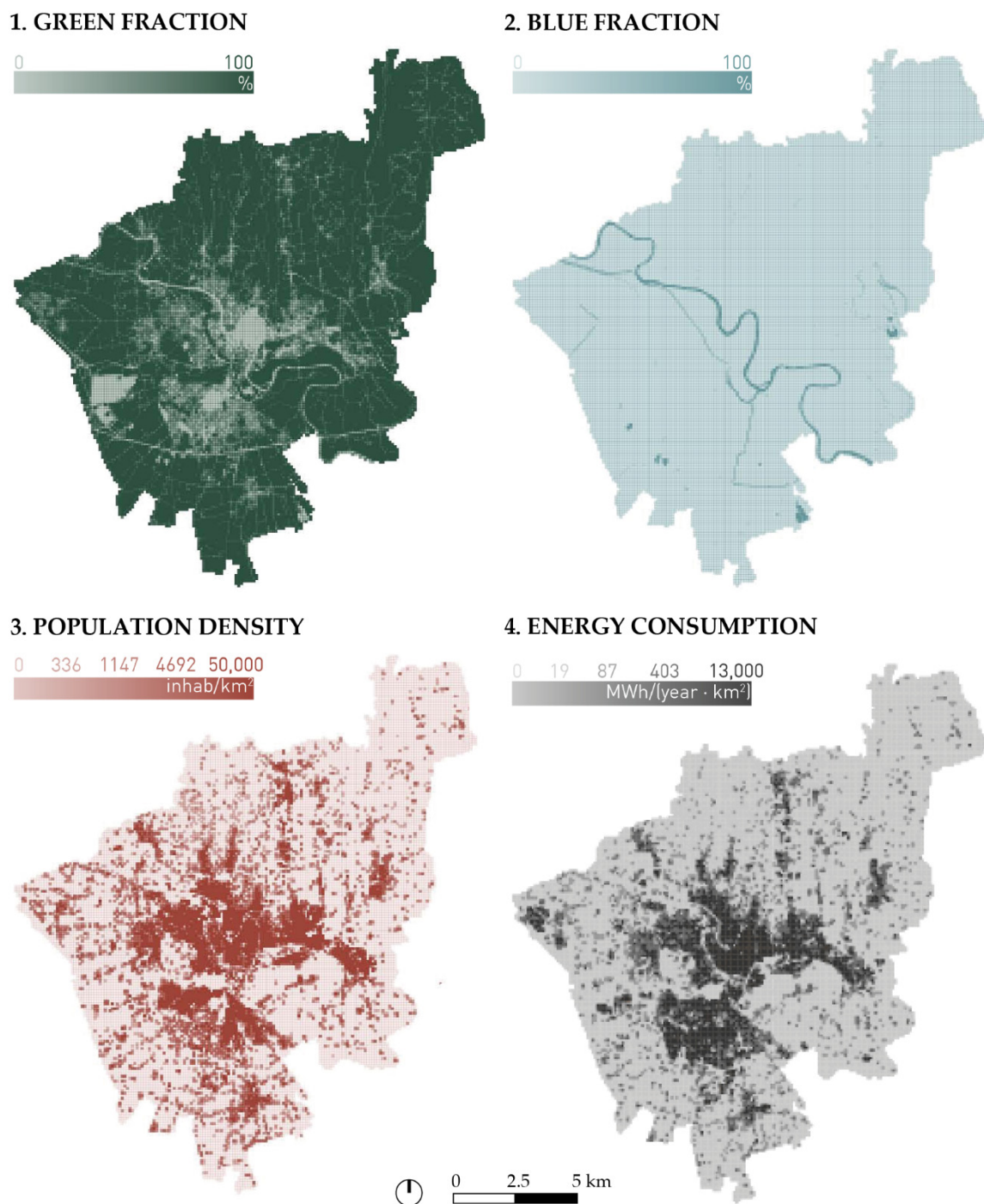
1. GREEN FRACTION

2. BLUE FRACTION

3. POPULATION DENSITY

4. ENERGY CONSUMPTION

Figure 6. Vulnerability analyses of the municipality of Verona.

4.2. The Urban and Climate Assessment of Verona South

Verona South is a 1300-ha area enclosed by the railways to the north and west and the highway to the south (Figure 7). To the North, a large freight terminal up for redevelopment is separating the district from the city centre. The main land uses detected by the LCZ classification are residential and commercial areas. The 500-ha industrial area separates the eastern and western residential neighbourhoods, which host 21% of Verona's residents [47]. The zoning character of Verona South undermines the citizens' well-being: beyond the pollution produced, the lack of recreational activities and natural surfaces prevent the liveability of this urban space.
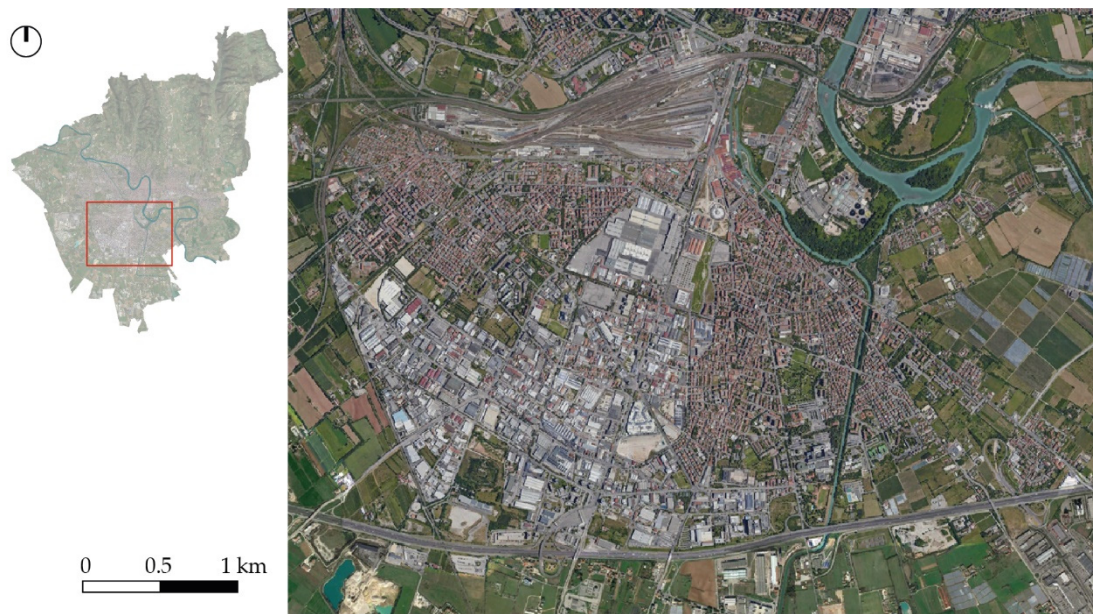
Figure 7. Zoom on Verona South (source: Google Earth).

The zoom to the nighttime UHI simulation on Verona South shows that the central and the northern areas are the most affected by hot temperatures; the cooling effect of the green areas can be detected (Figure 8a). Based on the WUDAPT classification, the buildings' morphology has been defined in more details (see Figures 8c and 9a). The residential neighbourhoods appear largely dense although semi-permeable (see Figures 8b,c and 9a). The productive sites have more impermeable surfaces and a relatively open arrangement, which enhances natural ventilation in summer and solar availability in winter (see Figure 8b,c). Therefore, both areas present both advantages and weaknesses with respect to climatic conditions. Cooling potential can be mainly provided by the Adige River and cultivated fields (see Figure 8d). Thermal contrasts between these areas and the city can cause the development of urban breezes that can cool the urban area, but this natural ventilation is often blocked by buildings. On the contrary, both heat and pollution sources within the area affect the closest zones because of the lack of barriers (see Figure 8e).

The main characteristic of Verona South is the presence of the industrial area flanked by two residential areas intermingled with collective interest facilities, like schools, the hospital, and recreational spaces (see Figure 9a). The green–blue structure is fragmented and not well-connected. The scarce green spaces are only connected through rows of trees or single plants. Regarding the blue infrastructure, some industrial channels are still present, however, most of them have been buried over the past years (see Figure 9b). The infrastructural network widely affects the urban structure because it separates the area from its surroundings (see Figure 9c). Many traffic routes are in the north–south direction, connecting the highway with the city centre. The main axis in this direction is Viale del Lavoro/delle Nazioni, an important source of air and noise pollution (see Figure 8e). A slow mobility network is not well-developed. The cycling network is fragmented, and little attention is paid to pedestrian paths within the ZAI, with a complete absence of them in certain streets. The lack of natural areas, space for recreational activities, and accessibility for pedestrians and cyclists, together with the UHI effect and the noise and air pollution, undermine the liveability of Verona South and the well-being of its citizens. Figure 9d shows the buffer zone analysis of accessibility to green public areas, according to the WHO guidelines [64]: the ZAI area is largely not included in this zone, thus any planning proposal must foster the strategic location of parks within the urban territory.
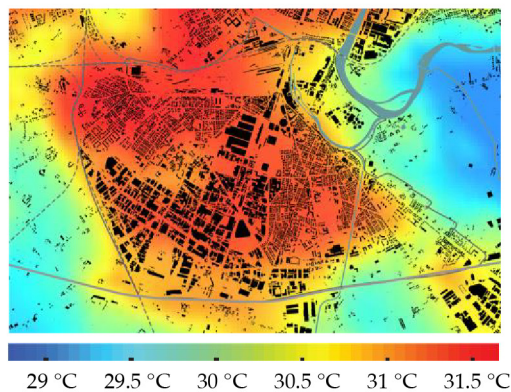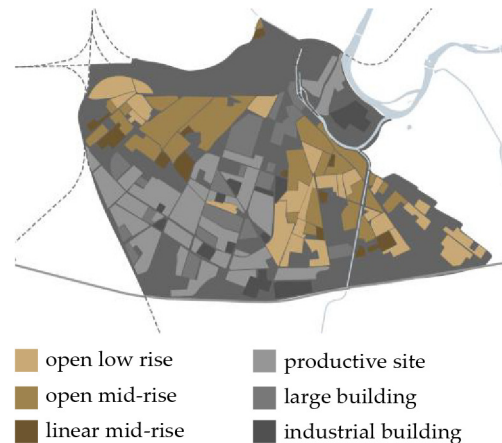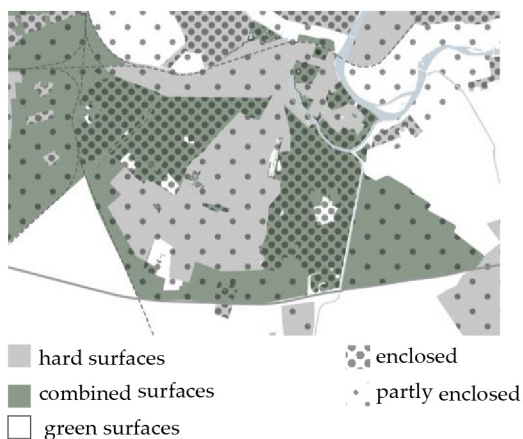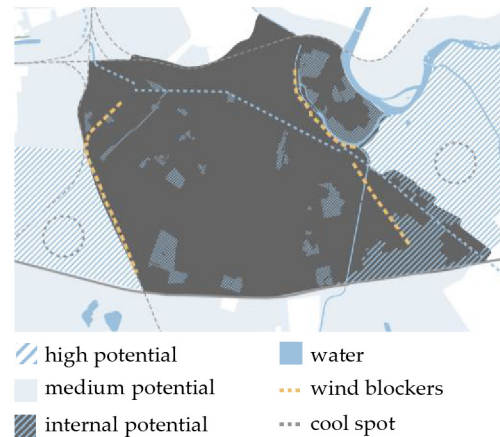
a. NIGHTTIME UHI

| 29 °C | 29.5 °C | 30 °C | 30.5 °C | 31 °C | 31.5 °C |

b. BUILDINGS MORPHOLOGY

- open low rise
- open mid-rise
- linear mid-rise
- productive site
- large building
- industrial building

c. MATERIALS AND DENSITY

- hard surfaces
- combined surfaces
- green surfaces
- enclosed
- partly enclosed

d. COOLING POTENTIAL

- high potential
- medium potential
- internal potential
- water
- wind blockers
- cool spot

e. HEAT AND POLLUTANTS SOURCES

- highway
- water treatment building
- 1° level street
- hot spot
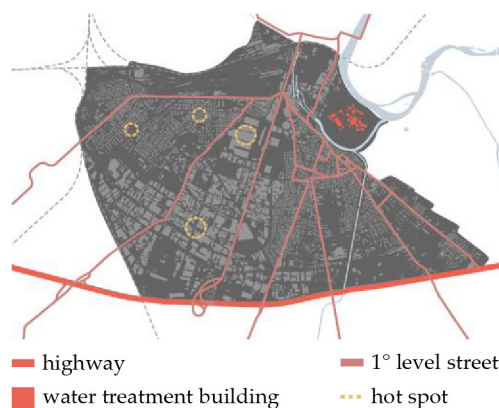
Figure 8. Climate analysis of Verona South.

To kick-start the climate adaptation process, we considered highlighting short-term transformation opportunities as an important strategy (see Figure 9e). The municipality master plan [65] provided informed insights into the potential future structures and uses of the area. The ongoing projects represent relevant areas that would represent opportunities to change the structure of the district; future projects proposals implied the transformation of the freight terminal and other smaller plots and the development of an electric public transport system (trolleybus). Two calls for interest (published in 2009) permitted high-

lighting whether landowners expressed the intention to make changes to their property: this captured an interesting potential in the area. The areas that are abandoned or no longer fall under restrictions represent attractive spaces for a strategic conversion of the district. Finally, the properties of the municipality were marked to indicate those areas that could start the intervention as pilot projects. At the time of the project, only 40% of the buildings could be classified as "industrial", while almost half of the buildings were reported to have changed into commercial and public establishments [65]. This "spontaneous" change in building functions opens possibilities to bring in new ideas.
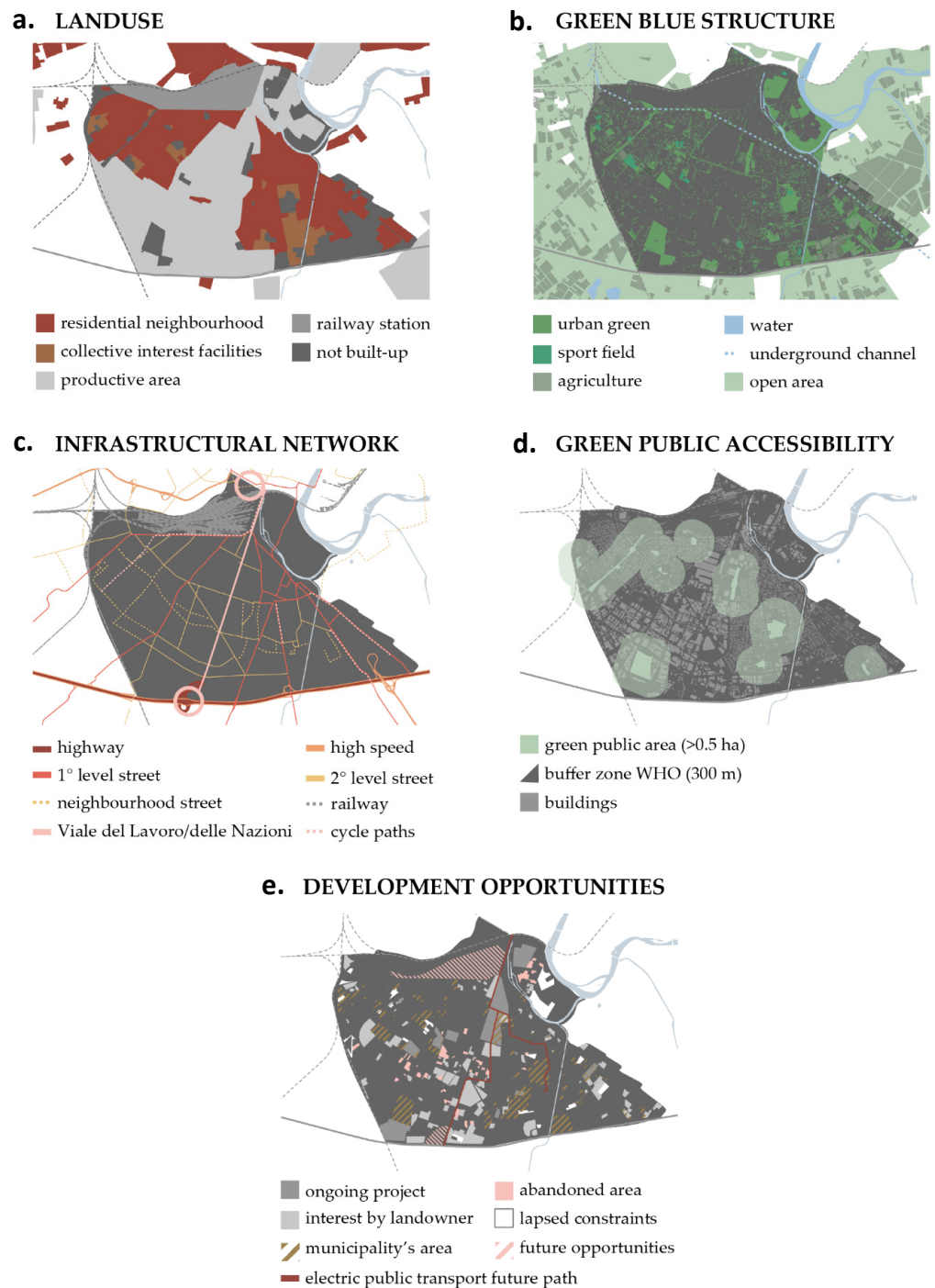
a. LANDUSE

b. GREEN BLUE STRUCTURE

c. INFRASTRUCTURAL NETWORK

d. GREEN PUBLIC ACCESSIBILITY

e. DEVELOPMENT OPPORTUNITIES

Figure 9. Analysis of the urban structure of Verona South.

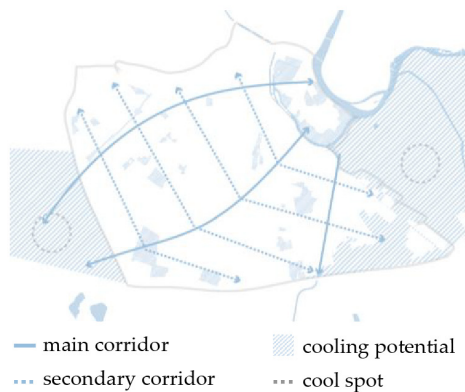*4.3. The Climate Adaptation Proposal for Verona South*

4.3.1. A Program for Wind, Green, and Grey

The main aims of the climate adaptation plan for Verona South are to reduce the UHI effect and to subsequently enhance the inhabitants' health and well-being. Three objectives for wind ventilation as well as green and grey areas were developed into spatial guidelines for climate adaptation, which form a framework for the climate-responsive master plan (Figure 10). To improve natural ventilation to cool the city during heatwaves, three main wind corridors were designated, which are connected to large cool spots, usually outside the built-up area (see Figure 10a). These corridors need to follow the prevailing direction of summer winds at night and should stay free from wind barriers. Secondary corridors connect the main corridors with one another and might allow ventilation from other wind directions. For the second objective, a continuous green network was envisioned that provides various benefits for inhabitants (see Figure 10b). The construction of a green network starts from existing vegetated areas and is extended with new green spaces, such as parks and gardens, but also with physical connections between green spaces through improving existing ones and developing new ones. Expanding the green network also permits reducing impervious surfaces, and in such a way reducing "grey" (see Figure 10c). This conversion does not involve only public spaces: private owners should be encouraged to contribute to the green transformation as well by de-paving their properties. The contribution of impervious surfaces to UHI and heat-related risks, as well as impeding water drainage, makes it necessary to replace them with nature-based solutions. The use of nature-based solutions on buildings also needs to be encouraged. The ongoing transformation of the ZAI area provides a unique opportunity to introduce nature-based technologies for new function changes in the industrial area. In addition, these nature-based solutions and technologies for buildings and open spaces must be promoted in the residential neighbourhoods as well.
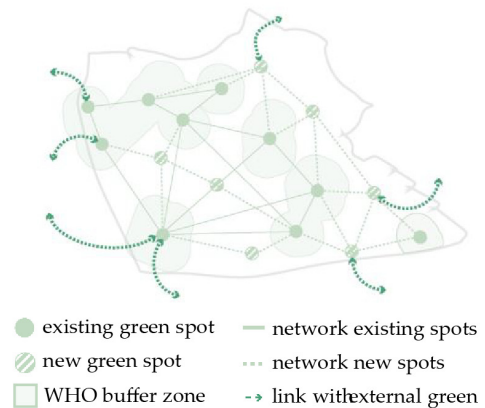
4.3.2. The New Master Plan

Through translating the spatial configurations of the guidelines into concrete nature-based solutions and other spatial measures within a time horizon of twenty years, a climate-responsive master plan was developed (Figure 11). The three main ventilation corridors connect the urban area with the main cool spots at the borders. Based on literature [44,69,70] and the current building arrangement, the western and the central corridors present a width between 60 and 100 m. This intervention does not only improve the performance of wind ventilation, but also provides the opportunity to create new public green spaces. The corridors are partly situated along the dismissed railway paths, which avoids massive urban restructuring. Moreover, the new green belt forms a buffer zone between the industrial area and the residential districts, replacing the current separation with a vegetated space of connection that is accessible and ameliorates the spaces facing the corridor. Of the former freight terminal north of the area, 50% of the available area is allocated to green public space, while the remaining surface is assigned to residential and office buildings. The underground water channels are brought back to the surface, making use of their cooling potential to improve human thermal comfort and providing ecosystem services. Thinning of the vegetation along the eastern channel should enhance the wind speed and create an attractive public space on the banks. Due to the proximity to cool spots, the width of this third corridor is limited to 50 m; in this case, the priority was given to creating a pleasant space, where the water body contributes to the amelioration of the environment.
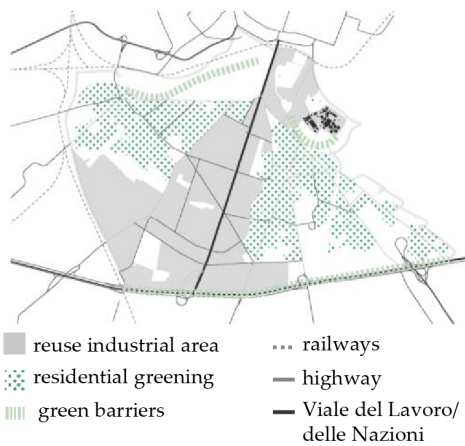
a. VENTILATION SYSTEM

— main corridor   cooling potential
··· secondary corridor   ··· cool spot

b. GREEN NETWORK

● existing green spot   — network existing spots
⊘ new green spot   ··· network new spots
□ WHO buffer zone   ·→ link with external green

c. ANTHROPIC SYSTEMS

▣ reuse industrial area   ··· railways
⊞ residential greening   — highway
║ green barriers   — Viale del Lavoro/
                        delle Nazioni

CLIMATE ADAPTATION PROGRAM

+ WIND
Creation of three ventilation corridors, linking the existing cool spots.

+ GREEN
Implementation of the existing network through new green areas and vegetated connections.

- GREY
Introduction of nature-based technologies for new projects in the industrial area and green devices within the existing buildings.

Figure 10. The climate adaptation program: +wind, +green, −grey.

Legend

▨ close public green
▢ open public green
— tree-lined avenue
▨ other green
▨ Adige river and channels
▨ buildings
▨ new development areas
···· bikepath
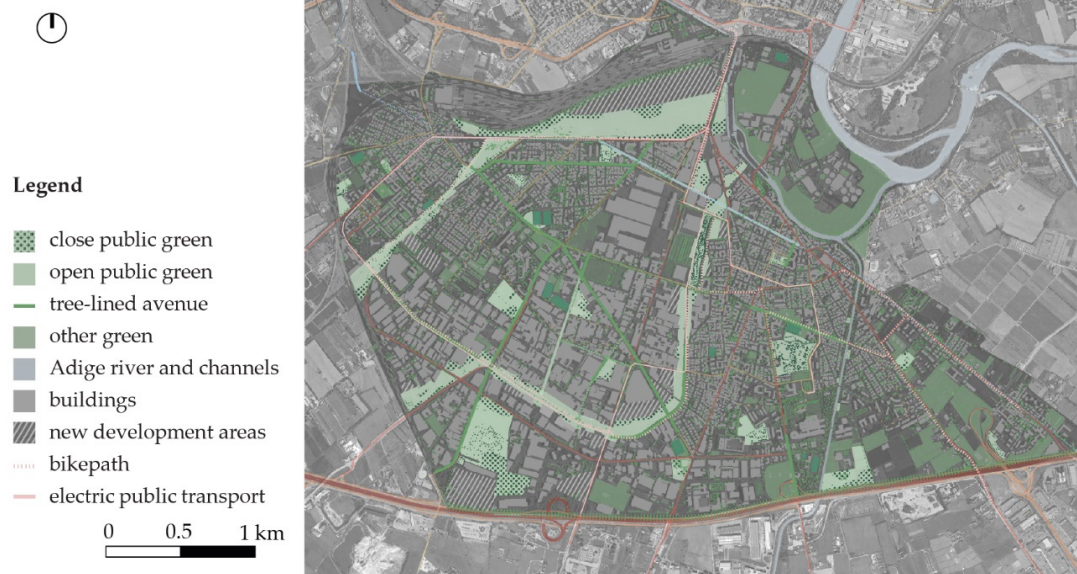— electric public transport

0   0.5   1 km

Figure 11. The climate-responsive master plan for Verona South: final scenario (2040).

The detailed design of the green spaces transcends the scope of this research, which focuses on providing indications at the mesoscale level to lead the design of local areas. For this reason, the only constraints in the new areas are dictated by microclimate-related exigencies: to enhance natural ventilation, green areas have been distinguished between "closed", where dense groups of trees can be found, and "open". Forested spaces, in fact, affect natural ventilation by creating barriers; nevertheless, they are fundamental to create a rich ecosystem and for thermal comfort. The master plan identifies which areas can host trees, mainly located on the edges of the ventilation corridors; the remaining green spaces should be kept open, with low vegetation (grass and small shrubs). The buffer zones in between are valuable. In her study, Klemm [71] reported that 20% of people preferred to stay at the edge between sunlit and shaded conditions. According to the previous consideration, no indication of the species used are provided; instead, some guidelines for the selection of typologies of vegetation are given. The use of various species is encouraged to increase the ecological richness and variety of the urban environment. The green spaces are thought to be flexible and accessible to several uses that can be identified by the administration: playgrounds, event plazas, dog areas, spaces for relaxation. The location of these collective services should be decided in collaboration with citizens to foster a participatory process. In this sense, the adaptive character of the proposal does not refer only to mitigate climate conditions but also to encourage the appropriation of the space by citizens to create collective opportunities. In addition to these spaces, some "less infrastructured" and low-maintenance spaces should be designed in which plants can grow spontaneously. Further variety would be provided by paying attention to the seasonality of the species, e.g., if a tree is deciduous or evergreen, or the blooming period of a shrub. An important aspect to encourage is the continuity of the network: along with strengthening the urban ecosystem, this enhances the accessibility and use of public spaces, providing people a more pleasant experience. New green connections between green open spaces also connect the eastern and western neighbourhoods by bridging the obstacle currently represented by the ZAI. The connections between the green open spaces are often combined with new cycle paths so that alongside the green spaces a continuous slow mobility network, safely separated from car-dominated roads, is developed. In public spaces, the cycle routes are as much as possible separated from pedestrian paths, which averts conflicts between these user groups. Based on the existing plan for the area, a new electric public transport is planned: in addition to the path currently under construction [67], another way is suggested to expand the network in the western direction. In designing the road section, particular attention was paid to avoid the so-called "tunnel effect", i.e., an excessive presence of dense tree canopies that traps air pollutants at the street level [72]; the alternation of rows of trees and lower bushes was chosen. In large parking lots, vegetating solutions (i.e., pavers that reserve room to plant grass) are encouraged to reduce the surface temperature and runoff during heavy rainfall events.

4.3.3. Simulating the Final Scenario

The resulting master plan was assessed and validated with the mesoscale meteorological model. Figure 12 shows the difference in air temperature at 2 m AGL between the simulation implementing the final proposal and the reference simulation. The contribution of the proposed interventions in reducing air temperature is clear: the maximum reduction is found in correspondence with the ex-freight terminal (0.8 °C). Moreover, results also highlight that the new green areas that permeate the city contribute to a distributed temperature reduction.
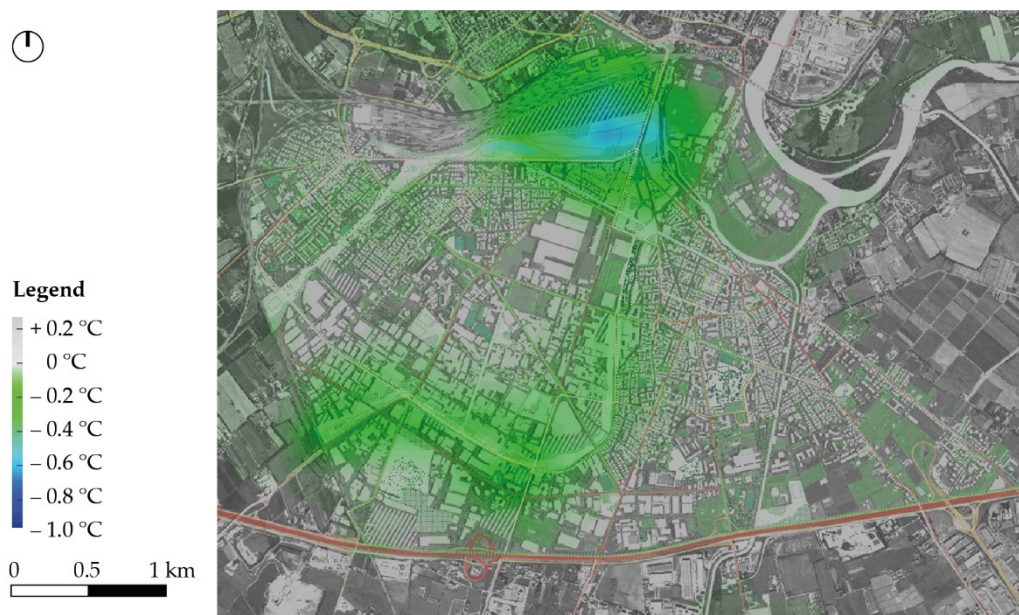
Figure 12. Difference in air temperature at 2 m AGL during nighttime between the 2040 scenario and the reference simulation.

Figure 13 shows that in the proposed master plan the increase in wind speed is also significant, demonstrating the positive effect of the ventilation corridors strategy. In particular, the large green open space on the former freight terminal improves wind ventilation and thermal comfort in the southern area of Verona as well as in the city centre.
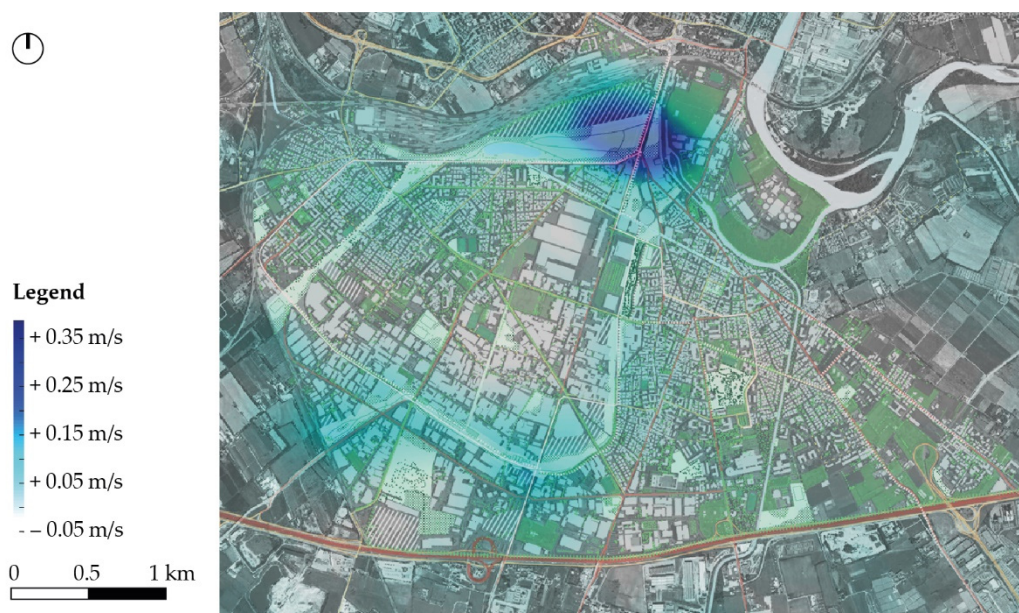

Figure 13. Average difference in wind speed at 10 m AGL between the 2040 scenario and the reference simulation.

In addition to the simulation of the final scenario, the utilization of the green roof module within the WRF model [73] also allowed for the investigation of the effects of the implementation of green roofs in the ZAI (Figure 14). This analysis aims to demonstrate not only the effect of green infrastructure but also the importance of taking this opportunity to ameliorate the urban environment. In the view of a deep conversion of the industrial area, the installation of green roofs could transform the current heat source, resulting in a positive effect also on the surroundings. In practice, the use of this nature-based technology was simulated in different scenarios, changing the covering percentage (green/total roof area).

The installation of green roofs was simulated only in the cells categorized as "LCZ 8" (large low-rise buildings), assuming an extensive green coverage, which needs little maintenance and no permanent irrigation system. This corresponds to the hypothesis of an intervention on the existing industrial buildings, with the addition of a light structural load.
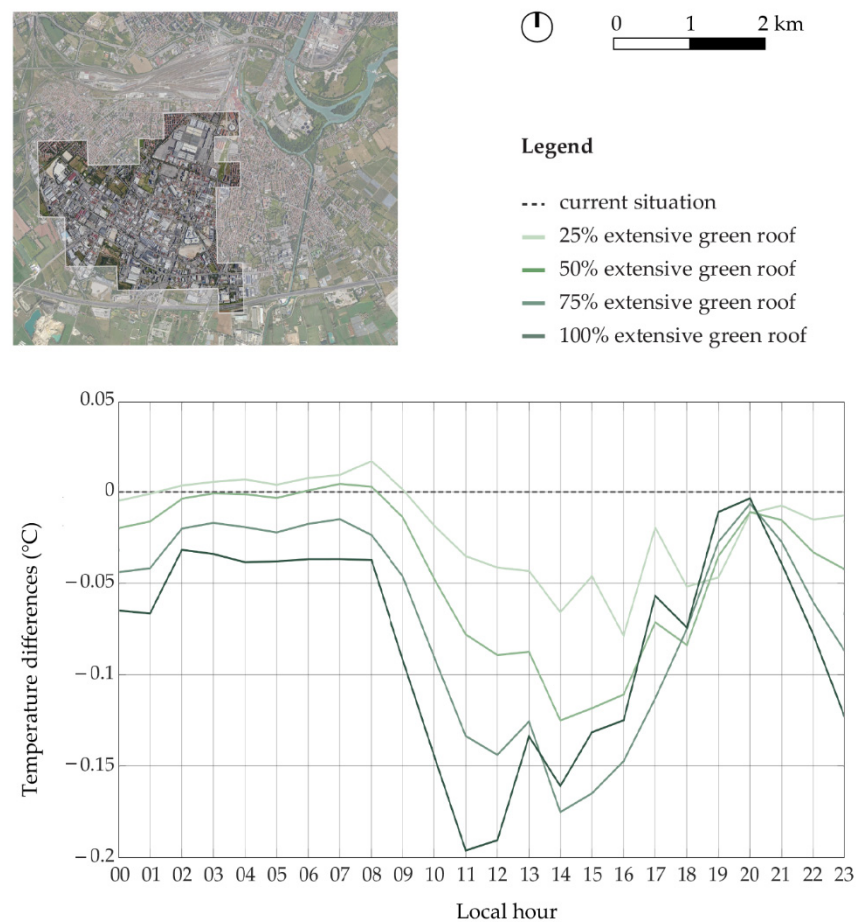

Figure 14. Identification of the analysed area (LCZ 8) and difference in air temperature at 2 m AGL for various percentages of green covers.

As expected, the results show that air temperature at 2 m AGL decreased with the increase of the green roof cover, with a peak around −0.2 °C. The cooling effect was more sensible during daytime: this is attributable to the increase of evapotranspiration and the lower temperature of green roofs compared to traditional roofs.

5. Discussion and Future Development

With the presented case study of the city of Verona, we wanted to exemplify an approach to address climatic conditions in urban and open space planning at the mesoscale. Through input from climate modelling, analysis of relevant aspects for climatic conditions, and transformation potentials, as well as from evaluation of the effectiveness of plans and scenarios, this approach supports the climate-responsive planning and design of urban environments. The simulations of the developed master plan with the meteorological model permitted evaluating the benefits of the NBS, providing a strong argument in support of the climate-responsive master plan. Within the case study, the master plan was tested only once, yet it shows the effectiveness of using meteorological modelling as a tool to optimise plans and design for urban environments with climate conditions in mind. A more iterative research-by-design process would allow testing the adaptation measures through meteorological models and adjusting them accordingly until the optimal climatic conditions would be achieved.

The applicability of the approach goes beyond master plans and open space design. The analysis at the city scale with the WUDAPT classification supports the identification of the areas most affected by the UHI effect in urban environments, and in such a way can support decision-making, determining which areas have priority for climate adaptation and allocation of funds to tackle the issues related to the UHI effect [11]. The analysis at the district scale can be applied in each city district or neighbourhood to support planners and other users to gain a better understanding of the vulnerabilities to the UHI effect/climate change [29], which is a first step to identify the potentials for climate adaptation. Climatic programs can be included into strategic plans for cities and city districts to identify which strategies need to be implemented on a larger scale to ensure adaptation to climate change. For example, to indicate which ventilation corridors need to stay or be opened or which green spaces need to be preserved due to their cooling potential. The simulation of the green roof technology in the industrial area allowed us to test the effectiveness of this light intervention to reduce the increase in air temperature caused by industrial buildings in addition to the other ecosystem services it provides. Such simulations can provide information on the effectiveness of adaptation measures in combating the UHI effect [29] and can support the establishment of regulations and incentives for green solutions.

Simulations with the WRF model make it possible to test different measures at the mesoscale [74], as demonstrated by the green roof simulations. The WRF model in particular allows for studying of the effectiveness of large-scale interventions [75] as can be experienced in urban regeneration projects, such as the large green infrastructures in the master plan. Moreover, different combinations of adaptation measures can be examined for their effectiveness. This would allow testing of alternative proposals, for instance in an urban design competition, on their climate-responsiveness and selecting the best proposal. Although the adaptation measures proposed tackle different impacts of climate change on the urban environment, the approach mainly considers adaptation in relation to the UHI effect. To address other impacts, the approach could be combined with urban flood models to assess the effectiveness of the measures on coping with floods due to extreme weather events (see for example [76]), as well as pollutant dispersion models, to evaluate the effect of the proposed solutions on air quality.

Although the approach can be divided into distinctive meteorological and planning parts, exchange between climate and planning experts is essential. Explanation of the methods from the climate experts supports the validity of the outcomes for planners, which they in turn can transfer to other involved actors. Climate experts can also help planners with interpreting the outcomes of the meteorological models, for instance on which areas to prioritise for interventions. In turn, as the comprehensive master plan provided realizable scenarios for the simulation tools, climate experts were able to move their expertise from theoretical analyses to the applicability in real-life scenarios, improving in such ways the quality of research [1]. The interdisciplinary collaboration emphasized the necessity for knowledge exchange, but also the need for comprehensible and effective communication of this knowledge as has been highlighted before by other authors (e.g., [13,23,77,78]). Coming from different disciplinary backgrounds and even different paradigms, the dialogue between climate and planning was occasionally difficult. The disparity was noticeable in terminology as well as in the familiarity with graphical representation, with planners being more used to maps but less to numbers and graphs referring to meteorological models than the climate experts.

In planning practice, implementing the SDGs requires an even more integrative approach in which different socioeconomical, environmental, and social needs and aims are balanced [1,79]. We see the climate-responsive approach as an add-on to integrative planning; as one of the many issues that needs to be balanced in relation to other issues [6]. Although the proposed approach mainly focuses on climate-responsiveness, it also addresses issues on health and well-being through the analysis of polluting points, access to green spaces, and a slow mobility network. The proposed NBS and UGI also address a range of other benefits [80,81]. The improved accessibility and availability of the green

infrastructure can ameliorate the biodiversity in urban environments [82,83], for instance the green roofs provide habitat for birds and pollinators [45]. Socioeconomic aspects have been regarded in the approach through analysis of existing plans and development opportunities. Yet, more in-depth analysis on the economic value of investments in nature-based solutions might be needed. Such analysis should include benefits that are more difficult to monetize [1], such as the reduced health risk due to a reduction of the UHI [41,84] or due to provision of recreational green spaces or safe corridors for slow mobility [42]. Moreover, trade-offs and indirect consequences need to be considered [1]. The improved accessibility to green space might raise the economic value of buildings alongside the green corridors [85], but this might in turn lead to green gentrification of the district [86].

To consider the different synergies and trade-offs between climate responsiveness and other issues, the climate-responsive approach has to be placed within an interdisciplinary setting [6,13]. Such a setting requires collaboration between climate and planning experts as well as with experts from other disciplines and with local actors, decision-makers, policy-makers, and businesses [1]. Already in the development of the climate-responsive approach, the need for collaboration became evident when different municipal departments supported the project with data input. If this approach took place in a more formal setting, cross-sectoral collaboration within municipalities or other government institutions would be essential [79]. Such additional approaches might put more strain on already complex integrative planning processes [6] and might lead to rejection of other experts. Yet, due to raised awareness and extreme weather events, climate approaches are slowly starting to be applied in urban and open space planning [6,13,87]. Implementing the proposed climate-responsive approach can still be hampered by a lack of relevant climate information but also the inability to interpret and apply this information [29]. Uittenbroek, Janssen-Jansen, and Runhaar [88] identified next to these barriers on understanding also barriers on the uptake of the climate adaptation in planning practice regarding planning and managing, such as organizational/institutional, technical, and financial barriers. Based on our experiences with the approach, we would claim that, next to improved interdisciplinary collaboration, in particular knowledge, expertise, and resources are needed to promote the uptake of the proposed climate-responsive approach.

Knowledge and expertise on climate modelling as well as on nature-based solutions supporting climate adaptation and other issues are needed to successfully execute the approach and to include it in more comprehensive plans [6]. Such processes often depend on individual persons as "agents of change". For example, the city of Milan appointed in 2018 Piero Pelizzaro "Chief Resilience Officer" in the context of the international project 100 Resilient Cities, pioneered by The Rockefeller Foundation [89]. Boundary spanners or "knowledge brokers" [1] like him can play a key role in applying climate approaches, improve communication with and knowledge transfer between external and internal actors, and institutionalization of climate adaptation within different administrative "structures and processes" [1,6], and enhance the participation of a wide array of stakeholders in identifying the city's resilience challenges, and therefore put available initiatives into action. Such people need to be trained in both planning and climate modelling. In such a way, they could use the climate modelling results as instruments to enhance understanding on climate impact within other sectors and support collaboration with other experts as well as policy- and decision-makers. To have in-house climate experts and boundary spanners might, however, not be in reach for all cities. We therefore see a role for research, government, and the private sectors to bring such experts and boundary spanners forth who can support cities applying the proposed climate-responsive approach.

To perform the approach, know-how on and access to the meteorological models and the accompanying software is required [57]. In particular, special add-ons, such as the green roof module, might prove difficult to attain [73]. This issue might hamper the upscaling of the approach to other cities. Yet, for understanding the interaction between climatic conditions and urban morphology, simplified analyses with the WUDAPT protocol can be applied [90]. Classification of the urban environment, such as with the LCZ framework, can

also be carried out by using satellite images and topographical maps, as is demonstrated in the analysis of climatopes in the urban climate atlas of Stuttgart [43] and by the student work described in [91]. Such simplified approaches, however, do not allow for testing the effectiveness of the proposed solutions. Another possible critical point in the present approach is related to the availability of meteorological data in urban areas [92]. However, the increasing diffusion of low-cost sensors with sufficient accuracy can at least partly solve this issue in the future. Moreover, the approach and its results are based on current available technologies and data. We recommend before application of the approach to review available technologies, data, and also resources and to adjust the approach accordingly. Over time, however, new technologies and new meteorological data will become available that will allow for updating the approach or specific parts of it. We propose to set the approach in an iterative process, which permits updating resulting designs and plans at regular intervals to be adjusted to changed conditions and needs. In this sense, the resulting designs and plans should not be seen as blueprints but as tools that evolve with time, adapting to the actual conditions.

With this climate-responsive approach, we aimed to offer different professionals a structured way to bring climate modelling into the planning of urban environments and to transfer the approach to other case studies. We demonstrated that what may be considered as a limit for the liveability of the area can represent a unique opportunity to enhance climate adaptation and improve living conditions. This proposed climate-responsive approach shows the possibilities for climate modelling for open space planning on a mesoscale. Moreover, it shows how climate modelling can be integrated and even enhance the planning of urban environments by supporting planning decisions on green and blue solutions. To use the full potential of the approach, we do stress that operational difficulties need to be overcome, which requires further collaboration and crossover between urban climatology, landscape planning, and governance.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.
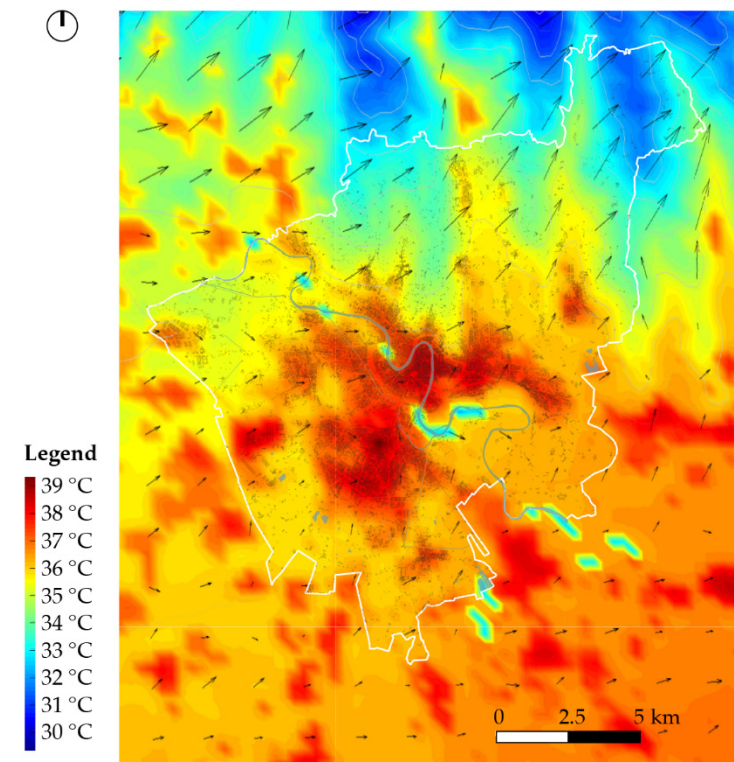
Appendix A

Figure A1. Air temperature at 2 m AGL and wind at 10 m AGL averaged over the 5 days simulated for the daytime hours (0900–1500 LST).

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