Applied Informatics in Urban Climate Assessment Methods – Status Quo, Challenges, Potentials

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2025 IEEE 19th International Symposium on Applied Computational Intelligence and Informatics (SACI) | 979-8-3315-1547-8/25/$31.00 ©2025 IEEE | DOI: 10.1109/SACI66288.2025.11030128

Abstract—**This paper explores various methods for assessing and mitigating urban heat islands (UHI), including observational techniques, numerical modeling, and satellite-based measurements. IDA ICE simulations provide insights into building-scale thermal behaviors, while mesoscale and microscale models facilitate detailed analyses of urban thermal dynamics. Satellite observations, particularly MODIS and Landsat, offer large-scale data but are affected by cloud cover and seasonal variations. Direct measurement methods, such as meteorological stations and mobile sensing, complement these modeling techniques by validating results. Integrating these varied methodologies allows for a comprehensive understanding of UHI phenomena. This study underscores the significance of interdisciplinary approaches and technological advancements in addressing UHI and promoting sustainable urban development.**

Keywords—urban heat island, simulation-driven design, built environment, decision support

I. Introduction

Urban Heat Island (UHI) is an increasing concern as urbanization accelerates worldwide, resulting in higher temperatures in cities compared to rural areas. Currently, over 50% of the global population lives in urban environments, and studies indicate that this number will rise to 6.4 billion by 2050 [1]. As the proportion of urbanized areas continues to rise, the severity of the Urban Heat Island (UHI) effect strengthens [2]. This phenomenon occurs when urban areas experience warmer temperatures compared to surrounding rural regions [3]. It is caused by the heat-absorbing properties of urban structures, which delay nighttime cooling in cities and are further intensified by human activities [4, 5, 6]. The negative effects of UHIs will worsen due to climate change [7, 8]. Consequently, UHI mitigation is a significant concern in urban and climate studies [9, 10], and one of humanity's greatest challenges of the 21st century [11]. In the search for solutions to UHI, researchers adopt complex numerical and simulation methodologies, along with various types of measurements, to assess, simulate, and validate urban thermal environments. These methods rely on different software (for example: ENVI-MET, ANSYS, IDA ICE, etc.), data, technology, and simulations to study UHI processes on a range of scales. This paper provides an overview of the available investigation technologies by analyzing the related potentials, limitations and possible improvement directions.

There are three primary approaches to studying UHIs: observational methods, remote sensing techniques, and numerical modeling. Numerical modeling is especially effective for simulating UHI dynamics in various urban contexts.

II. Building Scale Indoor Simulations

For the smallest-scale climate simulations, a commonly used program is IDA ICE (IDA Indoor Climate and Energy). This program studies the dynamic (time-dependent) indoor climate and energy behavior of individual zones, as well as the energy consumption for the entire building and its services systems.

The system to be simulated typically comprises a building with one or more thermal zones (multi-climate zone model with structures), including heat transfer units and artificial lighting, a primary system (plant), and one or more air handling systems. The building may be shaded by surrounding structures. Weather data is sourced from climate data files obtained from various meteorological databases. Pre-defined building components and other parameter objects can be retrieved from a database

The simulation model is not only defined in physical terms, but also in terms of coupled component models defined by equations (advanced level). At this level, the individual time evolution of variables can be studied, all equations, parameters and variables can be investigated.

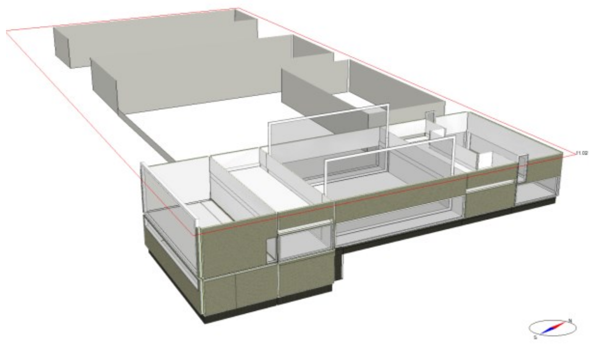

Fig. 1. 3D energy and climate model of a multi-zone building, IDA ICE

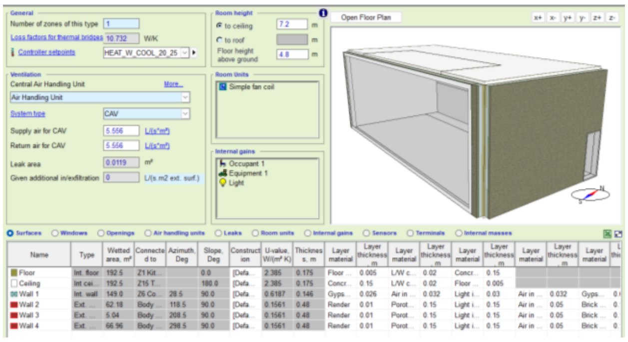

Fig.2. The model of the zone, IDA ICE

IDA ICE presents three distinct zone models. Two of these are the ‘Climate’ and ‘Climate with stratification’ models, which are quite detailed, while the Energy model is more conservatively accurate and is based on an average radiative temperature.

The zone models consist of various groups of components: supply and exhaust air terminals; ceiling and floor elements; air leakage to the environment; solar irradiation and external layer coefficients; one exterior wall and three interior walls; components for window and shading calculations; a proportional controller for automatic clothing adjustment for occupants; a PI controller for the ideal heating system; a cooling panel with its controller and the ceiling section behind it; the actual zone model incorporating radiation, convection, and loads; and post-processing components to record the results.

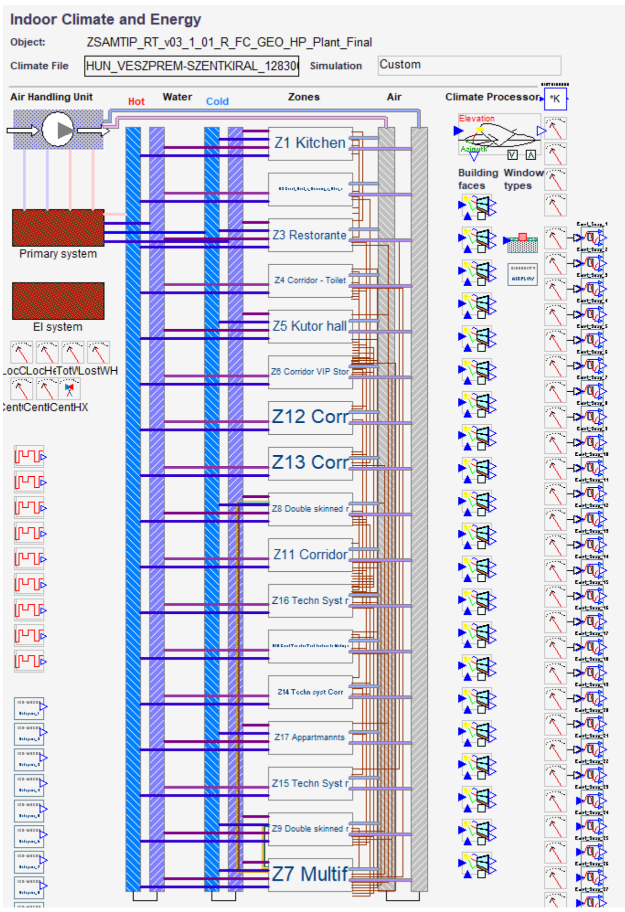

Fig.3. Complex scheme of a multi-zone building model (advanced level), IDA ICE

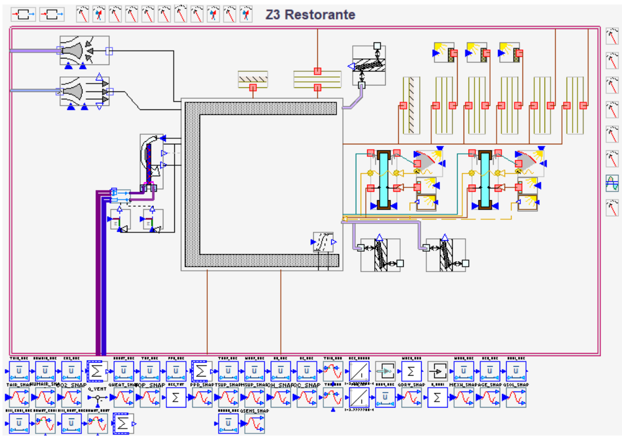

Fig. 4. The schema of the zone model (advanced level, IDA ICE)

There are several types of wall models for modeling opaque envelope structures (finite difference models, thermal RC networks, etc.) aimed at simulating the temperature distribution (temperature profiles) within a multi-layer component over time and assessing heat fluxes at its boundaries while considering the heat conduction and heat capacities of each layer. However, the limitation of this simulation modeling method is the poor capacity for airflow calculations (CFD is not included), as well as the lack of exterior environment calculation (weather profiles are calculated only as input data).

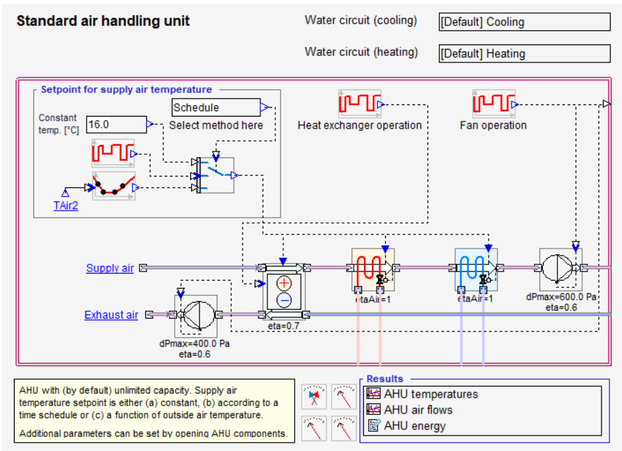

Fig. 5. The schema of the AHU model (advanced level), IDA ICE

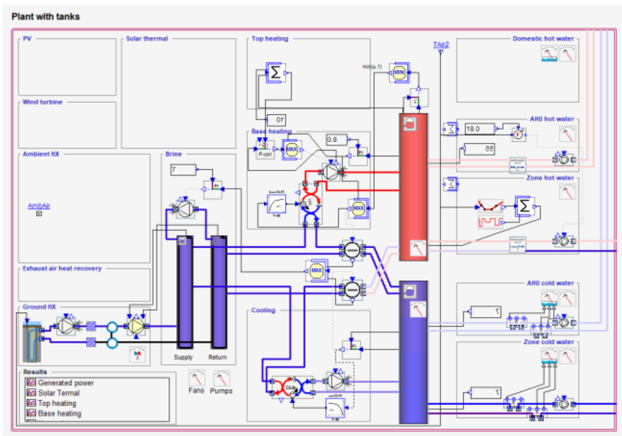

Fig. 6. The schema of the Plant model (advanced level), IDA ICE

III. Urban External Space Simulations – WRF-CFD

The two most commonly used types of numerical models are mesoscale and microscale meteorological models. The best-known mesoscale model is the Weather Research and Forecasting (WRF) model, which is designed for regional-scale weather forecasting and urban morphological scenario experiments. It is commonly used for global climate models (GCMs) to study the future evolution of UHI under different emission pathways. It includes physical parameterization schemes that simulate various urban and atmospheric processes [12, 13]. However, the limited horizontal resolution of the WRF (typically within a few kilometers) makes it less suitable for detailed urban simulations. It requires parametrization of urban effects: built urban schemes, urban heat fluxes, which reduces realism. [2, 14, 15]. These challenges can be addressed by coupling the local climate zone (LCZ) classification scheme with the WRF-UCM model, as shown in studies utilizing high-precision LCZ datasets for cities such as Wuhan [12] [13].

Microscale models are best suited for detailed small-scale urban simulations. CFD simulations, including ANSYS FLUENT, OpenFOAM, and ENVI-met, are particularly appropriate for this purpose, and their applications can effectively study urban UHI phenomena, ventilation corridors, pollutant dispersion, and thermal behavior [16]. Modeling an urban environment is a crucial first step in CFD simulations. This process involves integrating land features and objects, modeling the settlement domain in a 3D modeling program such as AutoCAD. The microscale 3D geometries are then converted into digital blocks with parameters and values understandable by CFD software [17]. For studies involving urban vegetation, trees can be depicted in simplified models using shapes like cylinders for trunks and cuboids for canopies. Additionally, types of vegetation and green land, such as punctate, banding, radial, and wedge, are often modeled within defined urban areas to assess their thermal effects [17]. Wind tunnel experiments and morphological analysis through GIS and least-cost path (LCP) modeling enhance these tools and are particularly effective for developing ventilation corridors [2] [18].

Despite their reliability, CFD simulations demand significant computational resources and are sometimes constrained by information requirements. For instance, ENVI-met struggles to account for anthropogenic thermal and solar variability [19, 20]. Likewise, traditional CFD models necessitate extensive modeling and computational resources, which can lead to challenges in urban-scale simulations due to limitations in scalability and available time. Some research proposes solutions to these challenges by suggesting new approaches such as Porous Medium Model (PMM) and Fast Fluid Dynamics (FFD) techniques. These methods offer greater computational efficiency, as simulations using FFD require 60 times less computational effort compared to conventional CFD models [21].

Recent developments have facilitated the integration of meso and microscale modeling techniques. Models that merge mesoscale atmospheric phenomena with finely structured microscale flow simulations utilize unstructured grids to simulate UHI circulation and flow around buildings, as well as pollutant dispersion. These models accurately forecast the impact of sensible heat flux on UHI strength and mixing height, providing comprehensive insights into urban thermal dynamics [22, 23].

With all this in mind, ENVI-met is one of the most common the appropriate software is applied to model the urban-scale environment and calculate data regarding climate conditions and human thermal comfort in external urban public spaces or rural areas. After collecting geometrical data, material properties, and vegetation data of the area, a simulation model of the examined area can be created that behaves similarly to reality.

The meteorological data needed for the simulation are available from meteorological databases, allowing ENVI-met to simulate heat, wind, precipitation, and humidity from a reliable source. Using this simulation data, the level of human thermal comfort in the investigated area can be determined. The program divides the model area and its elements into grids, and it's important to determine the size of these model grids for the respective research purposes.

The vertical grid size can be increased by a certain percentage above a specified height to reduce calculation time during the simulation. In the following example (Table I), the smallest grid size is set at 2.0 m, as a size smaller than this may cause the model to become unstable during the simulation. ENVI-met provides its own material database but also allows for the definition of customized materials, layers, as well as plants and traffic profiles, with the latter used to simulate emissions impacting the investigated domain.

Two types of simulation procedures are available: full forcing (based on meteorological databases) and the simple forcing method (looped 24-hour data). The smallest time unit that can be simulated is one hour. The resulting simulation outcomes can be visualized in various forms, thus facilitating the interpretation and comparability of the results.

TABLE I. Example for Simulation Parametres in ENVI-met

Settings of the simulation	***Input parameter***
Simulated area	part of Budapest VII. district
Simulated urban situation	narrow street with a park
Simulation method	full forcing
Meteorological database	Budapest.Met.Center.128400
Starting date	01.07.2025.
Starting time	07:00
Simulation time	11 hours
Grid size properties	2,0 × 2,0 × 2,0 m
Telescoping	above 20 m; 20 %
Persons (thermal comfort)	Default Male, average clothing (35 y, 0.90 clo; speed: 1,34 m/s)

The examples below (Fig. 7-10.) demonstrates the air temperatures, PMV, as well as the wind conditions evolving in a typical hot summer afternoon in a characteristic narrow downtown street in Budapest, Hungary.

IV. Measurements

In urban climate studies, the main metric is UHI, whereby finding the best option to measure this phenomenon recommends a deeper understanding of which properties and with which methods should be measured. Former studies highlighted only few methods [1] for instance in situ air temperature measurements [2], [3], [4], [5] and satellite surface temperature data assessment [2], [3], [4], [6]. These investigations provided an appropriate foundation to make improvements in the current studies, specifically in the field of satellite data technology [7].

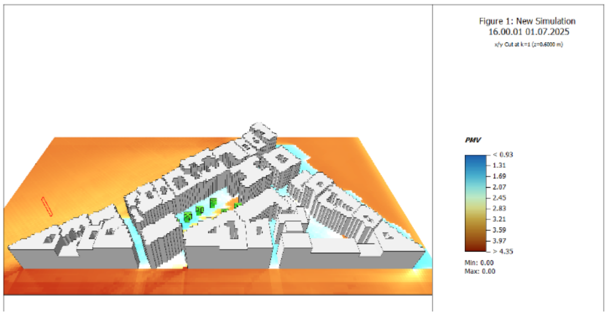

Fig. 7. PMV values in the modeled domain, ENVI-met

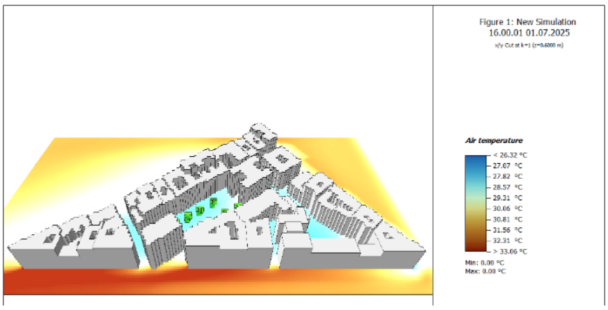

Fig. 8. Air temperature values in the modeled domain, ENVI-met

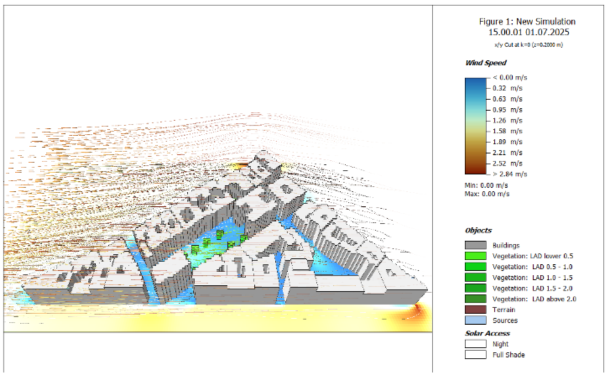

Fig. 9. Wind conditions (velocity and streamlines) in the modeled domain, ENVI-met

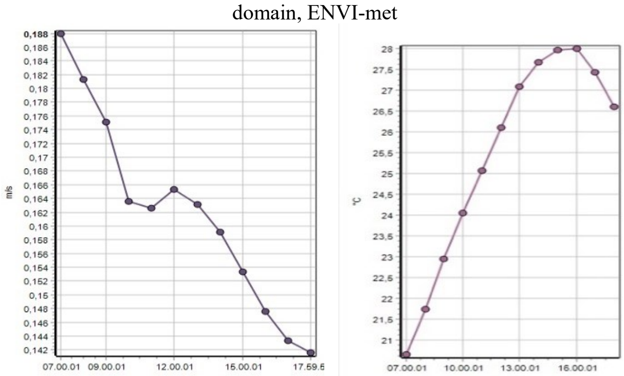

Fig. 10. Wind velocity (left); air temperature (right) in the modeled domain, ENVI-met

The latest studies apply further measurement techniques and their combinations as well. The meteorological stations and special urban metering networks [1], [2], as well as moving vehicles, mostly use data from temperature measuring devices mounted on cars [8]. Local surface temperature data set can be recorded with infrared thermometers [9], [10] based on remote sensing from aircraft [11] and satellite radiation measurements [7], [12].

Other factors, such as air pollution coming from traffic, can be considered when modeling UHI [26, 37].

Regarding the results obtained, it is important to consider which measuring methods are used. The UHI maximum intensity is based on air temperature occurs at night [38], while UHI based on surface temperature peaks during the day, when solar radiation is the strongest [39].

As the graph below shows, most of the reviewed studies used Modis and Landsat satellite measurements.

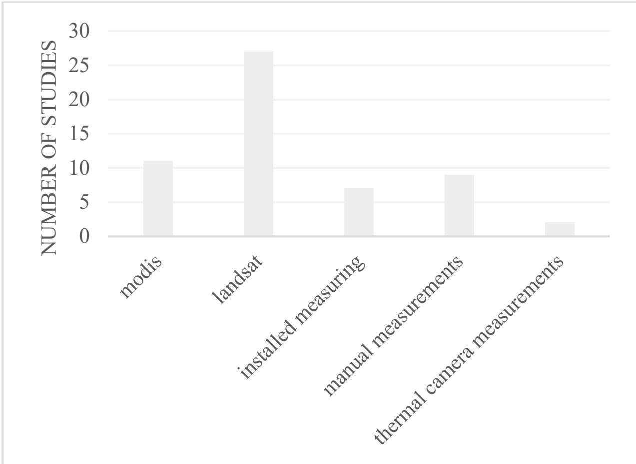

Fig. 11. Measurement exercises

It is important to emphasize that there are several generations of Landsat satellites; however, none of the research projects have utilized values from Landsat 7 or 9. The reason for this is that the images from the Landsat 7 satellite have been faulty since May 2003. Meanwhile, Landsat 9 has taken over the orbit of Landsat 7 and has similar sensors to Landsat 8. These two satellites have great potential when used in combination as a complementary pair; therefore, if one of them produces a cloudy image, the other can provide a clear one. With this combination, the results can be expected to be more effective accurate.

Research analyzing satellite data offers many benefits, particularly when it complements or replaces physical measurements of temperature or humidity relevant to the topic. These observations ensure extensive geographic coverage, yielding near-reliable data for areas that are geographically or politically challenging to access. Additionally, regular and frequent observations allow us to monitor changes over time. Cost-effectiveness, especially in large areas or difficult terrain, is also enhanced, as the necessity for costly and time-consuming on-site measurements is reduced. Moreover, satellite observations are independent of local infrastructure and can be utilized in resource-limited regions. Satellite data is often available for several decades, facilitating the analysis of long-term trends and changes, such as climate change or urbanization.

Besides temperature, many other parameters can be measured as well, such as soil moisture or vegetation indices, and in this way com-plex analyses can be made by combining different data. These data can be integrated and combined with other types of data, such as demographic or modeled data, enabling even richer analyses. Since these data are globally uniform, they provide an opportunity to objectively compare different regions. Overall, satellite observations are an efficient, reliable and versatile tool for various scientific research.

In contrast, satellite assessments possess some limitations as well. In general, the analysis of satellite data is only effective when the sky is clear of clouds, as clouds can obscure the earth's surface and, as a result, adequate data are not available in these timepoints and areas. For instance, due to Hungary's climatic conditions, the values measured by satellites are often not applicable, especially in the winter period due to significant cloud cover. At the same time, during the summer period – which is the focus of most studies – 20–25 days of usable measurements are available per month. During the analysis, the summer UHI (SUHI - Surface Urban Heat Island) intensity is calculated exclusively on days when at least 50% of the urban pixel units in the MODIS images are cloud-free [13], [14] already defined threshold, and in a subsequent study,[7] analyzed the significance of the threshold value selection. They concluded that the main difference still lies in the amount of satellite images used for the calculations. Lower thresholds reduce the number of satellite images, thereby increasing the relative weight of each image while placing less emphasis on individual pixels within the images. In contrast, higher thresholds would result in more satellite images, providing more robust temporal coverage, while placing more weight on cloud-free pixels within each image. All in all, the 50% threshold was considered an appropriate compromise [13]. Chen's 2024 research used a high-density street temperature analyzing network (HiSAN). One hundred measuring points were previously installed for similar research, which examined the heat and wind conditions in the city of Tainan. The Ta measuring device used at the measuring points is the Logpro SD-185 temperature and humidity recorder, which operates with a measurement interval of 100 seconds and an accuracy of ±0.5 °C. For their protection, they are equipped with shields that protect them from sunlight and water.

V. Conclusions

Urban Heat Island (UHI) remains a significant challenge in urban climate studies, especially as urbanization continues to expand globally. The rising temperatures in urban areas, driven by human activities and the heat-retaining properties of built environments, demand effective mitigation and assessment strategies. This paper examines various methodologies for studying and modeling UHI, highlighting observational techniques, numerical modeling, and satellite measurements as essential approaches to understanding urban thermal environments.

At the building scale, IDA ICE simulations provide valuable insights into energy consumption and indoor climate conditions but are restricted in airflow and external environment calculations. For urban external spaces, mesoscale and microscale simulations using WRF and CFD techniques offer detailed analyses of airflow, temperature distributions, and pollutant dispersion. However, these methods require substantial computational resources, leading to the development of alternative approaches like PMM and FFD to enhance efficiency.

In addition to modeling, direct measurements using meteorological stations, mobile sensing, and infrared thermometers play a vital role in validating simulation data. Satellite assessments, particularly using MODIS and Landsat imagery, have proven beneficial for large-scale UHI analysis due to their extensive coverage and historical data availability. Nevertheless, challenges such as cloud interference and seasonal variations can impact data accuracy, necessitating careful threshold selection and complementary ground-based measurements.

Overall, integrating different methodologies—numerical modeling, remote sensing, and direct measurements—provides a comprehensive approach to studying UHI. Future research should concentrate on boosting computational efficiency, improving data integration techniques, and exploring new mitigation strategies to address the increasing impact of UHI. By leveraging technological advancements and interdisciplinary collaboration, urban planners and researchers can create effective policies to mitigate UHI effects and cultivate more sustainable urban environments.

Future research should focus on enhancing computational efficiency, improving data integration, and developing effective mitigation strategies. In addition to that studies should explore interactions with other fields, such as economics or public health, to broaden the impact of the findings.

VI. Acknowledgments

Supported by the 2024-2.1.1 University Research Scholarship Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund.

GreenQual: Investigating the Role of Greenery to Improve Climate Resilience, Water, Soil and Air quality in Dense Urban Fabric project is co-funded by the European Interest Group (EIG) Concert-Japan and the Hungarian NRDI program under the Nr. 2024-1.2.2-ERA_NET-2024-00006.

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