Aarrevaara, E. & Maksheeva, A. (eds.)

# MUrCS Proceedings 2023

LAB University of Applied Sciences

Layout: Oona Rouhiainen

ISBN 978-951-827-475-2 (PDF)
ISBN 978-951-827-476-9 (painettu)

Lahti, 2024

Co-funded by the
Erasmus+ Programme
of the European Union

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# MUrCS

# Proceedings
# 2023

Glasgow Caledonian University

LAB University of Applied Sciences

uhu.es Universidad de Huelva

# Contents

## Sustainable mobility – air quality and active travel perspectives

# Authors

## Muhammad Abdullah

Environmental Engineer PhD Student,
School of Sustainability, Arizona State University

Muhammad Abdullah, an esteemed environmental engineer hailing from the picturesque city of Lahore, Pakistan. Having acquired his foundational education in engineering from a reputable institution in Pakistan, Muhammad's thirst for knowledge led him to pursue a Master's degree in Urban Climate and Sustainability, a program with a distinctly global perspective. This academic endeavor took him across international borders, immersing him in diverse educational environments in the United Kingdom, Finland, Spain, and Germany.

Muhammad's passion for investigating the intricate dynamics between urban development, climate, and human well-being culminated in his decision to further his studies. Thus, he embarked on a Ph.D. journey in Sustainability at the prestigious Arizona State University. With a resolute focus on advancing the field, Muhammad's doctoral research centers on the critical intersection of heat and human health.

## Elisa Bernal-Reino

Urban Mobility Specialist & Urban Planner

Architect and urban planner with experience in sustainable mobility. Worked as mobility officer at Municipality of Cuenca (Ecuador) engaging in several projects such as: sustainable mobility plan, complete streets, superblocks, electromobility and low emission zones. She has also worked as a university researcher covering topics of sustainable mobility and the effects of touristification in cities.

Driven by the need for safer streets and the urgency of reducing transport-related emissions. She has consolidated her expertise around climate sensitive design, air pollution assessment, and active transport planning. Interested in nature-based solutions, public policymaking and empowering women!

## Natasha Picone
Urban Climate Researcher

Argentinean Geographer with a Ph.D. in urban climate of intermediate cities. She is an Assistant Researcher at CONICET (National Council Research on Technology and Science) in Argentina. Her teaching centers on GIS, Climatology, and Physics Geography at UNCPBA (Buenos Aires Center Province National University) and UNS (South National University). Her research has focused on the application of urban climatology and geographical information technology to develop sustainable communities. Currently, her aim is to enhance the application of NBS to mitigate the effect of climate change and adapt to the new context in Argentinean cities.

## Apenuwa, Oluwaseun Samuel
Urban and regional planner

I was born and raised in the Southwestern part of Nigeria. My first and second degree was awarded by the Federal University of Technology, Akure in Urban and Regional Planning. I started my career as an urban planner where I was engaged in urban planning projects such as urban renewal, master plan design, and environmental impact assessment for several developmental projects in one of the leading consulting firms in Nigeria. This exposed me to about five years of planning experience. Academically, I delved into areas of resilient housing provision, GIS and urban planning, climate change and African cities, access to social amenities during covid-19, and infrastructure planning. I have also carried out studies on planning for sustainable communities within and outside Nigeria. The concern about the complexity of the threat posed by climate change in the face of unprecedented urban growth motivated my application for the MUrCS programme, which understudies climate change and sustainability in urban space from a multidisciplinary perspective. At the end of this programme, I hope to join other professionals in the built environment across the globe in building a sustainable urban environment for the future.

## Dechen Pema Yangki

Executive Engineer / Civil Servant

Dechen Pema has bachelor's degree in electrical engineering, and she has been working with the Department of Energy (erstwhile Department of Renewable Energy), Ministry of Energy and Natural Resources, Royal Government of Bhutan since January 2012. With her work focused on Energy Efficiency (EE) she was part of project conceptualisation, management and implementation of EE project and was also part of the team to develop the country's National Energy Efficiency Policy 2019. She was the member representing Energy sector in the country's GHG thematic working group and intends to pursue her interest in the field of Carbon Management. MUrCS has been a refreshing break from her work area and has given her the opportunity to explore more practical urban issues/challenges. Her thesis on outdoor thermal comfort in Thimphu city is a pioneer study which she hopes to be enhanced further by more robust and qualitative studies. Dechen has joined back the same department and hopes to enhance the focus of urban climate in the work mandates of the department.

## Ekundayo Olutayo

B. Tech, M.Sc. Urban Planning

Ekundayo Olutayo holds a B. Tech and M.Sc. in Urban Planning from the Federal University of Technology, Akure, and the University of Ibadan, Nigeria, respectively. With over five years of experience as an urban planner since 2015, he brought valuable expertise to the MUrCS program. During his time in the MUrCS program, he collaborated with Ramboll on climate impact assessment and ecosystem quantification. Additionally, he has earned certifications from prestigious institutions such as OpenLCA, Schneider Electric, the University of Illinois, Urbana-Champaign, USA, and the University of Oxford, UK. His thesis focused on optimizing bike-sharing in Glasgow using a multi-criteria Analysis approach. Olutayo's research interests encompass transportation and environmental planning, climate change adaptation, and the application of GIS and remote sensing for sustainable

## Bianca Borelli da Silva

Architect and Urban Planner, Sustainable Architecture and BIM Specialist.

Bianca has a bachelor's degree in Architecture and Urban Planning, and has been working in the design, planning, and management of projects from medium to large scale, such as neighborhoods, buildings, masterplans, and urban parks. Pursuing the implementation of sustainable approaches in the development of projects, she became a specialist in Sustainable Architecture and in Building Information Modeling, where she studied how sustainable architecture influences cities and how BIM softwares can be integrated into sustainability. Complementing this expertise with a master's in Urban Climate and Sustainability, where climate sensitive design and nature-based solutions were explored from a planning perspective, she aims to engage in developing sustainable urban environments, and to contribute in creating more inclusive and greener cities in Brazil.

## Mst Mahbuba Shabnam

Environmental Scientist

Earning both a Bachelor's and Master's degree in environmental science from renowned institutions in Bangladesh, Mst Mahbuba Shabnam laid a solid foundation for a career as an environmental scientist. Early in her career, she served as an Environmental Consultant in Bangladesh, where she played a pivotal role in developing sustainable solutions, conducting environmental assessments, and offering expert guidance. Seeking further specialization and international exposure, she came to pursue this Master's in Urban Climate and Sustainability, where this experience not only broadened her academic horizons but also introduced her to a myriad of global environmental perspectives and practices. Recently, Mahbuba worked on identifying suitable sites for nature-based solutions geared toward sustainable flood mitigation using AHP and GIS tools for her thesis. With a blend of local wisdom and global perspectives, her passion is now driven by the hope of safeguarding communities and nurturing a harmonious relationship between humanity and the environment.

## Joseph Anderson
Environmental Scientist

Joseph Anderson is an environmental scientist from the United States. He has a multidisciplinary background in sustainability, including sustainable agriculture, green stormwater management, passive building design, and climate mitigation science. His professional background includes climate adaptation biotechnology, green infrastructure planning, and sustainable community development.

Joseph currently works as a sustainability consultant for an architecture firm, and wants to use his experience in MUrCS to help integrate the built environment with natural systems. By bridging urban planning, climate science, and sustainable development, he hopes to develop innovative and regenerative solutions that support the wellbeing of people and the planet.

## Diana Reyes
Architect

Diana Reyes is an architect passionate about sustainable urban development. With experience across Asia and the Middle East, she pursues design excellence through a systems lens. Her background encompasses architectural design, public realm planning, research, and project management. She believes well-designed environments enhance quality of life by activating social nodes, benefiting diverse stakeholders. By undertaking the MUrCS program and an internship in Lahti, she has gained expertise in life cycle approaches, nature-based solutions, and policies enabling the transition to a circular economy. Her thesis explores planning frameworks to scale sustainable development in Lahti. She believes circular thinking, from design to end-of-life, is key to shaping resilient cities. Through research and practice, Diana aims to embed circularity in vibrant urban places, furthering environmental, social, and economic sustainability.

## Lorena Gebran
Landscape Architect

Lorena is a landscape architect and researcher from Lebanon. She is dedicated to mitigating climate change and promoting social equity by developing sustainable, innovative, and resilient solutions.

Through her professional experience, she has worked on international landscape architecture projects, and has conducted research on participatory landscape approaches, informing inclusive sustainable solutions, as well as advancements in inclusive urban planning and design for aging populations. Looking ahead, she aspires to take a leading role in pioneering sustainable design practices and contributing to global efforts in creating more environmentally conscious urban environments. She aims to continue pushing the boundaries of knowledge and actively seeks opportunities to collaborate on projects that drive meaningful impact in addressing complex challenges related to climate change and social equity.

## Maiha Hameed
B.Sc. Biotechnology

Maiha has a background in the biological sciences and holds a BSc (Hons) in Biotechnology. She is currently employed at the Ministry of Environment, Climate Change and Technology in the Maldives and recognises the need to formulate sustainable, science-based national policies. At the Ministry she explores the linkages of pollution and climate change to human health and led the development of the first Maldives National Chemical Profile in 2015, followed by the first National Action Plan to Reduce Air Pollutants in 2019.

She appreciates how MUrCS provides a specialized insight into the intersections of development and climate change, and its implications for Small Island States. This understanding plays a crucial role in her research on climate-conscious urban development in greater Male', Maldives. Her work involves characterizing the local microclimate, with the goal of understanding the complex relationship between urbanization, climate and heat stress in this rapidly growing urban area.

## Mayuresh Bhadsavle
Urban Development Practioner

Mayuresh is a dynamic and experienced Urban Development Practitioner from Mumbai, India. An alumnus of the Tata Institute of Social Sciences (TISS Mumbai)- the premier social sciences institute of India- Mayuresh has worked with reputable Non-profit organizations, Think Tanks and Academic Institutions in India in the domain of Urban Governance, Participatory Urban Planning and Public Engagement.

Mayuresh is a passionate documentary-photographer and a prolific columnist who believes in seeking meaningful community participation for creating inclusive, sustainable and climate resilient cities. The global perspective awarded by the MUrCS 1.5 programme and a unique opportunity therein to conduct innovative visual ethnographic research in Germany has helped him develop a nuanced understanding of urban sustainability communication as well as solution-oriented climate communication. Mayuresh is committed to take forward these crucial insights and technical prowess for furthering the participatory local climate action across different urban geographies.

## Mohammad Eshaq Khodayar
Urban planning

Mohammad Eshaq, an Urban Planning professional with a passion for climate action. With a strong academic background and experiences in planning, he believes in thinking globally and acting locally to combat climate change. Mohammad Eshaq actively engages in global climate diplomacy while focusing on practical solutions for local sustainability. His mission: to think globally, strategize, and initiate impactful solutions locally.

## Muhammad Tariq
Architect

Muhammad Tariq earned his architecture degree in 2014 from a renowned Pakistani university. Following his involvement in various architectural projects across Pakistan, he took on a role as a lecturer at CECOS University Peshawar in 2017. In addition to his academic endeavors, he founded a startup called 'ecokoor' that focuses on the built environment. Tariq is deeply passionate about urban green infrastructure, ecologically sustainable buildings and cities, nature-based solutions, and urban biodiversity.

## Najma Yusuf Lelei
Urban Planner

Najma has a bachelor's degree in urban and regional planning. She has worked as an Urban Planner in the local government of Mombasa before pursuing her master's degree in Urban Climate and Sustainability (MUrCS). She engaged in the physical, social and economic development of Mombasa County. With her focus on physical planning, she worked to ensure that urban areas are developed and managed in a sustainable and efficient manner to improve the quality of life for residents.

During her masters, she interned as a researcher in the Operandum UK project in Catterline Bay, Aberdeenshire where she engaged in data collection, monitoring, and management of hydrological performance of Nature-Based Solutions (NBS) for slope protection. Her thesis focused on assessing the influence of urban form on the cooling impacts of urban parks in mitigating UHI effects in urban areas. She is currently interested in the sustainability and climate change field and hoping to continue making a positive impact to the world.

## Navoda Rathnayake
Architect

Navoda is a graduate with a bachelor's degree in architecture from the University of Moratuwa, Sri Lanka. Her experience as a chartered architect in the private sector consultancy is ranging from design to construction completion of residential, commercial, hospitality and institutional developments projects. She joined MUrCS to enhance her academic and professional interests towards sustainable developments with a focus on issues related to climate change. During her undergraduate research work she extensively explored the correlation between urbanization and urban heat island effect. Considering a planning-based approach for her master's thesis, she evaluated the potential of implementing nature-based solutions for heat and flood hazard mitigation in Lahti, Finland. Her professional goals are to pursue sustainability consultancy in planning, policy and construction sectors while conducting further research on improving the built environment for climate change adaptation.

## Pragya Raut
Architect

Pragya Raut is a passionate architect from Nepal interested in socially responsible and environmentally friendly design. She practiced as a regular architect in private consultancies immediately after her graduation. A trained social entrepreneur, she runs a social initiative called 'Aankura' that promotes traditional and vernacular architecture as well as sustainable practice/systems in Nepal. She is an occasional author for the column 'sustainable housing/urban planning' for the e-magazine 'theecopreneur. in' where she features eco-friendly projects/practices from around the world. She believes MUrCs was a superb opportunity for her to reflect her earlier experiences of working in urban & rural communities of Nepal while exploring further avenues & international connections to collaborate in future. During MUrCS, Pragya had the opportunity to contribute to the Operandum project as an intern which gave her chance to explore and practically understand nature-based solutions in Caterline Bay. Pragya graduated with a Bachelor of architecture from Purbanchal University in 2017. Anything close to nature, life & philosophy attracts her.

## Shoaib Amin
Environmental Engineer

Shoaib enrolled in the MUrCS program, bringing his expertise in environmental engineering and management from the oil and gas construction industry in the Kingdom of Saudi Arabia. Engaging with the comprehensive MUrCS curriculum, participating in case studies across various European cities, and collaborating within the MUrCS community, Shoaib has grown into a more resilient and versatile sustainability professional. During the two-year MUrCS programme, Shoaib completed two internships. In the summer of 2022, he worked with Ramboll Oy Finland on two ongoing projects related to the quantification of Urban ecosystem services for Kuopio City and assessing the climate change impact of wind farm projects. Secondly, as a scientific intern at the Center of Energy, Environmental and Technological Research (CIEMAT) institute, his master's thesis work on the urban microclimate and building energy performance coupling contributed to the ongoing research project, Urban TherCOM in Madrid, Spain. Leveraging on his learning from the MUrCS programme, he has recently acquired LEED Green Associate certification. His dedication to continuous learning underscores his commitment to a more sustainable future.

## Sruti Modekurty
Software Engineer

Sruti has a BSc in Electrical & Computer Engineering from Carnegie Mellon University. During MUrCS, she interned with the UNDP Global Center for Technology, Innovation, & Sustainable Development and was a Community Resilience Fellow with Earth Science Information Partners (ESIP). Previously, she was the Platform Lead at OpenAQ building open source technology to help global communities fight air pollution. Her work is focused on using open data and technology to empower community-led solutions, particularly for building climate resilience. She will soon start a PhD on climate adaptation governance using computational social science methods at the Helmholtz Centre for Environmental Research (UFZ) in Leipzig.

## Yasmin Atienza

Architect, LEED Green Associate

Yasmin is an architect with a diverse background in planning, design, and project management, and has worked on airport, heritage conservation, and restoration projects in the Philippines and the Middle East. Her central goal is to enhance her sustainability expertise, championing environmentally responsible solutions and climate resilience in the built environment. Her passion lies in integrating innovative design with eco-conscious principles, bridging the gap between aesthetics, user experience, and environmental stewardship. Her MUrCS experience has provided a global perspective on urban and climate challenges and opportunities, driving her ambition to inspire others to prioritize sustainability in the built environment, leaving a lasting, positive impact on the world.

# Editorial


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The **MUrCS** Project (www.murcs.eu) is pleased to present the fourth volume of the Student Thesis Projects to highlight our efforts towards knowledge transfer to link research into the practice of sustainable management of urban climate. By continuing with the integration of our three thematic strands of education (Science, Planning and Management) we aim to showcase the possibility of a 'new professional' able to understand, plan and lead the urban changes needed to tackle climate

As in the previous year, the most common theme in the present volume is **URBAN CLIMATE AND ITS MITIGATION** to enhance urban resilience. **Muhammad Abdullah** explores the linkages between urban sprawl, loss of green cover and local climate in Lahore, Pakistan, where urban climate risk is at its peak. The rest of the papers in this section explore mitigatory opportunities afforded by a myriad of planning actions (especially urban form and green cover) in diverse and rarely studied contexts: **Yasmin Atienza** (cold, Northerly Tampere, Finland); **Aminath Maiha Hameed** (humid tropical island climate of Malé, Maldives); **Muhammad Tariq** (hot, dry Peshawar, Pakistan) and **Dechen Pema Yangki** (sub-tropical, mountainous Thimpu, Bhutan). While cooling provided by urban parks is well known, its modulation by urban form is explored by **Najma Lelei** in Glasgow, UK. A different take on local climate mitigation is provided by Shoaib Amin who explores the contradictory requirements of building energy efficiency and outdoor comfort in cities (Madrid, Spain). Finally, **Mayuresh Bhadsavle** explores a least studied aspect of local climate resilience – namely visual narratives to better facilitate 'climate communication' in the face of heat stress.

As in previous years, the role of **NATURE-BASED SOLUTIONS (NBS) TO MITIGATE CLIMATE CHANGE RISKS** in cities continues to be a popular topic. The second section of the present volume provides evidence to the breadth of NBS analysis provided by our students. **Joseph Anderson** critically evaluates and presents a proof-of-concept of using deep learning models to standardise the assessment of urban ecosystem services. **Oluwaseun Apenuwa** evaluates the utility of a novel NBS approach (artificial floating wetlands) in cities, while **Bianca Borelli Da Silva** evaluates the possibility of NBS to combat sea-level rise in coastal cities. The likely contribution of specific NBS approaches are studied by several students: **Lorena Gebran** (revitalisation of urban streams as a social cohesion tool); Sustainable Urban Drainage Systems (SuDS) as a mechanism to achieve the UN Sustainable Development Goals (UN SDGs); Mst **Mahbuba Shabnam** (flood control through NBS in urban vacant and derelict land).

As can be expected from MUrCS, climate change management continues to be an important theme of this year's proceedings as well. **Mohammad Eshaq Khodayar** presents a comparative evaluation of climate change adaptation plans of MUrCS mobility cities (Glasgow, UK, Lahti, Finland and Dresden, Germany). **Sruti Modekurty** explores a key plank of the U.S. renewable energy expansion (solar energy projects) from the point of view of fuel poverty alleviation. **Navoda Rathnayake** critically evaluates risk reduction approaches to heat and flooding in in climate change adaptation plans in cities, while **Diana Joy Dionson Reyes** evaluates the likely role of circularity in sustainable development planning in the built environment.

The emerging theme of active travel from the third edition of MUrCS Proceedings is further expanded to cover different aspects of sustainable mobility. Two papers empirically evaluate the air quality situation in urban streets – **Maria Elisa Bernal Reino** on the links between sustainable mobility scenarios and air quality; **Natasha Piccone** on the differing roles of greenery in on air quality in different local climate zones. The optimisation of bike-sharing schemes to enhance active travel provision and use, is the focus of the work by **Olutayo Ekundayo**.

Knowledge gained by these in-depth studies in specific contexts have several nuggets of actionable findings. We hope it would be of interest to urban practitioners and policy makers to enhance urban environmental quality in the face of local and global climate change.

# Urban Microclimate and its Mitigation

ABDULLAH,MUHAMMAD

# Environmental Impacts of Urban Sprawling and Shrinking Green Cover in Lahore, Pakistan

*Lahore, Punjab's provincial capital and 2nd largest metropolitan city of Pakistan, is facing an increasing population and migrational trend from rural to urban areas and socio-economic development resulting in rapid urbanization and Land Use Land Cover (LULC) changes recently. Rapid urban growth has influenced the Land Surface Temperatures (LST) causing Urban Heat Island (UHI) effect. The present research is an effort to estimate the LULC changes and their influence on the Land Surface Temperature mainly using remotely sensed satellite data and Geographic Information System (GIS). Supervised LULC classification was performed for May 2010, May 2015 and May 2020 using the QGIS-SCP plugin. LST temperatures were estimated using thermal infrared bands of the satellite imagery. Comparison of LULC classification of 2010, 2015 and 2020 reveals that the built class is increasing and vegetation is shrinking. A positive correlation has been noticed between increasing population and urbanization. Population density and area of built class/person is increased over the decade. The study of the LST reveals that the built class has the highest temperatures and several hot spots denoting the highest temperatures are observed over the built class showing that it is the biggest contributor to UHI effect.*

# 1 Introduction

Pakistan is the 6th largest country in the world in terms of population. Pakistan's annual population growth rate is 2.04% and the total population is projected to be 227 million by 2025 (Government of Pakistan 2015). 40.5% of the population resides in urban areas and according to United Nations estimates, more than half the population will be living in cities by the year 2025 (UNDP 2018). There is a huge gap between the standard of living in urban and rural areas of Pakistan. Masses are migrating to urban areas in search of better facilities, more opportunities and higher standards of living, resulting in rapid and unplanned urbanization. The pace of urbanization is increasing (United Nations 2018). LULC changes especially increasing built areas at the cost of greenery intensifying the SUHI by altering the heat transfer and storage. Cities in Pakistan are frequently hit by extreme heat waves and temperatures.

Considering the sustainable development of cities, there is a need to investigate the connection between urbanization and land surface temperature. To quantify the SUHI effect and its impact, it is essential to examine how increasing temperatures and changes in Land Use/Land Cover (LULC) influence the different components. This study aims to quantify the urbanization, how different LULC classes are changing over time to identify which LULC class contributes the most in SUHI, whether the SUHI effect is intensifying over time with increasing urbanization and shrinking green cover. By estimating each component and analyzing how they are changing over time with increasing urbanization and land surface temperature, it would be possible to make recommendations in the context of findings and what changes should be made in order to achieve the element of sustainability.

## 1.1 Study Area

Lahore was taken as the study area considering one of the world's rapidly expanding city in terms of population and urbanization (Uz-Zaman & Baloch 2011). City is facing more frequent events of heatwaves (Khan et al. 2019). District is mix of all land use classes (e.g. built, greenery, bare land and water, with a clear boundary between urbanized and rural areas that could help calculate UHI effect. The study area lies in central Punjab on the bank of river Ravi sharing border with India. The city is a rapidly expanding and is home to 13 million residents with a growth rate of 4.1 % in the last two decades (United Nations 2021), making it the second-largest city in the country.

# 2 Background

## 2.1 Urbanization and LULC Changes

Urbanization around the world is happening in different forms such as the creation of a new urban district, redevelopment of urban settlements and increasing residential density (Angel et al. 2007; Bhatta 2009). In the process of urbanization, vacant land, forest, and agricultural green fields are converted into built areas while reducing the area available for agriculture (Khan et al. 2014). The drawbacks of this conversion include environmental and ecological issues like urban flooding, water scarcity, deforestation. In countries like Pakistan, urbanization and urban sprawl are linked with population growth. According to world bank indicators of 2020, population growth is 1.97%, while the urban population growth rate is 2.67% (The World Bank 2020). According to the UN, Pakistan has the highest rate of urbanization in South Asia; according to the census of 2017, 36.4 % of the population is living in urban areas. UN population division estimates that by 2025, about 50% of the country's population will be living in urban settlements (UNDP 2018).

## 2.2 Urban Heat Island Effect

There is a consensus that urban areas alter the radiation balance (Arnfield 2003; Debbage & Shepherd 2015) but the spatial extent and influence of UHI are being discussed. The higher the density of the urbanized area, the more obvious is the UHI effect of the area (Oke 1982). However, recent studies have concluded that denser cities (Coutts et al. 2007; Schwarz & Manceur 2015) and urban sprawling (Stone Jr 2012; Stone Jr & Rodgers 2001) both can result in intense UHI. Urban settlements having a population of millions or more can be warmer by 1-3° Celsius from surrounding rural areas in a day and the difference of temperature can reach up to 12° Celsius at night (José A. Sobrino et al. 2013). Different types of LULC classes can be associated with land surface temperatures (Pease, Lewis, & Outclat 1976). Spatial and temporal changes in land use can induce changes in LST, hence impacting the intensity of the UHI effect (Lo et al. 1997).

## 2.3 Land Surface Temperature (LST)

Studies on the trends of 30-50 years of the surface temperature of the rapidly urbanized sites indicated that the UHI effect has resulted in an increase of 1-2 °C in these sites (Cayan & Douglas 1984; Karl et al. 1988). Intensifying UHI and increasing temperatures pose threats to human health (Patz et al. 2005) (McMichael et al. 2006) by reducing the air quality (Sarrat et al. 2006), elevated near-ground ozone levels (Cardelino & Chameides 1990) and more energy consumption in hot climates (Sarrat et al. 2006).

Land surface temperature mostly refers to the degree of hotness of the specific land class under observation. Thermal infrared sensors on remote sensing satellites can be used to calculate LST (Anderson et al. 2011; Wan et al. 2004). From the stance of satellite remote sensing imagery, the surface can be described as every object that can be detected on the ground depending upon the resolution of the sensor anyhow cloud coverage, shadows obstacles and scattering of signals may also impede the description of objects. Surface detected by the sensor can be categorized as e.g., the canopy of the forest, lawn of grass, snow or roof of the building. The LST of different surfaces sensed by the sensor is not the same as of the air temperature at the time of the pass of the satellite (NASA 2000).

The LST of the built land class that represents buildings, roads and parking is more as compared to other classes. The LST and built class have a positive association while vegetation or greenery have a negative relationship (Sun et al. 2012). Reduction in vegetation impacts the heat transfer and energy balance of the surface and is strongly linked with escalating the LST (Shukla & Mintz 1982).

# 3 Methodology

Landsat satellite data was downloaded through the Q-GIS Semi-Automatic Classification Plugin (SCP), which is a free open source plugin for QGIS that allows LULC classification of remote sensing data (Congedo 2016).

Satellite data extent was redefined according to the boundary of the area of interest provided by Urban Unit Lahore. A supervised LULC Classification of the study area was performed by SCP by visual interpretation of satellite imagery and defining of multiple regions of interest (ROI) to train a classification algorithm. Accuracy assessment of the LULC classification was performed by randomly distributed point data and the assigned LULC classes were visually compared with the google earth imagery of the same year.

LST temperatures were calculated by a thermal band of satellite data by converting Digital Number (DN) to spectral radiation and then to surface brightness temperature which was then converted to LST by using emissivity values. For a better interpretation and understanding of the SUHI average, the LST of the different LULC classes was calculated to compare the temperature in urban and rural parts of the district and which class contributes the most to SUHI.

## 3.1 Data Acquisition

Considering the recent wave of population increase and rapid urbanization and more frequent events of heatwaves, temporal scale of the study is limited to the decade from the year 2010 to 2020 with an interval of 5 years. Landsat imagery was acquired for the years 2010, 2015 and 2020. The data was acquired from Landsat 5 satellite for the year 2010 and Landsat 8 Satellite for the year 2015 and 2020. The local time of satellite overhead pass was almost 10:30 A.M for all the data used. One data set from each month of the year 2010, 2015 and 2020 was considered for land surface temperature estimation, only if any of the cloud-free data for the month was available. The data of all three years was taken from the same week of the year to avoid the seasonal variations in NDVI and its effect on LULC classification.

Data for the accurate delineation of the district boundary was obtained from Urban Unit Lahore. For the accuracy assessment of the LULC classification, visual interpretation of the randomly distributed points was carried out by making a comparison of LULC maps with past google earth imagery for the years 2010, 2015 and 2020.

### 3.2 Data Limitation

Substantial limitations were faced during the acquisition of the desired data, considering the availability of free-of-cost satellite imagery and cloud-free data. Landsat 7 imagery of the ETM+ sensor was considered inadequate for this study, owing to the failure of the Scan Line Corrector (SLC).

Difficulties were faced while acquiring the cloud-free data for June, July and August as the sky remains overcast during this period due to the monsoon season. The same problem was faced for December, January and February because of the winter rainy season.

There is no past data available for the ground sampling campaign of LST. Gathering multiple samples of different LULC classes scattered over the whole study area would have been preferred for the accuracy assessment of the LST estimated through satellite data. Unfortunately, temperature data collected for any other time than the satellite overpass cannot be considered useful for the accuracy assessment of LST.

### 3.3 Land Use Land Cover Classification

To perform the LULC classification, an open-source free plugin of QGIS named Semi-Automatic Plugin (SCP), version 7.8.6 Matera developed by Luca Congedo was used (Congedo 2016). A supervised classification was performed for the study area, in which classes are identified by the user to train the algorithm.

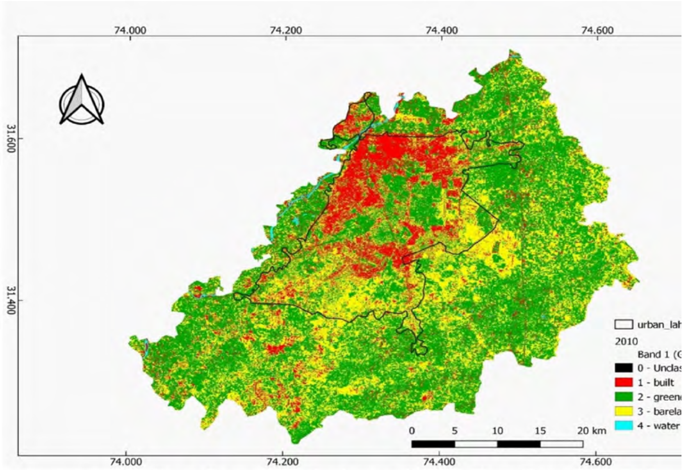
### 3.4 Land Surface Temperature

LST of the study area was calculated based on the thermal band (Band 6 of Landsat 5 and Band 10 of Landsat 8) of satellite data. The resolution of the thermal band of Landsat 5 is 120 m and for Landsat 8, it is 100 m.

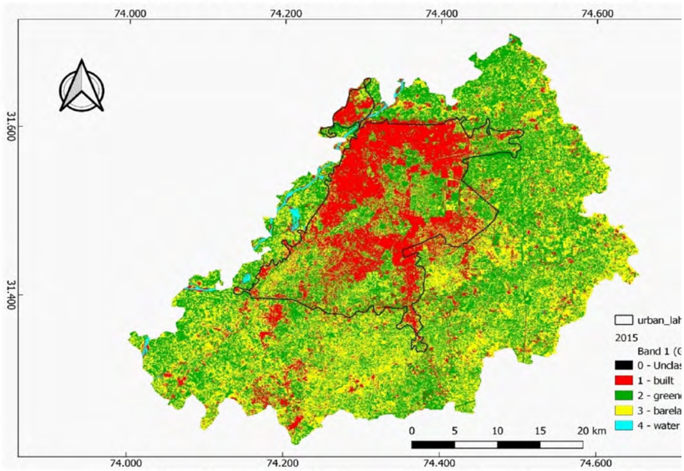
## 4 Results

### 4.1 Land Use Land Cover Classification

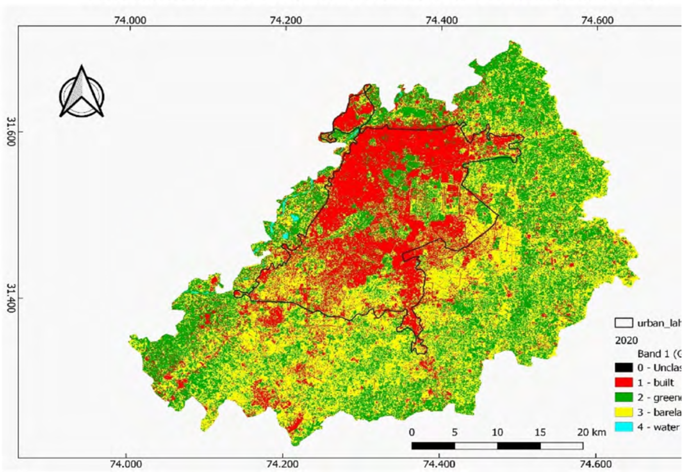
A supervised LULC classification for the years 2010, 2015 and 2020 was created by SCP plugin of QGIS; this plugin provides the map of LULC classification as well as a classification report carrying the information about the area and percentage of the specific class. The maps showing the pictorial view of the LULC classification are displayed below. Red color on the map represents the built class which expands over the course of the decade (2010-2020). Greenery or vegetation class is represented with green color which appears to be shrinking over the decade.




LULC classification of Lahore district for the year 2010




LULC classification of Lahore district for the year 2015

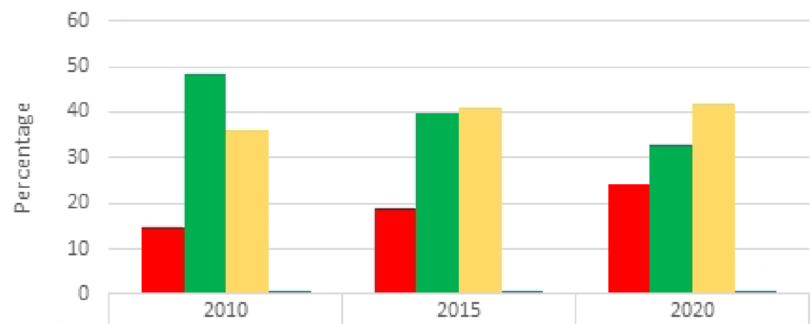



LULC classification of Lahore district for the year 2020

**Figure 1. LULC Maps 2010, 2015 and 2020**

Yellow color in the LULC classification represents bare land which is also increasing over course of study, it can be assumed that more land is being cleared to promote urbanization and sky color shows the water that is the smallest LULC class which is mostly constituted of the River Ravi.

From the pictorial map of LULC classification, it can be seen that urbanization has been taking place in the southwest direction of the district. Percentages of each of the four classes (built, greenery, barren land and water) reported by the LULC classification reports are shown in Figure 2. In other words, this picture shows how land uses and land covers change over the decade (2010-2020).  The built class




| | 2010 | 2015 | 2020 |
|---|---|---|---|
| Built | 14.8667712 | 18.71811418 | 24.3852504 |
| Green | 48.31690423 | 39.7977906 | 32.90092526 |
| Barren | 36.12896402 | 40.80582307 | 41.76838194 |
| Water | 0.687360547 | 0.678272146 | 0.945442394 |

**Figure 2. Percentage LULC Change Over a Decade (2010 - 2020)**

is increasing while greenery or vegetative class is on a decline over the decade. Considering the bar chart, in 2010 greenery was the dominant LULC class but, in the year 2020, barren land turned out to be the dominant class. Increasing barren land can be assumed to be linked with the clearing of greenery to promote urbanization. Most of the agricultural land is being cleared at the border of the urban and rural division of the district by private housing authorities.

Figure 3 expresses the relationship between the population and built land class over the decade. In 2010, the population of Lahore district was 8.43 million which increased to about 12.64 million in 2020 with a mean population change rate of 4.9% over the decade (United Nations, 2021). In 2020, the yearly population growth rate decreased to 3.58%. The built area in 2010 was about 261.87 km$^2$ which increased to 329.71 km$^2$ in 2015 having an average annual increment rate of 5.18%. From the period of 2015 to 2020, the built class further increased to 429.5 km$^2$ with an average annual increment rate of 6.05% during the period. In 2020, built class accounted for about one-fourth of the area of the district. Chart below indicates that with the growing population over the decade, urbanization is increasing at a rate faster than the population growth rate.

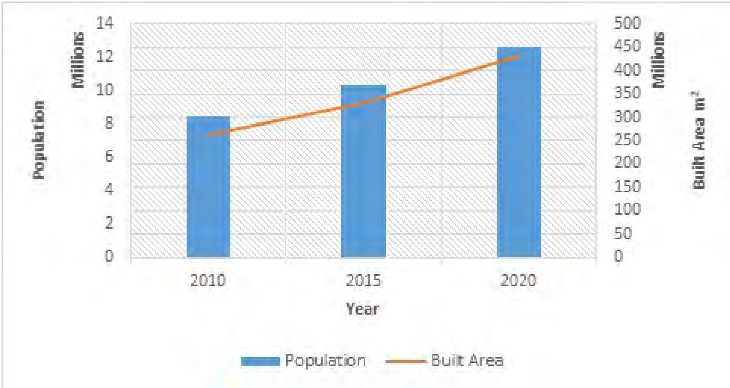



**Figure 3. Relationship between Population and Urbanization**

A graphical presentation of the change in urbanized land per person in $m^2$ is displayed in Figure 4. In the year 2010, land urbanized per person in Lahore district was 31.05 $m^2$, which changed to 31.79 $m^2$ per person in 2015 and in the year 2020, the area urbanized per person swelled to 33.97 $m^2$. On one hand we are dealing with the issue of population growth in the Lahore district while on the other hand, the urbanized area per person is also increasing continuously which indicates that that rate of urbanization is faster than the rate of population growth in the district. This can be explained by the spread of housing schemes and conversion of agricultural land to new housing societies due to the demand for housing land created by speculators as an investment for higher returns. Those are buying residential land at housing societies allotment prices at cost recovery with considerable development gain to allottees. The transfer of this gain serves little social purpose but it creates a huge demand for residential plots in Lahore. (Uz-Zaman & Baloch 2011).

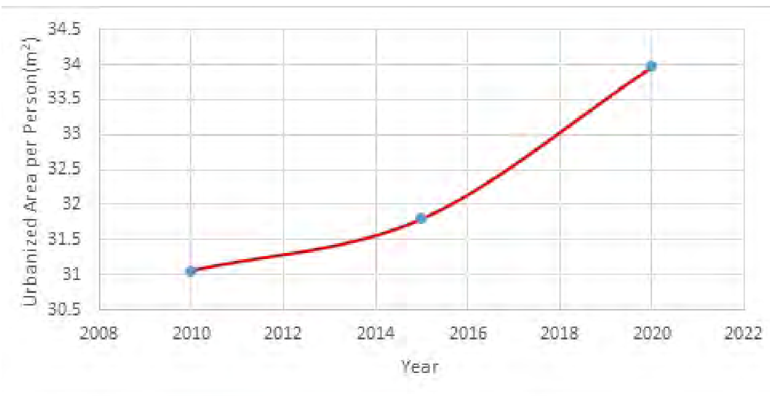



**Figure 4. Change in the Urbanized Area per person over time**

### Land Surface Temperatures

The study of the spatial variation of the land surface temperatures is essential for the calculation of the urban heat island effect. Figure 5 show the spatio-temporal variation of the land surface temperature of the Lahore district using remotely sensed Landsat satellite imagery. These figures also indicate the heat spots, marked red that refers to the intense UHI effect.

The highest temperature ranging from 30ºC to 32.5ºC is represented in the figure as bright red spots (indicated inside red circle marked red), it can also be called a heat spot which is an indication of the intense UHI effect. The LST maps indicate high land temperatures in the urban part of the district and lower land temperature in the rural part which itself is an indication of the existence of the SUHI effect.

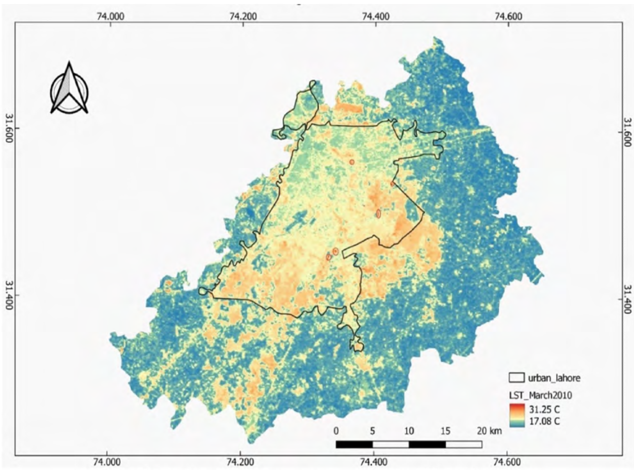
## 4 Conclusion and Discussion

### Conclusion

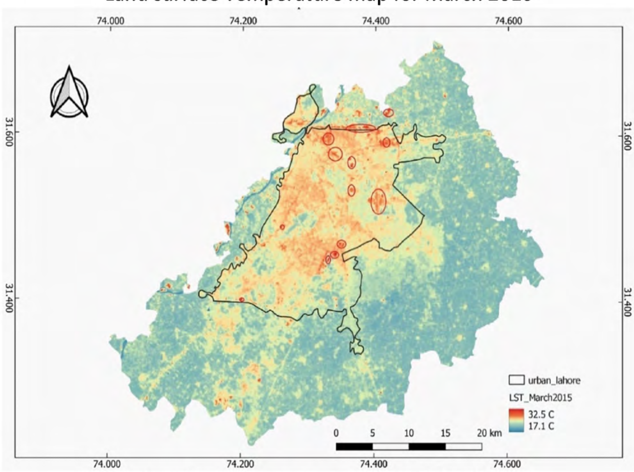
Findings of the research conclude that in the last decade (2010 – 2020), Lahore district has faced rapid growth in urbanization. LULC changes triggered by rapid urbanization has influenced the temperatures. One of the leading causes of these changes is the shrinking vegetative land class. Conversion of the vegetative and agricultural lands to built zones has given rise to a climatic condition termed as Urban Heat Island (UHI) effect in Lahore and this effect is obvious in urbanized regions on land surface temperature maps as a hot spot having a region that has a considerably higher temperature than its surrounding rural areas.

The results of the LULC classification revealed growth of the built class and impervious area for the decade 2010 to 2020. The increase in the built class area is momentous as it grew from 261.8 $km^2$ in 2010 to 429.5 $km^2$ in 2020. While the vegetative class decreased from 851.09 $km^2$ in 2010 to 579.53 $km^2$ in 2020. The spatio-temporal analysis suggests that built class increased by an area of 167.7 $km^2$ and vegetative class shrank by 271.5 $km^2$. For the same time period, the population of the district increased from 8.43 million to 12.64 million. Population density increased from 4730 person/$km^2$ in 2010 to 7093 person/$km^2$in 2020. Moreover, urbanized area per person increased from 31$m^2$/person to 34 $m^2$ per person over the decade.

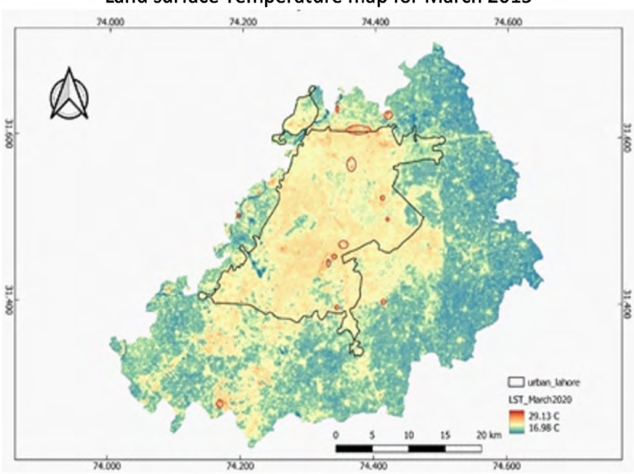
The results of the spatial and temporal analysis of LST indicate that the temperature of the built class is found to be relatively higher than the other classes reaching 45.9 ºC in May 2010, 36.1 ºC in April 2015 and 41.0 ºC in May 2020, which are the highest recorded LST for respective years. Meanwhile, it is also observed that the temperature of the land covered with greenery has lesser temperatures 43.21 ºC in May 2010, 33.87 ºC in April 2015 and 38.42 ºC in May 2020




Land surface Temperature map for March 2010




Land surface Temperature map for March 2015




Land surface Temperature map for March 2020

**Figure 5. LST Maps 2010, 2015 and 2020**

as compared to barren land having 44.19 °C in May 2010, 34.54 °C in April 2015 and 40.11 °C in May 2020. The highest temperature of the built class and heat spots that indicate the formation of the UHI is seen on the built classes in the urban region, making it the biggest contributor to the UHI effect.

## Discussion

Statistical surveys and census conducted by the Government of Pakistan suggest that the major reason for the increase in the population of big cities in Pakistan is the migration of masses from rural areas to cities in search of a better standard of living. Lahore is the provincial capital with the highest number of educational institutions, the highest number of hospitals, more industry than other cities in the province and better infrastructure for transportation and mobility with metro buses and intracity trains.

To discourage the increasing population in Lahore, the Government of Punjab should work to equally develop all the big cities of the province to provide basic facilities with good health and education infrastructure.

As the area urbanized per person is increasing, the government needs to implement a policy to change the spatial use in the construction sector. There is a need to shift from horizontal construction to vertical construction to slow down the pace of increasing urbanized land. Built class leads to higher LST hence contributing to the UHI effect. The Government should discourage the land consumption by housing societies which converts the highly fertile agricultural land into housing societies by threatening the food security of the country. Rather than allotting new lands for expansion, the government should force the construction sector to convert the already constructed single and double-story houses into multistory apartment buildings.

In order to restore the lost vegetation of Lahore, the government has started to plant the world's biggest Miyawaki Forest on the bank of the River Ravi. Government should plant more such forests in all major cities around Pakistan and such forests require 2 to 3 years of monitoring and watering to establish before they become self-sustainable. Government should force the horticulture departments to take good care of such initiatives until these forests can flourish on their own without external support.

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AMIN, SHOAIB

# Optimization Of The Urban Microclimate for Building Energy Demand And Thermal Comfort Under Climate Change

*Current energy efficiency policies focus on alleviating energy poverty by reducing heating demand needs (European Commission 2018). The negative impact of envelope retrofitting on thermal comfort and the rise in cooling demand due to UHI and climate change is neglected in energy efficiency studies. To address these challenges in a holistic way, this study proposes a tailored workflow employing advanced tools like the Urban Weather Generator (UWG), ENVImet, Ladybug Tools, and EnergyPlus. Findings reveal that considering the combined effects of UHI and climate change predicts a substantial rise in cooling demand. The results intend to inform the policymaking on addressing the predicted increase in cooling loads. Neglecting cooling demand in energy efficiency planning can aggravate energy poverty, deteriorate the health of vulnerable populations, and impede progress towards carbon neutrality. Furthermore, this study demonstrated the potential of combining sustainable urban planning with building retrofitting for effective climate adaptation under future climate scenario, RCP 8.5 2050. Enhancing the urban microclimate can attenuate cooling demand and address thermal comfort challenges stemming from envelope retrofitting.*

# 1 Introduction

Within the European Union (EU), buildings account for 40% of energy consumption and 36% of greenhouse gas emissions (European Commission 2023). Meeting the climate neutrality goals of the European Green Deal necessitates significant contributions from the building sector. However, the built environment confronts several obstacles hindering progress toward carbon neutrality. Santamouris's (2016) research focuses on major problems faced by the built environment in Europe. The research describes them as building energy consumption, energy poverty and local climate change. In Southern European countries, cooling represents 10% of the total energy consumption per dwelling. However, this is likely to be much higher under climate change (Isaac & van Vuuren, 2009) as the residential sector will rely more on the use of air conditioning systems to adapt to higher temperatures (Santamouris 2016). The Energy Performance of Building Directive (EPBD) developed by the EU focuses on energy efficiency through energy renovation as a way forward to tackle the issues of energy consumption, energy poverty and reducing emissions (European Commission 2018). However, issues at the building scale are not independent of the challenges faced by the urban environment. Along with climate change, the Urban heat island (UHI) phenomenon has a major impact on low income and vulnerable populations of the cities (Santamouris & Kolokotsa 2015). UHI results in urban areas experiencing different weather than rural environments due to a combination of urban morphology and the use of artificial materials (Oke 1988). The effect of urban form and fabric on urban climate, thermal comfort and energy demand has been extensively researched (Emmanuel & Steemers 2018; Salvati et al. 2017; Santamouris et al. 2015). Futcher et al. (2018) argued that even for buildings that are dominated by internal loads, neglecting the urban impact can lead to significant energy penalties. Santamouris (2016) proposed strategies to tackle UHI, energy poverty and building energy consumption such as reflective cool material and envelope retrofitting. However, if these strategies are adopted locally without consideration of the urban context can result in adverse impacts such as worsening of outdoor and indoor thermal comfort as shown in several studies (Maronga et al. 2022; Salvati & Kolokotroni 2023). In this regard, there is a need to study holistically the interaction of urban challenges and the mitigation potential of planning strategies to effectively design climate change adaptation.

Therefore, The focus of this study is to evaluate and minimize the impact of UHI and climate change on building energy demand, and indoor and outdoor thermal comfort in an urban district of Barrio Orcasur in Madrid City.

**The following objectives were achieved in this study:**

1. Developing a tailored workflow to effectively study the relationship between buildings and the urban environment with the latest tools available.
2. Understanding the combined impact of local Urban Heat Island and climate change on building energy demand.
3. Evaluation of progressive measures to reduce heating and cooling energy demand under reference and future climate.
4. Assessing the sustainable urban planning strategies potential in optimizing the triadic relationship of energy demand, and indoor and outdoor thermal comfort.

# 2 Background

A review of research investigating the influence of Urban Heat Island (UHI) intensity on building energy demand presented a comprehensive overview of the causal relationship. To highlight, the study conducted in Athens Greece (Santamouris et al. 2001) observed the impact of 10 °C UHI intensity on building energy demand. The results show an increase of 120% in cooling load and a decrease of 27% in heating requirements for a typical office building. Since 2001, several studies have researched this phenomenon in different cities such as Barcelona (Salvati et al. 2017), Rome and Antofagasta (Salvati et al. 2020), and Seville (Romero Rodríguez et al. 2022) to name a few. To initiate this research study, it was imperative to assess the influence of UHI intensity on building energy demand within the climatic context of Madrid City. Madrid makes an interesting case study based on the research study done by Yang et al. (2021). The authors conducted an evaluation of the energy performance of residential buildings across Europe under climate change scenarios, concluding that, on average, heating demand is expected to decrease while cooling demand will rise. Notably, the study revealed that the highest average temperatures, exceeding 40°C, will be experienced in Madrid, Spain, and Dipkarpaz, Cyprus.

Moving on, the focus of recent studies is on evaluating and suggesting planning strategies that can tackle the issue of energy inefficiency and UHI. These strategies include building envelope retrofitting, reflective cool material, and urban green infrastructure (Santamouris 2016). However, this is a research area where the knowledge gap lies. It’s mainly related to the urban context in which these planning strategies are adopted and the synergies between them. For example, a study done in Berlin, Germany evaluated the negative impact of envelope retrofitting on outdoor thermal comfort (Maronga et al. 2022). This is attributed to the decoupling of indoor and outdoor walls due to the addition of insulation. Similarly, another comparative study between the climates of Cadiz and London demonstrated a reduction in natural ventilation potential under the RCP 8.5 2050 scenario and hence the worsening of indoor thermal (Salvati & Kolokotroni 2023). This research implied that air tightness and the addition of insulation (i.e., envelope retrofitting) might have unintended consequences. Envelope Retrofitting is a cost effective strategy for reducing the heating demand. The question here is not to replace or consider alternate strategies but to adopt a holistic approach. An approach that also considers improvement in the urban microclimate that buildings are surrounded by.

Therefore, firstly, this research attempted to demonstrate the impact of UHI and climate change on building energy demand. Secondly, it progressed towards evaluating how the improvements in urban microclimate can help tackle the need for rising cooling demand and the adverse impacts of envelope retrofitting.

**For urban microclimate improvement strategies, the findings of the following three research studies were used as the foundation:**

- Tsoka et al. (2021) assessed the impact of foliage density on the cooling energy saving potential. Higher energy savings of up to 54% were achieved when trees formed a continuous canopy and found a direct correlation between foliage density and estimated cooling energy saving. This key finding was considered in replacing sparse trees with dense continuous canopies.
- Salvati et al. (2022) study suggests a combination of increasing road reflectivity and lowering façade reflectivity in lower parts as the best strategy to improve thermal comfort in the urban climate and building setting of London, United Kingdom. These findings were tested in pilot scale studies and further evaluated in full scale studies.
- Ge et al. (2023) assessed cooling energy savings from vegetation planting in Xian City, China. However, the methodology used focused on demonstrating cooling potential for specific thermal zones. The study further suggests studying the impact of large urban greening on cooling energy demand. These considerations were utilized in the design of methodology and scenarios.

As vulnerable and low-income areas are likely to be affected more by climate change and UHI (Santamouris & Kolokotsa 2015), a literature review was conducted in the local context to identify vulnerable areas.

**Three parameters were considered:**

- **Energy Poverty and Energy Inefficiency:** Martín-Consuegra et al. (2020) study combined the findings of Soutullo et al. (2020) and mapped the spatial distribution of energy inefficiency and deprived neighbourhoods and identified overlapping areas. The indicators of energy poverty were 1) Low Rents 2) Absence of Heating Systems 3) Ageing Population.
- **Energy inefficiency** was determined by energy performance certification with only heating demand in consideration.

- **Urban Morphology:** López Moreno et al. (2020) studied the influence of microclimate and outdoor thermal sensation in the city of Madrid. The study uses the classification of urban typologies provided by the Statistical Institute of the Community of Madrid along with measured data from the Climatic Network of Madrid's City Hall (CNM).

Based on the findings of these studies, the overlapping area of Barrio Orcasur was chosen as the case study area as shown in Figure 1.

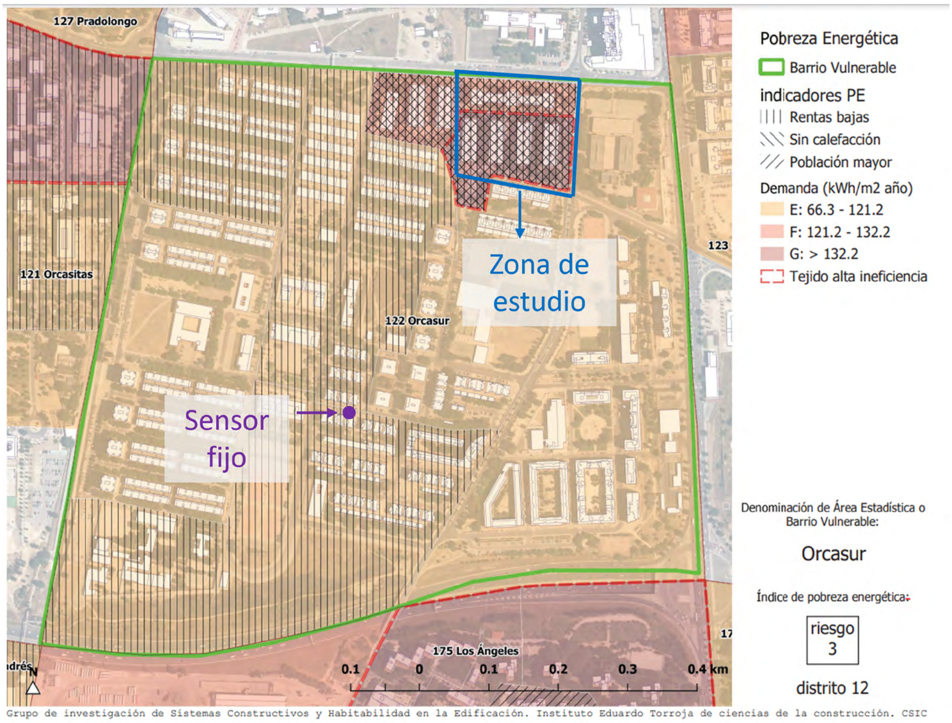


**Figure 1. Vulnerable neighbourhood, Orcasur Source: Martín-Consuegra, F. et al. 2020; Soutullo et al. 2020; López Moreno et al. 2020; CIEMAT 2022.**

# 3 Methodology

This study was part of the Center of Energy Environment and Technological Research (CIEMAT) institute's ongoing project, URBAN therCOM. The methodology was developed according to the Subprojects (SP3) with slight changes in the objectives to suit the goals of this master thesis. It focused on studying the impact of urban microclimate on building energy demand and optimizing the urban environment to reduce cooling energy demand, improve indoor temperatures, and enhance outdoor thermal comfort. The study was divided into phases, with Phase 1 assessing UHI's impact on annual energy demand and Phase 2 focusing on urban environment optimization. The chosen case study area is Barrio Orcasur in the south of Madrid, known for its Mediterranean climate transitioning to a cold semi-arid climate.

The workflow involved obtaining data on the built environment and urban area, including building footprints and vegetation information, using LIDAR data. This data was processed in ArcGIS Pro to extract the necessary information. A 3D model of the area was developed in Rhino, and Grasshopper was used for importing geometry and creating ENVImet and Dragonfly models for microclimate and energy simulations. Ladybug tools were employed for environmental analysis and integration with Radiance and EnergyPlus Engines. URBANopt API is utilized for urban block-scale energy modelling. Dragonfly facilitated model development, incorporating building geometrical and non-geometrical properties. Reference and future weather files were obtained from Meteonorm software V 8.0.

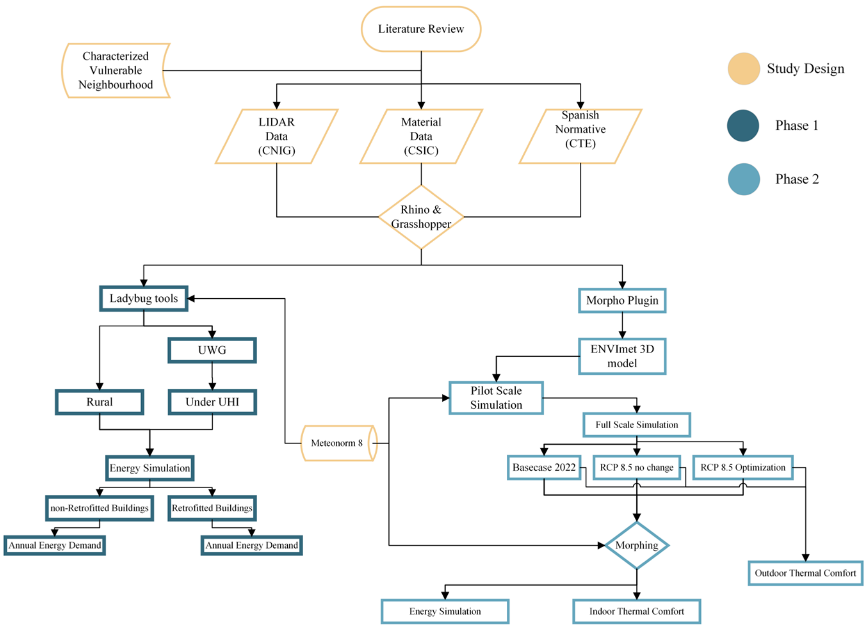


**Figure 2. Flowchart demonstrating the methodological workflow.**

The study adopted a progressive approach, leveraging the functionalities of various tools. Microclimate simulation tools were compared to assess their suitability for specific research goals. Urban Weather Generator (UWG) was used to evaluate UHI and generate morphed EPW files accounting for building waste heat and anthropogenic heat from traffic. ENVImet was preferred for its ability to accurately assess the impact of vegetation and reflective materials on microclimatic parameters. The ENVImet simulations were divided into pilot-scale and full-scale studies, involving various settings such as grid dimensions, building heights, and simulation times. Full scale study focused on three scenarios. They include base case, RCP 8.5 2050 no change scenario, and RCP 8.5 2050 optimization scenario. The optimization scenario considered reflective materials, dense trees with continuous canopies, and low vegetation such as hedges of 1,2 and 4 meters. The Dragonfly energy model was developed based on guidelines from the Spanish Building Technical Code and research done in the context of Madrid.

The energy demand and indoor operative temperature analysis incorporated the Dragonfly model and the URBANopt interface. This combination allowed for large-scale urban energy simulations. EPW files were manually adjusted based on ENVImet simulations. Energy demand was derived from room energy results, and indoor operative temperatures were derived from comfort results. The study also assessed outdoor thermal comfort using Physiological Equivalent Temperature (PET). Both static and dynamic PET were considered, with settings including clothing, time, and vertical range of analysis. The simulations assessed comfort levels for an older population (80 year old male), as this was a relevant demographic in the study area.

In summary, this research study employed a progressive quantitative methodology and workflow to study the impact of urban microclimate and optimize the urban environment for energy efficiency, indoor comfort, and outdoor thermal comfort. It integrated various tools, conducted simulations in different phases, and considered multiple scenarios to achieve its research objectives.

# 4 Results

## The results are summarized as per the objectives of this study:

**Objective A:** As the goal was to develop an integrated workflow that can allow assessment of UHI impact on building energy demand at an urban scale, model development achieved through Ladybug Plugin, Dragonfly was tested. The key advantages of developing an urban scale energy model through this process are as follows:

- The urban scale model maintains the model precision of a building scale model through the advanced functionality of dragonfly and control over the assignment of building programs, mechanical systems, window to wall ratio.
- Furthermore, it enables the accounting of shading that’s provided by neighbouring buildings.
- The dragonfly energy model can be integrated smoothly with an Urban weather generator to account for UHI assessment and URBANopt API for large district energy metrics. This is yet a challenge to other latest Urban Building Energy Modelling (UBEM) tools (Hong et al. 2020).
- The challenge is in the assignment of thermal zones. The larger the number of zones, the more intensive are computational requirements. However, assigning a perimeter offset of four resulting in five thermal zones per floor is a common practice in research (Natanian & Auer 2020) and provides fairly accurate thermal modelling.

**Objective B:** The following key findings are obtained from studying the impact of UHI and climate change on annual building energy demand:

- Max UHI intensity of +12.9 °C in summer and -3.2 °C in winter.
- In absolute terms, not accounting for UHI, using the rural weather file, annual cooling demand (91.3 kWh/m$^2$/year) is less than heating demand (185.9 kWh/m$^2$/year)
- While accounting for UHI, annual cooling demand is 239.3 kWh/m$^2$/year and heating demand is 149.7 (kWh/m$^2$/year).
- The impact of UHI on annual energy demand is evaluated as negative. Meaning that the increase in cooling demand is not compensated for by the decrease in heating demand.
- Furthermore, accounting for both UHI and climate change, the cooling demand is even higher i.e., 387.5 kWh/m$^2$/year.

In qualitative terms, the results for objective B highlight the drastic increase in cooling energy demand under UHI and climate change RCP 8.5 2050 impact. Therefore, implying that addressing the emerging challenge of cooling demand shall also be the consideration of energy efficiency policies.

Heating and cooling demand are calculated as the total heat that needs to be added or removed from the room to achieve set point temperatures. It is a different metric from energy consumption. Set point temperatures are determined by building technical codes as temperature ranges suitable for occupant indoor thermal comfort.

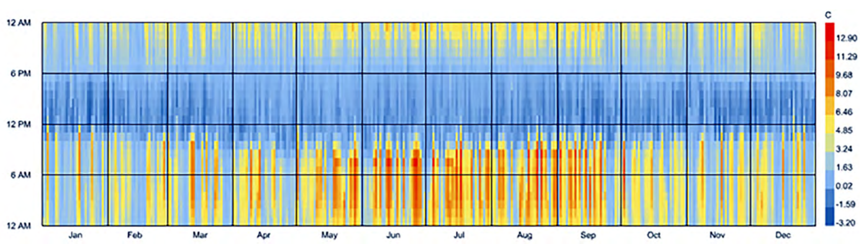


**Figure 3. Hourly UHI intensity obtained as the difference in dry bulb temperature for morphed and rural files.**

**Objective C:** attempts to evaluate the extent to which the building retrofitting strategies (improvements in envelope) shaped by current energy efficiency policies address the challenges of energy demand. The results indicate that:

- UHI, a hotter and dryer future climate combined with changes in thermal envelope can improve the energy performance category from G to E meeting the minimum requirements of the EU.
- However, there is minimal impact of envelope retrofitting on cooling energy demand simulated as a decrease of 2%.

## Just to recap:

- Objective A provides a way to study the impact of UHI and climate change on an urban scale.
- Objective B highlights the emerging issue of cooling demand.
- Objective C demonstrates that although retrofitting is good for heating demand, cooling demand remains a challenge.

**Objective D:** Therefore, at this stage of the research study, the focus is on evaluating the potential of urban planning strategies in reducing the need for cooling demand and addressing the interlinked issues of indoor and outdoor thermal comfort emerging from thermal retrofitting (Maronga et al. 2022) and climate change (Salvati & Kolokotroni 2023). Objective D evaluated two scenarios against the base case. The first scenario is developed with the assumption that no changes are made in the urban environment surrounding the urban block under consideration and named RCP 8.5 2050 no change scenario. The second scenario considers that certain improvements are performed in the urban environment that include

1. Street reflective material
2. Sparse trees replaced with dense continuous canopies of trees
3. Hedges placed close to the building façade.

The cooling impact simulated in ENVI met as the change in air temperatures in front of the façade is morphed into the weather file for 21st July, the design day 2. Therefore, the second scenario is named RCP 8.5 2050 optimization scenario.

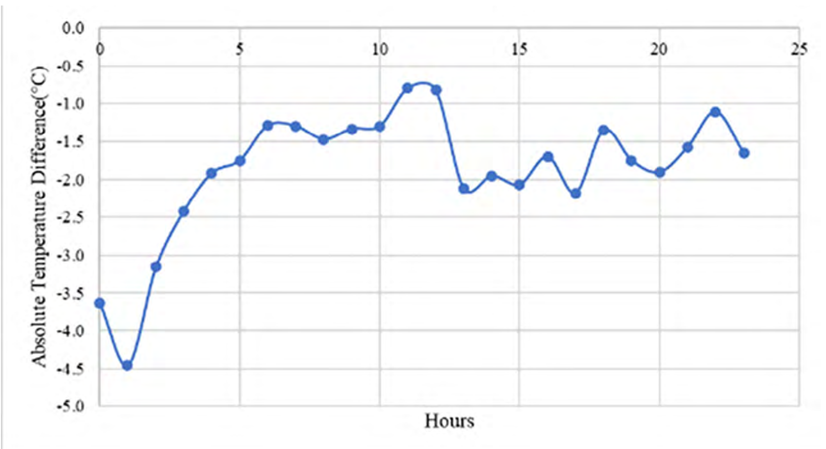


**Figure 4. Absolute differences of Potential Air Temperature in front of facade between RCP 8.5 no change and RCP 8.5 optimization scenario.**

**The results demonstrate that:**

- If no changes are made in the urban environment, the cooling demand for design day will rise by 120% compared to the base case with reference weather.
- Changes made in RCP 8.5 2050 optimization have the potential to diminish this increase by 44%.
- This means that urban planning strategies can improve natural heat sinks for the buildings and provide cooling benefits through a combination of shading, evapotranspiration, reduction in long wave exchanges (heat exchange between surfaces) and absorption of short wave exchanges (heat absorbed from solar radiation).
- Furthermore, urban planning strategies can improve the average indoor operative temperatures3 for the whole apartment block by 1.9 °C. This needs to be further evaluated in absolute terms rather than average in future studies for specific zones to obtain more accurate values.
- Moreover, outdoor thermal comfort measured as a static Physiological Equivalent temperature (PET) right next to the façade (within 2 meters) shows the potential of addressing the adverse impact of thermal retrofitting.
- What is another co benefit of urban planning strategies simulated? Evaluation of dynamic PET, a new feature of ENVImet demonstrates that the change in thermal comfort reduces from 12 °C to only 3 °C compared to the PET at the starting point of the walk.

**2 Design day:** used for sizing HVAC systems and to determine peak energy load.

3 Operative temperature: is a simplified measure of human thermal comfort derived from air temperature, mean radiant temperature and air speed.
In summary, the results first demonstrate the issues and then point out a way towards the possible solutions opening a door for further research in this direction and attempting to shift the perspective of energy efficiency policymaking.

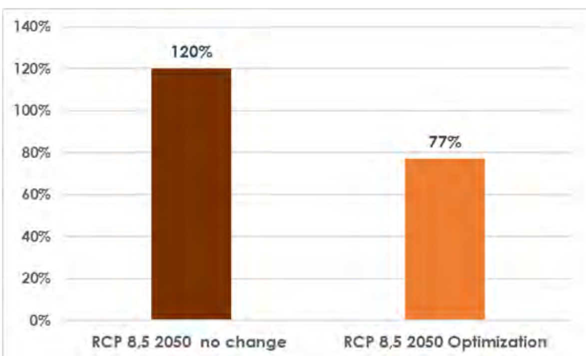


**Figure 5. Percentage change in energy demand with reference to base-case for Design Day 21st July.**

## Conclusions and discussion

In phase 1 of this research, the results highlighted the impact of a max UHI of 12 °C on annual building energy demand as a 162% rise in cooling needs and a 19.5% decrease in heating requirements. A strong similarity in results can be observed between the study done in Athens, Greece (Santamouris et al. 2001) where a UHI intensity of 10 °C was observed resulting in a 120% rise in cooling needs and a 27% decrease in heating needs. This study went a step further and highlighted the impact of the RCP 8.5 2050 scenario. It's important to consider climate change scenarios as one research has observed the second highest average temperatures in Madrid city under climate change scenarios (Yang et al. 2021). Should policies only focus on existing challenges (i.e. heating demand) or shall also plan for the future (i.e., cooling demand)?

Phase 1 demonstrated the change in energy needs if all influencing factors are involved (UHI and climate change) and if only one strategy is considered (Envelope retrofitting).

**The key findings from Phase 1 include:**

- A rise of 315 % in cooling demand in RCP 8.5 2050 climate change scenario with reference to using rural weather files and neglecting UHI and climate change.
- A decrease of 34% in heating demand due to UHI, hotter and warmer climate and envelope retrofitting.

Phase 2 carried on the work of phase 1 where the problem of cooling demand was highlighted and shifted towards the urban scale. Phase 2 endeavoured to demonstrate that urban planning strategies (reflective cool material, urban green infrastructure) can work together with building retrofitting strategies (envelope improvements). It is well understood that the potential of natural heat sinks and ventilation will be reduced under climate change (Salvati & Kolokotroni 2023). Can urban planning strategies be a solution that creates synergies? Shall urban planners, building performance specialists and landscape architects work together to create synergies among sustainable solutions?

**The key findings of the phase 2 demonstrate that:**

- For design day 21st of July, the cooling load will rise 120% from reference weather to future RCP 8.5 2050 weather.
- Planting dense continuous canopies of trees, hedges planted next to the façade and street reflective material can result in a cooling energy saving of 44%. The results align with the research done by Tsoka et al. (2021) that observed a cooling saving potential of up to 54% for dense continuous canopies alone.
- The co benefits include reducing the impact of the improved envelope on outdoor and indoor thermal comfort.

**The implications of these findings from Phases 1 & 2 include:**

- Accounting for all factors cooling demand is much higher. Neglecting this aspect in policymaking for energy efficiency projects and overfocusing on heating demand can hinder progress towards energy efficiency targets set for the built environment.
- Energy poverty (inability to pay for heating requirements) is already a challenge in southern European countries. Neglecting the need for cooling demand in energy efficiency and retrofitting projects can further aggravate energy poverty.
- This neglect can also lead to health problems. Research has shown that living under adverse indoor conditions can deteriorate health conditions, especially in vulnerable populations (Santamouris 2016).
- Similarly, the potential of renewable energy to meet the requirements is based on the accurate assessment of energy demand. In the absence of this, additional requirements emerging of neglect of UHI, and climate change might require prolonged reliance on fossil fuel generated energy.
- Although the benefits of urban planning strategies are clear. The difficulty is in the computational and resource intensity of evaluation methodologies. To effectively quantify the benefits, temporal and spatial scales shall be larger.
- The role urban microclimate can play in improving the building performance and thermal comfort is well accepted. However, lacks enforcement in urban codes. Legal codes shall address improvements in urban microclimate similar to building codes.

**This research has several limitations. Key limitations are listed as:**

- Temporal Scale: The study used design day for the evaluation of urban planning strategies. Future studies shall at least study entire periods of heatwaves or hot weeks to establish a better understanding of how buildings gain and lose heat and how this can affect the cooling potential of trees especially through evapotranspiration. This can be done effectively by designing detailed landscape plans and material catalogues to limit the number of simulation studies.
- Reference weather files: The reference year of the weather file used for the base case is 2005. Studies have shown that actual weather conditions in recent years are different from synthetic files such as TMY files (Soutullo et al. 2020). The purpose of this study was to highlight the problem of cooling demand and demonstrate the potential of urban planning strategies to improve it. For accurate assessments of cooling demand rise, recently measured data from fixed stations shall be utilized to develop future climate change scenarios instead of EPW files obtained from rural weather stations.

In summary, the literature is currently further developing in assessing building retrofitting strategies accounting for UHI (Romero Rodríguez et al. 2022), studies on assessing the benefit of urban green infrastructure on cooling (Tsoka et al. 2021; Ge et al. 2023) and demonstrating the problems resulting from energy efficiency strategies under current climate conditions (Maronga et al. 2022) and future climates (Salvati & Kolokotroni 2023). Therefore, this study attempted to address the research gap and contribute to the knowledge of complex interactions between buildings and their surroundings.

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ATIENZA, YASMIN

# The Role of Urban Vegetation in Urban Heat Island Mitigation and Outdoor Thermal Comfort Improvement: Case Study of Tampere Finland

*Nowadays, cities face the persistent effects of urban heat island (UHI) where urban areas experience higher temperatures than rural areas. In Tampere, hot days are predicted to rise by 64%, magnifying heat-related consequences. With this, urban vegetation has been become a key strategy for climate change mitigation and adaptation.*

*This study aims to assess urban vegetation's impact on land surface temperature (LST) and outdoor thermal comfort (OTC) at city and block scale levels. City-wide analysis employed remote sensing and statistical methods, revealing a weak direct and moderate inverse correlation between LST and Normalized Difference Vegetation Index (NDVI) in winters and summers respectively. LST distribution across Local Climate Zones (LCZ) showed that LCZs with less pervious surface exhibited higher LSTs.*

*ENVI-met simulations included the existing (BC), no vegetation (C1), greening (C2), and building height increase (23 meters) (C3) in both winter and summer. Results show that C2 brings significant OTC improvement than C3, while C1 led to increased discomfort. Overall, these findings can guide the city's planning, prioritizing greening interventions to create comfortable and climate-resilient urban environments.*

# 1 Introduction

## 1.1 Rationale

In the urban context, climate change has intensified extreme heat, air pollution, and infrastructure issues, adversely affecting cities as highlighted by IPCC (2023). Urban areas, accommodating half of the global population, are consistently exposed to the urban heat island (UHI) effect, causing higher temperatures than rural areas. This results in adverse consequences such as reduced thermal comfort, increased heat-related health issues, worsened air quality, elevated energy consumption for cooling, and unforeseen economic and social burdens (Acosta et al. 2021; Brozovsky et al. 2021; Saaroni et al. 2018) Particularly in colder European cities like Finland, rising temperatures are linked to increased mortality, especially among the elderly (Kollanus et al. 2021)

Northern European cities, less adapted to UHI compared to their southern counterparts, face higher vulnerability (Ruuhela et al. 2017; Ward et al. 2016). A UHI study in Tampere, Finland projected a 64% increase in hot days by 2035, with over 60% of the population residing in warmer urban zones (Sitowise 2022b). To combat this, UHI mitigation strategies are vital in urban planning to enhance climate-resilient development (Acosta et al. 2021; IPCC 2023). Urban green infrastructure (UGI), notably urban vegetation, is crucial for UHI reduction and thermal comfort improvement. While global research underscores the importance of urban vegetation, effective UHI solutions depend on local conditions (Balany et al. 2020; Gatto et al. 2020; Oke et al. 2017). Tampere's Climate Change Adaptation and Preparation Plan recognizes the role of UGI, including urban trees, in building resilience (Sitowise 2022a). Although the city's master plan recommends additional greening measures, analysing their effects on the thermal environment is essential to identify optimal approaches for mitigating urban heating challenges and creating a climate-sensitive urban landscape (Sitowise 2022b). Understanding Tampere's specific context is pivotal for crafting effective strategies against UHI and fostering a climate-sensitive cityscape.

## 1.2 Aims and Objectives

The primary objective of this research is to evaluate the influence of urban vegetation on LST and OTC at city- and block-scale levels respectively in Tampere, Finland. Specifically, this study aims to:

- Evaluate the relationship between LST and vegetation represented by NDVI in summer and winter seasons,
- Assess the spatial distribution of LST across different LCZs in the city centre,
- Explore the effect of deciduous trees in pedestrian thermal comfort based on simulated scenarios, and
- Support the urban planning decisions regarding the benefits of urban vegetation, specifically urban trees in curbing heat islands and OTC improvement in summer and winter seasons.

# 2 Background

## 1.1 Urban Heat Island

UHI can be categorised into four types, with the most explored lines of research mainly focused on UHIsurf and UHIUCL (Acosta et al. 2021; Bechtel et al. 2019). UHIsurf refers to the temperature differences of the outdoor atmosphere with the dry surfaces and the equivalent rural air to ground surfaces. It is sensitive to the surface cover and is more prevalent during the daytime and summers (Oke et al. 2017; Tesfamariam et al. 2023). It is commonly assessed through remotely sensed LST due to its availability and practicality especially for citywide, regional or global scale analysis (Acosta et al. 2021; Marando et al. 2022; Tesfamariam et al. 2023; Ullah et al. 2023; Yuan & Bauer 2007; Zhang et al. 2009). UHIUCL indicates the change between the air temperature in the UCL, the exterior UCL, and the corresponding height in the countryside near-surface layer (Oke et al. 2017). It requires a direct or field measurement at about 1.25 - 2 m above the ground, and is strong under clear skies, with its peak lasting several hours after sunset. Humans directly experience the effects of temperature in this layer which could be a detrimental factor to human thermal comfort. (World Meteorological Organization 2023).

According to Bechtel et al. (2019), previous studies on UHIUCL and UHIsurf has been hindered due to the lack of framework to interpret the results consistently. In this regard, LCZ was created as a standardized manual of local landscape types to understand the urban morphological pattern and UHI relationship (Das & Das 2020; Stewart & Oke 2012). The relationship between LST and LCZ has long been explored for assisting urban planning and climate management (Aslam & Rana 2022; Bechtel et al. 2019; Choudhury et al. 2021; Das & Das 2020; Del Pozo et al. 2021; Zhang et al. 2009; Zhou et al. 2022), and improving thermal comfort in urban environments. LCZ mapping can lead to the understanding of the urban fabric's influence on the spatial variation of UHIsurf (Aslam & Rana 2022; Feng & Liu 2022; Stewart & Oke 2012; Zhou et al. 2022). UHI is mainly caused by the replacement of vegetated areas with impervious surfaces due to urbanisation (Welegedara et al. 2023; Zhang et al. 2009). Due to this, several studies analysed the relationship of LST with land cover indices, including NDVI (Kaplan et al. 2018; Naserikia et al. 2022; Zhang et al. 2009). As NDVI refers to the health composition of greenery in an area, its relationship with LST has been explored to understand the effects of the presence of vegetation cover in surface temperature (Al-Saadi et al. 2020; Choudhury et al. 2021; Emmanuel et al. 2023).

## 1.2 Urban vegetation as a UHI mitigation measure in cold climate cities

In UHI concept, 'mitigation' is defined as the modifications or interventions in the physical environment to reduce the amount or extent of UHI, which includes adding vegetation cover. Meanwhile 'adaptation' is regarded as the adjustment to lessen the risks and harm caused by UHI, such as the response to thermal discomfort (Gago et al. 2013; Saaroni et al. 2018; Solecki et al. 2005). In cold climate cities, UHI can lead to excessive heat and higher air polution, thus exposing humans, especially the elderly and chronically ill, to heat related health risks and stress (Drebs et al. 2023; Suomi 2018; Venter et al. 2020). Studies reveal that increasing vegetation cover in densely built areas, adding more urban forests, and safeguarding trees during growth and redevelopment can reduce UHI effects in the summers while still reaping benefits during the winter (Welegedara et al. 2023). Several studies on LST show that areas with the highest temperature are in the commercial or industrial areas with lesser vegetation, while water bodies and areas with green cover such as forests and urban parks have the lowest (Brozovsky et al. 2021; Sitowise 2022b; Welegedara et al. 2023).

### 1.2.1 Urban Trees for Outdoor Thermal Comfort (OTC) Improvement

Human thermal comfort is defined as a condition of mind which states satisfaction with the immediate environment. It depends on human activities, clothing, and environmental elements which includes air temperature, wind speed, air velocity, and radiation. Radiation is significantly related to mean radiant temperature (MRT), which displays the short- and longwave radiation absorbed at the human body's outer surface (Oke et al. 2017). OTC is considered as one of the key variables which affects the liveability and functionality of the cities' pedestrian and public spaces (Nie et al. 2022; Potchter et al. 2018) and failure to achieve the desired user thermal comfort level would lead to the neglect of these spaces (Ahmadpour et al. 2021). Trees have been consistently considered as one of the most studied types and most versatile form of urban vegetation, especially in OTC research (Balany et al. 2020; Perini et al. 2018; Zhang et al. 2009). In cold climate cities, deciduous trees are considered more favourable than evergreen trees because of its seasonal characteristics. It increases thermal comfort through shading which provides cooling during summers, and relatively warms the area through allowing solar radiation to pass through during winters (Afshar et al. 2018; Oke et al. 2017; Perini et al. 2018; Yilmaz et al. 2021). About 10-30% and 50-80% of solar radiation is transmitted by deciduous trees during summers and winters respectively (Oke et al. 2017). Meanwhile, evergreen trees casts permanent shadows, thus lowering the temperature in winter, which is critical in OTC (Afshar et al. 2018).

In Tampere, urban vegetation, particularly trees, has been prioritized as a key measure for climate change mitigation and adaptation. While the UHI study (Sitowise 2022b) conducted for the city centre represents a step forward in analysing heat islands, there remains a need to understand how vegetation can effectively regulate the microclimate and enhance OTC.

# 3 Methodology

## 3.3 Research Framework

The research employs qualitative methods including literature review, case studies, and policy analysis, with quantitative techniques such as GIS, ENVI-met modelling, and statistical analysis. This multi-method approach progresses from city-scale GIS to block-scale ENVI-met simulation, providing a comprehensive understanding of the research topic across different scales.

### 3.2 Overview of Study Area

Tampere (Figure 1a) (61°29°53°N; 23°45°36°E) is in southwestern Finland and covers an area of 689.6 sq.km. - with 24% of which is water area. The northern region houses a variety of landscapes and forests while the more urbanised areas are in the southern part. The city centre is between two lakes - Lake Näsijärvi (north) and Lake Pyhäjärvi (south) - and has a footprint of about a quarter of the whole region land area (City of Tampere, 2022). Belonging to Köppen-Geiger climate classification subtype 'Dfb', the city experiences a humid continental climate characterised by severe cold winters, absence of dry seasons, warm summers, and strong seasonality.

### 3.3 Data Collection and Processing

The data used in this research include Landsat 8 OLI/TIRS images with 30m resolution for the years 2018 and 2022 obtained from the USGS Explorer for the LST-NDVI calculation and maps retrieval. The city LCZ map was clipped from the 'European LCZ Map' (Demuzere et al. 2019) obtained from the WUDAPT website. Shapefiles were collected from the municipality including the boundary map, land cover, surface cover, urban trees, and buildings. These spatial data and images were processed using the GIS–based remote sensing software ArcGIS Pro 2.8. All images were clipped to fit the city centre (Figure 1b) boundary map and resampled from 30m to 100m for a uniform resolution.

A sample with 1,395 generated points was analysed for LST-NDVI correlation analysis, where points located in water bodies were omitted (Ullah et al. 2023; Yuan & Bauer 2007). Using MS Excel, a simple line regression analysis was used to determine the correlation between the two variables from February and July.

### 3.4 Microclimate Modelling and Simulation

The analysis narrowed down to the focus area (Figure 1b) within Tampere's inner-city centre. Four scenarios (Figure 1c) were developed using the ENVI-met software, and employed a simple forcing simulation where basic meteorological parameters are used to analyse the models on both critical cold (January 15, 2021) and hot (June 22, 2021) days.

- **Base Case (BC)** exhibits the current scenario with the existing trees, buildings, and surface cover, where buildings cover up to 35% of the area, impervious surfaces at 55%, and vegetation or pervious surface of 10%.
- **Case 1 (C1)** displays the no vegetation scenario where all trees and vegetation are removed. In this scenario only buildings (60%) and impervious surface (40%) make up the land cover area.
- **Case 2 (C2)** displays the addition of more deciduous trees, following the existing trees and spacing from the current scenario. Vegetation is increased to 25% with two rows of Tilia were added along the Hämeenkatu main street while a row of Acer platanoides were added for Kuninkaankatu, Kauppakatu and Aleksis Kiven katu streets. Tilia and grass cover were added on open spaces where the open parking and bus stop parking were.
- **Lastly, Case 3 (C3)** exhibits the increase of building height up to 23 meters, with the same land cover percentage as the existing scenario.

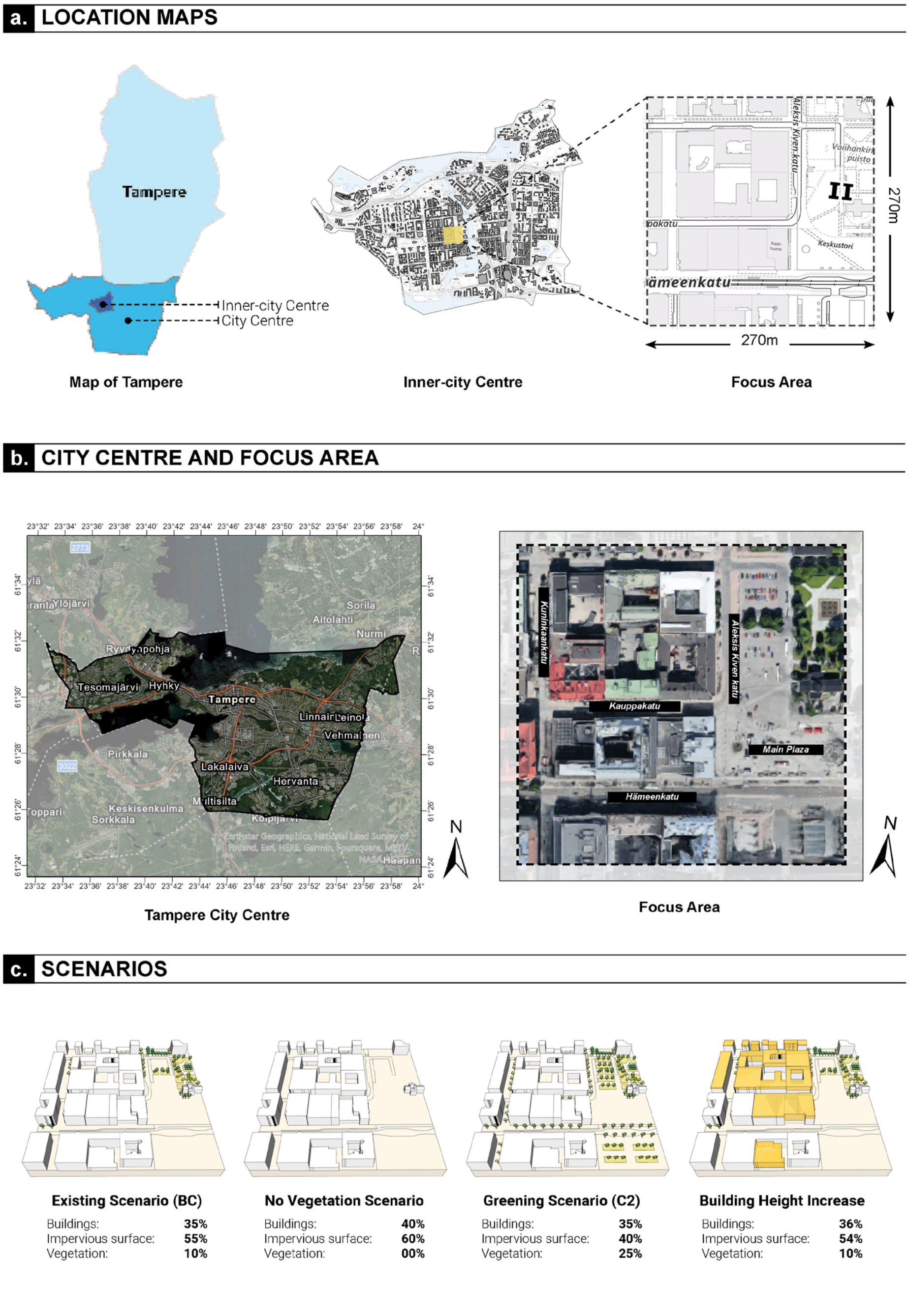


**Figure 1. (a) Location Maps, (b) City centre and focus area, (c) Scenarios for microclimate modelling and simulation**

For OTC analysis, results were assessed based on air temperature (Tair), mean radiant temperature (MRT) and physiological equivalent temperature (PET). Tair is used as it is considered as one of the main micro-meteorological parameters. MRT is used to understand the influence of shadow patterns brought by trees and buildings to the spatial variation (Duarte et al. 2015; Gatto et al. 2020; Lindberg et al. 2014). PET values display a range of thermal perception and physiological stress grade, and was adopted to further analyse OTC, as this index considers the effect of radiative fluxes on body heat balance (Duarte et al. 2015; Morakinyo et al. 2017; Zhang et al. 2009). For this study, the simulated microclimate data from ENVI-met were obtained and imported to Bio-Met using the default parameters for a standardised person.

# 4 Results

## 4.1 Seasonal and Spatial Variations of LST and NDVI

In winter it can be observed that the temperature difference (-12.50°C to -28.50 °C) is less pronounced as Tampere experiences cold temperatures and is mostly blanketed by snow cover during this season. Meanwhile, summer results (6.00°C to 38.00°C) show profound surface temperature contrasts, as high LSTs are observed in the built-up areas while relatively cooler areas are seen in parks and forests. It also shows that during this season, waterbodies are clearly defined having the lowest LST values. Generally low NDVI values are observed during winter as the maximum value (0.25) representing sparse vegetation can only be seen in the northeastern and southern parts of the city centre. During summer, a higher maximum value is observed (0.55) as dense vegetation is evident in several portions of the city while low values can be clearly observed in water bodies. Results show that LST-NDVI relationship (Figure 2a) varies across different seasons. In winters, it is observed that LST and NDVI has a weak positive correlation, correlation with r = 0.18 for February 2018 and r = 0.25 for February 2022, and during summers LST and NDVI has a moderate negative correlation (r = -0.55 for July 2018; r = -0.59 for July 2022).

## 4.2 Tampere City Centre LCZ Map and analysis

Results show that five out of ten built up LCZs (LCZ 2, 5, 6, 8, 9) and five out of seven land cover LCZs (LCZ A, B, D, E, G) were recognized in the extracted map of Tampere's city centre (Figure 2b). Overall, LCZ A is the most dominant LCZ land cover type, covering 32% of the area, while LCZ E (1.1 sq.km.) has the smallest. In terms of built types, LCZ 6 (19.1 sq.km.) is the most dominant at 11%, while LCZ 2 (1.2 sq.km.) has the smallest area at 1%. LCZs 2 and G have the highest and lowest mean LST for both seasons respectively. LCZ 2 (compact midrise) recorded high LST values with 29.3°C (2018) and 19.8°C (2022) for summers and -20.4°C (2018) and -15.4°C (2022) for winters. LCZ G which represents water bodies exhibited the lowest with -23.3°C (2018) and -17.5°C (2022) for summers and 20.1°C (2018) and 8.3 °C (2022) for winters. The analysis also shows that the distribution pattern is more consistent in summer as it followed the rank order: LCZ 2 > LCZ8 > LCZ E > LCZ 5 > LCZ 6 > LCZ 9 > LCZ D > LCZ B > LCZ A > LCZ G.

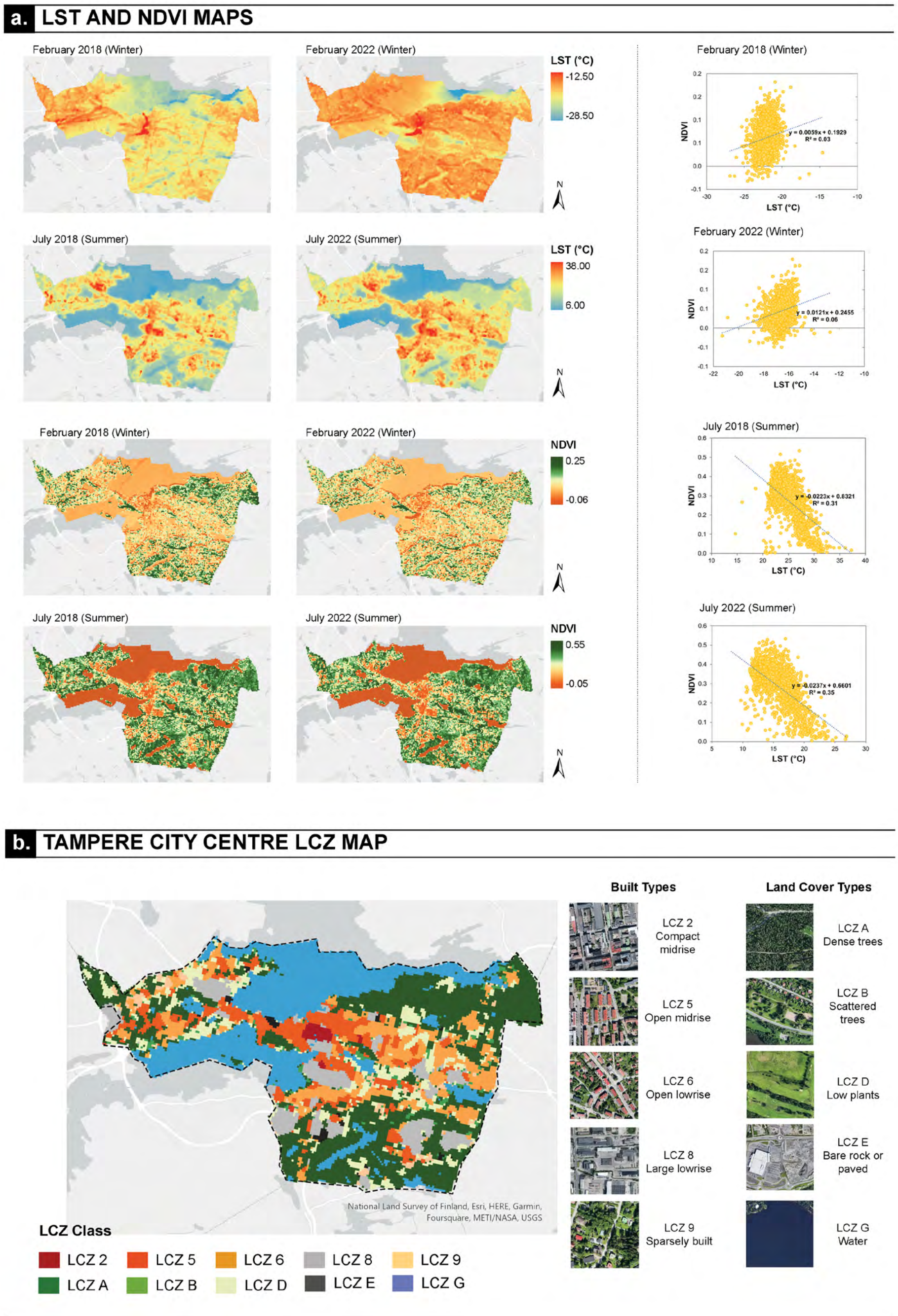


**Figure 2. (a) LST and NDVI Maps (b) Tampere City Centre LCZ Map**

## 4.3 ENVI-met Simulation Results and OTC Analysis

### 4.3.1 Air Temperature (Tair)
Overall, it can be observed that there is little variation of Tair across all scenarios in both seasons, however, C2 exhibits a more distinct outcome. Notably, C2 scenario brings a more pronounced effect C3, as seen in the mean Tair rise of 0.40 °C in streets and 0.32 °C in open spaces. In summer, the results are reversed. C1 leads to a warmer Tair across all receptors while both C2 and C3 scenarios resulted to a cooler Tair. (Figure 4,5)

Spatially at 14:00 (Figure 2), both seasons display that cooler areas are found within the building courtyards, extending to streets where the building shadows are cast, while open spaces exhibit a relatively warmer Tair.

### 4.3.2 Mean Radiant Temperature (MRT)
MRT displays larger temperature variation across all the scenarios. C1 decreases MRT during winter, while increases it during summer. Meanwhile both C2 and C3 brings an inverse effect. However, brings more improvement in OTC than C3. In winter, C2 warms the streets by about 1.58 °C and the open spaces by 1.12 °C. In summer, there is a more pronounced effect as it cools the streets by 6.69 °C which is about 5 times cooler than C3's 1.42 °C. Moreover, C2 cools the open spaces by about 11 times higher at 6.18 °C than C3 at 0.57 °C (Figure 4,5). This effect may be attributed to the limited impact of building shadows on open spaces due to the location, highlighting the advantages of having flexibility in tree placement.

At 14:00 in winter (Figure 2), long shadows from buildings and trees lead to increased areas of lower MRT. Tree shading, as in C2, provides a slightly warmer effect. In summer, vegetation and shadows create cooler areas. Warm spots persist in open spaces, courtyards, and partially shaded streets.

### 4.3.3 Physiological Equivalent Temperature (PET)
Overall, results show that C2 is observed as the best scenario for OTC improvement, while the C1 as the worst. In winter, average PET values follow the same trend, and all are in the 'very cold' range where users experience 'extreme cold stress'. However, it is evident that C2 brings OTC improvement during winter as seen in the PET increase all throughout the day, while C1 generally brings further PET decrease.

In summer, the existing scenario (BC) experiences 'strong heat stress' starting at 8:00, and then gradually increasing to 'extreme heat stress' from 10:00 to 17:00. This pattern bears a resemblance with C3 and C1. Remarkably, it can be observed that C2 improves OTC as it has the lowest PET values especially during the peak hours where users generally experience 'strong heat stress'. It extends the 'comfortable' range by 3 hours and lessens the 'extreme heat stress' and 'slight cold stress' by 7 hours and 3 hours respectively (Figure 4,5).

In winter (Figure 2), warmer spots are evident within courtyards and areas close to buildings and trees, while colder areas are observed in open spaces. During

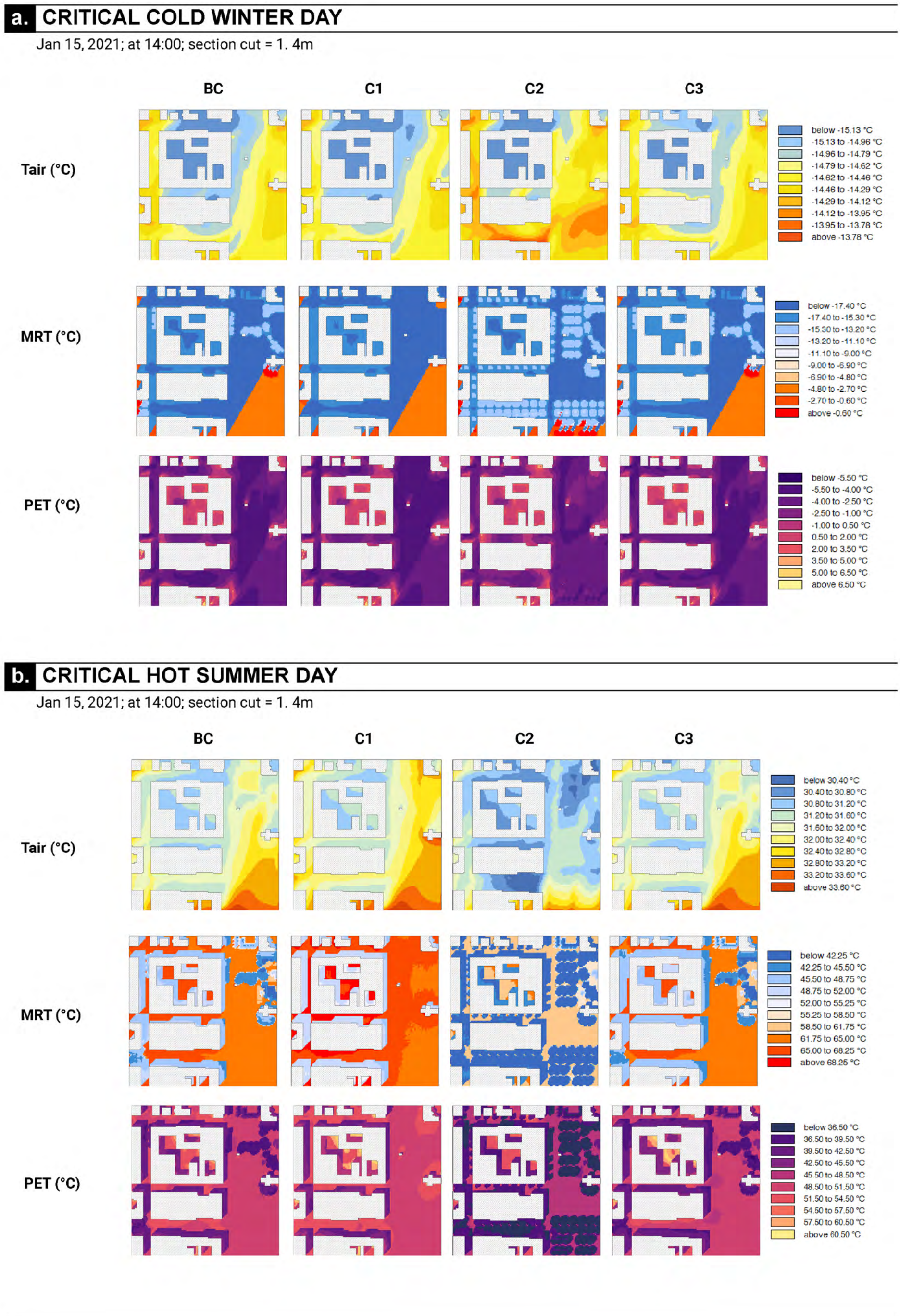


**Figure 3. Spatial analysis at 14:00 during (a) Critical cold winter day (b) Critical hot summer day**

summer, distinct differences emerge between hot and cool zones, with significant OTC enhancement visible in streets and open spaces shaded by tree canopies.

# 5 Conclusions and Discussion

With the increasing occurrence of urban overheating, even in cold climate cities, it has become imperative to implement measures that address and adapt to this phenomenon. Tampere, guided by plans, policies and climate reports, recognizes the significance of vegetation as a priority measure for mitigating the adverse effects of UHI brought by climate change. Through the city scale and block scale analysis, this study supplements the city's vision and further supports its urban planning decisions and draws the following conclusions:

## 5.1 Seasonal and Spatial Variations of LST and NDVI

The analysis underscores the importance of recognising and leveraging the seasonal dynamics of LST and NDVI in urban environments, as it can guide decisions related to climate adaptation and mitigation strategies. The weak, direct (winter) and moderate, inverse (summer) correlation suggest that factors other than NDVI exert a more pronounced influence on LST variation. The winter correlation indicates the need to consider vegetation density to maximise heat retention and facilitate OTC improvement, while the summer correlation highlights the cooling potential and heat stress reduction benefits offered by urban vegetation.

## 5.2 Distribution of LSTs across different LCZs

The LST-LCZ distribution highlights the significance of surface cover in UHIsurf distribution. LCZs characterised by lesser pervious surface generates higher LSTs, suggesting that addition of more pervious surface such as vegetation can reduce surface temperatures and generate a more comfortable environment. This distribution pattern is more consistent in summers than in winters.
These insights contribute to a more informed decision-making process for urban planners and policymakers, allowing them to prioritize and implement appropriate greening interventions in areas where they will have the greatest impact in mitigating the adverse effects of UHI.

## 5.3 Microclimate modelling and simulation

The OTC analysis outcomes demonstrate that the addition and presence of urban deciduous trees (C2) led to significant OTC enhancement during summer and winter seasons, surpassing the effect of increasing building height (C3). Conversely, the absence of vegetation (C1), causing increased impervious surface cover, results in discomfort for users.

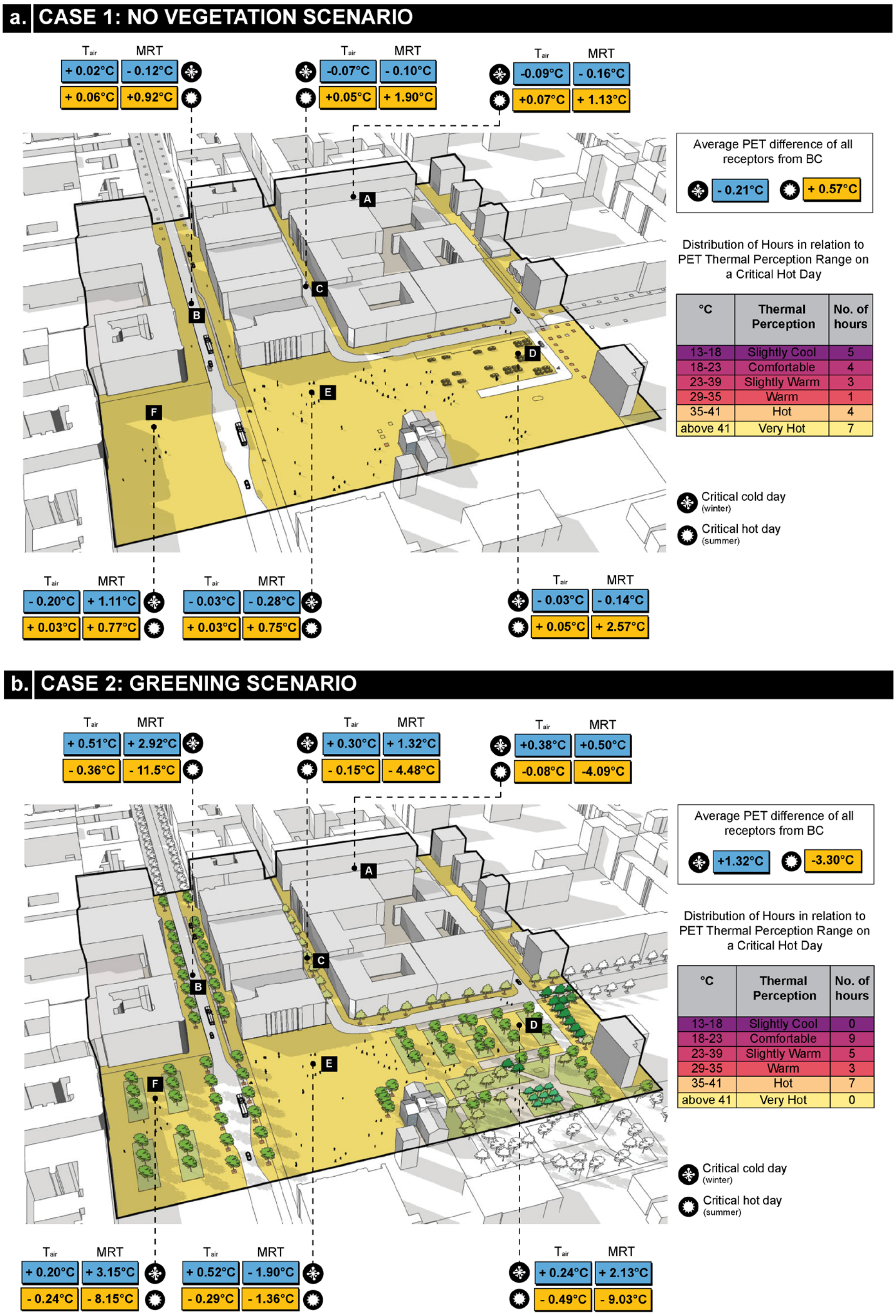


**Figure 4. Results of the (a) Case 1 – No Vegetation Scenario (b) Case 2 – Greening Scenario**

In the no vegetation scenario (C1) (Figure 4a), discomfort is consistent, with the lowest comfort levels for air temperature (Tair), mean radiant temperature (MRT), and physiologically equivalent temperature (PET) in winters and the highest in summers. The small disparity between C1 and BC indicates that the present situation might need to implement strategies to improve thermal comfort. The potential impact of an underground parking network on the area, which can lead to the removal of vegetation cover, could counteract the city's efforts to improve pedestrian comfort and shade provision.

The best scenario, Case 2 (C2) (Figure 4b), exhibits significant overall OTC improvement. This configuration elevates Tair, MRT, and PET in winter and reduces them in summer for all receptors. While this brings overall improvement during winter, it could bring a further decrease in temperature during specific hours. This result agrees with the previous study (Lindberg et al., 2014), where it was recommended to create a more diverse outdoor space. C2 supports the city's objective in increasing the vegetation in the area, protecting, and enhancing urban trees, as well as providing comfortable conditions to pedestrians.

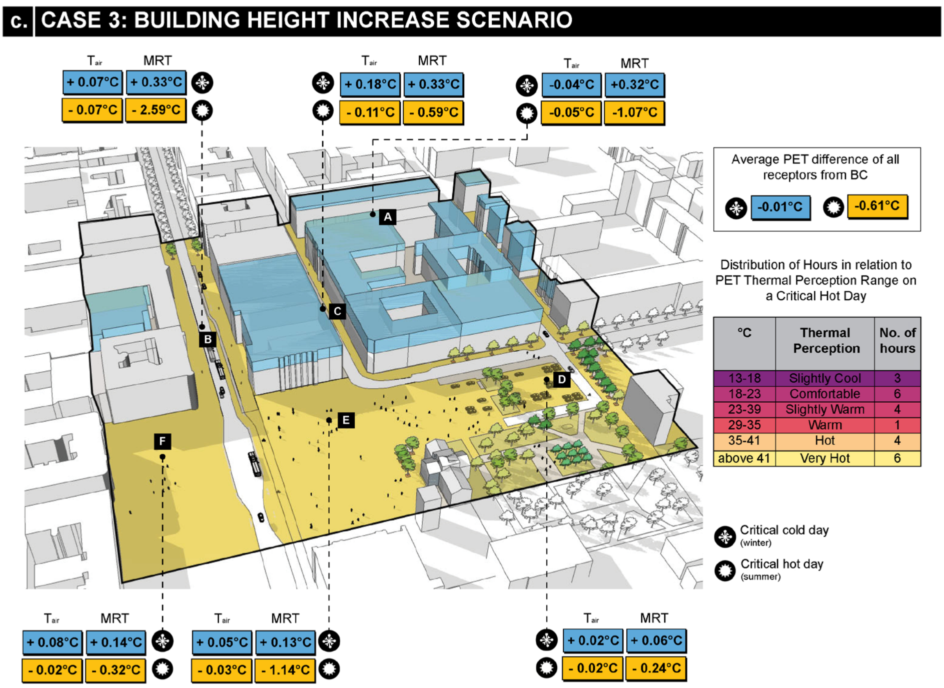


**Figure 5. Results of Case 3 – Building height increase scenario**

Case 3 (C3) (Figure 5) displays similar trends to C2 but to a lesser extent, indicating that combining increased building height and tree cover might offer improved thermal comfort solutions. Yet, the potential for increased shadows during winter necessitates further investigation.

## 5.4 Limitations

The limitations of the study include the limited availability of Landsat 8 images with minimal cloud cover, limited expertise of the area to improve LCZ mapping accuracy, and ENVI-met software drawbacks including lengthy simulation process and limited computational power.

## 5.5 Recommendations

The research recommends conducting site-investigations and more ground truth-verification to improve data accuracy, PET range calibration, and analysing the benefits of trees in different themes for a holistic approach.  For the city planners, it is recommended to incorporate microclimate analysis into urban planning to gain insights in the benefits, risks, and potential vulnerabilities associated with the proposed developments. This will enable informed decision-making and the integration of climate considerations into the planning process.

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BHADSAVLE, MAYURESH

# Climate Change Communication for Enhanced Urban Resilience - Communicating Urban Heat Stress through Visual Narratives

*The existing discourse of climate change communication faces an image problem and perceptual barriers. Under-addressing the image problem is a serious missing link in climate change communication. Visual media can be highly instrumental in influencing the perceptions of the viewer about various climate challenges and inspire them to engage with climate action. In the broader context of climate change induced urban heat stress in Germany, this research attempts to develop an understanding about the effective usage of documentary photography as a credible visual communication tool at city level, to enhance urban stakeholders' responses towards local climate challenges. Using visual ethnography, a first-hand repository of urban heat stress visuals was created and visual frames were used to elicit the response from various key stakeholders to understand their perception of the visual frames. This data was analysed to develop recommendations for effectively using photographic images in urban climate change communication. Results confirmed that the defining features of documentary photography make it a potent tool to capture visuals of urban heat stress. The discussion outlines that right kind of visual frames and visual narratives depicting local context open myriad possibilities of creating multiple engagements and dialogues with stakeholders to enhance their engagement with local climate action.*

# 1 Introduction

Climate change is undoubtedly the crucial-most and complex challenge ahead of us. In the backdrop of post-Paris landscape, climate change communication has assumed a greater significance for accelerating public engagement, climate action and achieving the ambitious national net-zero targets. The widely recognized and popular understanding about climate change communication is driven by Information deficit model (Suldovsky 2017) and assumes the form of science communication. The discourse on climate change communication is also believed to be influenced by Environmental communication where impacts of climate change on environment and natural resources are highlighted through a range of nature-centric narratives (Katz-Kimchi & Goodwin 2015). Climate Change Communication goes far beyond these two approaches, spans multiple disciplines, and is used as an umbrella term for all types of communications centered around climate change (Agin & Karlsson 2021). However, the wide-ranging spectrum of climate change communication has paid scant attention to communicating multitudinal dimensions of urban climate change unfolding in cities.

On one hand, the Urban Centers and City-systems are major contributors to overall carbon emissions but on the other hand they are at the receiving end of the climate crisis. In the backdrop of rising global temperatures cities face climate hazards like extreme heat, flooding, sea-level rise, drought, and wildfire. Amongst all, Extreme Heat is a far more serious challenge because the impacts of heat hazards are compounded by the Urban Heat Island (UHI) effect, that further leads to the rise in urban temperatures. However, the urban climate hazards, urban risks, vulnerabilities and adaptation solutions in general are highly underrepresented in the climate communication discourse. Climate Imagery can be a great source of visual evidence to drive the point across public mind but the available climate imagery and visuals are either cliched, abstract, emotionally distant, or devoid of human stories. (Agin & Karlsson, 2021; O'Neill, 2020). In this backdrop, this research identifies and addresses the gap about effective usage of photography based visual narratives to communicate the climate change induced urban stress, risk and vulnerabilities to key stakeholders and enhance their response towards the local climate action.

Unlike other climate challenges, urban heat stress is invisible to human eye yet far more disastrous, especially for urban ecosystems and viability of cities (Crisman et al. 2023). Different studies by Germany's national meteorological service, the Deutscher Wetterdienst (DWD) indicate that Germany can expect an increase in the number of hot days in summer and more pronounced, longer heat waves in future. German media company DW reported (DW 2022) that, Year 2022 was the year when Germany saw record-breaking heat, drought and hot days as the country was an average of 1.7 degrees C warmer than when the record keeping began. Considering the gravity of heat-challenges in Germany and the practical limitations of scholarly enquiry, the research focuses only on urban heat stress in German cities. Objectives of the research are as follows:

- Recognize major gaps in existing discourse on climate change communication and identify the specific requirements for communicating climate change induced Urban Heat Stress and vulnerabilities.
- Using documentary photography, develop a visual repository of climate change induced urban heat stress and vulnerabilities, as a grassroot level visual evidence.
- Explore the potential of 'Documentary Photography' as a credible tool to engage with key urban stakeholders to communicate the city-level impacts of climate change induced heat stress
- Present a set of recommendations to key stakeholders for effectively using photographic images in urban climate change communication to influence the informed decision-making, advance planning, and inclusive climate actions towards augmenting Urban Climate Change Resilience.

# 2 Background

## 2.1 Climate Change Communication as Domian of Knowledge

Climate Change Communication is an emergent domain of knowledge in academic research and there have been different trends, challenges and strategies of communication contributing to this field of study. One comes across a range of approaches adopted to communicate climate change, from risk communication to advocacy journalism and from sustainability communication to solution-centric journalism. Each of these approaches address a different dimension of the great climate challenge yet the multidisciplinary understanding might be overwhelming and confusing at times.

### Science Communication and Beyond

Communication Researcher-practitioner Susanne Moser presents an extensive review of the field through historical development of climate communication from the 1980s till now. She observes that the scholarly contribution to this field has been dominated by the work of scientists communicating about climate change and this sort of communication is not developed from the field of communication studies (Moser 2010). Another important critique is that theory of climate change communication has evolved within the theoretical developments in the field of science communication (Nerlich, Koteyko & Brown 2010). Science communication is based on the information deficit model (Suldovsky 2017) which assumes that people lack nuanced understanding of the scientific nature of the issue of changing climate, which is attributed to lack of scientific information and therefore more scientific information is transmitted. However, the transmission model of scientific communication has proved inadequate to prompt behavior change and public engagement and communicators in this field need to go beyond and understand the audiences in a wider perspective (Cook & Overpeck 2019). Given the inefficacy of the 'information-deficit' model-led science communication approach, the discourse is shifting from deficit to dialogue. A shift towards carefully designed public engagement brings into discussion the importance of effective ways of communicating, apart from the usual forms of communication as well as that of identifying the right audience. This is where Visual Communication comes into picture.

## 2.2 Visual Communication of Climate Change

Visual communication takes different forms like videos, still photographs, images like cartoons-memes, data visualization graphs and so forth. This can be far more powerful than the textual communication, especially when it comes to behavioral change or identifying a problem. Visual communication researchers Dr. Saffron O'Neill and Nicholas Smith demonstrated that the investigation of climate communication through visual imagery is a multidisciplinary, and often interdisciplinary, research area (O'Neill & Smith 2014). What images are chosen for communication, what message do they convey, who conveys the message and in what manner are some of the key themes researchers try to address. The major takeaways are explained further.

### 2.2.1 Climate Visuals and Emotions

The emotions invoked by climate visuals is one of the criterions for selecting images for communication. Fear inducing images of climate change (extreme weather events, large scale destruction, environmental conflicts) have a great potential for attracting public's attention to climate change but in the longer run it becomes counter-productive. Fear cannot be an effective tool for enticing genuine personal engagement as it tends to generate non-productive emotional responses like hopelessness and apathy. Research shows that nonthreatening iconography and imagery with links to individuals' everyday life and concerns in the larger context of macroenvironmental issue like climate change tend to be more engaging. (O'Neill & Nicholson-Cole 2009).

### 2.2.2 Climate Visuals and the geographical context of images

The geographical context of climate imagery plays a major role in deciding the efficacy of the communication. The localised imagery may create a connect with the population but may also get trivialised, losing the appeal for popular action or participation. Distant imagery may invoke fear or great concern in peoples mind but may create a kind of geographical helplessness as people may not 'travel' that far to participate in action. O'Neill mentions two dimensions of distance, as geographical distance, and psychological distance (O'Neill 2013). Elaborating further on the geographical and psychological appeal of climate images, Sheppard recommends to use the climate images that bring relevant information down to the local level, into a community context that people care about, using the climate issues in local landscape (Sheppard 2012).

#### 2.2.3 The Perception Problem

Images can easily become the core of climate change communication but often remain overlooked, underutilised, and understudied. Climate Outreach, the UK based leading organization in the domain of 'public engagement and climate change' describes this issue as an 'Image problem' which can be characterised by a restricted set of visual associations in the public mind (Corner 2018).

#### 2.2.4 Solution Journalism and Adaptation Communication

In order to further the engagement of people, the solution-oriented imagery has a great role to play. A mixed methods investigation of public perception of climate images (Chapman et al 2016) shows that images of solutions produce positive affective responses and less polarization. The catch is that as the images of climate solutions elevate the self-efficacy and tend to make people feel more able to do something about climate change, it may at the same time reduce people's sense that the issue is an important issue demanding participation. Solution journalism and adaptation communication are crucial for engaging a diverse set of audience. This background literature review helps recognize major gaps in existing discourse on climate communication. At the same time, it underscores the absence of a distinct focus on urban climate change communication in general and visual communication of urban heat stress in particular. This scholarly inquiry contributes to the body of knowledge on visual climate communication from a practice-based, urban-specific approach to advance the visual communication of climate stress at the local scale.

# 3 Methodology

## 3.1 Theoretical Paradigms

This research aspires to understand the role of photographic images in communicating urban climate risks and vulnerabilities, particularly urban heat Stress, in day-to-day life. It also involves photographic documentation of urban heat Stress in Germany, to develop into a visual repository. Given the nature of research, this scholarly inquiry draws inspiration from a detail-oriented qualitative methodology like ethnography, mainly from the perspective of Visual Ethnography. The practice based visual ethnography in the digital age of 21st century can be comfortably situated into phenomenological anthropology, spatial theory in geography and to certain extent, theories of practice (Pink 2009; Pink 2012; Pink 2020). Since a large part of my research is related to understanding how people experience, negotiate and deal with climate change induced urban heat Stress, Visual Ethnography situated in phenomenological anthropology provides one of the theoretical frameworks to my research work.

Another theoretical paradigm of this research is the framing theory and framing analysis that has larger implications for creating visual repository of urban heat stress. Framing is an important concept and area of research spanning across many disciplines of social sciences. In its most general sense, Framing refers to "communicative process of sense-making in which some aspects of reality are

emphasized and others are de-emphasized" (Schäfer & O'Neill 2017). The scholarly research in Framing focuses primarily on the text-based communication and there is not enough attention to the visual and multimodal framing, except some exemplary analytical frameworks. Rodriguez and Dimitrova (2011) have developed a four-tiered model of identifying and analyzing visual frames, that applies to any type of visual media content or audiences' perception of that content. I have referred to this model, while analysing the photographs I have captured.
Visual Ethnography is not a linear process and involves combination of methods to reach to results and analysis. A schematic diagram depicting the flow from methods to results, helps explain the methods used at various stages of research. Description follows in further section.

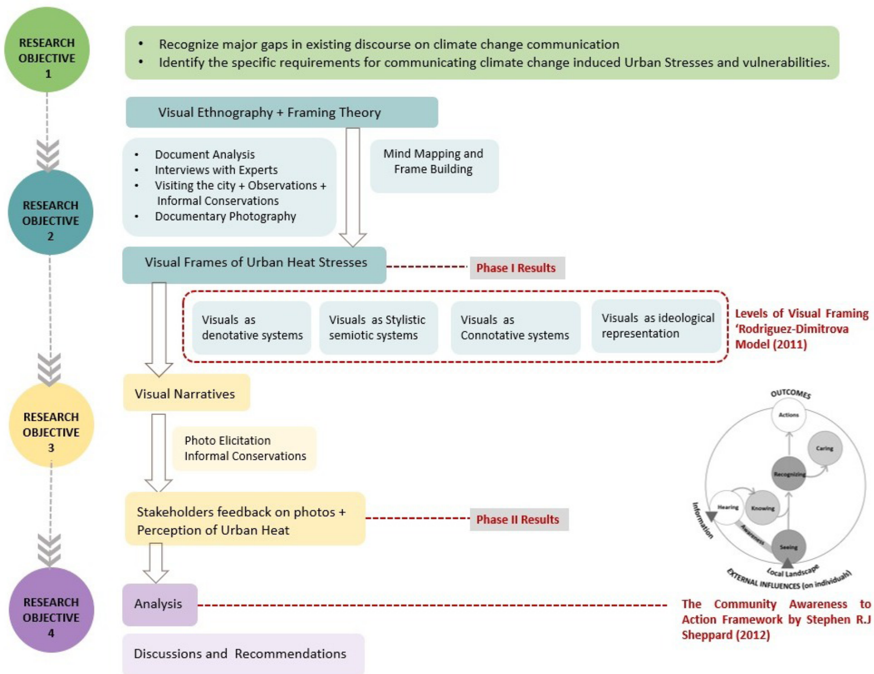


**Figure 1. Schematic Diagram depicting flow from methods to results**

## 3.2 Planning the Visual Research

The very heart of visual research is Ethnographic fieldwork which is a unique and personal experience. Though visual ethnography has a set of methods available to all the ethnographers, the context of the research and different circumstances demand using either a combination of methods or innovative use of methods, to produce knowledge. My approach and choice of methods was shaped by following factors.

#### 3.2.1 Field Location or Selecting the Cities for Visual Documentation
Research publications and climate projection studies about heat stresses in Germany, published by Deutscher Wetterdienst (DWD) or the German Weather Service and comprehensive analysis of urban climate studies in German cities helped me zero on the 'Upper Rhine Valley' cities of South West Germany that are the warmest in the country. Specific city profiles obtained through newspaper archives and city-council reports were helpful to select cities like Frankfurt, Stuttgart and Ulm.

#### 3.2.2 The Opportune Time Frame and Micro-locations for Visual documentation
Weather reports and weather projections by DWD and by web-portals like accuweather and a daily assessment of weather forecast in Frankfurt, Stuttgart and Ulm led to decide that month of June and July would offer maximum heat Stress in these cities. A combination of Interactions with Experts, Informal Conversations with people associated with these cities (for example tapping social networks of friends, colleagues or their friends living-studying-working there), YouTube videos, podcasts, films about the cities helped me identify urban neighbourhoods or micro-locations for visual documentation.

#### 3.3.3 Interaction with Experts
From Europe's first ever Chief Heat Officer to academician-practitioners in Climate Journalism Network, I interacted with a wide range of highly influential stakeholders, that helped me develop major insights for photographic work and proceed with visual documentation.

#### 3.3.4 City-Visits, Observations, and Informal Conversations
I visited Frankfurt between 11 June to 18 June and Stuttgart-Ulm-Munich between 7July -10 July, when the maximum temperatures were at 30°C or more. Before taking my first picture in Frankfurt, I collected richer local nuances through informal conversations and observations.

### 3.3 Documentary Photography
This research uses documentary photography style to capture the perceived impact of heat Stress on people, across different urban locations. I focused more on Frame-building or composing the picture through different elements that indicate or give a sense of heat. This contributed to building the visual repository, as envisaged in research objectives.

Using the four tier, 'Levels of Visual Framing' model given by Rodriguez-Dimitrova (2011) I interpreted visual frames, reorganised them in visual narratives and presented to people through photo-elicitation workshop and informal photo elicitation conversations.

### 3.4 Photo Elicitation
Photo-elicitation is an effective way of using photographs to interview people, to bring out the deeper, richer insights. The word elicitation may suggest extracting

information from the participant but Sarah Pink (2020, pp 92-93) goes beyond the process and looks at the photo-interviews as an activity "informed by the ideas of inviting, co-creating and, making knowledge with photographs rather than the notion of eliciting knowledge from respondents through them."

I conducted one full-fledged photo-elicitation workshop with the members of Green Party, Dresden Unit. I conducted informal photo-elicitation conversations with several urban-practitioners like Urban Planners, Environmental Engineers, Urban Designers and Landscape Architects in Dresden.

### 3.5 Field-based Improvisation: Photo-Exhibition and Photo-Display

While I was coordinating for photo-elicitation session with the members of Green Party, two opportunities came my way unexpectedly. First was a chance to display my photographs at a workshop themed around 'Urban Climate Change and Nature Based Solutions' and second was an invite to organize a full-fledged photo-exhibition of Urban Heat Visuals in the Green Party Office at Dresden. This was never a prescribed method in my research design but it aligned with my methodology very well. The method helped me learn more about the perceptions of the viewers and audience frames. The results are presented in the following section.

## 4 Results and Analysis

### 4.1 Phase I Results: Visual Frames of Urban Heat Stress

The first set of results is a collection of photographic visuals, more specifically visual frames, depicting different situations. The visual frames are part of a visual repository of different dimensions of urban heat stress. Presented below is the representative sample from the visual repository.

**Figure 2. Visual Frames**

The composition of these visual frames implies the heat stress. However, further visual analysis of the frames using the four tiered 'Levels of Visual Framing' model helps develop nuanced interpretation and arrange these frames in virtual narratives. The model was developed by Rodriguez and Dimitrova (2011) in order to bring more clarity on how to identify visual frames, how to analyze the assigned meanings to visual depictions and seek help in visual analysis and meaning making. The four levels of visual framing namely visuals as Denotative Systems, Visuals as Stylistic-Semiotic Systems, Visuals as Connotative Systems and Visuals as Ideological Representations provide a coherent and multi-layered understanding of the visual frames. I used these framing levels- not necessarily in the same order they are presented- to analyze the visual frames captured so far and developed a coherent categorization of the visuals. The major outcomes of the analysis are as follows:

- The visual frames of urban heat stress can be best interpreted using the third level of framing, 'Visuals as connotative systems.' Heat is intangible, one cannot see the heat but can only experience it. How an individual senses the heat can best be understood by the objects used to negotiate with the heat and in that process, the objects assume an indicatory role, just like a symbol. The example of such symbolization is the presence of water as coolant for distraught people. The numerous ways water is used to negotiate with the heat, assigns a context-specific and symbolic meaning to water, which indicates presence of heat.
- 'Visuals as denotative system' or the first level of framing talks about meaning-making through presentation of visuals with texts, captioning or groupings. The concept of applying Gestalt principle of proximity and similarity can be used to group the images for presenting to different stakeholders.
- The second level of framing- 'Visuals as Stylistic-Semiotic Systems'- talks about subject behaviour, which implies that the human actions and poses in the frame facilitate the interaction between the viewer and people shown in the images. The 'subject behaviour' depicts the heat stress in a vivid manner.

Based on this analysis, I grouped and reorganized the visual frames to develop thematic or virtual narratives. Virtual narratives are groups of visual frames that narrate a story together or have similar visual elements to express an idea, more vividly and effectively. The examples of visual narratives are 'People Actively Seeking Shade', 'People negotiating with Heat', 'Vulnerability to Heat Stress' etc.


**Figure 3. Visual Narrative -People actively seeking shade in cities**


**Figure 4.Visual Narrative-People Negotiating with Heat at Water Places**

The visual narratives and a few Visual frames were used for Photo-elicitation workshop, exhibition and displays to understand people's response to the images. In photo-elicitation workshop, the visuals were shown to members of the Green Party and Urban Practitioners (Urban Planners, Landscape Architects, Environmental Engineers etc.), their response was elicited in focused group discussions. The photo-display and Exhibition in Dresden were meant for general public, where viewers response was collected through participant observation and informal conversations.

## 4.2 Phase II Results: Viewers Response to the Photographic Images

- The visuals invoked a sense of increasing heat or urban neighbourhoods getting warmer, among the viewers. People reacted expressing concern as well as a sense of better familiarity with the experience of increasing heat in daily life.
- Visual-frames of Concrete Spaces or Visual narratives involving 'Glass-facades and Buildings' did not generate any response from general viewers, though the pictures resonated exceptionally well with urban practitioners.
- The urban practitioners as well as green members mentioned that the visuals pointed out a lack of greenery in many parts of urban landscapes, especially around concrete spaces and it could be addressed through carefully thought landscaping or urban designs.
- Many of them expressed concerns about inadequate drinking-water stands or insufficient cooling zones in public places with more daily footfall.
- The heat stress for children was a major point in the Focused group discussion. Participants highlighted the urgent need to train children to speak about the heat-stress experienced by them.
- The informal conversations with the general public brought out nuances of visual frames. Many viewers expressed familiarity with the situations depicted (People actively seeking shade or Splashing water on body) or the locations shown in the visuals (in the market, at the bus-stop) and expressed an increasing frustration with the heat stress.

# 5 Discussion

The visual frames and visual narratives of urban heat stress, as presented in this research, lead to several takeaways. A wholistic discussion on the results follows ahead:

## 5.1 The Missing Link in Climate Change Communication

The challenge ahead of using visuals effectively is the image problem characterised by a restricted set of visual associations with climate images in the public mind. The image problem looms over the visual communication. The image problem has its roots in a deeper, more serious 'Perception Problem' stemming from the disconnects or gaps in people's perception about climate change. The perceptual barriers prevent people from seeing climate change as a serious problem or an issue that requires urgent action (Sheppard 2012). Under-addressing the perception problem is a serious missing link in climate change communication, more so in the visual communication. Sheppard (2012) argues that visual media can be used innovatively and effectively to create more awareness among people and address perpetual barriers. The visual repository of Urban Heat Visuals is an attempt in the same direction.

## 5.2 Repository of Urban Heat Stress Visuals

The idea behind developing a repository of visuals is to create a collection of visuals that would capture maximum possible dimensions of urban heat stress, their impact on people's day to day life, the associated vulnerabilities and adaptation solutions. The repository was not to include the stock images or existing body of work but the visuals were thought to come through first-hand, on-field photography, using documentary style. Unique features of the repository are as follows:

- People centric visuals
- Everyday Urban Experience of Living with Heat
- Everyday Vulnerability to Extreme Heat
- Different Layers of vulnerability based on age, gender, and socio-economic profile
- Peoples Agency and Coping with Heat, with individual strategies covered visually
- Use of Documentary photography

This repository can richly complement the existing image libraries like 'Climate Visuals' curated by the UK based organization Climate Outreach, that has a sparse representation of urban heat stress. The repository also brings to fore urban heat stress in everyday life as opposed to a misleading and problematic conceptualization of heatwave, depicted as 'Fun in the Sun' by the popular print media in Europe (O'Neill et al. 2023.)

Speaking about limitations, the repository does not feature visuals of 'Indoor thermal stress'. This could be attributed to the time-constraints as well as the lack of access to homes and personal spaces, on the count of privacy concerns.

## 5.3 The Significance of Documentary Photography

Urban heat stress is a difficult challenge to depict in photographic form because nature of heat is intangible, the audience frames of urban heat stress are not yet established in peoples mind and urban climate change is a specialized topic that needs a nuanced treatment. The fast-paced nature of photojournalism hardly allows time to develop this understanding about the field or the frame-building around urban heat stress. On the contrary, documentary photography allows the requisite time-frame for registering consistent observations over a longer period and understand the unfolding of urban heat stress at ground level.

## 5.4 Towards enhancing Urban Resilience

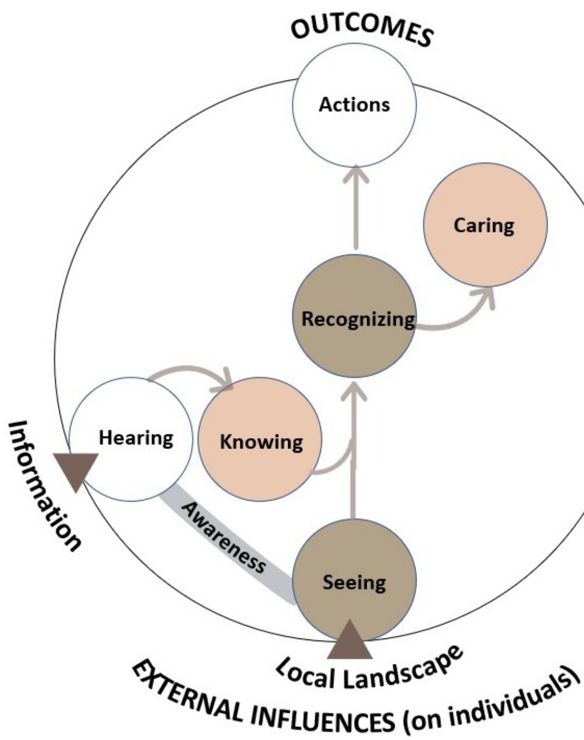


**Figure 5. The Community Awareness to Action Framework, Sheppard 2012**

Resilience is highly associated with people's engagement in climate action. The Community Awareness to Action Framework (Sheppard 2012) explains ways of creating awareness about climate problems. Visuals of Urban heat Stress experienced by people can help them see Urban Heat Stress in a local, visual and connected manner. Visual frames have the potential of shifting the level of awareness from 'seeing' to 'recognizing' and eventually leading to 'caring' about urban heat stress and acting on the same. The transition from seeing to action in local landscape can be achieved with the help of visual communication through documentary photography.

As shown by this research, visual narratives open myriad avenues of engagement with key stakeholders through photo-exhibitions, photo elicitation workshops and informal conversations. However, identifying the right audience and selecting right visuals are the most crucial factors for an effective communication.

# 6 Conclusion and Recommendations

Urban climate change communication involves multiple actors like media, urban practitioners, Climate City Networks and City Councils, Advocacy NGOs, and climate educators. These actors continuously communicate with each other and with their target audience. Visual communication is an integral aspect of their routine communication practice. Following is a set of recommendations developed for these stakeholders, for effective communication.

- Establish the idea of urban heat using photographic visual frames
- Use documentary photography to create visual frames of urban heat stress
- Keep it Local, keep it Connected
- Establish Peoples Agency through Visuals
- Create visuals of vulnerability to urban heat
- Develop nuanced visuals of indoor heat stress and thermal discomfort
- Sensitize the Influencers using Visual frames
- Integrate Urban Heat Visuals with the Intra-actor, Inter-actor communication
- Use urban heat visuals for specific educational purposes.

## 6.1 Future Scope

This research has contributed to creating a unique visual repository of urban heat visuals, in turn establishing the potential of visual narratives to engage with key stakeholders and build their perception and awareness about nuances of urban heat stress. The visual communication approach shown in the research is highly relevant for the sensitization, training, and capacity-building of Urban practitioners across city levels. The research presents numerous possibilities of effectively integrating photographic visuals in strategic communication, organizational communication, and rhetoric studies within the larger domain of climate change communication.

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HAMEED, MAIHA

# Mapping Thermal Hotspots in Malé, Maldives:

## Assessing the Relationship Between Urban Heat Islands, Climate, and Heat Risk for Sustainable Urban Planning

*This study supports climate-conscious urban development in greater Malé, Maldives, based on local microclimate characterizations. It investigates temperature variations within Malé and Hulhumalé phase 1 to inform climate-resilient urban strategies. Data was collected in March 2023 through mobile transects and fixed sensors and analyzed on ArcGIS Pro. The findings indicate that intra-urban temperature patterns in the cities are influenced by, but not limited to, factors such as land use, cloud cover and wind. An Urban Heat Island effect is also evident, with cities recording higher night temperatures than nearby Hulhulé. It is a phenomenon which follows urbanization, where cities are generally warmer than their surroundings. Both cities also experienced an urban cool island effect in the early mornings, with maximum temperatures occurring later in the day compared to Hulhule'. Cloudy days noted slightly higher temperatures, indicating heat entrapment. Calmer nights were slightly cooler than windy nights, indicating a radiative cooling effect. Certain land uses display higher temperatures than residential areas, indicating their impact on intra-urban heat patterns. However, at night, impacts of land use on temperature variations appear to be low suggesting that the influence of land use on temperature was more pronounced under solar loading. Heat Index consistently signaled 'extreme caution,' emphasizing the need to address impacts of outdoor humidity on thermal comfort. Although addressing extremely high outdoor humidity presents a greater challenge than reducing temperature, the study suggests interventions to integrate heat-resilient and targeted green infrastructure into national plans as effective approaches.*

# 1 Introduction

The Maldives is experiencing noticeable shifts in response to changing climate patterns. Specifically, the capital city of Malé has seen a consistent annual temperature increase of 0.17ºC (Ministry of Environment, Climate Change, and Technology 2020). According to high-confidence projections from the Ministry of Environment, Energy, and Water (2007), maximum daily temperatures are expected to rise by 1.5ºC by the year 2100. Moreover, this projection suggests that a rare event characterized by a maximum temperature of 33.5ºC which occurs once every 20 years, is predicted to recur every three years by 2025.

The latest IPCC Assessment Report (AR6) reinforces this concern: South Asia faces heightened humid heat stress with greater severity and frequency (Simath & Emmanuel 2022). Matthews (2018) highlights that the study of heat and humidity dynamics uncovers a potential future in which substantial regions of the world could become too hot and humid for human comfort. While more optimistic scenarios offer some relief, the consequences for society, particularly in densely populated low-latitude areas remain severe.

Although research on thermal comfort trends in this region is limited (Simath & Emmanuel 2022), a crucial link emerges between heat stress and urbanization. Urbanization, coupled with climate change exacerbates urban heat stress and exposure, necessitating adaptive measures (Yang, Zhao & Oleson 2023) and resulting in increased deadly heat exposure (Lohrey et al. 2021). Urbanization also gives rise to the urban heat island (UHI) effect, as defined by Oke (1987) where cities consistently maintain higher temperatures than surrounding rural areas. While the UHI effect can yield both positive and negative outcomes in temperate climates, its predominantly negative impact is felt in equatorial tropical climates (Emmanuel 2010).

The presence of UHI in Malé hinges on multiple factors, such as urbanization, vegetation, local meteorology, and built environment. Notably, no UHI research in the Maldives has been published as of 2018 (Kotharkar, Ramesh & Bagade 2018). To determine if it experiences a UHI effect, a comprehensive temperature measurement campaign is required, given its potential impact on a substantial portion of the Maldivian population, as 41% reside in the capital region (Maldives Bureau of Statistics 2022).

While the climate significantly shapes Maldives' policies, existing knowledge primarily focuses on regional impacts (Ministry of Environment and Energy 2015). Therefore there is a gap in understanding these impacts at a city or country level. While UHI mitigation strategies have yet to significantly influence urban development policies (Simath & Emmanuel 2022), it's crucial that efforts to mitigate urban warming align with global warming policies. To effectively address cooling interventions in a warming climate such as that of the Maldives, an approach to comprehend the impact of local urban heat is necessary (Pfautsch, Wujeska-Klause & Walters 2023). This approach contrasts with conventional regional temperature projections but is important to enhance daily human experiences. This study seeks to provide theoretical support for climate-conscious urban development by characterizing the intra-urban climate and investigating urban heat islands and potential risks in greater Malé. It aims to integrate climate change impacts into mitigation strategies, enhancing urban resilience and sustainable planning. To achieve these goals, the study includes objectives such as mapping temperature variations across urban areas, identifying factors influencing UHI intensity, analyzing potential heat risk impacts of climate change, and proposing interventions to mitigate both UHI and associated heat risks.

# 2 Background

The background review aimed to link global UHI studies to the Maldivian context, to back research goals through literature, and to justify the research design.

**Preliminary information from selected papers were grouped into three themes:**

- the role of weather,
- impact urban morphology on UHI, and
- UHI investigation methods.

Notably, the analysis conducted by Wu and Ren (2019) highlights a shift in the focus of UHI research from atmospheric science to urban infrastructure over the decades. This shift likely reflects a growing emphasis on human influence and neighborhood-scale climatic urban design with a particular focus on health-related aspects.

## 2.1 The role of weather conditions influencing UHI

The well-documented UHI effect, characterized by cities being warmer than rural areas, results from various factors, including solar radiation (Oke 2002), cloud cover (Anjos & Lopez 2017), and wind patterns (Oke 1973). Wind plays a pivotal role in influencing UHI intensity, as it can either dissipate urban heat or affect wind speed and pressure (He 2018). UHI reduction also becomes feasible when wind speed surpasses a population-dependent threshold (Park 1986; Oke 1973).

Wind direction is crucial in UHI dynamics, as demonstrated by variations in Crete, Greece, by obstructed northerly versus unobstructed westerly winds (Kolokotsa & Karapidakis 2009). Similarly, in the Maldives, the monsoonal wind reversals contribute to the two distinct seasons, affecting ambient temperatures and humidity levels. These weather patterns are closely tied to rainfall patterns, a factor known to influence temperature and heat stress, aligning with previous studies on relative humidity and UHI by Chow and Roth (2006) and Zhao et al. (2014).

Mahlia and Iqbal (2010) establishes a connection between high relative humidity and rainfall in Malé, highlighting the significance of humidity in the region. Due to the equatorial climate, temperature fluctuations are minimal (Mahlia & Iqbal 2010), but precipitation amplifies humidity levels, exacerbating heat-related risks. Additionally, cloud cover may play a critical role by blocking and trapping radiation, as highlighted by He (2018), Oke (2002), and Yow (2007), which has implications for UHI dynamics.

Furthermore, the presence of aerosols in the atmosphere can impact UHI. Stanhill and Kalma (1995) have found that aerosols tend to decrease short-wave radiation, but this effect can be offset by greenhouse gases. It is worth noting that Malé experiences regional pollution, as reported by Budhavant et al. (2015), which may further influence UHI (He 2018).

## 2.2 Urban morphology in UHI mitigation and adaptation

Urban morphology plays an important role in the formation of UHI as discussed in literature (Boukhabla et al. 2013), underscoring the need for UHI mitigation and adaptation strategies. In the case of island cities like Malé and Hulhumalé, which are surrounded by the sea and constrained in space, the influence of street attributes on micro-climate and UHI mitigation becomes evident (Datta et al. 2016).

Factors such as density (Cecinati et al. 2019) and land cover (Emmanuel 2003) play a critical role in shaping anthropogenic heat, energy retention, and evapotranspiration, all of which directly impact the formation of UHI (Zhao et al. 2014). Concrete surfaces from urban growth reduce evapotranspiration due to a lack of green spaces.

Increasing vegetation to over 35% and reducing building density can also effectively cool street canyons (Sun 2011). In Malé, where park space accounts for only 6% of the urban area (Malé City Council 2019), the green-to-street ratio remains uncertain or uncalculated. While urban cooling studies tend to favor green spaces over water bodies (Qiu et al. 2017), a proximity to the sea also has a discernible impact on urban climate (Emmanuel & Johansson 2006), introducing variations in the effects of green spaces.

However, it is important to recognize the limitations of green infrastructure in humid tropics (Stepani & Emmanuel 2022). In compact cities like Malé, form-based shading emerges as a more effective approach (Stepani & Emmanuel 2022). To mitigate UHI, strategies generally recommend focusing on increasing evapotranspiration, or enhancing albedo (Akbari & Kolokotsa 2016), and promoting the use of reflective materials. Given that residential areas dominate Malé at 70% (Malé City Council 2019), addressing their intra-urban temperature contributions becomes a crucial aspect of mitigation efforts.

### 2.3 UHI investigation methodologies

UHI investigations traditionally center on climatological observations and comparisons of minimum temperature differences between urban and rural areas. Various methodologies are employed, including remote sensing (Voogt & Oke 2003), modeling (Xing et al. 2017), and mobile traverse studies (Rodríguez et al. 2020).

Remote sensing, utilizing aerial and satellite imagery for temperature data collection, offers broad coverage and consistency (Liu & Li 2018). However, it has limitations like susceptibility to weather disruptions and recording surface temperatures instead of canopy air temperature (Azevedo et al. 2016).

Models, ranging from building to meso-city scales, encompass spatial regression techniques (Xing et al. 2017). Although integrating urban canopy models into regional climate models effectively simulates UHI (Masson 2006), data scarcity in urban areas presents a challenge (Johansson et al. 2014).

With research shifting towards UHI mitigation, measurement methods remain vital (Sun et al. 2019). Mobile traverse studies provide precise urban environment readings (Pfautsch et al. 2023) and overcome limitations of fixed meteorological stations in non-representative locations (Shih & Kistelegdi 2017). Combining GPS mobile observations with ground monitoring proves cost-effective for UHI monitoring in developing countries like the Maldives (Kotharkar et al. 2018). Ultimately, method selection hinges on research goals, scale, and available resources, impacting accuracy and reliability. Given the practical constraints, the mobile traverse technique is well-suited and offers replication potential across the country. No universally optimal method exists, emphasizing the importance of aligning methodology with study objectives and available resources.

## 3 Methodology

In light of the above review, a link can be established between thermal comfort and factors such as the built environment, surface attributes, and local climate. Building on this premise, this study aims to validate whether the greater Malé region, characterized by high urban density and a warm climate, indeed exhibits significant intra-urban variations or UHI effects. Additionally, it seeks to explore whether specific land use and city form contribute to elevated heat risks. These hypotheses underpin the research framework.

The central focus of this study involves employing mobile surveys through predefined routes known as ‘transects’ to estimate urban temperatures reproducibly. This approach is derived from the comprehensive framework developed by Rodríguez et al. (2020). A mixed-methods research design combines quantitative techniques, such as temperature measurements and statistical analyses, with qualitative methods, including document analysis (Figure 1)

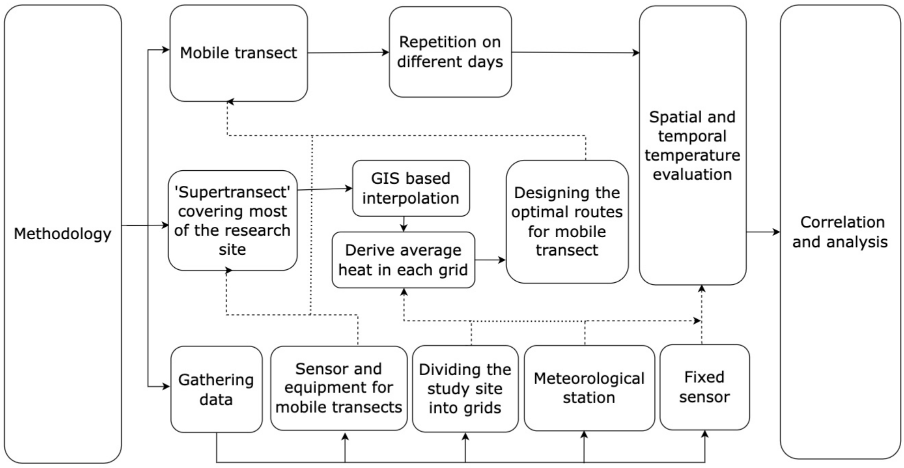


**Figure 1. Research methodology adopted from Rodriguez et al. (2020)**

## 3.1 Research Objectives

The methodological approaches used to address the research objectives are as follows:

- **Mapping Temperature Variations:** Objective one entails creating high-resolution temperature maps across diverse urban areas using representative mobile transects. This captures nuances in intra-urban temperature differences.
- **Understanding UHI Formation:** Objective two involves analyzing temperature data from mobile transects and correlating it with urban indicators like land use and population to comprehend factors contributing to UHI formation.
- **Assessing Climate Change Impacts:** Objective three examines the impact of climate change on urban heat risks by analyzing UHI patterns, intra-urban temperatures, and their links to land use and socio-economic factors. Vulnerable areas prone to heat stress are identified, informing urban climate policy.
- **Mitigation Strategies:** Objective four aims to identify interventions to mitigate UHI and associated heat risks. Decision support tools, such as heat maps, aid policymakers and urban planners in implementing effective measures.

### 3.2 Study Site

The research takes place in two key locations: Malé, the capital city of the Maldives, and Hulhumalé phase 1, a reclaimed and planned city. The region is particularly significant locally as it experiences high population density driven by urbanization and migration.

### 3.3 Designing Mobile Transects

Mobile transect routes are determined using data from a single 'supertransect', covering the entire study area. This route involves a motorcycle equipped with the mobile monitoring station. Collected temperature and humidity data are used for spatial interpolation, generating heat maps illustrating temperature distribution. The optimal mobile route is selected based on temperature ranges within grid cells.

### 3.4 Mobile Monitoring Station

A radiation shield made from PVC pipe housing a TinyTag TGP-4500 datalogger, is mounted on a motorcycle. The datalogger records temperature data, and the shields positioning minimizes heat from the engine. An iOS GPS app ensures precise coordinates during the transect, validated using Google Maps.

### 3.5 Data Collection and Calculation

Twelve mobile transect observations were conducted, six at 4AM (just before dawn) and six at 1PM (just after midday) on the same day (Heat Index is calculated from data collected by fixed sensors using the Rothfusz regression equation below:

$$HI = c1 + c2T + c3R + c4TR + c5T2 + c6R2 + c7T2\,R + c8TR2 + c9\,T2R2$$

**Where:**

HI = Heat Index in °F
T = ambient air temperature in °F
R = relative humidity (%)
c1 = -42.379
c2 = 2.04901523
c3 = 10.14333127
c4 = -0.22475541
c5 = -6.83783 x10-3
c6 = -5.481717 x 10-2
c7 = 1.22874 x 10-3
c8 = 8.5282 x 10-4
c9 = 1.99 x 10-6

# 4 Results

## 4.1 Supertransect Measurements and Heat Map

The data collection operation was executed on March 3rd and 4th, 2023. The focus was to record air temperature, humidity, and dew temperature from 22 locations in Malé and 17 from Hulhumalé phase 1. This data collection window was strategically set from 4:00 AM to 5:00 AM, effectively mitigating the influence of daily temperature variations brought about by solar radiation. By selecting this timeframe, the impact of dawn at 6:17 AM was minimized.

## 4.2 Heat Cluster Analysis and Optimal Mobile Transect

The study area was systematically divided into grids of 200m by 200m in accordance with Rodríguez et al. (2020). It yielded 48 grids in Malé and 52 in Hulhumalé Phase 1. Leveraging the Inverted Distance Weighting (IDW) interpolation tool in ArcGIS Pro, these grids were categorized into four distinct temperature clusters. Cluster 1, represented by yellow, was the coolest, while cluster 4 (red) represented the warmest temperature range (Figure 2)).

A notable distinction emerged in the temperature ranges between Malé and Hulhumalé. In Malé, the temperature span in cluster 1 ranged from 28.148ºC to 28.273ºC, and for cluster 4, it ranged from 28.359ºC to 28.484ºC. In contrast, Hulhumalé experienced relatively lower temperatures during the same period, with cluster 1 ranging from 27.324ºC to 27.431ºC, and cluster 4 spanning 27.523ºC to 27.581ºC.

The focus of the above supertransect was placed on figuring out an optimal mobile route in order to conduct the study within a short time frame and for ease of replication. Consequently, a selection of 10 grid cells was made for the mobile transect in each city, incorporating grids from each cluster while considering cluster frequencies (Figure 2).

## 4.3 Mobile Transect Routes and Temperature Analyses

The optimal mobile transect was executed eight times in March 2023. Each site underwent mobile transect measurements at two distinct time points within a 24-hour cycle. The first measurement occurred at 13:00 h, just post midday, and the second at 04:00 h, right before dawn. This strategy was implemented to capture two significantly different conditions. Notably, each measurement session was accomplished within an hour or less. The results stemming from these mobile measurements were processed into a heat map using the Inverted Distance Weighting approach within ArcGIS Pro (Figure 3).


**Figure 2. Grids displaying heat cluster categories and the optimal mobile route for Malé (above) and Hulhumalé Phase 1 (below). Ten white circles indicate the measurement points connected by a dotted line.**

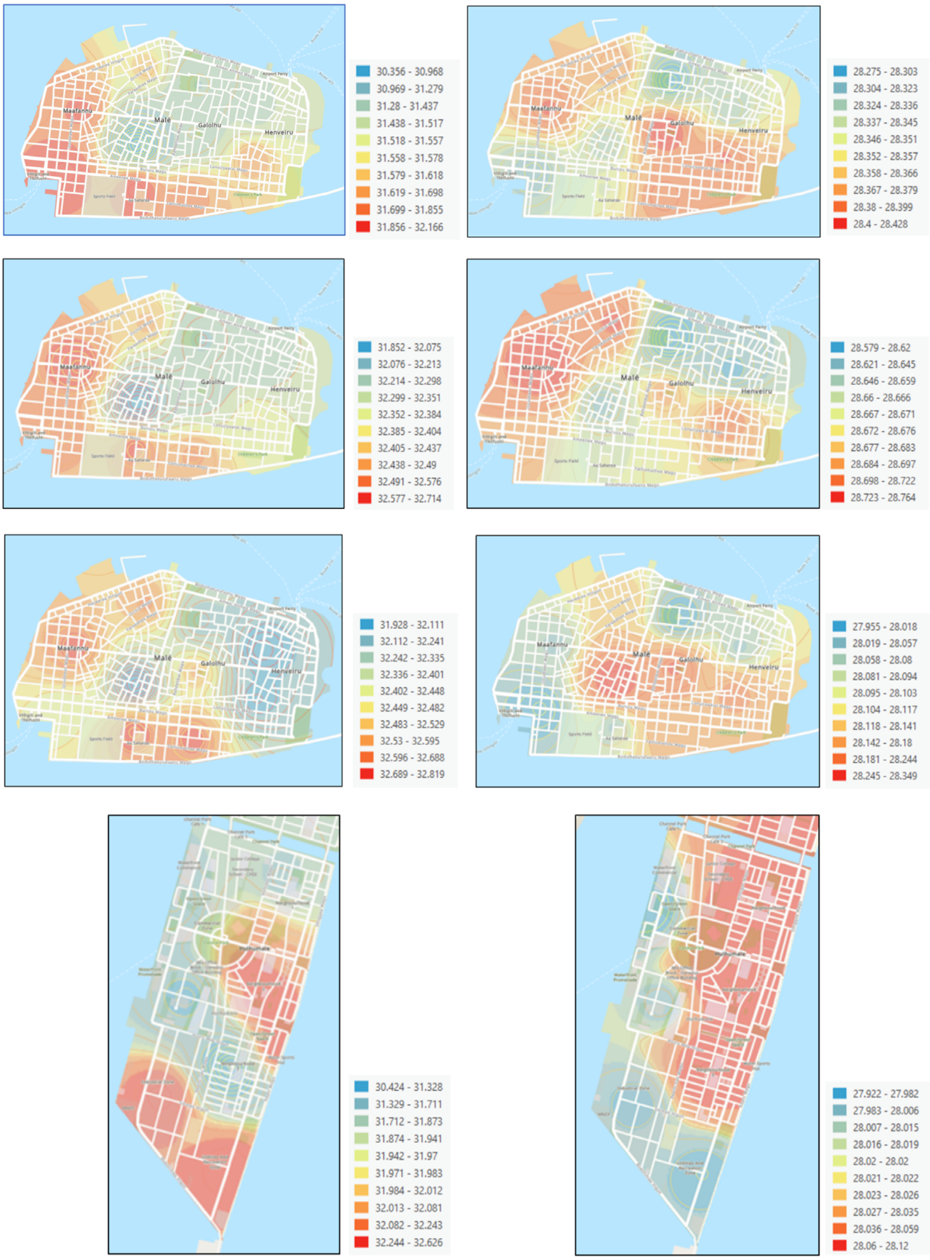


**Figure 3. Heat maps for Malé and Hulhumalé phase 1 at 4am (left) and 1pm (right) displaying the intra-urban variation in temperature**

Further analysis of Malé routes were carried out based on cloud cover and wind speed (Figure 4). The study classified Malé routes 1 and 2 to observe temperature variations under differing cloud covers in consistent wind speed conditions. Malé routes 2 and 3, on the other hand, facilitated a comparison of temperature differences with varying wind speeds while observing similar cloud cover conditions.

Temperature data gleaned from Route 1 in both Malé and Hulhumalé were also analysed against their respective land use categories to shed light on distinct variations in urban temperature patterns. While the categorizations of each city varied in accordance with official land use map categories, all zones lacked comprehensive explanations for their assigned categories in the maps. Consequently, aerial images were employed to elaborate on these categories.

In Malé, daytime readings revealed that utility, municipal, institutional, and community areas presented higher temperatures compared to residential zones. However, pre-dawn temperatures in Malé exhibited a general low across all land use categories, all at a similar temperature range. This consistency hinted at a uniform nighttime cooling effect across the city. Parallel findings emerged in Hulhumalé, where daytime measurements pointed toward elevated temperatures in industrial, educational, sports, and recreational zones, with residential areas experiencing the lowest temperatures. At night, temperatures uniformly dipped across all land use categories in Hulhumalé, mirroring the cooling effect seen in Malé.

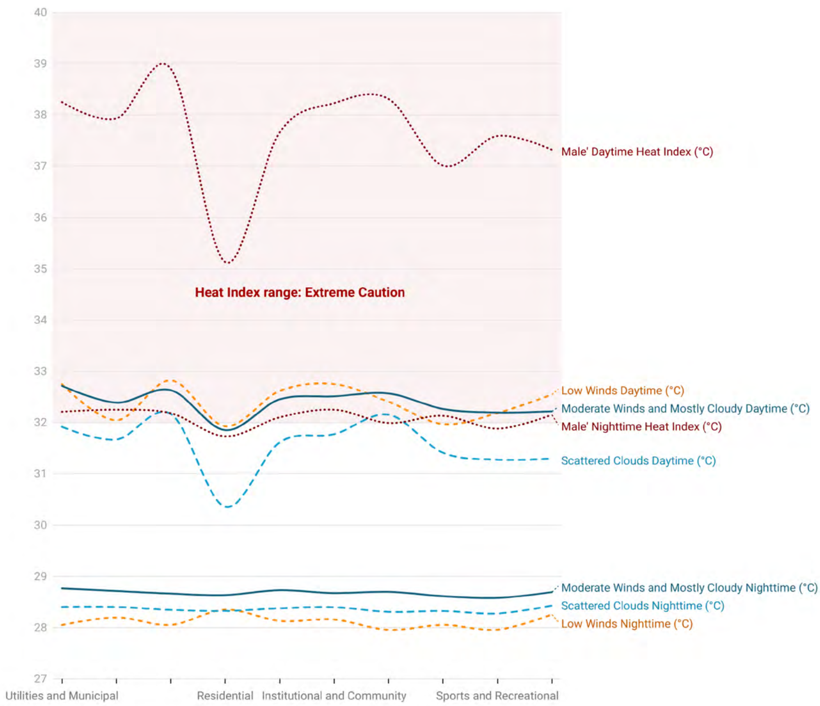


**Figure 4. Comparison of temperatures under different cloud and wind conditions, and heat index across different land use categories in Malé.**

An analysis into potential correlations between temperatures and population density was carried out using ArcGIS Pro by utilizing the ESRI webmap of planned population density based on residential parcel sizes (Mahaath 2022), coupled with a spatial heat map for Hulhumalé Phase 1. The analysis aimed to identify spatial patterns by employing spatial statistics tools such as Spatial Correlation Analysis (Moran's I) and Hot Spot Analysis (Getis-Ord Gi*).

The absence of statistically significant hot spots suggested a lack of clusters characterized by high temperatures or population density. Conversely, the presence of cold spots indicated clusters of lower temperature or density. These cold spots were represented with varying colors, each corresponding to different confidence levels (99%, 95%, 90%). Notably, areas depicted in white on the Hot Spot Analysis map showcased non-significant clustering.

Collectively, these analyses pointed to positive spatial autocorrelation, implying a tendency for similar values to cluster together. The noteworthy Global Moran's I value of 0.676568 and the significant p-value of 0 affirmed this observation. However, the Hot Spot Analysis yielded no significant hot spots, indicating the absence of clusters with high values. In contrast, the presence of cold spots illuminated areas marked by clusters of low values. Evidently, the clustering pattern primarily revolved around cold spots.

## 4.4 Fixed Sensor and Weather Station Data

To complement the study, additional data was procured by installing fixed sensors in both cities and incorporating information from the national weather station at the airport in Hulhule' located between the cities.

March 2023 witnessed prevailing wind patterns primarily originating from the East, and then from the North East. The study observed limited rainy days but had a notable precipitation event on March 5th with a recorded rainfall of 40mm. Relative humidity levels spanned from 65% to 99%, with the lowest humidity levels occurring between dawn and noon.

A comparison between temperature over time unveiled noticeable patterns between the fixed and national meteorological stations. The meteorology station in Hulhule' exhibited greater temperature fluctuations, characterized by higher peaks and lower lows, indicating more pronounced temperature variations compared to the milder fluctuations recorded at the Malé fixed station (Figure 5). Particularly, nighttime temperatures at the fixed stations were consistently warmer than those recorded at the meteorology station during the same time frame.

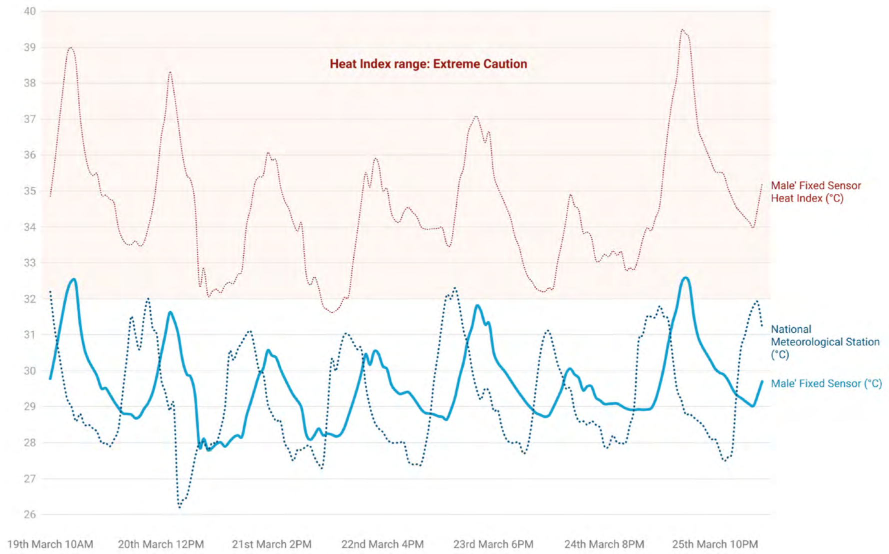


**Figure 5. Hourly temperature trend and Heat Index in Male. Chart illustrates the temperature fluctuations between a fixed sensor in Malé and the meteorological station in Hulhule'.**

# 5 Discussion and Conclusion

During mobile transects, higher temperatures were consistently observed across northwestern Malé both day and night. Daytime temperatures were slightly higher in Hulhumalé than Malé (Figure 3). In contrast, nighttime temperatures were higher in Malé than in Hulhumalé. Malé also exhibited wider temperature ranges, suggesting more fluctuation attributable to diverse urban microclimates within.

Weather conditions also appear to play a role. Prevailing winds from the East and Northeast helped disperse heat, resulting in cooler temperatures in northeastern Malé. Cloud cover was observed to trap heat, leading to warmer temperatures both day and night. Wind patterns further influenced temperature variations, with low wind speeds contributing to higher daytime temperatures, while moderate winds helped moderate temperature fluctuations.

Land use influenced daytime temperatures, with areas officially zoned as utilities, institutional, and community activities displaying higher temperatures. Whereas at night the temperature is even across all land use types in both cities, indicating a consistent and uniform cooling effect. Population density seemed to have a more complex effect, as there were no significant correlation observed between high population density and high temperatures, but rather, cold spots were associated with lower density and lower temperatures. However, a more comprehensive dataset for population density is required to be conclusive.

Analysis also revealed that the 'rural' meteorological station at the airport peaked between 6am and 10am, while urban stations peaked between 12pm and 4pm (Figure 5). This is consistent with the trend of urban areas reaching peak temperatures later rural areas, since a deeper atmospheric boundary layer over urban areas result in the formation of urban 'cool islands' early in the morning (Earl, Simmonds and Tapper 2016). However at night, urban temperatures consistently remain 0.5ºC to 1ºC warmer than rural temperatures. This data highlighted the presence of a UHI effect, with the cities experiencing warmer nights than the nearby less-urbanized airport island. Although Sky View Factor (SVF) was not calculated, Malé likely had lower SVF with its narrower streets and taller buildings, exacerbating the nighttime heat island effect. In contrast, Hulhumalé likely offered better thermal comfort at night thanks to a higher SVF. Urbanization, including densely built areas and materials like concrete that enhance heat retention, can also explain these disparities (Acosta et al. 2022), as well as thermal inertia, the ability of materials to retain heat, can also influence this phenomenon (Lizarraga & Picallo-Perez 2020).

## 5.1 Heat Risk and Interventions

The Heat Index (HI), which factors in temperature and humidity, is a crucial gauge of how heat affects humans (National Weather Service NOAA 2023). In Malé, the HI consistently falls within the range of 'extreme caution', even at night, signaling potential fatigue risks (Figure 4). Similarly, Hulhumalé experiences levels of 'extreme caution' and 'danger', highlighting potentially significant heat-related concerns. Specific zones as 'utilities and municipal' in Malé, and categorized industrial, educational, sports, and recreational areas in Hulhumalé, in particular exhibit higher heat indices, suggesting a need for design changes to improve thermal comfort in those zones.

The impact of heat already restricts some lifestyles, curtailing outdoor activities in the Maldives (Rasheed 2012), and affects educational experiences as heat disrupts learning environments especially in outer islands (Kagawa 2022). In neighboring Sri Lanka, extreme heat stress is on the rise due to evolving heat dynamics (Simath & Emmanuel 2022), while Maldives itself faces escalating temperatures under the Representative Concentration Pathways 4.5 and 8.5 (Asian Development Bank 2020). As temperatures continue to climb, human adaptability to heat diminishes (Matthews 2018).

These anticipated temperature trends also have implications for urban infrastructure and energy consumption. High-rise buildings contribute significantly to energy demand, often met by diesel generators and enhancing energy efficiency can play a vital role in cost reduction. On an economic front, labor capacity reductions in the worst-hit regions, like Southeast Asia, become a pressing concern (Matthews 2018).

Managing extreme outdoor humidity is more challenging than reducing ambient air temperature, given that a combination of high humidity with high temperatures intensifies heat perception through heat index values. While urban greening can mitigate temperatures, its impact on heat-humidity indicators remains uncertain (Matthews 2018). The effectiveness of vegetation in enhancing thermal comfort in humid tropics is also debatable (Stepani & Emmanuel 2022). Nonetheless, compared to reflective materials, vegetation proves superior for ground-level comfort as reflective materials lead to increased heat re-radiation on the street (Taleghani 2018).

Since addressing urban heat risks and urban climate is often overlooked nationally in favor of climate change impacts such as vector-borne diseases and sea-surface temperatures, such as that in the National Adaptation Programme of Action (Ministry of Environment, Energy and Water 2007), recognizing these as also urgent concerns represents a crucial first step. Incorporating associated interventions into national action plans offers promise in effectively addressing urban heat challenges. Two key strategies which may be useful to integrate into short-term climate plans are climate-resilient zoning; by applying smart urban design to optimize energy efficiency and regulate temperatures in identified areas, secondly targeted green infrastructure; to implement green interventions in areas with higher temperatures, benefiting thermal comfort and urban design.

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LELEI, NAJMA YUSUF

# Assessing the Influence of Urban Form on the Cooling Impacts of Urban Parks: A Case Study in Glasgow

*The Urban Heat Island (UHI) effect in the UK has raised concerns about sustainable urban development. Research has shown that green infrastructure, particularly urban parks, can effectively mitigate UHI effects by regulating thermal comfort through heat exchange and shading. Previous studies have focused on the cooling effect of urban parks but often neglected the surrounding spatial context. To comprehensively understand this mechanism, a study examined 30 urban parks in Glasgow using Remote Sensing, GIS, and statistical analysis with buffer rings of 150 m and 300 m was undertaken.*

*The study introduced two key parameters: Park Cooling Intensity (PCI) and Park Cooling Distance (PCD) to assess the cooling effect. Park characteristics such as area, perimeter, shape index, and canopy cover were considered, alongside urban form parameters like Mean Building Height (MBH), Floor Area Ratio (FAR), Canyon Aspect Ratio (H/W), and Sky View Factor (SVF) of the surrounding built-up area.*

*Findings revealed that urban parks between 1.7 ha and 6.9 ha provided an average cooling intensity of 1.6ºC within a cooling range of 252.7 m. Positive correlations were observed between park characteristics (area, perimeter, NDVI) and PCI, while shape index showed a negative correlation. Conversely, urban form parameters exhibited negative correlations with PCI, except FAR, which had a positive correlation. This study contributes to our understanding of park cooling effects and offers insights for policymakers to plan urban parks more equitably for climate adaptation on a local scale.*

# 1 Introduction

## 1.1 Rationale

The increasing urbanization trend, with an estimated 68% of the world's population projected to reside in cities by 2050 (UN 2018), is a critical concern in the context of climate change. Urbanization and industrialization have led to significant alterations in land use, land cover, and local climatic conditions, exacerbating the Urban Heat Island (UHI) effect worldwide (Deilami et al. 2017). The UHI effect's adverse consequences include heightened cooling energy consumption, physical discomfort, and even fatalities. Climate projections suggest that if no action is taken, extreme temperatures will surpass current levels in many regions by 2100 (Power & Delage 2019), posing substantial environmental and public health risks.

In the United Kingdom, the growing frequency of heatwaves has raised alarm. In 2022, the UK experienced a record-breaking temperature of 40.3°C, marking the warmest year since 1884, according to the Met Office. Furthermore, Scotland saw a heatwave with temperatures reaching 35°C in the same year, highlighting the increasing heat risk in historically cooler regions due to climate change (Undorf et al. 2020). Therefore, urgent adaptation measures are required to address temperature extremes, particularly in areas prone to frequent heatwaves. Creating cities that are inclusive, safe, resilient, and sustainable is essential for fostering a more comfortable urban living environment.

Green and blue infrastructures are recognized as effective and sustainable cooling strategies and are integral to evaluating urban life equity. Urban parks, play a crucial role in mitigating UHI effects (Chen et al. 2022). While researchers have acknowledged their potential as natural cooling mechanisms, simply increasing the number of large parks without effective planning may not efficiently alleviate urban heating. Urban Park planning is essential because a park's cooling range is significantly influenced by its landscape configuration, especially the extent of impervious surfaces in its vicinity. As the Park Cooling Effect (PCE) depends on both park characteristics and the surrounding built-up area, assessing cooling equity is vital for efficient cooling and environmental justice (Tan & Samsudin 2017).

While numerous studies have independently quantified the cooling effects of parks using various indicators, simulations, and methods, few have considered the influence of surrounding urban characteristics on PCE. Urban areas possess unique infrastructure layouts that alter microclimates within the Urban Canopy Layer (UCL), and different urban forms can impact PCE through radiation transfer and airflow dispersion (Lin et al. 2015). Therefore, assessing the effect of urban form on PCE is essential, particularly in the context of climate change, where climate-sensitive planning has gained increasing recognition.

### 1.2 Aims and Objectives

This study aims to analyse how urban parks' cooling potential varies with changing urban form, providing valuable insights for optimizing urban park planning and design in Glasgow, UK, to mitigate and adapt to UHI effects. The study has four main objectives:

- To develop a comprehensive understanding of the cooling impact of urban parks on urban heat island intensity.
- To quantify the cooling effect of urban parks and identify influencing factors.
- To analyse how spatial form influences the Park Cooling Intensity (PCI).
- To evaluate the relationship between urban morphology parameters, PCI, and Urban Heat Island intensity.

To achieve these objectives, the study employs a methodology encompassing critical literature review, spatial analysis, and statistical analysis. Remote Sensing and Geographic Information System (GIS) techniques are used to analyse Land Surface Temperature (LST), vegetation cover, and potential cooling effects through buffer analysis. Various software tools, including ArcGIS Pro 3.0, Microsoft Excel, Google Earth Pro, and SPSS, are utilized to facilitate the research process.

## 2 Background

### 2.1 Overview of the UHI Phenomenon

The Urban Heat Island (UHI) effect, driven by factors like urbanization, lack of vegetation, and human activities, is a global concern due to rising temperatures and heatwaves. Urban areas can become significantly hotter than rural areas, with UHI intensities reaching up to 8°C, particularly noticeable at night. This exposure to extreme heat poses serious health risks, especially to vulnerable groups like the elderly and children. Heat-related illnesses, including heatstroke and exhaustion, can lead to fatalities (Akbari & Kolokotsa 2016).

In 2022, the UK experienced record-high temperatures, with a peak of 40.3°C in Coningsby, Lincolnshire, resulting in increased mortality rates (Office for National Statistics 2022). Europe also saw over 15,000 heat-related deaths during a three-month summer period, with significant numbers in Germany, Spain, the UK, and Portugal. Scotland has witnessed a warming trend and shifting rainfall patterns, with projected temperature increases of 1.2 - 1.5°C by 2050 and more frequent heatwaves (Adaptation Scotland 2021). Glasgow, in particular, recorded its hottest summer since 1884, with urban areas being 4-6°C warmer due to the UHI effect. These trends underscore the urgent need for strategies to address UHI and its associated risks.

### 2.1.1 Causes of Urban Heat Island (UHI) Effect

The causes of the Urban Heat Island (UHI) effect can be divided into two categories: Uncontrollable and Controllable factors. Uncontrollable factors are influenced by atmospheric and natural conditions, including climate, weather, and geographic location. In contrast, controllable factors result from human activities related to urbanization, urban morphology, and the generation of waste heat from activities like transportation. This waste heat contributes to the higher temperatures observed in cities, leading to UHI effects (Kamboj & Ali 2021). These rising temperatures can cause heat stress and discomfort in humans. Consequently, there is a pressing need for cities to implement measures to mitigate urban warming and its associated impacts.

### 2.1.2 Heat Mitigation Strategies

To mitigate the Urban Heat Island (UHI) effect, scholars and policymakers employ various strategies, which can be categorized into three main approaches: The first approach involves altering the thermal properties of urban materials. For example, changing the colour of roofs and pavements to lighter, more reflective shades reduces heat absorption and, instead, reflects energy back into the atmosphere. This helps lower the heat stored within the urban environment, mitigating UHI. The second approach focuses on modifying urban morphology and design to minimize heat gain. Emphasizing urban layouts that facilitate maximum airflow and shading can significantly impact UHI intensity. Research indicates that urban form plays a crucial role in UHI dynamics, and poor urban morphology can trap heat, leading to higher temperatures (Liu et al. 2022). While the third approach involves the use of green infrastructure as a key UHI mitigation strategy. Studies have demonstrated that combining various green infrastructure strategies yields positive results in improving microclimates and thermal comfort (Shashua-Bar et al. 2011). For instance, incorporating green spaces and urban parks in city centers can offset solar radiation through processes like evapotranspiration and air circulation (Li et al. 2012). Trees, vegetation, and water bodies within urban areas contribute to cooling by providing shading and intercepting radiation before it reaches the surface. These strategies collectively aim to reduce the impact of UHI by altering the urban environment to make it more resilient to heat and by promoting the use of natural elements like vegetation and reflective surfaces to cool urban areas.

### 2.1.3 Green Infrastructures on Mitigating UHI

Urban Heat Island (UHI) research is advancing by exploring the cooling effects of green infrastructure (GI) in urban areas. GI, including urban parks, is a recommended strategy in city adaptation policies to mitigate UHI and enhance thermal comfort (Degirmenci et al. 2021). Urban parks are found to be notably cooler, with temperatures ranging from 0.5°C to 1.7°C lower than the surrounding built-up areas. They are often referred to as "cool islands." Urban parks are open spaces with vegetation and water bodies designed for public use (Konijnendijk et al. 2013). These parks cool cities by spreading their cooling effect to the surrounding urban areas, covering distances of up to 400 meters. This cooling effect is referred to as the Park Cooling Effect (PCE) and is influenced by various factors, including climate, park size, vegetation coverage, vegetation type, the surrounding urban layout, and wind conditions (Zhao et al. 2011; Zhang et al. 2021).

Climate differences, such as diurnal and seasonal cycles, impact a park's cooling potential (Ren et al. 2013). Maximum temperature reduction occurs during the day due to shading and the absorption of direct solar radiation. Conversely, at night, when heat is emitted back to the atmosphere, temperature differences between urban parks and their surroundings diminish. Seasonally, cooling potential is most pronounced in summer when evapotranspiration is highest but decreases in autumn and winter as trees lose leaves and canopy cover diminishes.

The geometric scale of urban parks plays a significant role in their cooling efficiency (Id et al. 2017). Larger parks have a greater cooling impact due to reduced sensible heat flux and fewer anthropogenic heat sources. Wind conditions also affect cooling potential, with stronger winds enhancing cooling. Buildings around urban parks should be designed to maximize ventilation to optimize cooling.

The shape of an urban park matters too, as regular shapes like squares or circles exhibit higher cooling efficiency than complex shapes (Yu et al. 2017). Polygonal parks are particularly efficient at trapping cool air, due to small trees and shrubs. Additionally, the type and arrangement of vegetation in the park influence its cooling effect. Trees, with larger canopies provide more cooling than shrubs and grasses (Park et al. 2017).

## 2.2 Impacts of Urban Morphology on UHI and PCE

Urban morphology is referred as the physical layout of cities, significantly influences microclimates and the cooling effect of urban parks. Factors such as the density of skyscrapers and high-rise buildings surrounding a park can hinder the dissipation of heat, impacting the park's cooling capacity. Key factors affecting Park Cooling Effect (PCE) include the Floor Area Ratio (FAR), Canyon Aspect Ratio (H/W), building density, Sky View Factor (SVF), and impervious surfaces (Gunawardena, Wells and Kershaw, 2017). Understanding these factors helps optimize existing parks and design new ones to maximize their cooling impact and mitigate Urban Heat Island (UHI) effects.

The Local Climate Zone (LCZ) classification system developed by (Stewart & Oke 2012), categorizes urban forms based on properties like building height, density, land cover, and thermal characteristics, is widely used in UHI studies. LCZ mapping helps identify local warming effects of urban development and informs urban planning and policy decisions. Researchers have applied LCZ methods in cities like Taipei (Chen et al. 2019) and Islamabad (Aslam et al. 2021) to map temperature changes in rapidly evolving urban areas, demonstrating its effectiveness in studying urban forms and their impact on climate.

Despite efforts to study the cooling benefits of urban parks and their connection to park characteristics, there is a need for more in-depth research. Few studies have explored the influence of urban morphology on the ecological effects of urban parks comprehensively. Addressing this gap is crucial for promoting equitable distribution and sustainable urban planning strategies in regard to urban parks. To fill these knowledge gaps, it is essential to assess Park Cooling Intensity (PCI) in relation to various urban morphological factors. This study employs remote sensing to analyse temperature differences between urban parks and their surrounding areas during summer.

# 3 Methodology

## 3.1 Research Framework

The research philosophy and approach for this study involve a combination of positivism and interpretivism, primarily leaning towards positivism. The research follows both deductive and abductive approaches. It integrates quantitative and qualitative methods, employing GIS-based spatial analysis and statistical analysis techniques. This research comprises of four main steps:

- **Literature Review and Data Acquisition:** The initial step involves reviewing existing literature and collecting relevant data.
- **Data Processing:** The collected data is processed and prepared for analysis.
- **Spatial Analysis:** GIS-based spatial analysis techniques are employed to analyse geographic data.
- **Statistical Analysis:** Statistical methods, particularly correlation analysis, are used to examine relationships between variables.

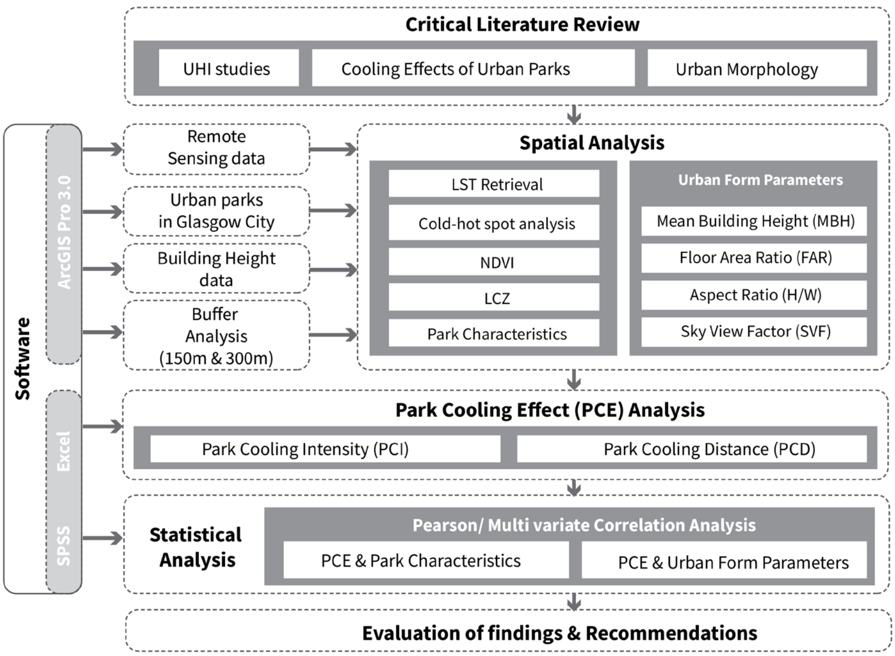


**Figure 1. Research Framework and methodology used in this study.**

### 3.2 Overview of Study area and its Climate Conditions

Glasgow, located in West Central Scotland along the River Clyde, is Scotland's most populous city and the third most populous in the United Kingdom. Its geographical coordinates are approximately 55.8642° N latitude and 4.2518° W longitude, covering a total surface area of 176.4 square kilometres. As of the 2021 census, Glasgow City has a population of 635,130 residents (Glasgow City 2022).

Glasgow experiences an oceanic climate according to the Köppen-Geiger climate classification (Peel et al. 2007). The city has an annual average temperature of 9.6°C, with December being the coldest month at a minimum temperature of 4.3°C and July being the warmest month with a maximum temperature of 15.9°C, based on daily mean temperature data from 2021 provided by the Met Office.

### 3.3 Data Collection and Processing

The data used in this study include Spatial analysis data such as, Landsat 8 OLI_TIRS imagery in raster format provided by USGS Earth Explorer for LST and NDVI map retrieval. LCZ data in shapefile for urban physical characteristics. Building Height data from Digimap and LiDAR Digital Surface Model (DSM) and Digital Terrain Model (DTM) in raster format provided by UBDC. Climate Data such as the Met office Hourly Observations Data in Excel format was provided by UBDC, covering the years 2018 to 2022. It includes parameters such as Mean Temperature, Wind Direction, Wind Speed, Relative Humidity, and Weather type in Glasgow. Moreover, green spaces in Glasgow City obtained as PAN 65 in Package Layer format provided by Glasgow City Council which is used for the mapping of urban parks.

### 3.4 Quantification of Cooling Effects of Urban Parks

The cooling effects of urban parks were quantified by analysing various park structure characteristics and their impact on cooling. Three key metrics were used to assess how the spatial arrangement of urban parks influences their cooling effects such as the area, the perimeter, and the shape index (SI) of urban parks. SI measures the relative shape complexity of parks. It is calculated using the formula (Ewers & Didham 2007):

$$SI = \frac{P}{2 \times (\pi \ \times A)^{0.5}}$$

An SI of 1 indicates a circular shape, while higher values represent more irregular and complex shapes.

Buffer analysis (Yu et al. 2017)was employed to determine the cooling distance within a 300-meter radius from each park, divided into 10 concentric rings of 30 meters each. This method allows for quantifying the cooling effect. To calculate the cooling effect, a conceptual model (Lin et al. 2015) was used, generating temperature data from the urban surroundings within the buffer zone relative to the park's distance. Park Cooling Distance (PCD) represents the distance between a park and the limit of its cooling effect, while Park Cooling Intensity (PCI) measures the temperature difference between the park (T_p) and urban areas (T_u) using the formula:

$$\Delta T_{max} = T_u - T_p$$

### 3.5 Statistical Analysis

Statistical analysis was conducted to understand the relationship between urban morphology parameters and PCI. Pearson correlation analysis, curve fitting methods, and multivariate regression models (MRM) were employed to investigate the influence of park characteristics and urban form on PCI intensity. MS Excel and SPSS were used for these statistical analyses.

## 4 Results

### 4.1 Park Cooling Effect (PCE) of Urban Parks

In this study 30 parks were selected of varying sizes falling within various LCZ classes and Land uses ranging between 0.0134km2 to 0.17km2. Landsat 8 satellite image from June 4, 2022, to extract Land Surface Temperature (LST) in Glasgow. The results indicate high temperatures in built-up areas, especially those with high impervious surfaces, highlighting the Urban Heat Island (UHI) effect in the city centre. Conversely, lower temperatures were observed in areas with green spaces and urban parks. The study also calculated the Normalized Difference Vegetation Index (NDVI) to assess greenness levels and found a strong negative correlation between LST and NDVI, indicating that areas with higher vegetation cover have lower LST values.

Two concentric rings of 150 m and 300 m were used as buffer zones around each park, and the average LST of each park and its buffers were analysed to calculate PCI. Park Cooling Intensity (PCI) is determined as the temperature difference between the first point of temperature decline within the buffer area and the temperature of the park. The park's characteristics are considered independent variables, while PCI and PCD (Park Cooling Distance) serve as dependent variables in the analysis.

Results showed that parks were averagely 1.6ºC cooler than their surrounding built-up areas. Among the 30 parks, 28 parks were cooler than the surroundings whereas only 2 (Drumchapel & Milton Park) showed no significance cooling effect. The urban park with the highest cooling effect was Cowlairs Park with an area of 3.3 ha (3.26ºC) and the lowest was Kelhead Avenue Park with an area of 1.8 ha (0.4ºC). However, there was no significant difference in temperature compared to the average LST of Glasgow City (25ºC). These findings demonstrate that green spaces contribute to lowering Land Surface Temperatures (LST) in urban areas.

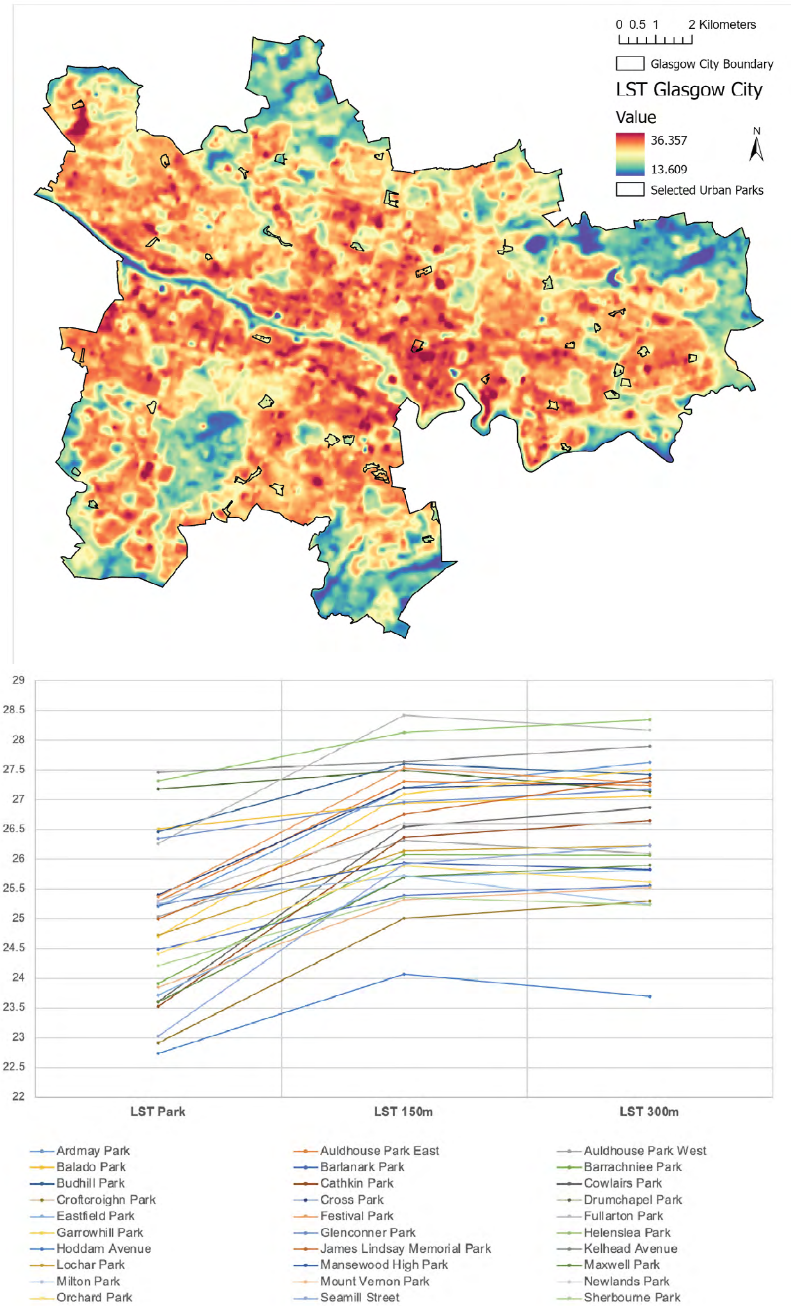


**Figure 2. Distribution of Land Surface Temperature (LST) map of urban parks**

Similarly, Park Cooling Distance (PCD) referred as the maximum distance from a park where its cooling effect on the surrounding area reaches its limit is explored. The relationship between cooling distance and temperature follows a cubic polynomial curve as shown in figure 3 where the temperature rises sharply and then gradually decreases as the distance increases. The point of inflection on this curve identifies the maximum cooling influence distance (L_max) of an urban park, which can be used to determine the maximum temperature reduction (ΔT_max) achievable within the park's cooling range. The average cooling distance of the selected urban parks obtained is 252.67m.

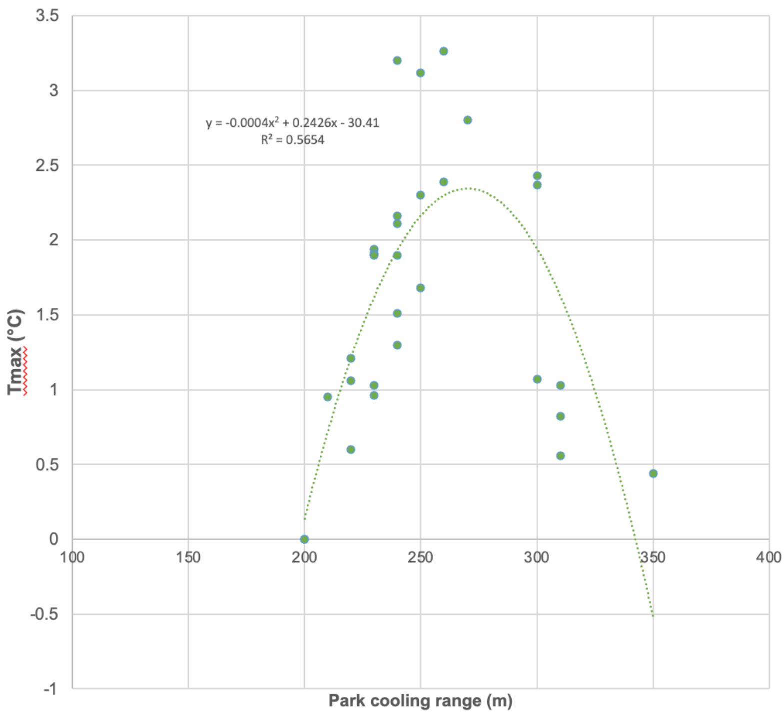


**Figure 3. Fitting results between Tmax (PCI) and Lmax (PCD)**

## 4.2 Analysis of Urban Park Characteristics and PCI

A multivariate correlation between the Parameter of Cooling Intensity (PCI) and these park characteristics was calculated. The analysis revealed the following that the R2 coefficient of determination for the park characteristics with respect to PCI was found to be 0.3416. This indicates a positive correlation between these variables and PCI. There was a positive correlation observed between park area, perimeter, and NDVI with PCI. Similarly, larger park areas, longer perimeters, and higher NDVI values are associated with a stronger cooling effect. Conversely, there was a negative correlation found between the shape index of the park and PCI. This suggests that parks with a more irregular or complex shape may have a weaker cooling performance.

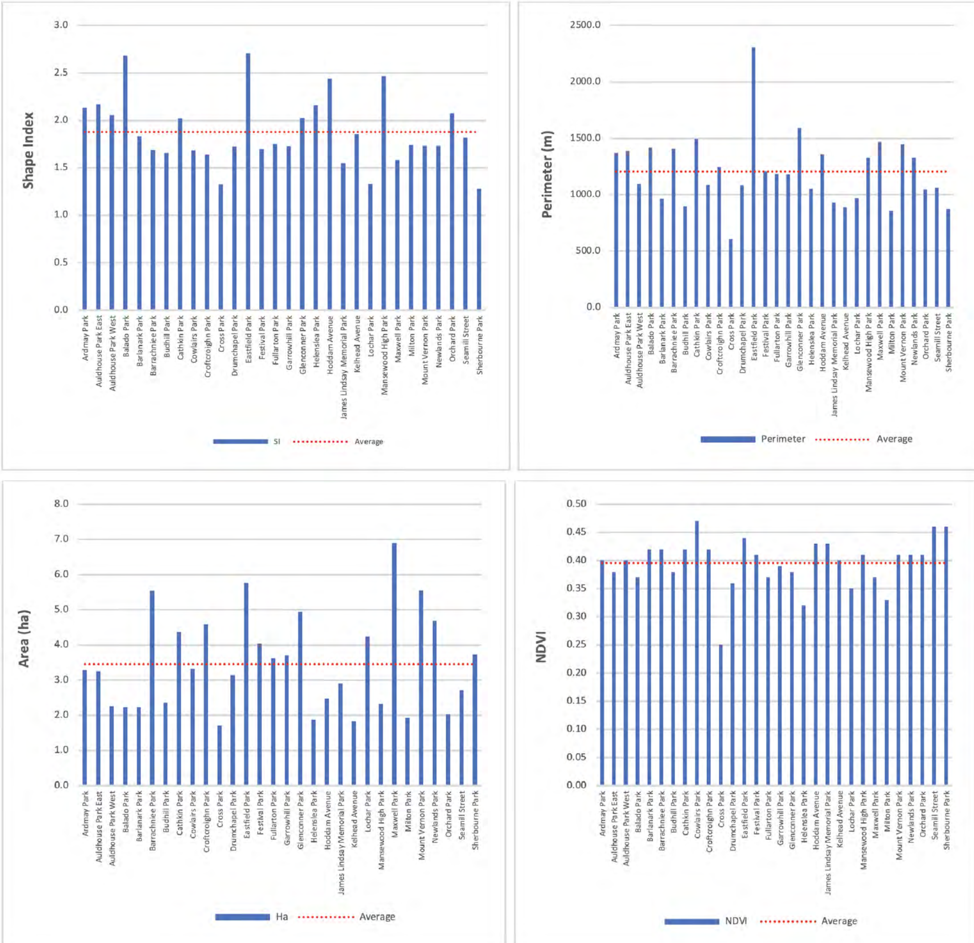


**Figure 4. Park Characteristics analysis results for the 30 parks (a) Shape Index (b) Perimeter (m) (c) Area (ha) (d) NDVI**

## 4.3 Analysis of Urban Parks Surrounding Urban form and PCI

The analysis of selected urban parks surroundings was done using urban morphological parameters, including building height, FAR, SVF, and aspect ratio, within a 300-meter buffer area surrounding urban parks. The results obtained showed the mean building height among the 30 urban parks was 7.68 meters. The highest building height (11 meters) was observed around Cross Park, characterized by a mix of open midrise and low-rise buildings. The lowest building height (6 meters) was observed around Barrachnie, Fullarton, and Mount Vernon Park. FAR was analyzed for the built-up areas surrounding all 30 urban parks within a buffer zone. The FAR values ranged from 0 to 8. The highest FAR was recorded around Festival Park (7.99), while the lowest was around Garrowhill Park (0.70). The mean FAR for the built-up areas around all 30 urban parks was 2.31. Similarly, the average SVF of the surrounding park areas was 0.753. The highest SVF values (0.9) were observed around Newlands Park and Orchard Park, indicating more open sky views, while the lowest SVF (0.625) was recorded around Eastfield Park. Lastly the average AR for all 30 urban parks was 0.369. The highest aspect ratio (1.063) was observed around Orchard Park, while the lowest (0.125) was observed around Newlands Park.

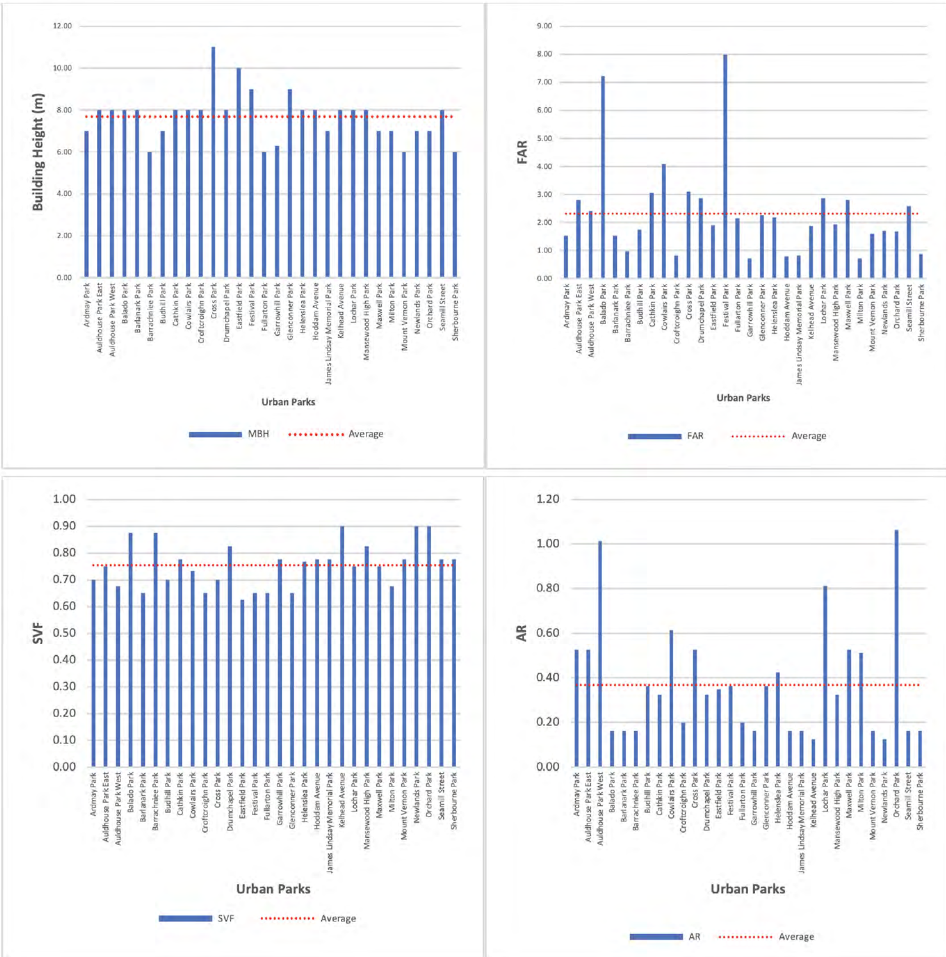


**Figure 5. Analysis of the surrounding urban form on the selected urban parks (a) Mean Building Height (MBH) (b) Floor Area Ratio (FAR) (c) Sky View Factor (SVF) (d) Aspect Ratio (AR)**

From the results obtained in correlation analysis it reveals that the Mean Building Height (MBH), Aspect Ratio (H/W), and Sky View Factor (SVF) are negatively correlated with Park Cooling Intensity (PCI), implying that higher buildings, greater aspect ratios, and reduced SVF tend to decrease PCI. Specifically, higher Mean Building Height can diminish park cooling since tall buildings may obstruct cool air circulation and ventilation, which are vital for heat dissipation. On the contrary, the Floor Area Ratio (FAR), a measure of urban density, exhibits a positive correlation with PCI, indicating that higher urban density can enhance the cooling potential of urban parks. Additionally, high SVF values suggest more direct sunlight exposure and increased solar radiation, potentially affecting the park's cooling capacity. The aspect ratio (H/W) of urban canyons, representing tall and closely spaced buildings, has a detrimental effect on park cooling, as it can trap and retain heat, exacerbating Urban Heat Island (UHI) effects.

# 5 Conclusions and Discussion

This study assessed the cooling potential of urban parks in Glasgow by measuring Park Cooling Intensity (PCI) and Park Cooling Distance (PCD). It found that, on average, urban parks were 1.6ºC cooler than the surrounding built-up areas, with an average cooling distance of approximately 252.67 meters. The study identified several factors influencing PCE, such as park characteristics like the size, shape, and vegetation (NDVI) of parks. Similarly, the urban form surrounding the urban parks like, building height (MBH), aspect ratio (H/W), Floor Area Ratio (FAR) and sky view factor (SVF). It was also noted that parks located in LCZ classes 8 and 9, characterized by low-rise and sparsely built areas, showed higher PCI values. It can be understood that taller buildings, higher aspect ratios, and greater SVF reduced the cooling potential of nearby parks. Also, larger parks with more greenery exhibited greater cooling effects. Less complex park shapes were also associated with higher cooling potential.

Despite these findings, the study had limitations, such as focusing on a single summer season, using remote sensing data without field measurements, and analysing a limited number of parks in a somewhat homogeneous urban environment. Moreover, the study of the cooling effect of urban parks is an evolving topic and further research is needed to refine these findings. Some of the recommendations is that the research should be conducted across different seasons and latitudes to develop planning recommendations that consider seasonal and geographical variations. By analysing the existing urban form, scenarios should be simulated to explore how urban form, wind, and Park Cooling Effect (PCE) interact with each other in the neighbourhoods surrounding urban parks. Also, scenario-based simulations can be used to investigate different threshold values of PCE, which may provide insights into optimal cooling strategies. Similarly, the relationship between Park Cooling Intensity (PCI) and park characteristics, particularly size, appears to be non-linear. Therefore, further research is needed to explore the threshold at which the cooling effect remains constant for various park sizes.

Urban parks play a vital role in cooling cities amid rising global temperatures. This study shows they reduce heat in cities, with park characteristics and surrounding areas affecting cooling intensity. Designing parks with strong cooling effects is essential, even in small spaces. Measuring Park Cooling Effect (PCE) helps plan better and mitigate Urban Heat Island (UHI) effects. The findings obtained will benefit researchers, urban planners, and policymakers, offering practical guidance for cooling urban parks in diverse settings particularly in the context of climate change and urban heat island effects. Equitable access to cooling is crucial, especially in heat-vulnerable areas and disadvantaged communities (Tan & Samsudin 2017).

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TARIQ, MUAHAMMAD

# A Comparative analysis of the Cooling effects of Green Infrastructure Types on Peshawar's Urban Microclimate in selected public squares

*This thesis examines the cooling impact of different green infrastructure (GI) types on Peshawar's urban squares. Using Land Surface Temperature data, microclimate measurements, ENVI-met simulations, and NDVI maps, the study investigates how various GI features affect temperature. Three squares with diverse GI were analysed during summer to understand their role in mitigating Urban Heat Island effects. Results showed that trees combined innovatively with fountains can reduce temperatures by up to 6°C, while grass has minimal cooling benefits of 0.4 to 0.8°C. This research offers valuable insights for public authorities and designers on effective GI for urban cooling. A notable output is the "PeshawarTreeFinder" mobile app, designed to guide stakeholders in choosing suitable GI types for different squares, available for free. The study underscores the importance of collaborating with city officials and public involvement. Factors like budget constraints affecting fountain functionality were considered, highlighting the need to understand the local context when implementing GI.*

# 1 Introduction

## 1.1 Rationale

The Urban Heat Island (UHI) effect leads to higher temperatures in urban areas than in rural ones due to factors such as heat absorption by construction materials and reduced vegetation (Oke 1982). Such effects can lead to increased energy use, degraded air quality, and health issues (Khan & Rehman 2019). Rapid urbanization in Peshawar has exacerbated these challenges, making it one of Pakistan's hottest cities (PBS 2017). Green infrastructure, comprising elements like parks and green roofs, is seen as a potential solution (Benedict & McMahon 2006). While Peshawar has invested in traditional green infrastructure like water fountains and trees, their effectiveness in UHI mitigation remains unclear. It's noteworthy that 83% of green infrastructure studies are from the northern hemisphere, leaving tropical areas less explored (Bartesaghi Koc & Osmond 2017).

Out of the 178 individual locations studied, most of the research has been focused on Asia (39.9%), Europe (34.8%), and North America (14.6%), with significantly fewer studies conducted in Oceania (3.9%), South America (3.9%), and Africa (2.8%).

## 1.2 Aims and Objectives

The research will explore the relative effectiveness of three different green infrastructure types in reducing the urban heat island effect. By examining these strategies within the local context, the study aims to shed light on their efficiency. This information will be vital for urban planners, architects, and policymakers in Peshawar, enabling them to make well-informed decisions that foster sustainable urban planning practices.

Furthermore, the study's findings will directly contribute to the progress of Sustainable Development Goal 11 (Sustainable Cities and Communities). This goal strives to create cities and human settlements that are inclusive, safe, resilient, and sustainable. The study specifically targets the advancement of objectives 11.6 and 11.7, reinforcing the commitment to sustainable urban development.

### To achieve the defined aim, this study focuses on the following four objectives:

- To evaluate the effectiveness of green infrastructure in mitigating the UHI effect in urban areas.
- To assess the current state of urban microclimate of Peshawar in different public squares, in terms of temperature, humidity, and wind speed.
- To compare the cooling effects of different green infrastructure types, such as trees, grass, and water features on the urban microclimate of selected squares.
- To provide recommendations for the implementation of green infrastructure in urban planning and design to mitigate UHI & create thermal comfort.

# 2 Background

## 2.1 Urban Heat Island & its causes

Urban Heat Island (UHI) is a phenomenon in which urban areas are significantly warmer than surrounding rural areas. UHI is a growing problem, especially in hot regions where it can cause severe health and environmental impacts. In this literature review, we will explore the causes of UHI in urban areas, with a focus on hot regions.

One of the main causes of UHI is the alteration of land surfaces due to urbanization, such as replacing natural vegetation with impervious surfaces like concrete and asphalt. This leads to reduced evapotranspiration and increased absorption and re-radiation of solar energy, resulting in higher surface temperatures. According to Oke (1982), urban areas with high-density development, low vegetation cover, and extensive impervious surfaces tend to have a more significant UHI effect.

Another significant cause of UHI is the anthropogenic heat release from human activities such as transportation, industry, and buildings. According to Santamouris (2015), the increase in energy consumption and the use of air conditioning systems in buildings can significantly contribute to UHI effects in urban areas.

Peshawar is one of the largest and fastest-growing cities in Pakistan, experiencing a significant UHI effect due to the rapid urbanization and the high population density. The UHI effect has led to a rise in temperatures in Peshawar's urban microclimate, affecting the health and well-being of its inhabitants. Being a big industrial city that includes food processing and the manufacture of cigarettes, firearms, cardboard, textiles, pharmaceuticals, furniture, and paper. It is also a major center of the steel industry in Pakistan (Alam et al. 2011).

The urban heat island (UHI) effect can offer benefits to urban regions. In colder seasons, UHI can reduce heating needs, thus cutting energy costs. It can also stimulate economic activity, especially in tourism. As noted by the Khyber Pakhtunkhwa Tourism Department, Peshawar's warmth attracts tourists, particularly from colder European regions, enhancing their experience of the city's attractions. This warmth can boost business revenue and has health benefits, like potentially reducing respiratory issues such as asthma. Concerning COVID-19, some studies, like Tosepu et al. (2020) in the Science of the Total Environment, suggest that a 1ºC temperature rise links to a 3.08% decrease in daily new cases in 50 nations. However, the relationship between temperature and COVID-19 spread is complex and not fully understood.


**Figure 1. UHI Impacts. reproduced by the author based on literature review.**

## 2.2 Urban Green Infrastructure types

Throughout history, humans have had a deep appreciation for greenery as a source of vitality and have developed physical and psychological dependence on nature. The availability of fresh air, natural beauty, and landscapes have shaped public perceptions of nature and influenced social behavior (Wuqiang et al. 2012; Gökyer et al. 2012).

However, the rapid population growth and urbanization of recent times have led to significant changes in ecosystems and natural landscapes (Barnosky 2012). These changes also manipulate the Urban microclimate thus resulting in Urban Heat Island phenomena.

Extensive research has been carried out in recent years to investigate the effects of green infrastructure on urban microclimate, with previous reviews providing ample documentation of these results. Bowler et al. (2010) conducted a comprehensive meta-analysis on the cooling effects of parks, trees, and green roofs, which suggested that urban parks are on average up to 1°C cooler than non-green sites.

### 1.2.1 Urban Trees, grass & fountains

Tree plays a crucial role in mitigating UHI effects by providing shade and transpiring water, thus reducing the urban surface and air temperatures. Many studies have investigated the impact of trees on the urban microclimate, and the majority suggest that trees can significantly reduce urban temperatures.

For instance, a study conducted in the city of Istanbul found that the presence of trees reduced the surface temperature by 10ºC during the day and 8ºC at night (Cetinkaya, 2017). Similarly, a study in Chicago found that increasing tree cover by 10% could lower the temperature by 0.25-0.5ºC (Nowak et al. 2006).

The species and placement of trees are essential factors that influence their effectiveness in mitigating UHI effects. Some tree species are better at reducing urban temperatures due to their higher transpiration rates and shading capacity. For example, deciduous trees are more effective at shading buildings during the summer months and allowing sunlight to penetrate during the winter months (Wang & Zhao 2017). Furthermore, the placement of trees also plays a significant role in reducing UGI. Numerous studies have demonstrated the effectiveness of trees in mitigating the UHI effect.

For example, a study conducted in Guangzhou, China, found that increasing tree canopy cover from 20% to 40% reduced surface temperatures by 1.5ºC (Liu et al. 2011). Another study in Los Angeles, California, found that increasing tree cover by 10% could reduce the UHI effect by up to 0.7ºC (Heisler et al. 2000).

In Guangzhou, southern China, a study was conducted to measure the cooling effect of five shrub types commonly found in the region. The results showed that, on average, the surface temperature of the shrubs was 6.7 ˚C lower than that of a concrete pavement (Zhang 2020).

According to Balany et al. (2020), while trees have been found to be more effective in reducing temperatures, other vegetation types may also play a role in mitigating urban heat islands like grass & shrubs but lower than trees.

Ali et al. (2021) conducted a simulation study which showed that the presence of grass could result in a decrease of up to 0.44 ˚C in air temperatures. However, in terms of thermal comfort, Lobaccaro and Acero (2015) and Müller et al. (2013) found only reductions of 4.0 ˚C and 3.9 ˚C, respectively, in PET.

Grasses can contribute to the reduction of UHI effects by increasing surface albedo, which is the ability of a surface to reflect solar radiation. They can also reduce temperatures by providing shade, transpiring moisture into the atmosphere, and increasing the evaporation of moisture from the soil. Similarly, shrubs can provide shade and reduce solar radiation absorption by surfaces, as well as enhance moisture retention in soils.

During hot weather periods, it is common for water bodies to have lower temperatures than the air above them, particularly during the hottest parts of the day. This is supported by research such as that conducted by Broadbent et al. (2017) and Gross (2017). Consequently, the surface temperature of water bodies tends to be lower than the surface temperature of urban structures in their vicinity, as evidenced by studies such as those carried out by Sun and Chen (2012) and Méndez-Lázaro et al. (2018). Water bodies are often considered to be highly effective absorbers of radiation.

However, their thermal response is limited due to water's high heat capacity, which means it takes approximately three times more heat to raise the temperature of one unit volume of water than it does for soil. As a result, architects and planners often incorporate water features in their designs, as noted by Manteghi et al. (2015).

# 3 Methodology

## 3.1 Research Framework

The study employs a quantitative design, incorporating a multi-method approach that combines GIS-based spatial analysis, fieldwork, microclimate modeling, and statistical analysis techniques. To achieve its aim and meet its objectives, the research progresses through four distinct steps:

1. **Literature Review:** An examination of existing research and studies related to the subject.
2. **LST & NDVI data using GIS to find hotspots:** Investigation of city-wide Urban Heat Island (UHI) patterns and the relationships between UHI and Urban Green Infrastructure (UGI) in different squares.
3. **Fieldwork:** Fieldwork in the comparative analysis of the cooling effects of green infrastructure types on Peshawar's urban microclimate in three public squares involves on-site investigations to explore local-scale temperature variations, examining how different types of green spaces influence urban heat patterns & how users perceived it.
4. **Envi-met & Statistical analysis:** different analysis techniques & simulation techniques used to assess the cooling potential of UGI at the micro-scale level in these public squares.

## 3.2 Overview of Study Area

Peshawar, one of Pakistan's largest cities in terms of population and area, has experienced rapid urbanization, leading to heightened temperatures and urban heat island effects. Peshawar's climate is influenced by the local steppe environment, resulting in a hot semi-arid climate classification (Köppen BSh). The city experiences extended, scorching summers and brief, mild to chilly winters.

The summer months, ranging from mid-May to mid-September, bring intense heat to Peshawar. During the peak of summer, the mean maximum temperature often exceeds 40 °C (104 °F), with a mean minimum temperature around 25 °C (77 °F).

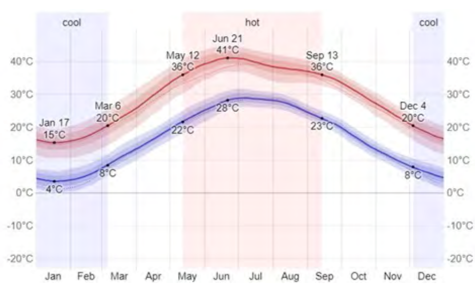


**Figure 2. Average High and Low Temperature in Peshawar. Source:** WeatherSpark.com

## 3.3 Data Collection and Processing

### 3.3.1 Identification of Hotspots in Peshawar

Peshawar is divided into three key areas, considering four main variables that shape its urban landscape:

1. **Urban Growth and Public Squares:** This measures the city's development and the existence of communal spaces where residents can congregate.
2. **Green Infrastructure and Vegetation:** This evaluates the distribution of green spaces like parks and green roofs, as well as the density of plant life, showcasing the city's commitment to sustainability and aesthetics.
3. **Construction Materials and Reflectivity:** This assesses the materials used in buildings and their surface reflectivity, impacting the city's temperature regulation and environmental footprint.
4. **Government Focus on Public Spaces:** Highlighting the government's role in developing communal areas, with the Asian Development Bank's contribution indicating global partnerships and funding for urban projects.

Three public squares were selected in Peshawar based on hotspots locations.

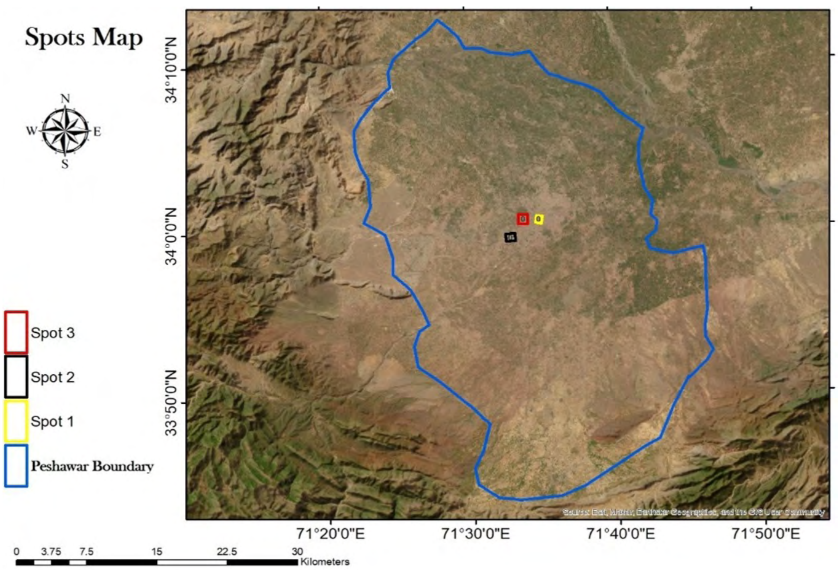


**Figure 3. Google Earth. (2023)**

### 3.4 LST Data & NDVI to find hotspots.

Spot 1 is characterized by a public square with historical significance, adorned with surrounding trees. This area is further distinguished by the presence of heritage buildings, primarily constructed from stone and mud, reflecting the rich architectural tradition of the region. The variety of tree typologies includes species such as orange, olive, Ber, and Jaman.

In spot-2 a private owned square is selected but currently serve as community space called Malik Plaza square.

Spot 3 is defined by its contemporary architectural landscape, featuring modern buildings that reflect the area's progressive development. It is a hub for commercial activities, bustling with business and trade. This commercial vibrancy leads to increased traffic, contributing to the dynamic nature of the area. However, Spot 3 also exhibits certain environmental limitations, such as a scarcity of green spaces and street vegetation.

All these selections of public squares are made on the hot areas in Peshawar.


**Figure 4. satellite views & images of public squares**

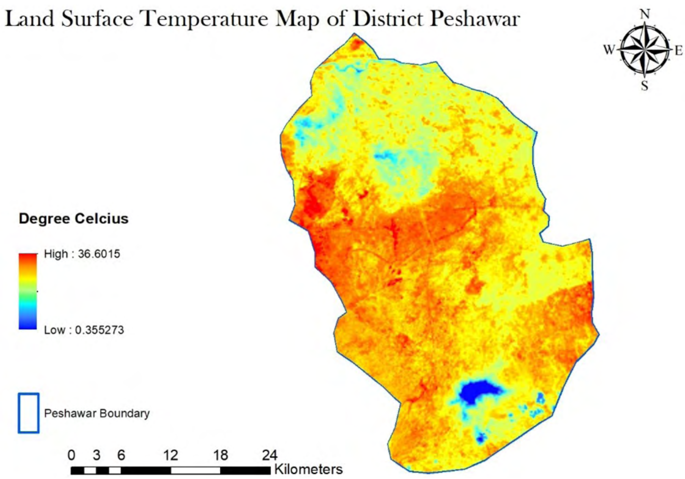


**Figure 5. LST map for Peshawar. Source: Satellite Landsat 8, 20 June 2020, 12:00 PM**

# 4 Results

## 4.1 Variations in temperature across three sites with different green infrastructure types

Different temperatures were recorded at three public squares using the Tinytag gadget. The graph illustrates the surprising results, where the square with a fountain, intended for evaporative cooling, showed the least cooling effect. In contrast, the square with grass demonstrated only negligible effects on cooling, challenging c

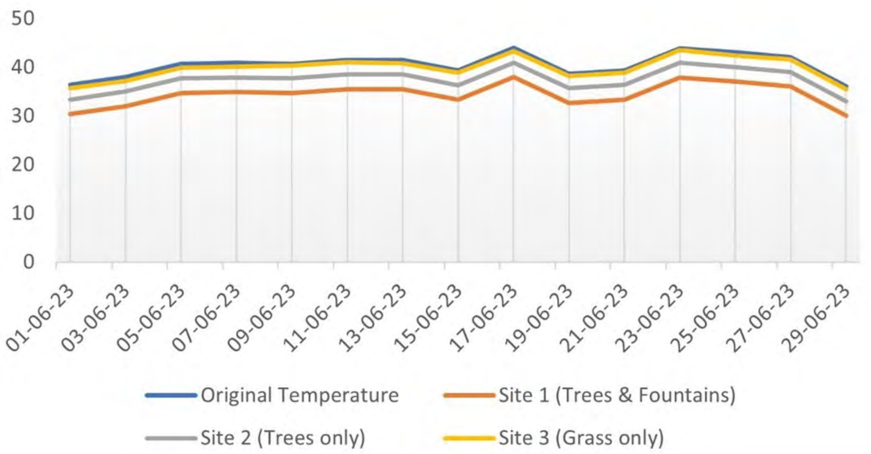

**Figure 6. Temperature variations across sites with different GI.**

- The blue line now represents the original temperature in Peshawar for the odd days in June, fluctuating between 35°C and 45°C.
- The orange line represents Site 1 (with trees and fountains), showing a reduction in temperature of up to 8°C.
- The Gray line represents Site 2 (with trees only), showing a reduction in temperature of up to 3°C, as requested.

### 4.2 ENVI-met Simulation Results

A base case scenario was simulated using ENVI-met to investigate the potential effects of a design decision for certain public squares. The government is considering a plan that would replace traditional soft scaping elements, such as vegetation, with hardscape features like concrete pavements. The simulation was conducted to analyse the temperature variations that might occur if no vegetation were placed in these public squares.

The simulated results revealed a significant increase in temperature, ranging from 35°C to 42°C, in the absence of vegetation. This increase can be attributed to the use of concrete pavements, which tend to absorb and retain heat. If the public squares were to be completely paved, the lack of soft scaping elements would exacerbate the heat effect.

## 5 Conclusion

The exploration of Land Surface Temperature (LST) across three distinct sites (public squares) provided a detailed understanding of how different green infrastructure elements influence temperature variations. Site-1, characterized by the presence of both trees and a fountain, exhibited the lowest temperature of 38°C on a hottest day. This combination of vegetation and water features demonstrated a synergistic cooling effect, contributing to a more pleasant microclimate.
Site-2, with a blend of trees and grass, recorded a slightly higher temperature of 39°C. The presence of trees played a vital role in moderating the temperature, reflecting the cooling benefits of shade and transpiration. Site-3, with only grass, showed the highest temperature of 40°C, indicating that grass alone had negligible effects on cooling.

In conclusion, Site-3's reliance on grass as the primary green feature results in limited temperature reduction capabilities. The absence of shade, limited evapotranspiration, lack of water features, and potential heat retention all contribute to this outcome. While grass may offer aesthetic appeal, its ecological benefits in terms of cooling are minimal, especially when compared to more diverse and thoughtfully designed green spaces.

Among all the sites, site one has minimum temperature recorded due to combination of trees & fountains.

## Recommendations

In Peshawar's urban setting, the blending of green infrastructure stands out as a crucial approach to improve the city's ecological sustainability and liability. This research, which actively involved architecture students from CECOS University, moved beyond typical academic confines. By organizing practical activities in urban design and landscape architecture, a hands-on learning environment was fostered among students and the community. The combined use of trees and fountains emerged as an effective solution to counter the Urban Heat Island effect, advocating for a city that balances aesthetic appeal, functionality, and environmental consciousness. The findings present valuable guidance for city planners, landscape architects, and policymakers, emphasizing community engagement, sustainable designs, and educational collaboration for a harmonious urban future.

For stakeholders, the study offers several recommendations. Policymakers should emphasize green infrastructure, promote strategic tree planning tailored to Peshawar's climate, and prioritize community involvement. Landscape architects and urban planners should advocate for combined green approaches, sustainable fountain designs, and engage users from diverse backgrounds in the design process. On the academic front, further exploration of green infrastructure's multifaceted impact is encouraged. Universities should promote student competitions, innovative research, and adapt curricula to address the unique challenges and global priorities surrounding urban ecological harmony.

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# Impact of urban greening and verticalization on the outdoor thermal comfort

## - A case study of Thimphu city, Bhutan

*The Urban Heat Island (UHI) phenomenon, closely tied to urbanization and impervious surfaces, remains a focal point in urban climate research. Addressing its consequences, such as reduced outdoor space usability due to increasing UHI intensity requires diverse interventions. This study investigates the influence of trees and increased building heights on outdoor thermal comfort in Thimphu, Bhutan's capital. Using Land Surface Temperature as the key variable, UHI intensity and hotspots in Local Climate Zone (LCZ) classes 5 and 9 are examined. ENVI-met is used to assess the outdoor Air temperature (Ta), Mean Radiant temperature (Tmrt), and Physiological Equivalent Temperature (PET) during peak summer and winter days in 2019. Street trees notably lowered temperatures and enhanced summer comfort in LCZ 5, while taller buildings proved more effective in LCZ 9. Both interventions reduced Tmrt and PET, with minimal Ta change. Deciduous trees yielded no significant winter temperature variations and was mainly influenced by the buildings. For Thimphu's growth, tall buildings positively impact summer comfort. The benefit can be enhanced when coupled with urban greening as they improve thermal comfort considerably. Street trees not only emerge as effective summer thermal comfort improving strategy, but it can multiple it's benefits by improving air quality in an urban environment.*

# 1 Introduction

The global population today is more than 8 million with an estimated with 55% of the population living in the urban areas (United Nations 2022) resulting in rapid urbanisation. Urbanization is an inevitable phenomenon for social and economic development, but it also results in an increase in the world's greenhouse gas emissions making both urban areas and their rural surroundings more susceptible to the impacts of climate change (IPCC 2023; Oke et al. 2017). The population expansion due to urbanisation poses challenges in meeting the demand of liveable spaces resulting in alteration of land morphology, commissioning more infrastructures, increased energy demand resulting in the Urban Heat Island (UHI). UHI is a phenomenon where the temperature in urban areas is higher than its rural surroundings (Oke 2010) and the increasing intensity of UHI greatly impacts the human thermal comfort and health making it difficult to stay outdoors for longer duration (Jamie et al. 2016). It is important to understand the urban microclimate to design a better environment for thermal comfort (Erel et al. 2012). Enhancing greenery within urban areas can transform the urban microclimate via processes like evapotranspiration and shading, mitigating the heating effects of solar radiation on impermeable surfaces (Gatto et al. 2021). Urban green spaces exhibit temperatures 1.5-2ºC cooler than street temperatures, largely due to the higher albedo of vegetation (Perini & Magliocco 2014).

# 2 Study area

The study area under this research is Thimphu which is the capital city of Bhutan. It has an area of 26 sq.km and accounts for 19.1% (114,551) of the total population which is the largest share of population in the country. The area saw about 45% increase in the population in 2017 compared to 2005 (National Statistics Bureau 2018). The rapid urbanisation brought immense changes in the land use with the expansion of the city and installation of socio-economic infrastructure. The open green spaces got decreased by more than 50% in 2017 due to the increase in the construction sector (Thimphu Thromde 2022), and in 2018, the built-up area saw an increase of 12.77% as compared to 2005 (Wang et al. 2020). The introduction of green and blue infrastructure has been seen as a key opportunity in ensuring a sustainable urban development plan and providing strategic direction in urban planning (Thimphu Thromde 2022).

This research aims at assessing the influence of urban greening and verticalization on the outdoor thermal comfort of Thimphu city as pioneer study, highlight the possible mitigation and adaptation strategies in urban planning.
The objectives of the research are:

1. Study the SUHI occurrence with Land Surface Temperature for Thimphu city.
2. Employ the LCZ classification system to study the different LCZ classes in Thimphu city.

3. Identify the urban "hot" areas across all LCZ classes defined by the seasonal change.
4. Study the pedestrian thermal comfort level in the identified hot spots in summer and winter.
5. Identifying potential strategies for mitigation and adaptation of improving the thermal comfort in summer and winter.

# 3 Background

## 3.1 Urban heat island- Context setting and studies in South Asia

Studies on urban climate has been explored across the world at regional, micro, local and street scales as urban areas have been rapidly exposed to the risk and vulnerability imposed by climate change and continues to be the most explored and intensively studied urban climate field (Souch & Grimmond 2006). There are four types of UHI; Surface UHI (SUHI), Canopy-level UHI (CUHI), Boundary Layer UHI (UHIubl) and Substrate UHI (UHIsub) amongst which the SUHI and CUHI are the most studied UHI types. The UHIubl corresponds to air temperature above building heights and UHIsub corresponds to soil temperature below the ground surface (Voogt & Oke 2003). SUHI is based on the temperature of the urban surfaces such as ground, walls, and rooftops while CUHI is based on the near-surface air temperature below the building roof height (Voogt & Oke 2003) and the extent of CUHI is essentially connected to the properties of the urban surfaces such as the thermal properties of the urban fabric, presence of vegetation, sky view factor and heat generated from the buildings (Azevedo et al. 2016). Climatic variables like air temperature, mean radiant temperature, wind and humidity can vary within the city itself and between cities. Urban climate within the city is also a multiscale phenomenon occurring at micro scale (10-200 meters), local scale (0.5 -2km), meso/city scale (<25 km) and regional scale (25-100 km) and is characterised by the urban morphology, urban geometry, building materials, vegetation cover and anthropogenic heat (Oke et al. 2017; Grimmond et al. 2015) thus creating unique climatic effect factored by its individual element and influenced by its neighbouring elements.

South Asia is home to 24% of the world's population (UN DESA 2022) that includes Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka. The increasing surface temperature has been increasingly posing threats in the region resulting in heatwaves, droughts, floods, and the melting of the glaciers in the Hindu Kush Himalayas. Researchers have been continuously contributing to the UHI studies in areas across this region studying its origin, causes, effects and mitigation options but most of the studies are conducted for India, Bangladesh, Pakistan, and Sri Lanka (Kotharkar et al. 2018). Hassan et al. (2021) studied the temporal and spatial LST, LULC, and vegetation for 10 years aimed towards comparative analysis for UHI in the South Asian cities including Thimphu. The study resulted in +0.07 °C average LST change rate for Thimphu. Most of these studies are carried out using remote sensing techniques, since in-situ data with fixed meteorological stations are resource and time intensive and limits the spatial extend (Weng 2009).

### 3.2 Land surface temperature and UHI

In urban climate, thermal infrared remote sensing techniques have been used primarily for analysing Land Surface Temperature (LST) and its variation with surface types, assessing UHI and emphasising LST to be a critical indicator of SUHI (Bechtel et al. 2019; Ferreira & Duarte 2019; Weng 2009). Voogt and Oke (2003) focussed on the principles of thermal remote sensing and concludes with LST being a potential parameter for urban climate studies. LST is defined as the radiative skin temperature of the land surface measured by the sensors in Kelvin and usually corresponds to the LULC characteristics (Weng 2009; Bokaie et al. 2016) such as composition of vegetation, water, and built-up patterns (Tian et al. 2019; Zeng et al. 2015).

### 3.3 Outdoor thermal comfort

Studies have showed that outdoor spaces have help promote physical activity, greater social cohesion, mental health, and overall physical health of the people (Freeman & Eykelbosh 2020; Triguero-Mas et al. 2015). Being exposed to nature outside has proven to bring intangible benefits for the people specially during and after the COVID-19 pandemic after being confined indoor for longer duration (Pouso et al. 2021). Additionally, the presence of vegetation such as trees, grass and parks in urban settings, particularly green spaces, has been linked to a reduction in air pollution, noise, and excessive temperatures in cities (Gascon et al. 2017). To study the thermal comfort, the air temperature, mean radiant temperature and relative humidity serves as important variables (Lee et al. 2013) as these variables it considers all relevant conditions that brings changes in the thermal regulation in the body (Fröhlich & Matzarakis 2020). From the indices available, this study utilises the Physiological Equivalent Temperature (PET) as the thermal comfort index. PET is the air temperature at which, in a typical indoor environment setting of no wind and sunlight, the heat gain and loss from the body is maintained same with core and skin temperatures in the outdoor setting with complex conditions (Fröhlich & Matzarakis 2020). It is expressed in degrees Celsius (°C) with higher values indicating heat stress and lower indicating cooler environment. The range of PET developed by Matzarakis & Mayer (1996) is used under this research to study the PET intensity.

### 3.4 LCZ classification

Conducting a study on thermal comfort in outdoor spaces requires to account the local climatic parameters (air temperature, humidity, wind speed, and solar radiation) and personal factors (metabolism and clothing) that affect human thermal comfort (Nikolopoulou 2011). While these are done by in-situ measurement and observations, the LCZ framework developed by Stewart and Oke (2012) allows studies on the thermal environment to be conducted at the street level and map temperature changes using satellite images (Chen et al. 2021; Oke et al. 2017). The classification consists of 17 standard local scale classes based mainly on properties of surface structure (e.g., building and tree height & density) and surface cover (pervious vs. impervious). Since the LCZ classes are defined by urban morphology, materials and by the properties of the surfaces that influence the air temperature of 2m above ground, each LCZ class has a unique air temperature regime and differs from the other LCZ classes.

# 4 Methodology

The research follows a deductive approach with analysis of quantitative data on land surface temperature, micro-climate parameters (air temperature and mean radiant temperature) and thermal comfort values (PET) using computer-based simulations are used. Since micro-climate and thermal comfort varies with the sites, this research is based on Case study: Thimphu, the capital city of Bhutan. The assessment of the thermal comfort relies on the study of SUHI over the prevailing LCZ classes and developmental plans under the municipality office. Furthermore, the seasonal thermal comfort is assessed for summer and winter.

## 4.1 LCZ mapping

The LCZ map is derived using the World Urban Database and Access Portal Tools (WUDAPT) which enables mapping of a city of interest into LCZs by providing a valid training area file and relevant metadata as input with the LCZ generator tool developed by Demuzere, Bechtel, & Mills (2019). The training areas were created using the Google Earth template provided on the website (Level 0 template) and LCZ map is generated from the LCZ generator.

## 4.2 Land Surface Temperature (LST)

A total of 7 Landsat 8 Operational Land Imager /Thermal Infrared, collection 2 level 1 data were used. The cloud cover range was 0-24% which resulted with only 2019 having the summer month. Therefore, the year 2019 with the most recent quality images available was chosen under this study. The standard method to retrieve LST includes converting the Digital Number (DN) value of the band 10 to radiance value. The radiance value is used to derive the brightness temperature (BT) which is the black body temperature (Spampinato et al. 2011). BT is further corrected with spectral emissivity values to account for the roughness of the surface and proportion of vegetation (Wang et al. 2015). The LST is calculated in Kelvin which is converted to Celsius. The Normalised Difference Vegetation Index (NDVI) which quantifies the greenness in the land is a dominant factor in deriving the LST. The Normalised Difference Built-up Index (NDBI) was also used to study the built-up intensity and compare with the vegetation.

## 4.3 Delineation of urban “hot” areas

LST maps were used to identify the urban “hot” areas with higher-than-average temperatures in the resulting LCZ classes. It is defined by the equation given below which was adopted from Guha et al. (2019).

$$LST \geq \sigma * 0.5 + \rho$$

Where σ is the mean and ρ is the standard deviation values of LST.

### 4.4 Micro-climate analysis

ENVI-Met version 5.1.2 used to evaluate the micro-climate air temperature (Ta), mean radiant temperature (Tmrt) and its sub-module Bio-Met was used to assess Physiological Equivalent temperature (PET) thermal index in the model areas in LCZ 5 and LCZ 9 which were chosen because of the method 4.3. The scenario development consists of the 3 cases:

1. Base case which represents the existing situation in the model areas.
2. Case 1 represents the situation with increased street trees and is referenced from the town planning "Norzin Lam re-development" project under the Thimphu municipality. The Norzin lam is the main city road, and the project aims are making the road pedestrian friendly, reducing cars, and incorporating urban green infrastructure such as trees.
3. Case 2 represents the situation with increased building heights and is referenced from the GIS data developed by Prior and Partners (2023) which consists of new Floor Area Ratio (FAR) plan for the existing buildings in Thimphu.

The sub-module BIO-met in ENVI-Met enables to derive the thermal comfort index PET. It considers the output generated from the ENVI-core simulation and summarises the effect of air temperature, radiative temperature, wind speed and humidity on human thermal sensation. This study analysed the thermal comfort in summer and winter and the settings for human model parameters were set to default male (35 y) with ISO 7730 for summer clothing standard of 0.5clo where clo is the unit for the thermal insulation of clothes. For winter, the clothing insulation was increased to 0.9 clo as the study area has cold winters.

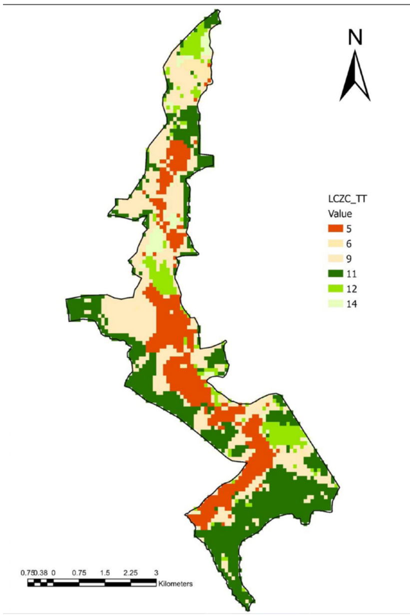
## 5 Results

### 5.1 LCZ Mapping

The LCZ classification for Thimphu resulted with the overall accuracy score of 0.6. The dominant classes, ranked from high to low, are LCZ 5, 9, 6, 11, 12, and 14, each characterized by distinct features as shown in figure 1 on the next page.

### 5.2 Spatial variation of LST and delineation of urban "hot" areas

In summer, a negative correlation of was observed between LST and NDVI indicating that areas with higher NDVI values tend to exhibit lower LST values. Conversely, a positive correlation was found between LST and NDVI winter due to reduced vegetation in cold seasons. The spatial maps in figure 2 shows that the LST in summer is higher with higher LST concentrated in the centre and in winter, the LST is lower.




| LCZ Class | Name |
|---|---|
| 1 | Compact high-rise |
| 2 | Compact mid-rise |
| 3 | Compact low-rise |
| 4 | Open high-rise |
| 5 | Open mid-rise |
| 6 | Open low-rise |
| 7 | Lightweight low-rise |
| 8 | Large low-rise |
| 9 | Sparsely built |
| 10 | Heavy industry |
| 11/A | Dense trees |
| 12/B | Scattered trees |
| 13/C | Bush, scrub |
| 14/D | Low plants |
| 15/E | Bare rock or paved |
| 16/F | Bare soil or sand |
| 17/G | Water |

**Figure 1. Thimphu city LCZ map and the most prevalent classes**

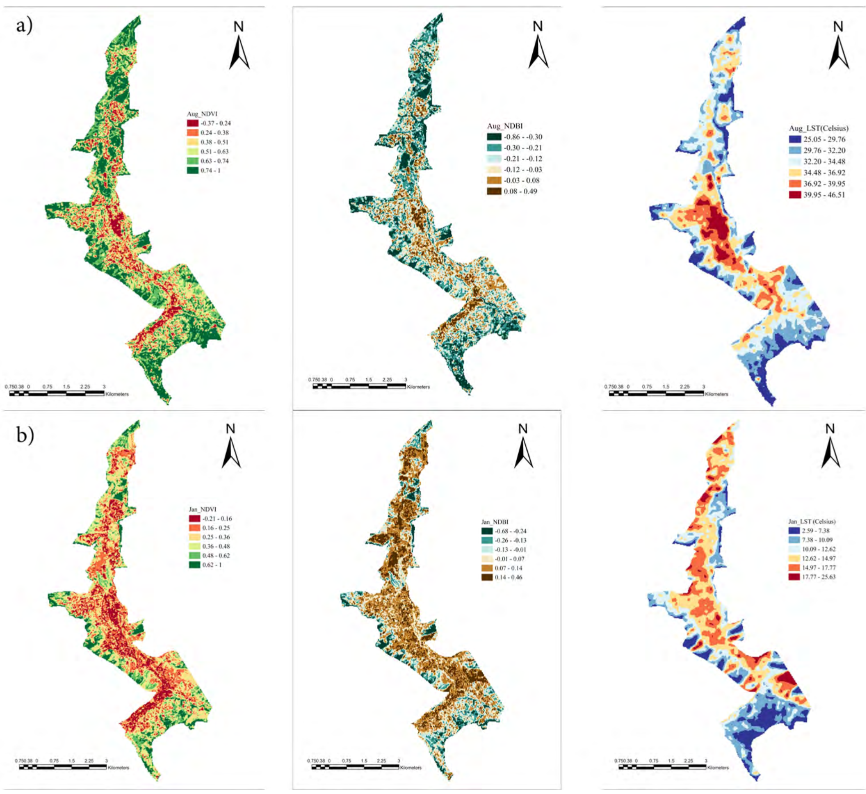



**Figure 2. Spatial variation of NDVI, NDBI and LST in a) Summer (August) and b) Winter (January) 2019**

The LST variation across all the LCZ classes for both summer and winter resulted with the LST intensity consistently higher in built-up classes (L CZ 5, 6, and 9) compared to non-built classes (LCZ 11, 12, and 14) as given in figure 3. LCZ 5, being the most densely built class, exhibits the highest LST in summer and it gradually decreases in LCZ classes 6 and 9 as the building density reduces. The lesser the trees, the increase in temperature can be seen in LCZ classes B and D in winter. The average LST differences between built-up classes (5,6 and 9) and non-built classes (A, B and D) is 1.4 °C indicating the SUHI prevalence. Following the equation LST ≥σ*0.5+ρ, adopted from Guha Govil and Diwan (2019), urban "hot" areas were identified as those areas with LST ≥ 27.7 °C in summer and LST ≥ 10.6 °C in winter. The analysis reveals that majority of the "hot" areas, characterized by higher LST predominantly falls under LCZ 9, closely followed by LCZ 5 in both the seasons. The non-built classes are not considered for micro-climate analysis and for studying the human thermal comfort due as they are non-habitable lands.

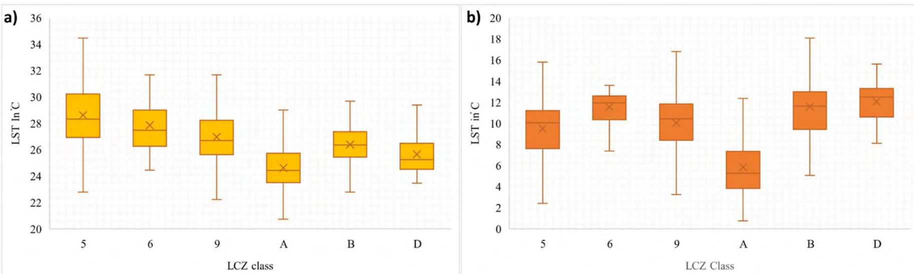



**Figure 3. Variation of LST in a)Summer, b)Winter and corresponding model areas in LCZ 5 and LCZ 9**

## 5.3 Microclimate modelling results from ENVI-Met

The Ta, Tmrt and PET resulted from Case 1 (C1) and Case 2 (C2) were compared with Base Case (BC). In summer, the average values derived from the whole model area resulted with minimal change in Ta as there was 0.09 °C reduction in C1 and 0.04 °C in C2. The average Ta resulted with 23 °C in BC, 22.9 °C in C1 and 23 °C in C2. Contrary, the reduction in Tmrt was significant with 2.1 °C reduction in C1 and 1.7 °C reduction in C2. The average Tmrt in the model area was observed with 30.5 °C in BC, 28.4 °C in C1 and 28.7 °C in C2. The PET reduction was also significant with 0.9 °C in C1 and 0.6 °C in C2. The duration of discomfort hours is reduced by an hour each in C1 and C2. The maximum PET in BC is reduced to 42.1 °C (-5 °C) in C1 and to 44.9 °C (-2.2 °C) in C2.

The spatial variation map in figure 4 measured during the highest temperature time at 12:00 in summer exhibits that C1 has the significant changes in the Tmrt and PET as compared to C2 with the footprints of trees and shadows from the higher buildings depicting lower temperature. The impact of trees not only reduces the temperature in the areas where the trees are placed but also influences the surrounding which can mainly be seen in the centre of the model area which consists of city's main square.

In winter, the change in the temperature is majorly influenced by the taller buildings. The average values from the whole model area shows no or minimal change in the Ta. The average Ta in BC is 5.26 °C, 5.25 °C in C1 and 5.26 °C in C2. The average Tmrt in BC is 9.36 °C which is reduced to 9.08 °C in C1 (-0.28 °C) and to 8.17 °C in C2 (-1.19 °C). The PET values are less than 24 °C which is within the comfortable/neutral range according to the standard PET range developed by Matzarakis & Mayer (1996). The average PET of 11.70 °C in BC is reduced by 0.1 °C in C1 and 0.5 °C in C2. The maximum PET is 23.7 °C, 23.4 °C in C1 and 21.9 °C in C2.

The spatial map of the temperature at the hottest time of 13:00 in winter is given in figure 4. As can be seen, the changes in the C1 are minimal as compared to BC and the changes in C2 is more prominent. The increased building heights influences the temperature around the areas where it casts the shadow and has lesser influence on the main square.

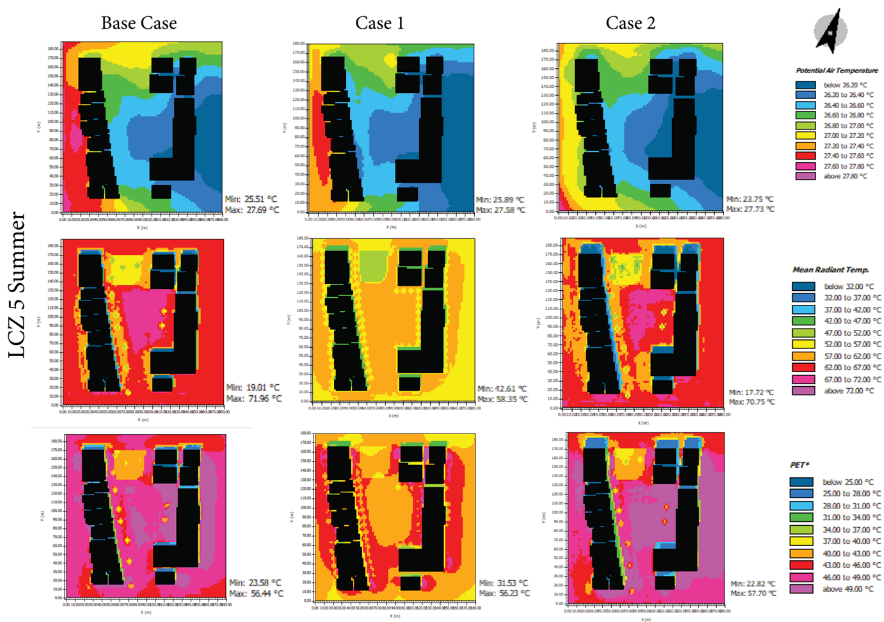



**Figure 4. Variation of Ta, Tmrt and PET simulated in LCZ 5 in summer and winter (both the figures goes here)**

In LCZ 9 spatial map provided in figure 5, C2 displays larger gradient of changes in between the buildings than C1 during the hottest time of the summer day at 12:00. Tmrt is pronounced with the trees in C1 which seems to make an impact in the surrounding area as well. The area shows extreme heat stress in all cases, with few exceptions at places where the trees are located and in the shadow areas from the buildings. The average values measured in the whole model area shows that C1 does not reduce the Ta while there is 0.1 °C reduction in C2. Tmrt is reduced by 1.6 °C in C1 and 1.1 °C in C2. The PET intensity in LCZ 9 is lower as compared to LCZ 5 and is influenced more by C2 with 0.9 °C reduction while C1 reduced the PET by 0.5 °C.

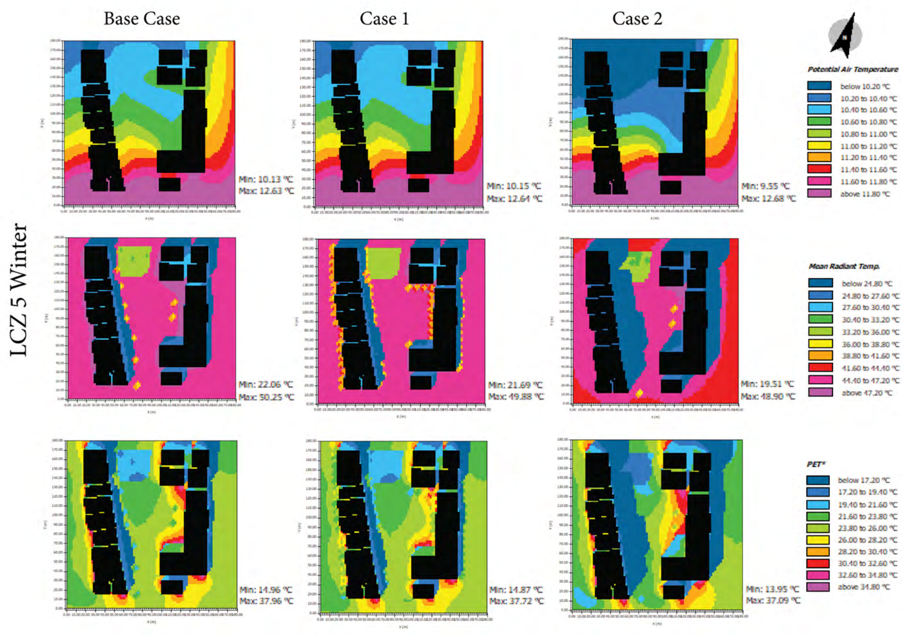



**Figure 5. Variation of Ta, Tmrt and PET simulated in LCZ 9 in summer**

# 6 Conclusion and discussion

In this research, LST was used to investigate the SUHI over the study area of Thimphu city. The LCZ classification resulted with 7 dominant LCZ classes: LCZ5,6 and 9 (Built-up) and LCZ A, B and C (non-built up). LCZ 5 exhibits higher temperature while it decreases in classes 6 and 9 as the density reduces. This difference is attributed to the limited presence of vegetation in LCZ 5, making it relatively warmer than LCZ 6 and 9, which feature a more pronounced presence of vegetation. The mean LST ranges from 7.9 °C to 26.5 °C. Higher LST are associated with hotter months and lower LST with colder months. Lower vegetation (NDVI) is associated with lower LST, while higher LST correlates with increased coverage of built-up areas (NDBI). The disparity in NVDI values in the centre of study area and its surrounding areas provides the delineation of urban and rural. It resulted in UHI where the LST in the centre is higher than its surrounding areas which was expected considering other similar case studies (Imran et al. 2021). The LST in winter resulted with positive correlation with the NDBI due to the withering of trees and grasslands as also studied by Hu et al. (2020).

The mitigation effect is more pronounced in the Tmrt and PET than in Ta due to the shading from the trees and the taller buildings. Increased trees show higher reduction of Tmrt in the LCZ 5 in summer. In winter case of LCZ 5 and summer of LCZ 9, the reduction is more with the taller buildings. However, the PET reduction is more with trees in LCZ 5 and with the increased building heights in LCZ 9. The pattern of reduction PET in winter for LCZ 5 is like LCZ 9 with more reduction shown in C2. This can be attributed to the deciduous trees which sheds leaves in winter and do not provide any shading or evapotranspiration. With the replication of the main city road re-development plan, the pedestrianisation of the road with street trees not only improves the usability of the area but provides improved thermal comfort. The Ta and Tmrt in LCZ 9 resulted in values slightly higher than LCZ 5 though being sparsely built primarily due to the lack of shading and the land being mostly covered by impervious surfaces (Lin et al. 2010; Aminipouri 2019).

With the aim of evaluating Thimphu's thermal comfort, this research can link to three key sectors in Bhutan's National Adaptation Plan: Energy, Health, and Urban Planning. While NAP mainly addresses energy supply, it's important to note that energy consumption, particularly cooling energy for air conditioning, is closely tied to outdoor heat release. Urban greening and verticalization are crucial strategies for mitigating this heat impact, offering shade and cooling through evapotranspiration. They also play roles in reducing greenhouse gas emissions and moderating air temperatures. Coupled with energy-efficient appliances and good insulation, verticalization effectively lowers outdoor summer temperatures, aligning with sustainability and climate resilience goals.

Bhutan faces rising temperatures, particularly in densely populated urban areas, which entail hazards. Urban planning and national climate strategies have not prioritized tackling Urban Heat Island (UHI) effects due to limited research. National climate plans assess risks at a broad scale but lack local-level insights for urban challenges. The two scenarios for micro-climate modelling aligns with Thimphu's Structure Plan (2002-2027), emphasizing urban regeneration and open space distribution. However, in winter, temperature reduction may not be ideal given the already cold climate. Hence, alternative interventions are needed for this season. Research results can strengthen the implementation of these concepts by enhancing outdoor comfort. Urban greening and verticalization also aligns with the Low Emission Development Strategies planned under the Human settlement and sector and thus contributes to the carbon neutrality committed of Bhutan made under the Paris Agreement.

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# Nature – Based Solutions

## to mitigate environmental risks

ANDERSON, JOSEPH ARTHUR

# Using Deep Learning Models for Standardised Assessments of Urban Ecosystem Services

*Here, a novel approach was developed to assess urban ecosystem services (UES) through remote sensing and deep learning, with the goal of creating a standardized and replicable methodology. Because the current research on UES is predominantly case studies with locally contextualized methodologies (García-Pardo et al. 2022), this study simplifies and standardizes the approach, thereby generating data that can be compared across multiple sites, while reducing the entry barriers for UES assessments.*

*To address contextualization, a universal "traffic light" UES matrix was developed. This was based on the MAES 4th Report from the EU JRC, a first-of-its-kind study which analyzed UES assessments from 10 different pilot cities across Europe (Maes et al. 2016). A geospatial methodology employing deep learning models and aerial imagery was designed to classify landcovers and estimate UES presence. Ten pilot cities in the western United States were tested, resulting in an average accuracy of 88.8%.*

*The study demonstrates the potential to create standardised UES assessments allowing for comparative research and data-driven policymaking. Additionally, it identifies areas for future research, specifically the potential of expanding the methodology to include all UES categories outlined in the MAES 4th report. Ultimately, this research contributes to the development of ecologically-informed and climate-smart urban planning by providing a reliable tool for assessing UES across diverse urban environments.*

# 1 Introduction

To better understand the interactions between natural systems and the urban environment, urban ecosystem services (ES, UES) has been identified as a useful metric. And given the geospatial nature of urban planning, it becomes important to find tools for mapping the distribution of UES throughout a city. Currently, there are many approaches to this topic (Harrison et al. 2018), and a major shortcoming in the field is that most research is predominantly case studies (García-Pardo et al. 2022). As such, methodologies are frequently altered between cities to contextualize for the environment. Although contextualization is useful for more nuanced understanding of the site-specific impacts of UES, this makes it challenging to compare between cities, which limits the development of a standardised approach for federal or international-level mapping and policymaking.

The aim of this research is to investigate the feasibility of assessing UES through remote sensing, using a methodology that is replicable across multiple cities, standardised so results can be compared between sites, and is efficient enough to be accessible to cities with limited resources. That way, the field of UES can grow based on wider datasets that encompass multiple cities and multiple contexts. The objectives necessary to achieve this aim are as follows:

- Design a remote sensing protocol that can classify urban landcover effectively enough to estimate relative presence of urban ecosystem services
- Optimize this protocol to be easily replicable across a variety of sites
- Test this methodology across multiple pilot cities to assess accuracy and identify shortcomings
- Interpret the experimental results to create recommendations for the applicability of the methodology to other researchers, geospatial analysts, and urban planners

Despite an increase in geospatial data availability, it cannot support sustainable urban development unless there is an accessible methodology for converting raw data into actionable insights. Furthermore, to develop state or federal policy that creates specific, measurable targets for UES, universally applicable metrics are necessary for benchmarking the current status of multiple cities and to create tangible milestones to measure progress. Therefore, the rationale behind this research is to expand the quantification of UES to include simplified metrics that can be used to compare between cities effectively and support top-down policy to ensure all cities include meaningful sources of UES.

# 2 Background

## 2.1 Urban Ecosystem Service Assessments

Due to the wide variety of tools and approaches to ES mapping, there has not yet been any standardised procedure for UES assessments. To determine the best technique for ES quantification, it can be helpful to organize established methods based on the desired outcome and data available. Harrison et al. (2018) developed a decision tree for comparing ES quantification methodologies, with the initial decision being whether method focuses on biophysical, social or economic factors of ES. Because this study focuses on distribution of biophysical characteristics of UES through mapping, a landcover-based ES matrix was determined to be the ideal technique. ES matrices have become a popular approach to ES quantification over the last ten years, because they allow for the comparison of more categories of ES than other methods (Campagne et al, 2020). And understanding multiple ES at once is preferred for land use planning, so that multiple ES can be appropriately considered in land use plans. There have, however, been notable critiques of the ES matrix approach.

According to Luederitz et al., “Urban ecosystem services research needs to be carefully contextualized in relation to the specific locations in which such services arise” (2015). However, a meta-analysis of over 100 studies using ES matrices revealed that 51% of these studies simply copied an ES matrix from another paper, and 27% did not clearly explain the methodology used to assign values within their matrices (Campagne et al. 2020). Herein lies one of the major issues with ES matrices. When the dimensionless unit of “Ecosystem Service Supply” is contextualized to a specific place, it means very little outside of that city. And when the contextualizaton process is note clear from the literature, it can be a source of increased error and ambiguity in the outcomes.

## 2.2 the MAES 4th Report

An alternative approach would be to create UES matrices that can function with little or no contextualization, to create a consistent unit for comparitive research. Because ES quantification has relevance on a global level, using an internationally accepted standard of ES is preferred. The European Commission launched an initiative in 2013 to develop quantitative and consistent approach to ES assessment, entitled, “Mapping and Assessments or Ecosystem Services” (Burkhard & Maes 2017). In 2016, the 4th report of this initiative was released, which focused specifically on ES in the urban environment (Maes et al. 2016). Using ten pilot cities across Europe, different UES assessments were performed, and then synthesized to develop a more standardised framework. At the time of this writing, this had been the only attempt to develop consistent metrics for UES across a continent.

| CICES Section | CICES Class | Class type (urban ecosystem services) | Service providing unit (SPU) | Demand |
|---|---|---|---|---|
| Provisioning | Cultivated crops | Vegetables produced by urban allotments and in and the commuting zone | Crop fields, fruit trees, private and public gardens | Consumption |
| | Surface water for drinking | | Watershed | |
| | Ground water for drinking | | | |
| | Surface water for non-drinking purposes | | | |
| | Ground water for non-drinking purposes | | | |
| Regulating | Filtration/sequestration/storage/accumulation by ecosystems | Regulation of air quality by urban trees and forests | Forest, trees, shrubs | Risk of exposure to pollutant concentration beyond thresholds |
| | Global climate regulation by reduction of greenhouse gas concentration | Climate regulation by reduction of $CO_2$ | Vegetation, soil | |
| | Micro and regional climate regulation | Urban temperature regulation | Forest, trees, shrub, herbs, lawns, wetlands, water bodies | Risk of exposure to high temperatures |
| | Mediation of smell/noise/visual impacts | Noise mitigated by urban vegetation | Forest, trees, shrubs, vegetated surfaces | Risk of exposure to noise |
| | Hydrological cycle and water flow maintenance | Water flow regulation and run off mitigation | Trees, shrubs, vegetated and permeable surfaces | Risk for flood sensitive areas or land use |
| | Flood control | | Wetlands | Exposure to flooding |
| | Pollination and seed dispersal | Insect pollination | Crop fields, fruit trees, private and public gardens | Dependency on insect pollination |
| Cultural | Physical use of land-/seascapes in different environmental | Nature based recreation | Parks, gardens, forest, trees, agricultural areas in the commuting zone, | Preferences; Potential and direct use |

**Figure 1. Sample page of the UES and Service Providing Units in the MAES 4th Report (Maes et al. 2016).**

One of the outcomes of the report was a table of key UES and the landcover types that provide that UES, also known as Service Providing Units, (See figure 1). These UES and the Servicing Providing Units have the potential to be combined for a novel, universally-applicable ES matrix that offers consistent categories for urban applications.

### 2.3 Data Management in Urban Ecosystem Service Assessment

As of 2015, remote sensing was identified as “the only practical and realistic approach” to ES assessment (de Araujo Barbosa et al. 2015). Furthermore, remote sensing was also identified as an ideal tool for UES assessments, where “the diversity of remote sensing data available…shows the possibility to diagnose and estimate vegetation impacts in the environment without the need for ground-based monitoring, leading to decision making in urban management and planning” (García-Pardo et al. 2022). The high volume of remotely sensed data can be helpful, but one barrier of its widespread utilization in UES assessments is the time and skills from a geospatial analyst to generate conclusions from a large amount of raw data. Fortunately, advances in artificial intelligence (AI) and deep learning models have shifted how geospatial data can be assessed. One meta-analysis found 140 papers from as early as 1997 through 2016 that used AI to process urban geography data, and found the AI techniques worked better than a conventional approach in 75% of studies (Grekousis 2019). And at the time of writing, Esri Analytics has 56 deep learning models available on the Living Atlas database, many of which perform classification on spectral data (Esri 2023b).

Though these deep learning and AI tools are very useful, widespread implementation in geospatial analysis has been slow compared to other fields (Grekousis 2019). Because many of these tools are fairly new, there is a smaller pool of geospatial analysts who are familiar with and comfortable using these models. Another challenge in the adoption of these tools is that many of them are considered black box technologies (Grekousis 2019). Researchers sometimes avoid black box tools, because if there are errors or unusual results, it is difficult to understand the mechanics which caused the problem, let alone resolve them. Despite these limitations, deep learning and AI have already changed data management in the field of geoanalytics and will continue to do so. For this research, deep learning models can be a helpful tool for processing large amounts of data to generate consistent results for UES assessments, informed by the MAES 4th report framework.

## 3 Methods

The methodology for this thesis was split into three sections: universal UES matrix development, geospatial methodology, and data analysis.

### 3.1 UES Matrix Development

An ES matrix based on the MAES 4th report ES Providing Units that does not require individual site contextualization was created for this study. The Service Providing Units were compared to the landcover classes in the selected deep learning model (discussed in section 3.2), and it was determined that six regulating ecosystem services could be estimated using the deep learning classification model. This number was reduced to five given the significant overlap between the categories of “Hydrological cycle and water flow maintenance” and “Flood control”. These five urban ES were combined with the landcover categories of the deep learning model to create the framework for the ES Matrix.

In order to address the challenge of contextualization, the spectrum of values assigned in the matrix were reduced to categorical assignments. A "traffic light" approach to the values assigned to given landcovers was developed, which assigned a value of "1" to a landcover that "directly provides the ecosystem service", "0.5" to a landcover that "indirectly or partially provides the ecosystem service", and "0" to landcovers that "do not provide the ecosystem service". This approach, is more simple than the traditional 0-5 qualitative "value" of a given landcover in most ES matrices, and means that the values can be transferred between cities without contextualization.

## 3.2 Geospatial methodology

In terms of geospatial methods, figure 2 shows the model builder for the GIS protocol. First, 1m multispectral data was combined, and clipped to the urban extent. ArcGIS extensions were installed for the compatibility of python-based deep learning plugins, and then the "Classify Pixels Using Deep Learning" tool was used to process the clipped multispectral imagery.

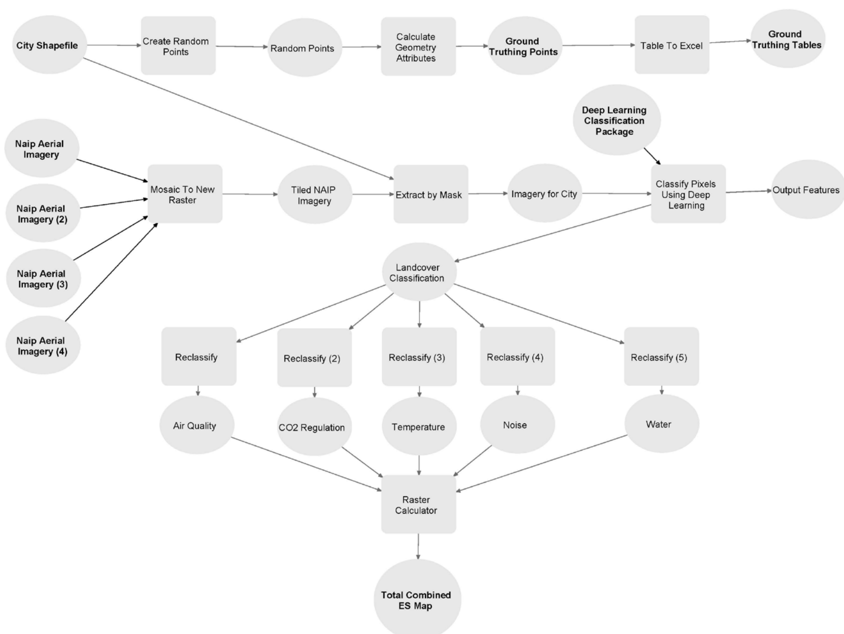


**Figure 2. Model builder in ArcGIS Pro for the geospatial methodology in this study**

Among available AI-driven high-resolution landcover models, the "High Resolution Land Cover Classification – USA" deep learning model, developed as a collaboration between the USDA and Esri (Esri, 2023a), was utilized. This classification model was selected for several reasons. First, Esri, a respected company in the GIS field, made the model freely available on the Living Atlas database, which increases the accessibility of the model. It requires no supervised classification on the part of a geospatial analyst, thereby removing a potential source of variability. This model is designed for high resolution data (up to 80cm pixels), which is necessary for the spatial heterogeneity of the urban environment.

After classification, values were assigned to the different landcovers based on the MAES Service Providing Units. This was done five times, once for each of the UES being investigated in this study. Values had to be integers, so the values of "1", "0.5", and "0" (as in the "Traffic Light" ES matrix) were changed to "10", "5", and "0". These maps were then combined using the "Raster Calculator" tool to create the combined UES map with values of 0 (built environment) to 45 (tree canopy). Finally, random points were generated within the city's extent. These points were given specific X,Y coordinates and then exported to a spreadsheet. These points were used as ground truthing points, to assess the accuracy of the deep learning model and generate F1 scores for the classification types. This workflow was repeated for a total of 10 cities in the western United States.

## 3.3 Data Analysis

Fifty ground truthing points were assessed per city. The deep learning class of each point was identified, then digitally verified in triplicate, using the NAIP 1m imagery, Google Maps, and Google Earth Pro to verify the true landcover type at that point. Any time a point did not have a clear result across all three sources of verification aerial imagery, that point was skipped, and another point was assessed.
Mean accuracies per-landcover category and per city were calculated. This was considered the "raw data". the matrix was adjusted in response to the initial results. Furthermore, landcover categories with the same value in the matrix (e.g., "Impervious Surfaces" and "Structures" are both categorized as "Built" in the ES matrix) were combined. The accuracy analysis was repeated and mean accuracies per-landcover and per-pixel were generated for the "adjusted data". ES maps were created with the updated ES matrix. Cities had their UES score calculated based on the mean per-pixel values of the combined ES maps to determine relative concentration of UES between cities.

Confusion matrices and F1 Scores were developed for landcover classification accuracy of both the raw and adjusted data. F1 scores were calculated with the following equation:

$$F1=2 * ((Precision * Recall) / (Precision + Recall))$$

These values were then compared to the F1 scores initially published by Esri and USDA for each landcover classification in the deep learning model, to compare how the model performed in this application as compared to its original development.

# 4 Results

After initial ground truthing, the “Barren”, “Shrubland”, and “Wetland” landcovers were not effectively classified by the deep learning model. In response, the original ES Matrix was adjusted to reflect these changes (see figure 3). The “Barren” pixels were most often impervious surfaces, and the “Wetland” pixels were “Low Vegetation” at 80% of the ground truthing sites. As such, “Barren” pixels were given equal value to the built environment, and “Wetland” the same as ground vegetation. The “Shrubland” class almost never occurred across all cities (only .02% of all pixels), so any perennial vegetation with notable height was combined as “trees/shrubs”. Finally, all impervious and built categories were combined under built environment for accuracy assessment, since they all did not provide any UES.

**Original**

| | Trees | Shrubs | Ground Vegetation | Soil/Barren /Pervious | Water | Wetlands | Built |
|---|---|---|---|---|---|---|---|
| Air Quality | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| CO2 Reduction | 1 | 1 | 0.5 | 0 | 0 | 1 | 0 |
| Urban Temp | 1 | 0.5 | 0.5 | 0 | 1 | 1 | 0 |
| Noise Mitigation | 0.5 | 0.5 | 0.5 | 0 | 0 | 0.5 | 0 |
| Water Flow | 1 | 1 | 0.5 | 0.5 | 1 | 1 | 0 |

**Edited Based on Ground Truthing**

| | Trees | Shrubs | Ground Vegetation | Soil/Barren /Pervious | Water | Wetlands | Built |
|---|---|---|---|---|---|---|---|
| Air Quality | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| CO2 Reduction | 1 | 1 | 0.5 | 0 | 0 | 0.5 | 0 |
| Urban Temp | 1 | 0.5 | 0.5 | 0 | 1 | 0.5 | 0 |
| Noise Mitigation | 0.5 | 0.5 | 0.5 | 0 | 0 | 0.5 | 0 |
| Water Flow | 1 | 1 | 0.5 | 0 | 1 | 0.5 | 0 |

**Figure 3. Original UES matrix versus after adjustments were made based on the initial data assessment.**

Results from the adjusted data accuracy assessment can be seen in figure 4. The adjusted data had a mean accuracy of 87.6%, with a standard deviation of 10.5 and a Coefficient of Variation (CV) of 11.9%. The only class with less than 80% accuracy is “Low Vegetation/Wetlands”, with a mean accuracy of 73%. The “Impervious/Barren Soil”, “Water”, and “Trees/Shrubs” categories had mean accuracies of 96.5%, 82.4%, and 98.5%, respectively.

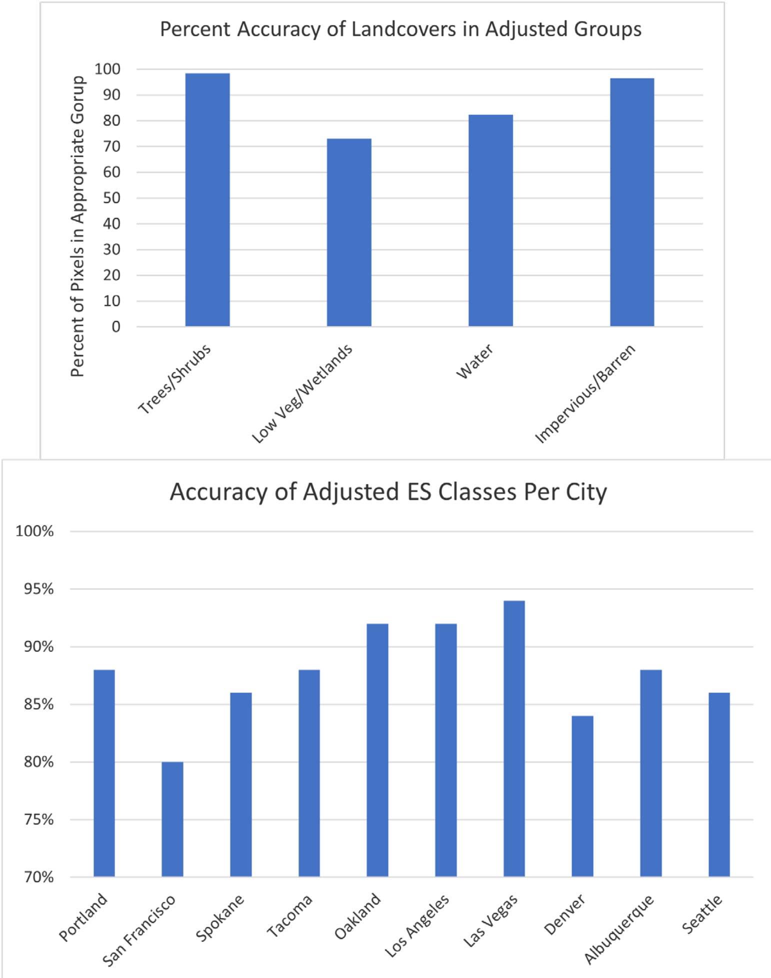


**Figure 4. Results of the accuracy assessment of the adjusted data**

F-1 scores for the landcover classification of the adjusted categories had a mean value of 87, with a range of .82-.94 with a standard deviation of .06. Therefore, when the classification management is adjusted to reflect the results from the initial assessment of the raw data, the deep learning model can be considered a statistically accurate landcover classification tool for this application.

The mean per-city accuracy of the adjusted data reached 88.8%, with a standard deviation of 3.1 and a CV of 3.6%. The range of accuracies was from 84-94%. Given this high accuracy and low coefficient of variation, this can be an effective tool for assessing the distribution of five UES across a variety of urban environments. Beyond the accuracy assessment of the deep learning model in relation to the novel standardised ES matrix, it can be helpful to understand the distribution of values generated by the model. Figure 5 includes the successive map generation process for determining the overall ES value for a sample city: Portland, OR. Across the 10 pilot cities, the range of mean pixel values as a relative presence of UES ranged from 7.68 in Albuquerque, NM to 17.79 in Portland, OR. The mean for the ten cities is 12.08, with a standard deviation of 3.31. When separated into broad environmental categories (Portland, San Francisco, Tacoma, Oakland, and Seattle as temperate; Spokane, Los Angeles, Las Vegas, Denver, and Albuquerque as arid), there are some differences. The temperate city average is 13.64 and the arid city average was 10.53. Because this is a dimensionless metric, it cannot necessarily be used to quantify specific benefits. However, it can be very useful for comparisons between cities or understanding relative distributions within a city.

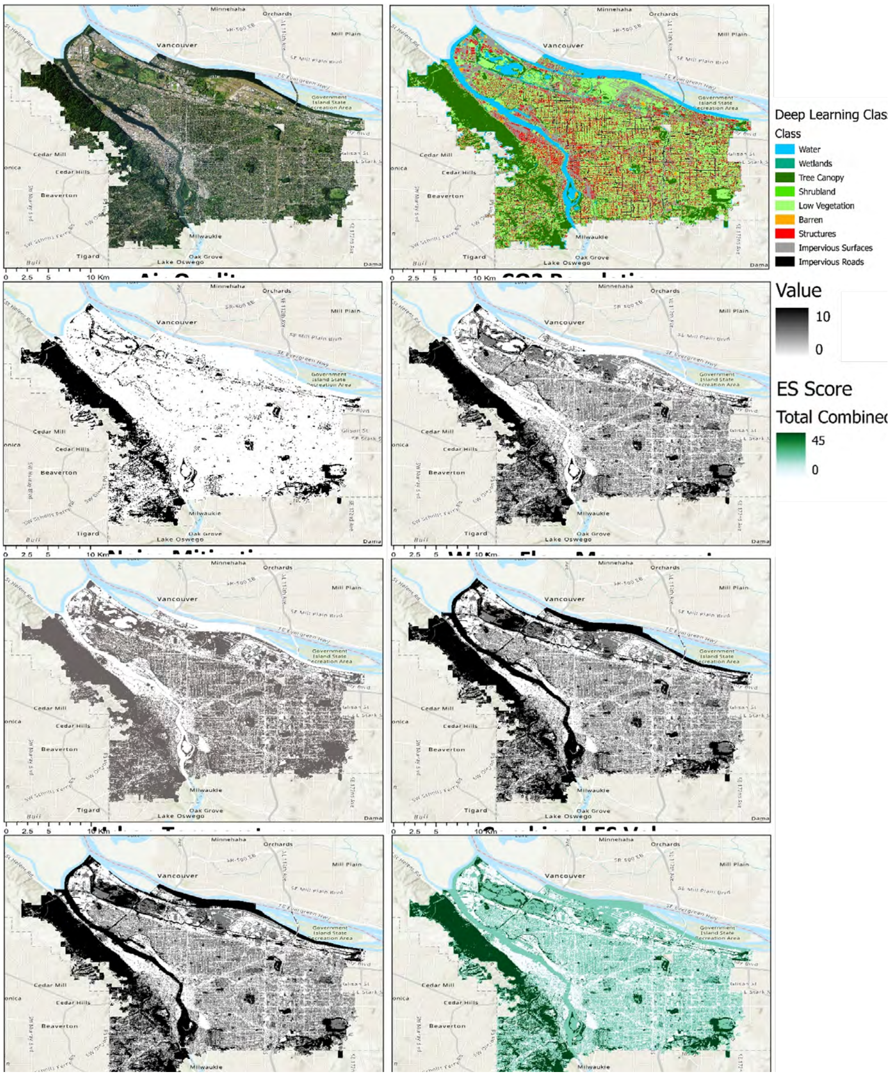


**Figure 5. Results of successive map generation to create a final combined ES map. 1) NAIP Aerial Imagery, 2) Deep Learning Classification 3) Air Quality ES Layer, 4) CO2 regulation ES layer, 5) Noise Mitigation ES Layer, 6) Temperature Regulation ES layer, 7) Water Management Layer, 8) Total Combined UES Map**

# 5 Discussion

In a meta-analysis, Grekousis found a mean of accuracy 87.1% in AI landcover classifications (2018), mirroring these results. Given the high accuracy (84-94%, average of 88.8%) and low CV (3.6%) of the per city analysis of adjusted data, this deep learning model could be an effective starting place for the development of a standardised methodology for UES assessments. The adjusted data's F1 score range of .82.-94 and mean of .87 supports this claim. This study only looked at five of the regulating ecosystem services outlined in the MAES 4th report, and a complete ES analysis would require additional data beyond aerial imagery, but this methodology can act as a starting point for cities with no UES data.

## 5.1 Applications

The deep learning model identified the relative presence of 5 of the UES defined in the MAES 4th report using only aerial imagery. Although any value from an ES matrix is dimensionless, having a methodology that does not require any contextualization between cities allows for this unit to be used in comparative research across multiple cities. It also allows planners to identify neighborhoods with relatively low supply of ES compared to the city average. These more granular assessments can be used to identify neighborhoods with higher climactic vulnerability or be combined with demographic mapping to support climate justice initiatives.

A comparative metric allows for the development of UES-informed policy at state or federal levels. Without a standardised metric, quantifiable benchmarks and measurable progress is difficult. And with the relatively low entry barrier of this methodology, broader datasets can be more easily generated despite resource limitations in some cities. Without the deep learning model, a geospatial analyst would have to perform multiple supervised classifications, which could introduce variability or bias. Using AI for the classification process saves time and labor, while simultaneously increasing consistency across different cities.

## 5.2 Limitations

Despite the successes of this model outlined above, its shortcomings must be discussed. These include limitations with the model and data limitations.

### 5.2.1 Model Limitations

The results showed there was low accuracy in the "Wetland" and "Barren" classes, and vegetation with a vertical aspect ("Shrubland" and "Tree Canopy") could not be effectively differentiated. This led to changes in the ES matrix in response to these shortcomings. The barren soil was most commonly found in arid climates, and only had an impact of water management, so the impact of the changes to the matrix is minimal. However, wetlands had a different value than low vegetation for 3 of the 4 UES. Therefore, the inability to measure wetlands through remote sensing must be addressed.

Wetlands can be challenging for remote sensing classification, because they can have a variety of vegetation structures and aerial photography struggles to discern differences in soil conditions. Furthermore, ephemeral water bodies common in wetlands can be challenging to identify when there are not multiple time-points in the analysis. However, U.S. federal policy requires urban wetland delineation in most major cities (Tiner, 1993), so many cities have wetland delineation maps. The wetland maps could be included in the geospatial assessment, and any pixels that intersected the wetland shapefiles could be reclassified as "Wetland" pixels, dramatically improving the accuracy of wetland classification.

There was also a clear increase in error from the model classification near the boundaries of the city extent. The "edge effect" is often identified as a source of error in a variety of fields, and it was seen here as well. Examination of how urban extents are defined in this methodology could further reduced error.
As mentioned earlier, the internal processing of many deep learning models is often proprietary, meaning that model users cannot see the mechanism behind the outputs. As a result, it is more challenging to troubleshoot the shortcomings of the tool beyond informed speculation.

### 5.2.2 Data Limitations

Despite the benefits of remotely sensed data, there are some limitations. Shadows in the aerial photography caused error in the Seattle pilot city. This is a common challenge with remote sensing, where shadows are classified as water. Future research could consider including a local analyst to review landcover classification maps prior to the "Reclass" step, to catch any major errors like this. There are also limitations in data resolution availability. 1m resolution data, used in this study, is higher than average for UES research (García-Pardo et al. 2022). In some regions, spatial data of this resolution may be costly or unavailable. Alternatively, 1m spatial data could be out of date due to low temporal resolution, increasing potential error.

## 5.3 Future Research

The future research with the most potential is utilizing the concept of the universal "traffic light" UES matrix to include all the UES and Service Providing Units outlined in the MAES 4$^{th}$ report, and finding corresponding standardised GIS protocols for their assessment. If created, the EU would have a consistent and replicable tool for generating UES values for all cities in alignment with the JRC research. This would allow consistent reporting across any cities willing to participate, with minimal contextualization or risk of variability from different methodologies.

With regards to the Service Providing Units in the MAES 4$^{th}$ report, many of them can still be challenging to estimate with remotely sensed data or common datasets. For example, it is difficult to use spectral data to determine if a backyard garden is producing food, which changes estimates of provisioning UES. And for the insect pollinator UES, 1m resolution is still too coarse for identification of flowering plant cycles. Additionally, the model was not successful at identifying permeable land (barren), which must be prioritized over impervious surfaces for UES-informed land use planning. For these reasons, there are still several obstacles to a remote sensing methodology that includes all UES outlined in the MAES 4th report. However, as the field progresses, it would be beneficial to include future breakthroughs in geospatial tools. Moreover, many cities will already have GIS data that includes public parks, areas of natural preservation, wetlands, watersheds, and cultural heritage sites. Including data directly from cities increases the potential for mapping of provisioning and cultural UES with fairly straightforward geospatial methodologies.

There are also areas of future research for improved accuracy of the model. More accurate results could be achieved by reassessing how urban extents are defined prior to classification. The shapefile used here to define city boundaries included nearby freshwater within a city's boundaries, but not saltwater. As a result, coastal cities could not account for the UES provided by marine coasts. Furthermore, by creating a buffer area wider than the area of interest for each city, this would address the edge effect error, increasing overall accuracy.

In terms of usability, the data from this methodology could be more helpful to planners by changing how the final results of the combined ES maps are displayed. In this study, overall UES values were displayed from 0-45. However, this range as a dimensionless unit could be challenging to interpret. For easier interpretation, the combined ES values could be divided by the highest possible pixel value, and the overall ES value could be a percentage. Those numbers might be easier for non-researchers to utilize. This could also make future analyses easier to interpret when multiple categories of UES are assessed (i.e. cultural, provisioning, and regulating, which could have different total sums in the assessment).

Finally, the field of AI is rapidly developing, and as such, new models are consistently being released. Future research should review new models, as they might have better accuracy or capacity to process different data types for other UES. Furthermore, future models might be better contextualized for classification in different climates. The training site for the model was the Chesapeake Bay Inlet along the East coast of Vermont, United States (Esri, 2023a). The pilot cities here were in temperate coastal, temperate continental, and arid environments. Although the CV between these cities was only 3.6%, tropical and boreal cities were not investigated in this study. Future classification models optimised to different climactic regions could help address unique spectral signatures across different environments.

## 5.4 Conclusion

Although this model functioned for this initial trial in UES evaluation, there is still growth potential in this methodology. The average 88% accuracy is also a strong result for a first study; however, the continued improvements outlined in section 5.3 could push that average even higher. And the expansion of this research to include a universal UES matrix including all UES outlined in the MAES 4$^{th}$ report could generate an incredibly useful tool for UES assessing and reporting.

Global ES mapping is an important issue, and the spatial heterogeneity and population density of urban environments presents unique challenges to this endeavour. However, the rapidly expanding field of AI and deep learning will offer many new tools for transforming raw data into actionable research. Here, an EU-funded UES research project was combined with a deep learning model to streamline the assessment of regulating UES across multiple cities with a unified methodology. Hopefully, we will see many more intersectional studies that decrease the obstacles and costs in UES assessments, thereby increasing the data-driven tools available to policymakers, and supporting the development of ecologically-informed and climate-smart urban planning.

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APENUWA, OLUWASEUN

# Quantifying The Benefits of Nature-Based Solutions in Urban Environment, A Case Study of Glasgow, UK

*Nature-based solutions (NBS) are innovative and sustainable approach for city resilience. This research aim to value eco-services provided with a focus on trees and artificial floating wetlands(AFWs) to promote better management and investment in Glasgow. A multi method methodological approach was adopt to achieve this. Spatial coverage of trees was processed using ARCGIS with Landsat 8 imagery from year 2013,2020 and 2023. Tree valuation was carried using i-Tree Canopy and existing literature for AFW. Management issues was assessed through interviews for both. Glasgow spatial analysis showed a reduction in canopy cover from 18.4% to 16.1% between 2013 and 2023. Glasgow eco-services estimation was valued at about £5 million annually and carbon storage valued at over £55 million. AFW on the other hand offers water treatment eco-services valued at £346,410 which is more than twice the cost of installation. Its use is limited due to low awareness and rigid planning laws. Conclusively, the lack of a detailed policy document and synergy among stakeholders played a significant role in the poor management and limiting efforts to increase canopy cover. Both NBS are important urban infrastructure and unique in their respective use and are expected to complement each to achieve urban resilience.*

# 1 Introduction

Cities' growth over recent decades have increased in size and density, this is expected to continue in upcoming decades as it absorbs most of the global population (Cohen 2006; UNDESA 2012). Migration and natural increase are two important factors in urban population and are closely interconnected (WHO 1993). Developing countries in Africa and some parts of Asia are expected to grow naturally accounting for almost all of the global population growth during the next decades. These countries' urbanisation process is likely to overwhelm their capacity to meet the requirements to fully harness their economic growth potential. At the same time, demographic shifts and economic incentives will increase the need for migration from developing countries to aging and developed countries.

The increase in urban population are needed to provide working force for cities' growing economy Unfortunately, the speed of city's growth comes with challenges. These challenges include meeting the demand for affordable housing, well-connected transport system, jobs, as well as other infrastructure such as energy, water, security, etc. (UN 2018). The increasing urban population makes it account to 71-76% of CO2 emissions which has made cities vulnerable to the effect of climate change (IPCC 2014).

Consequently, green spaces within cities have come under pressure due to large scale urbanisation and land use transformation. This encroaching into these green spaces have negative effect on the ecosystem services, cultural association, psychological well-being, and the health of urban dwellers (Tian et al. 2011). Nature-based solutions as a concept that uses natural or modified ecosystem to address urban sustainability challenges has been given less attention because decision-makers cannot quantify the benefit derived from green infrastructure. Infrastructure such as power, transport, telecommunication, water, sanitation, and waste management have remained central to economic development and have continually enjoy priorities by policymakers and planners to attract investment (Démurger 2001; Gramlich 1994).

It is widely acknowledged that street trees are essential parts of urban ecosystems that can enhance environmental quality by offering important ecological advantages. An increasing amount of literature emphasizes the ecosystem services offered by street trees, including carbon storage, air quality regulation, and improvements to the streetscape and amenities. Another solution for reducing the Urban Heat Island (UHI) effect appears to be street trees. Additionally, trees are crucial for the hydrology of urban catchments because they intercept rainfall through their canopy and allow it to seep into the soil (Dover 2015: Livesley et al 2014).

A direct comparison between the services offered, the expenses of establishing and maintaining the green infrastructure, and the potential financial returns from other land use choices is made possible by using economic data to describe the benefits of green infrastructure in monetary terms. The advantages of green infrastructure might be taken for granted or ignored in the absence of such data (Natural England (2013). Hence the project aims to establish a value case for urban nature-based solutions in Glasgow using appropriate assessment tools in order to understand their economic benefits for better investment and management.

## 2 Background

The birth and expansion of contemporary cities across practically every continent is clearly the most notable aspect of collective human development during the past 200 years. Widespread changes in land use over the past two centuries have required enormous amounts of energy and resources, but they have also put enormous strain on local, regional, and global natural ecosystems, leading to significant habitat fragmentation, biodiversity loss, the depletion of natural resources, and degradation of crucial ecosystem functions (Haase et al. 2014; Boumans et al. 2015). Therefore, modern cities cannot disregard the disproportionate effects that their continued development has had on local and global life support systems (Pickett et al. 2008).

Additionally, cities are leading the global response to climate change mitigation and adaptation due to the risks and repercussions of extreme events on vulnerable urban populations (Frantzeskaki et al. 2019). Cities are under increasing pressure to reduce their greenhouse gas emissions, increase the resilience of urban infrastructure to future climate change, and address their urban challenges with solutions that also benefit human well-being and biodiversity. This is because climate change is accelerating and urbanisation is largely continuing in an unsustainable manner. This suggests a departure from traditional urbanisation paradigms and a trend toward travel routes that are more in tune with nature. One of the most effective strategies for adapting to climate change is the implementation of green infrastructure, which has been shown to offer various benefits related to climate change mitigation and adaptation (Emmanuel & Loconsole 2015). In 2017, the United Kingdom’s natural capital in urban areas, which represents 8% of the country’s total land area, was estimated to have an annual total value of £243.6 million in labour productivity savings and avoided air conditioning energy costs from cooling provided by green and blue space. The removal of air pollution by urban green and blue space equated to a saving of £162.6 million in associated health costs. Additionally, the carbon removed by woodland in UK urban areas was estimated to be worth £89.0 million, noise mitigation by urban vegetation led to a saving of £14.4 million in avoided loss of quality of life years, and recreation spent in nature in the UK urban environment was valued at £2.5 billion in 2017 (Office of the National Statistics 2019).

Recently, a study was conducted for the first time to rank urban centers in the United Kingdom based on their green attributes, such as trees, greenness, and green spaces. This study revealed significant variations in the percentage of green attributes between urban centers, with Glasgow ranked the lowest with a mean NDVI of 0.02, a tree cover of 1.95% and an OS Greenspace coverage of 0.00% (Robinson et al. 2022). Urban planning must prioritize improving access to green and blue spaces for the growing populations of city regions. The pandemic has also presented an opportunity to redevelop urban areas and increase the public realm, particularly since many believe that the changes to the way we work will be permanent.

## 2.1 Urban Trees

Urban and peri-urban forests (UPF), which refer to ecosystems dominated by trees located in and near human settlements, are vital components of livable and healthy cities, particularly in our increasingly urbanized world. They play a crucial role in shaping a sense of place, preserving environmental quality, and enhancing well-being in and around urban areas where most people reside today (Endreny 2018; Nowak 2018). There are two key developments that have contributed to the recent surge in scientific and policy attention towards UPF, they provides numerous ecosystem services and are increasingly recognized as a potential source of 'nature-based solutions' (Dobbs et al. 2018, Cohen-Shacham et al. 2016). One of such notable benefits is the capacity of trees in Glasgow to eliminate UHI in the city center through the Avenue Programme, which is expected to increase significantly thermal comfort when heatwaves occurs (Ananyeva & Emmanuel 2023).

Despite the considerable academic recognition of the benefits of street trees, the importance of these trees is often not fully appreciated by local governments due to a lack of knowledge regarding their economic value. Meanwhile, the costs associated with tree-related damage, such as leaf litter and infrastructure damage, are widely reported (Rogers et al. 2015; Rötzer et al. 2021). It is crucial to provide evidence of the monetary value of street trees to decision-makers as this information forms the basis for long-term management and maintenance practices.

## 2.2 Artificial Floating Islands

In recent decades, Artificial Floating Islands (AFIs) have gained popularity as a low-cost technology for large-scale wastewater treatment (Afzal et al. 2019). The treatment of agricultural runoff, urban effluents (including domestic greywater, municipal sewage, residential/landscaping runoff, and stormwater runoff), industrial effluents (including aquaculture operations, dairy operations, textile operations, refineries, and acid mine drainage), and synthetic effluents have all been reported to use this method. In comparison to conventional methods of treating wastewater, AFIs offer a range of benefits which include their ability to float and not require land and can accommodate changes in water level, they are environmentally friendly and the costs associated with constructing, operating, and maintaining AFIs are low due to their simplicity and use of locally available materials (Yu et al. 2019; Queiroz et al. 2020).

There is a large gap to fill in encouraging relevant stakeholder to utilise the use of naturebased solutions for a sustainable urban development. Glasgow tree survey was done in 2013 and requires and update every 5-10 years, this research will be an update on the performance of the city council. With growth rate of urban environment, floating wetlands is another option for building city resilience despite the competitive use of land. Nature based solutions are eco-friendly solutions that requires proper management to maximise its benefits. In view of this, we need to have detail understanding about them and their value to ensure proper implementation of the right management strategy and encourage investment.

# 3 Methodology

## 3.1 Study area

Glasgow city council is located around 55.8642°N and 4.2518°W in the West Central region of Scotland and known as the largest city in Scotland by area and population among the 32 local authorities in Scotland. The city is made up of 23 political wards which occupies an area of 176 km2 (Figure 1) The city's population fell by 0.1% from its initial estimate of 635,640 in 2020 to 635,130 in 2021. This is thought to be an accurate representation of the entire effects of COVID-19 and the related lockdown at this time. By 2028, the city is expected to grow by 2.9%, compared to Scotland as a whole, which is expected to grow by 1.8%. (National Records of Scotland 2022)

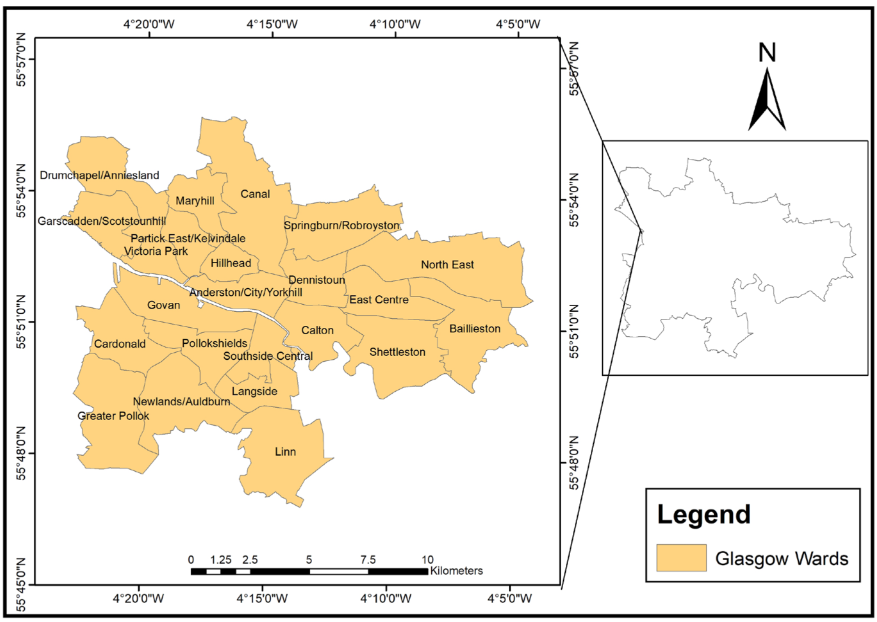


**Figure 1. Map of Glasgow showing 23 political wards (Figure: Apenuwa 2023)**

The climate of Glasgow is categorised as warm and temperate. Glasgow experiences significant annual precipitation. A respectable amount of rain can occur during even the driest months. The region's typical climate falls under the Köppen-Geiger classification (Cfb), its maximum temperature on average does not exceed 20ºC, and average temperature of 10ºC for at least five months. Precipitation is abundant (annual average = 1300 mm) and evenly distributed throughout the year (Oertel, Emmanuel & Drach 2014).

## 3.2 Data Collection and Processing

Data collection and its processing is a key part of this research work. This study utilises both primary and secondary data. Primary data were obtained for spatial mapping of the green infrastructures which were process to determine their location and spatial distribution. In the case of Glasgow tree mapping, Landsat 8 satellite imageries were collected for 2013, 2020 and 2023. The satellite imageries were collected in summer months for year 2013 and 2023 (20/07/2013 and 15/06/2023), year 2020 data was collected in September (18/09/2020) due to unsuitable data during summer months. Artificial floating wetlands was mapped using location information gathered during interview.

To determine the value of tree ecosystem services, I-Tree Canopy was used to analyse this using canopy cover value estimation, this application does not require individual tree survey to make an estimate like in the case of using I-tree Eco. I-tree Canopy requires some knowledge about the study area for ground truthing. To further understand the management of both trees and artificial wetlands in Glasgow, relevant stakeholders were consulted and interviewed to better understand this. Glasgow city council was consulted on tree management and Biomatrix Water (an ecological technology company) responsible for the installation of floating wetlands in Glasgow. Secondary data such as research publications were used to quantify and analysis the benefits of floating wetlands since there were no available software for this.

## 3.3 Methodological Approach

### 3.3.1 Tree canopy spatial mapping

In other to map out tree canopy cover for Glasgow city covering the last 10 years, Landsat 8 which has global coverage and readily available from 2013 and beyond was used. These imageries (Landsat 8) were acquired for 2013, 2020 and 2023 in summer months. This was further subject to processing using ARCGIS (ArcMap). From figure 2, the methodological framework outlines all the processes that were followed. Since the landuse classification was focused on vegetation, unsupervised classification was used. The accuracy of the landuse classification was assessed before reclassification to select the class category for trees. This was used to generate tree canopy map for year 2013, 2020 and 2023. To further understand spatial change analysis, year 2013 and 2023 canopy results which showed a 10-year period of tree canopy change in Glasgow city.

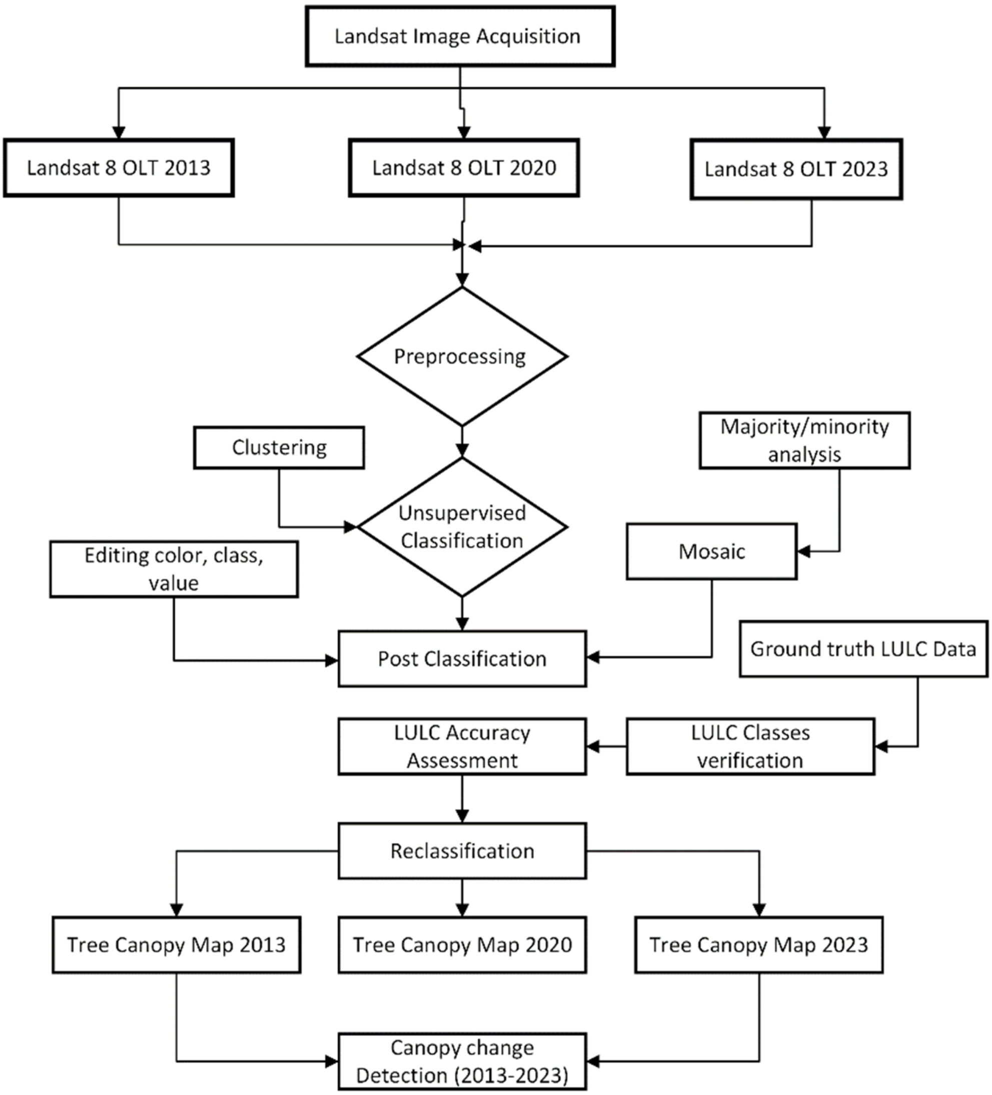


**Figure 2. Methodological Framework for Tree canopy mapping (Figure: Apenuwa 2023)**

### 3.3.2 Ecosystem valuation (i-Tree Canopy)

i-Tree Canopy is one of i-Tree tools developed by USDA Forest Services for forestry benefit assessment for use in the United States and other countries in Europe, e.g United Kingdom. It is a web browser application that can be used to determine the amount of an area of interest covered by tree canopy and other user-defined surfaces. From figure 3 showing the methodological framework of i-Tree canopy, the application operation is categorised into three states (Project setup, survey and result generation). The survey stage requires assigning categories to the randomly generated point on the map until a standard error of less than 1.5 has been achieved or survey of 1000 points (Woodland Trust 2021).

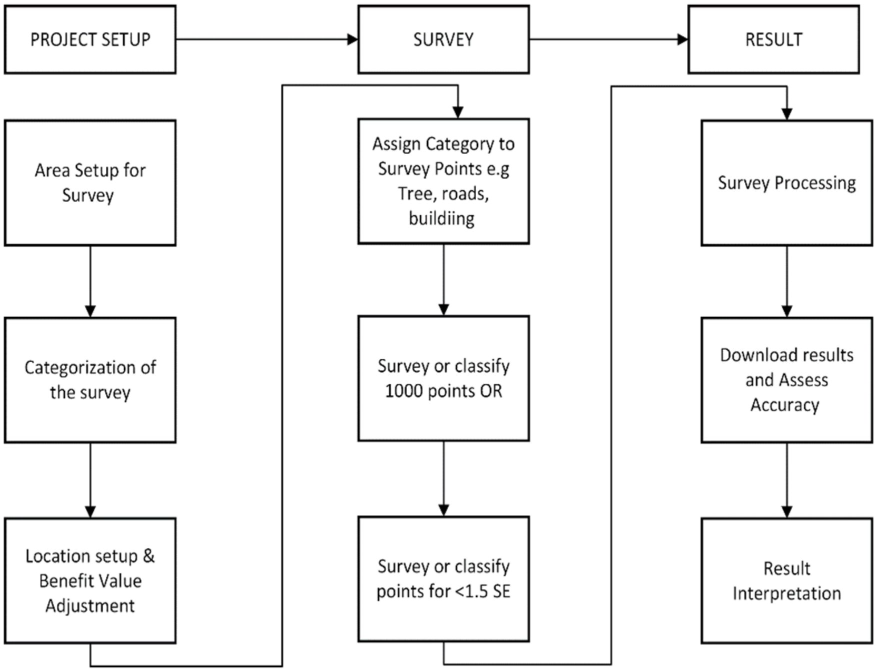


**Figure 3. Methodological Framework ecosystem valuation using i-Tree Canopy (Woodland Trust 2021)**

# 4 Results

## 4.1 Spatial Analysis of Nature-based Solutions

### 4.1.1 Trees canopy cover

The spatial analysis estimated 18.4% coverage of trees in the city in the year 2013 (Figure 4a). At ward level, the canopy cover was not evenly distributed. From the 23 political wards within the city, the three highest canopy cover were in Northeast, Linn and Canal which represent 36.6%, 27.9%, 26.9% respectively of their land areas. The least three canopy wards were Anderston/City/Yorkhill, Govan and Calton which represent 1.6%, 4.96% and 7.6% respectively of their wards' land area.
In 2020, Glasgow tree stock depleted to have 15.8% coverage of the total land area of the city (Figure 4b). The wards canopy cover was also mapped which made Northeast, Canal and Greater Pollok the highest canopy cover with 32.29%, 22.99% and 21.76% of their total land area. The least three wards were Anderston/City/Yorkhill, Govan and Pollokshields with 2.91%, 3.85%, 5.56% respectively of their total land area.

From figure 4c, the present tree canopy cover for 2023 is 16.1% which is 2.3% reduction from 2013 record. At ward level, canal, Northeast and Springburn/Robroyston led with 24.93%, 24.28% and 20.92% respectively of their total land areas. The least three wards were Anderston/City/Yorkhill, Govan and Southside central with 2.33%, 5.83% and 8.66% respectively of their total land areas.

Over the period of 10 years (2013 – 2023), there were some significant increase and decrease of canopy cover across political wards in Glasgow city council. Wards with the highest reduction in canopy cover were Northeast, Linn and Springburn/ Robroyston with a reduction of 12.35%, 8.54% and 5.25% respectively in their wards. Three notable wards had the highest increase during the 10-year period, they include Victoria Park, Drumchapel and Calton with a percentage increase of 3.24%, 1.65% and 1.46% respectively. The city center ward (Anderston/City/Yorkhill) has a percentage increase of 0.78% (Figure 4d).

It is clear that there was more decrease than increase at ward level. Northeast ward lost the highest canopy cover of 12.35% within the ward while Victoria Park Ward made the highest canopy gain of 3.24% within the ward. Using the canopy change detection at city level, the city lost 4.6km2 land area of canopy cover which represent 2.6% and gained 0.6km2 which represent 0.3% of the city total area. Losing the existing stock of urban trees cannot be easily replaced with new trees, for example, the city will be losing 90,000 ash trees due to dieback disease which is one of the many diseases prevalent in the city while only planted 64,220 trees (Glasgow Tree Plan) between 2018 and 2022 with the possibility of loose some before maturity.

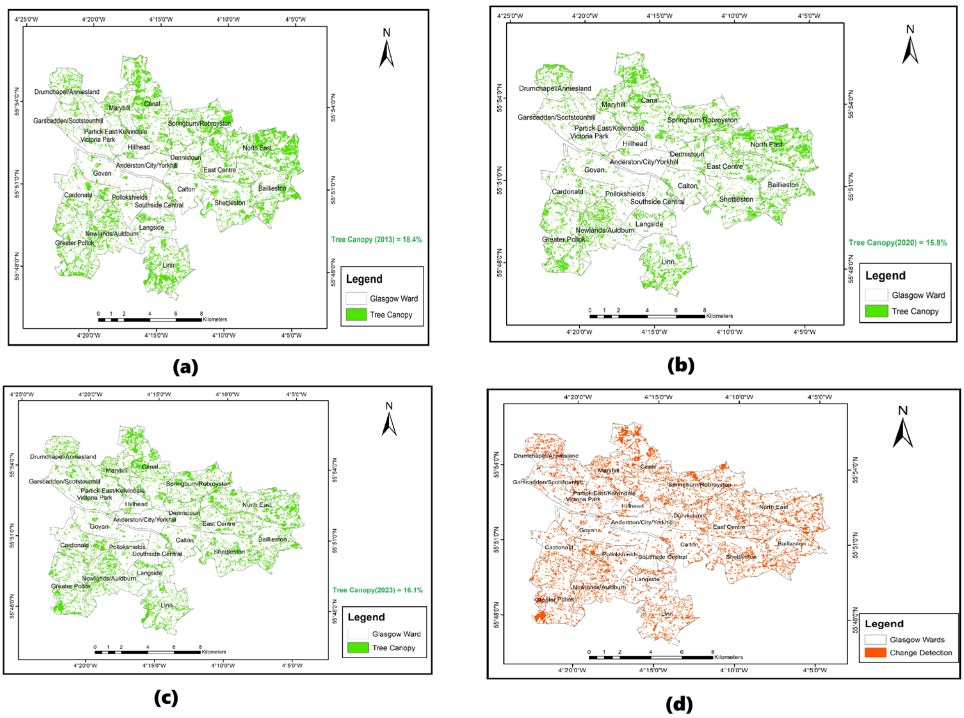


**Figure 4. Glasgow tree canopy map coverage (a) for 2013, (b) 2020, (c) 2023 and (d) Change Detection of Tree Canopy Cover between 2013 and 2023. (Figure: Apenuwa 2023)**

### 4.1.2 Artificial Floating Wetland (AFW)

The installation of artificial floating wetland is limited to two locations with Glasgow city. The first installation was at Pinkston. It was installed in 2020 and has an area of 36 square meters with about 1000 plants. The second location is at the Glasgow Science Center which was installed recently in March, 2023. It spans across 192 square meters on three wetlands (53,53 & 86m$^2$). The three wetlands are made up of over 4000 plants and tree couple with nesting platforms as new habitat for wildlife to thrive.

## 4.2 Valuation of Nature-based solutions

### 4.2.1 Tree

Glasgow tree canopy coverage was estimated to be 16.14%(28.41km$^2$) of the total area of area of the city council (175.96km$^2$).

**Carbon Sequestration and Storage**

The annual sequestered carbon by trees in Glasgow is 8.69kt which is equivalent to 31.87kt of $CO_2$. This is values at £2,199,069 worth of carbon annually. Trees is an important carbon sink, presently Glasgow trees stores 218.29kt. This is calculated based on 7.685 kt of Carbon, or 28.178 kt of $CO_2$, per km² and rounded. This stored carbon is presently valued at over £55 million.

**Air Pollution**

i-Tree canopy application covers six air pollutants captured by urban trees namely Carbon monoxide (CO), Nitrogen Dioxide (NO2), Ozone (O3), Sulfur Dioxide (SO2), Particulate Matter less than 2.5 (PM2.5) and Particulate Matter greater than 2.5 microns and less than 10 microns (PM10). The total quantity of these pollutants is estimated to be 214,453,932.05g removed annually which is valued as £1,476,517.

**Hydrological Services**

Glasgow tree infrastructure offers range of hydrological benefits that can be quantify, this include Avoided runoff(AVRO), Evaporation (E), Interception (I), Transpiration (T), Potential Evaporation (PE) and Potential Evapotranspiration (PET). The value of only avoided runoff was estimated by i-Tree Canopy. Annually, 703.63ml of water was avoided as runoff with an estimated value of £1,090,556. The measure ecosystem service derived from trees is about five million pounds annually as at year 2023. The total annual ecosystem services from Glasgow trees is estimated as £4,766,142 annually.

### 4.2.2 AFW

Limited information was available to assess and quantifying the ecosystem services provided by artificial floating wetlands. Biomatrix Water confirm the nutrient removal capacity of their wetland installations. The wetlands have established capacity to remove 1.5g/m$^2$/per day of Nitrogen and 0.1g/m$^2$/per day of Phosphorus. The total area of floating wetlands in Glasgow is 228m$^2$ (36m$^2$ in Pinkston and 192 m$^2$ in Glasgow Science center). It can be estimated that the nitrogen uptake is 342g/m$^2$/per day and 22.8g/m$^2$/per day of phosphorus in Clyde river and its tributaries. Annually, this is a total of 124.8kg of nitrogen and 8.3kg of phosphorus removed from Glasgow water. According to Kavehei et al., 2021 and Bashar et al., 2018, this will cost the city council $13,728 to remove nitrogen and $1,114 to remove phosphorus annually (USD 110 kg-1 for Nitrogen and $60.88 per lb of Phosphorus). A floating wetland is expected to have 30 years and more lifespan, the lifetime nutrient removal ecosystem services provided will be £346,410 in a 30-years lifespan

### 4.3 Management Challenges with Nature-based solutions

Proper tree management in Glasgow city is limited because the government lack necessary policies such as Forestry and Woodland Strategy and stakeholders' synergy to achieve this. The limitation of the existing tree plan which is quantitative in approach and the cost retrofitting trees which ranges between £6000 – £30,000 per tree. The lack of tree records has also posed a challenge in managing urban tree, making increasing tree canopies difficult to achieve. Tree disservice are we limiting factors, the promotes crime in poor neighbourhoods, fallen trees affects nearby properties, increase in insurance cover and the damage to underground infrastructure. Increase canopy cover continue to be a major challenge as Glasgow trees because they are vulnerable to diseases (with over 90,000 ash tree to be lost), cost of planting, competitive land use, poor management and the effort put in to replace lost tree stock.

An installed floating wetlands has a lifespan of 20-30 years or more. The wetlands require little maintenance to make it a suitable habitat for wildlife and aquatic animals. Dead plants are replaced after winter and also the need for regular weeding. This is easy carried out as the platform can accommodate the weight of a person. It is also required that the anchor is checked to ascertain the stability on water, this is not an annual maintenance but done at interval during the lifespan of the floating wetlands. Government policies are major limiting factor to its use due to the maritime use of Clyde River.

## 5 Conclusions and Discussion

This research was aimed at creating a value case for ecosystem services provided by nature-based solutions in Glasgow city council so has to better understand the benefits to prompt better invest and management by the city authority. These research focused on two nature based solutions, trees which is a land based infrastructure and Artificial floating wetlands which is water based solution. Tree canopy cover is a well visible infrastructure in Glasgow landscape. Cities with no Forestry and Woodland strategy is likely to be losing its tree stocks as there is no policy to protect trees and encourage increase through effective management approach (Hr et al. 2019). The higher the canopy cover the higher the ecosystem services expected from trees, this applies to floating wetlands and any other nature-based solutions.

Over the past 10 years, the decrease tree canopy cover from 18.4% to 16.1% is a direct effect of many factors. Firstly, it could be established that poor management system by the city authority played a major role in the reduction of canopy cover in the city. Management starts with the full understanding of the tree stocks in Glasgow which will further help to under the condition of these trees so as to design suitable management strategies which will also influence the plan to further increase its stocks, this was missing in the case of Glasgow.

Secondly, protecting the stock of trees from weather, deforestation and especially disease is an important approach to increasing tree stock. As earlier mentioned, the death of 90,000 ash trees in the next few years is a loss that might be difficult to restore easily. Growing about 65,000 trees in the last 5 years is nowhere near the expect loss of trees. The existing tree stock is more valuable at the moment due to their mature stage and ecosystem services provided, hence the need to protect them.

Thirdly, the density of an urban environment has great influence on tree canopy cover. High density wards with most deprived tree canopy cover such as Glasgow city center (Anderston/City/Yorkhill) has low tree cover across the three observed years which is influenced by the city administration prioritizing other competitive land use such as development over GI. It is further observed that other wards close to the most deprived ward also experience low level of canopy cover as these wards receive the overflow of development and population from the city center. Lastly, quantitative and qualitative data about urban trees are very important for successful management of trees, in a situation when only one is available in the case of Glasgow, the city is prone to losing tree canopy cover and might not progress in increasing tree canopy cover. This situation will further limit the Glasgow tree plan to achieve 17.1% in the next year as the city is set to lose a large stock of its existing trees.

The use floating wetlands as a nature-based solutions has not been adopted in Glasgow city council, this might be due to low awareness despite its benefits been more than the cost and its effectiveness in cleaning urban waters. Government influence in terms of policies and aware could be a positive part to adopting the use of floating wetland. With the ecosystem services provided by trees which is more compared to artificial floating wetlands in Glasgow, they are both important urban nature-based solutions for sustainable development and are expected to play complementary roles which will further increase the resilience of the city to combat climate change.

Acknowledgements

The author expresses his gratitude to Professor Dr-Ing Henning Günther and Prof. Rohinton Emmanuel for the mentorship and guidance of this research. The author also appreciates Glasgow City council and Biomatrix Water for providing valuable information towards the success of this research.

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BORELLI DA SILVA, BIANCA

# Safeguarding Coastal Cities: Linking Nature-Based Solutions to Sea Level Rise Adaptation - A Case Study of Florianópolis, Brazil

*Coastal cities face escalating climate change risks such as rising sea levels, storm surges, and coastal flooding from high tides. Traditional approaches, often involving hard infrastructure, harm natural systems. Hence, there is a need to explore sustainable alternatives like nature-based solutions (NbS) to tackle these risks. This research focuses on Florianópolis, a Brazilian coastal city, to identify NbS opportunities for adapting to sea level rise and to offer replicable insights for other coastal cities.*

*The study employs diverse methods, including literature review, questionnaires, and spatial mapping of NbS possibilities in Florianópolis, taking a multifaceted approach. Strategies for adapting to sea level rise are selected, including the preservation of mangroves, sandy shores, urban forests, and coastal green corridors. Mapping risk-prone areas pinpoints priority zones susceptible to coastal flooding and identifies feasible NbS implementation areas. The discussion outlines challenges and barriers in implementing NbS in the city's context, along with recommendations to overcome them. In a broader context, the collection of strategies, constructed based on research results, can serve as crucial initial steps for coastal cities in their adaptation to sea level rise projections.*

# 1 Introduction

Coastal cities are exposed to several risks related to climate change, including sea level rise, storm surges, and flooding from high tides (IPCC 2021), as well as the increase in precipitation, and changes in the frequency and intensity of storm events (PBMC 2016). There is a limited amount of research focusing specifically on coastal cities, and how they can adapt to flooding events and sea level rise using nature-based solutions (NbS) strategies.

From all the risks caused by natural and anthropogenic situations, flooding present a significant risk to society in social and economic fields, therefore the cities' capacity of adapting to these events is extremely important to its sustainable development. Conventional protection can be helpful on reducing the risk of flooding in coastal cities, but this type of infrastructure usually causes negative impacts in natural ecosystems (Lopes & Casseb 2015), leading to future problems in the city as a network, highlighting the need of alternative strategies such as NbS. For NbS to work effectively, careful planning and strategic distribution are imperative, considering both spatial and temporal aspects.

Therefore, mapping opportunities for the implementation of NbS targeting specific issues and challenges can be the first step in planning NbS, furthermore providing concrete alternatives for the decision-making process (Longato et al. 2022). Thus, the need for identifying a case study coastal city was recognized, providing the opportunity to apply mapping and spatial analysis methods in a practical approach.

Brazil is a country with more than 60% of its population living in coastal cities (PBMC 2016), and the population allocated in the coastal cities of Santa Catarina state is facing an increase in the number of natural disasters, and in the medium level of the sea (Sedec/MIDR 2023). Different cities in the state suffer from different disasters, according to its geographical characteristics. In that sense, moving to a municipal and regional level is necessary to identify and plan specific strategies in line with the challenges of each city.

In the capital city of the state, Florianópolis, the human intervention and other activities severely increased the risk of coastal flooding (Marengo & Scarano 2016), and the coastal zone has been experiencing severe flooding events caused by high tides and other factors. Florianópolis is registered as the 11th city in the state in a list with the 15 cities with the biggest number of natural disasters occurrences (UFSC 2013), being the only coastal city in the list, and presenting the biggest number of flash flooding events.

Thus, this proposal observed that there is a significant issue to tackle, specifically coastal flooding predictions in Florianópolis. However, it also brings to light an opportunity to map potential areas for implementing NbS as a strategic approach for coastal cities to adapt and cope with the challenges posed by rising sea levels. Mapping allows city planners to visualize spatial patterns and inform decision-making, identifying suitable locations for the implementation of NbS, which can enhance resilience and provide long-term protection against sea-level-induced impacts.

# 2 Background

## 2.1 Climate Change Scenarios as a Guiding Tool

Despite all the recent efforts to reduce emissions, they are still going up for every major greenhouse gas (GHG) (IPCC 2022), and there is strong evidence stating that climate variability and extreme weather events will increase each year, causing a reduction of the resilience in the whole socio-ecological system (Gómez Martín, Máñez Costa  Egerer 2021). The Intergovernmental Panel on Climate Change (IPCC) Reports aim to provide policymakers with regular assessments of the scientific basis of climate change, its impacts, and future risks (IPCC 2022). Based on the current climate situation, recent trends, and driving forces, the Sixth Assessment Report of the IPCC presents a set of scenarios projected to show potential future climatic outcomes, assisting in the analysis of impacts, adaptation, and mitigation strategies related to climate change (IPCC, 2022).

The Scenario 1 (SSP 1–1.9) is the most optimistic one, envisaging global carbon dioxide (CO2) emissions reaching zero by 2050. This aligns with the Paris Agreement's objective of limiting temperature rise to 1.5ºC by the century's close. Achieving these demands societal shifts toward sustainability, reduced inequality, and mitigated climate impacts. Scenario 2 (SSP1-2.6) mirrors the first but with less abrupt changes, targeting zero emissions post-2050. This path could restrict temperature increase to below 1.8ºC by 2100 (IPCC, 2022). Scenarios 1 and 2 are optimal outcomes in the report. Conversely, Scenario 3 (SSP2-4.5), an intermediate projection, envisions emission decline starting by 2050, yet net zero is elusive till the century's end. Dire options include Scenario 4 (SSP3-7.0) and 5 (SSP2-8.5), depicting a future without climate policies (Ritchie H., Roser M., and Rosado P., 2020). These pathways could yield a 2.8 to 5.7ºC temperature surge by 2100 (IPCC 2022). All the scenarios present multiple consequences caused by climate change, and globally the large-scale effects are the increase in the global temperature and ocean warming, as well as the decrease in the extension of the arctic sea ice and ice sheets, and consequently, the increase in SLR (NASA 2023), showing a need for society to shift to a more sustainable development and policies.

The policies related to climate action fall under two broad categories: mitigation and adaptation. The mitigation strategies aim to reduce the emission of GHG in the atmosphere, while adaptation strategies aim to reduce risk and vulnerability to the consequences of climate change. Addressing climate change does not mean pursuing one or another category, and when possible, climate actions should work with methods and technologies able to adapt to climate change consequences, while also reducing the emission of GHG. To more efficiently and effectively allocate resources and achieve long-term sustainability, planners can use adaptation pathways to support decision making under uncertainty. These pathways can help overcome the policy paralysis brought upon with uncertainty by breaking down adaptation decisions into manageable steps over time, visualizing alternative pathways and their costs and benefits, defining which decisions are needed for adaptation, and when they are needed (Haasnoot et al. 2019).

## 2.2 Sea Level Rise and Coastal Cities

Sea level rise is one large uncertainty related to climate change, depending on the mitigation strategies and achievements, SLR can reach from 0,26m to 0,98m by the end of the century, which is a big range to be considered (Haasnoot, Brown & Scussolini, 2019). This put cities and settlements by the sea in a scenario of constant insecurity, meaning they are at the frontline of initiatives to combat GHG emissions, plan for climate-resilient growth, and adapt to climate change (Glavovic et al. 2022). Coastal cities have always been attractive for humans because of its richness in natural resources, providing recreational and cultural activities, they also have strong economic relevance for being able to provide access to marine trade and transportation (Neumann, et al. 2015).

Coastal zones have floodings as one of the most significant concerns facing their population, and the susceptibility to these extreme events increases when these settlements are placed in low-lying zones (Woodruff et al. 2013). Floodings in coastal cities can be caused by multiple drivers, and coastal cities in low-lying zones are at risk of flooding from a combination of more than one driver (Moftakhari et al. 2017). Adaptation strategies related to SLR are typically classified in terms of protect, accommodate, advance, and retreat, and moving from rigid strategies to more flexible interventions can be the key to deal with the uncertainty of future scenarios (Glavovic et al. 2022). NbS are classified in the IPCC report as a part of protection strategies, and these strategies offer the possibility of working closely with nature in adapting to future changes, reducing the impact of climate change, and improving human well-being (Ruangpan et al. 2020), and offering co-benefits such as climate change mitigation (Castellari & Zandersen 2021).

## 2.3 Coastal Cities Adaptation Using Nature-based Solutions

The existent literature discusses NbS in different perspectives, most of them understand NbS as an "umbrella concept", which covers a range of approaches, and this research considers the concept of NbS as "actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits" (UNEP 2022). Additionally, these solutions should safeguard the rights of communities and indigenous peoples.

NbS can be implemented in multiple approaches and spatial scales, and preliminary findings (World Bank Group 2021) show 3 categories suitable specifically for addressing coastal floodings: mangrove forests, salt marshes, and sandy shores. Additionally, large-scale NbS applied in a regional scale prove to be highly effective in mitigating coastal flooding due to their comprehensive and holistic approach (Somarakis et al. 2019). By integrating natural ecosystems into the coastal landscape, these solutions provide multiple layers of protection (Sutton-Grier et al. 2015), acting as natural buffers by absorbing and dissipating the energy of incoming waves.

# 3 Methodology

This study follows a case study research strategy, using the city of Florianópolis in the context of coastal cities, focusing on gaining a holistic understanding of the case to reach the aim of the research, which is to identify the opportunities for using nature-based solutions strategies in Florianópolis for its adaptation to sea level rise and coastal floodings, as well as provide replicable perceptions for coastal cities to implement nature-based solutions in their adaptation process to sea level rise. For a better understanding of the research subject, the methodology is divided into two phases: contextualizing and mapping, according to the description below and using the following methods in a mixed-method approach. The first phase, contextualizing, is directly linked to the two first objectives of this research, and it uses descriptive and thematic analysis of the case study city, as well as questionnaires with professionals, to help in the identification of challenges and barriers for NbS implementation, while also providing the opportunity to develop a better understanding of how to overcome these issues in a broader context. It also provides the evaluation of existent categories of NbS based on proposed criteria and selection of the best NbS strategies suitable for the targeted issue.

The second phase, mapping, is focused on spatial analysis of the city to provide an opportunity to achieve the third objective of this research. The spatial analysis will be based on the "needs and opportunities" methodology, to spot problem areas with need for intervention and to evaluate where the conditions are favorable for the implementation of the NbS.

## 3.1. Literature

Papers, reports, books and websites were used to provide background knowledge about the research topic, further, the profile of the city is also presented using a focused literature review. Complementary literature is also presented along the research to make comparisons, analysis and to reinforce ideas.

## 3.2. Questionnaire

A questionnaire with professionals was carried out to provide insights on the climate agenda of Florianópolis, as well as the perception of the professionals working in the city about the topic of this research. The goal was to obtain information that could be useful to understand challenges and barriers for the implementation of NbS in the city, as well as a comprehensive idea of how the population is affected by climate change and natural disasters. Therefore, the questionnaire was chosen because it is a fast and efficient method for gathering a large amount of information, providing more comprehensive results. The participants were contacted by online means, and a minimum of 10 answers were expected to provide enough material for the analysis. The questionnaire was carried out in the beginning of the research, aiming to inform the next methods and chapters, and the form was closed after two weeks with 14 participants. The questionnaire was organized into 30 questions with different formats, providing answers in open-ended texts, ranking, and multiple choice. It was required from the participants to have professional relation with the case study city, and to have a background connected to city planning.

### 3.3. Spatial Data

The spatial data was found mainly on the municipality and universities pages, but also in the Brazilian Institute of Geography and Statistics (IBGE). All the spatial data was obtained from open sources, and the maps produced in this research are mostly descriptive, drawing comparative results focused on the spatial distribution. Most of the maps were produced by overlaying and arranging the obtained data source, however, some maps were created using analytic tools.

### 3.4. Scenarios Development

The mapping phase presents the development of three scenarios for SLR projections, and the maps were generated according to recent projections based on the IPCC 6th Assessment Report, moving to a regional level of SLR projections, using a Projection Tool provided by NASA (NASA 2023). Besides mean SLR, coastal cities also must plan for tide variation. There is a limited amount of information on how the tide variation will behave in Florianópolis with climate change impacts, therefore, this value was defined based on the Tide Chart provided by the Brazilian Navy for the year of 2023, being 1.3m the highest tide prediction. Thus, the following pathway with the described scenarios is created to guide this research, where the optimist pathway is the assumed scenario for the mapping phase.

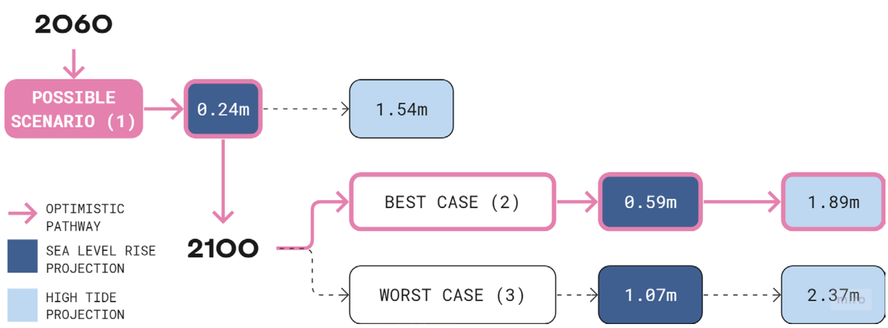


**Figure 1. Optimist pathway in the scenarios proposed for the mapping phase. Elaborated by Author, based on source (IPCC 2022; NASA 2023).**

# 4 Results

## 4.1. Contextualizing

This section aims to provide a context of the case study city in the NbS perspective, and besides the literature review, a questionnaire with professionals of the city was made to address three main topics: climate change in the city, nature-based solutions, and public spaces, followed by the NbS selection.

### 4.1.1. City Context

The questionnaire provided multiple insights for the development of the research, as well as complementary information on NbS and environmental aspects from professionals with environmental background. Therefore, a thematic analysis based on planet, people and profit is presented below.

#### Environmental (Planet)

The environmental assessment identified that Florianópolis needs to find solutions to regulate its unorganized urban sprawl, which has been transforming old agricultural plots into urbanized land without adequate regulations, creating a negative influence in the expansion of the urban area, leaving it with low density indices and advancing over areas with urban constraints and limitations, as well as over protected areas. This phenomenon in the city is not necessarily connected to social classes, and it occurs in high income neighborhoods as much as in lower income areas. The conservation of these areas has potential to help overcome the land use problems facing the city, while also providing climate mitigation, natural resources conservation and biodiversity enhancement.

#### Socioeconomics (People and Profit)

Climate change is not only an environmental crisis, but a social one, and in the face of SLR and coastal flooding risks, cities need to come up with adaptation strategies to protect the community and their physical assets. In that sense, the transformation of natural areas into conserved public spaces can play an important role in the city adaptation in a regional scale, providing a space for educational activities and environmental awareness.

Furthermore, flood maps found during this study, together with the questionnaire, show that many physical assets in Florianópolis are in risk of being exposed to coastal flooding, and the damaging of infrastructure such as sewage systems and roads were highlighted by professionals. Allocating more funds to adaptation strategies such as NbS can avoid future expenses with damages caused by these climatic events, since all adaptation measures in coastal zones become more cost-effective over time, when sea level rises, land subsides, and storms increase in frequency and intensity (Reguero et al. 2018).

Following the economic approach, this study identified a great potential for ecotourism as a strategy for sustainable development, by minimizing negative impacts on the natural and sociocultural environment, promoting the long-term preservation of the natural areas, providing alternative employment and income opportunities for locals, and raising conservation awareness among locals and visitors alike (UNWTO 2023).

#### 4.1.2. NbS Selection

For the selection of the NbS strategies, three criteria were considered, (1) its potential to protect the city against coastal flooding in a regional approach, (2) its potential to be used as sustainable public spaces, and (3) their suitability to the city context. These criteria were defined with an evaluation of the inputs from the literature review and questionnaire, as well as the complementary assessment of literature in previous chapters. Four strategies were selected to be evaluated in the mapping phase: urban forests, coastal green corridors, mangrove forests, and sandy shores. The following steps, based on the criteria, were taken to select these strategies.

1. Mangroves, sandy shores and saltmarshes are the solutions described by literature as the main strategies specifically for coastal flooding protection and adaptation to sea level rise (World Bank Group 2021), additionally, urban forests, and coastal green corridors have been observed in the case studies as efficient strategies to dissipate the effects of flooding and/or storms.
2. All the strategies selected have the potential to work as public spaces.
3. Salt marshes were eliminated from the selection because there are no saltmarshes in the city, as mentioned in the questionnaire.

### 4.2. Mapping

The maps in this chapter were generated using secondary data sources and the software ArcGIS Pro. The spatial analysis will be based on the “needs and opportunities” approach, aiming to map risk areas and opportunities to the safeguarding, enhancement and creation of NbS.

#### 4.2.1. Needs

The coastal flood maps generated using elevation provide an understanding of which areas would be affected by SLR, and which areas would be flooded during high tide periods. With these maps, and according to the described scenarios, it is possible to observe (Figure 2) that many urban areas in the city would be affected by SLR in all the districts of the city, and if the worst-case scenario happen, some neighborhoods would be completely inaccessible and many communities would need to be reallocated, like the Barra da Lagoa district (Figure 2), which would be one of the most affected due to its low-lying settlement and limited current protection strategies.

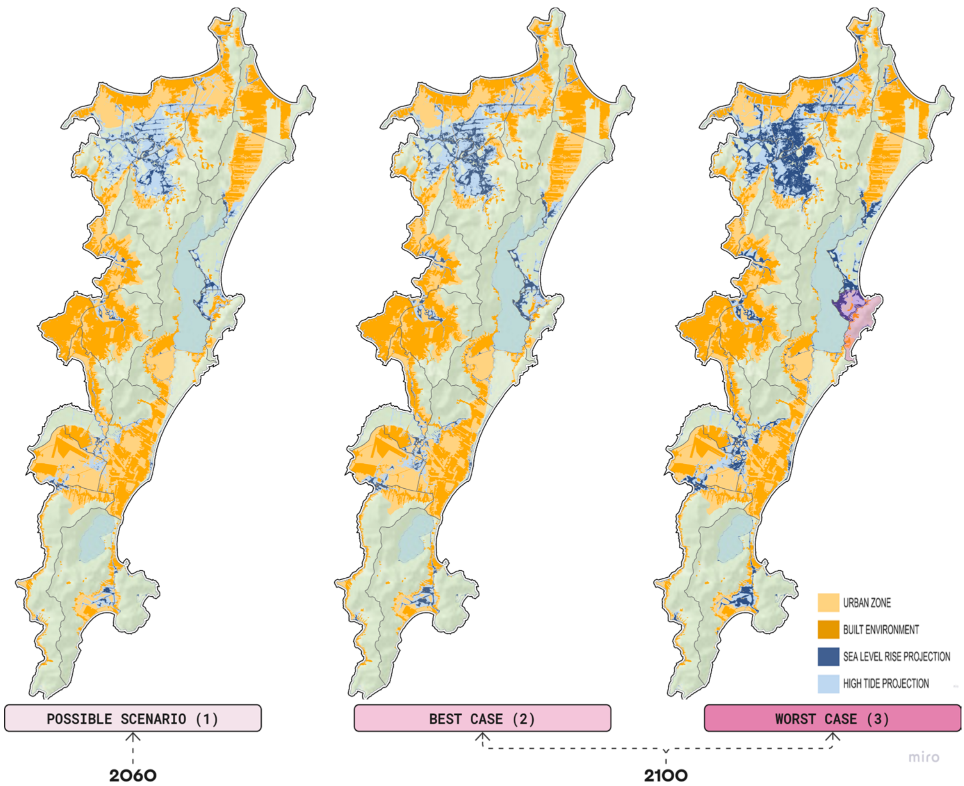


**Figure 2. Coastal flooding projections based on elevation maps and IPCC scenarios. Elaborated by Author.**

The results from the crossing of risk areas with the average household income shows that there are four lower-income regions where the risk for the built environment is highly concentrated, this could be used to define priority areas in the planning process, although that doesn't mean that other risk areas should be neglected, but that the perspective in these lower income regions are different, with a need for reinforcing social strategies such as creation of "green jobs", planned reallocation of informal residents in high risk areas, and guidance for remaining residents.

### 4.2.2. Opportunities

Sandy shores, urban forests, and mangrove forests, should have their approaches based on safeguarding and enhancing these natural areas, blocking the urban growth towards these environmentally important places. From the map (Figure 4) it is possible to observe that some at-risk areas have nature-based opportunities in their surroundings to enhance their protection, however, other areas are not close to these existent NbS and would need to introduce the creation of additional NbS, or hybrid approaches.

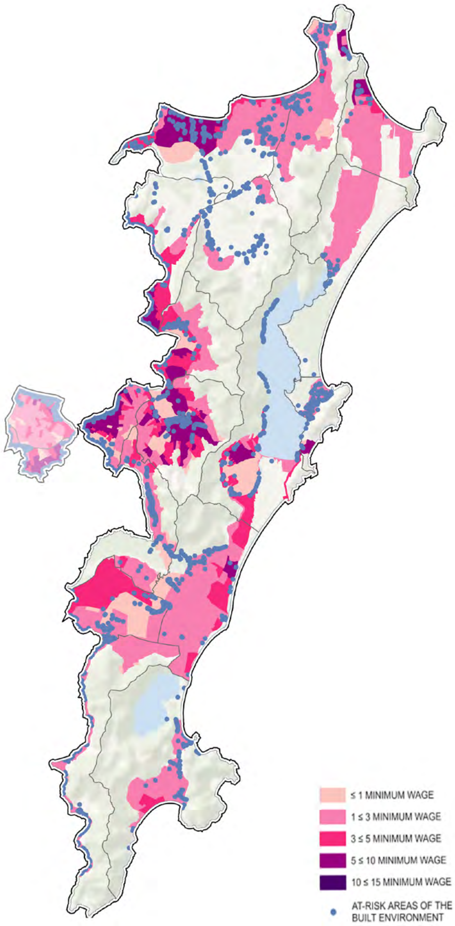


**Figure 3. Average household income map of Florianópolis with areas of the built environment in risk of coastal flooding. Elaborated by Author.**

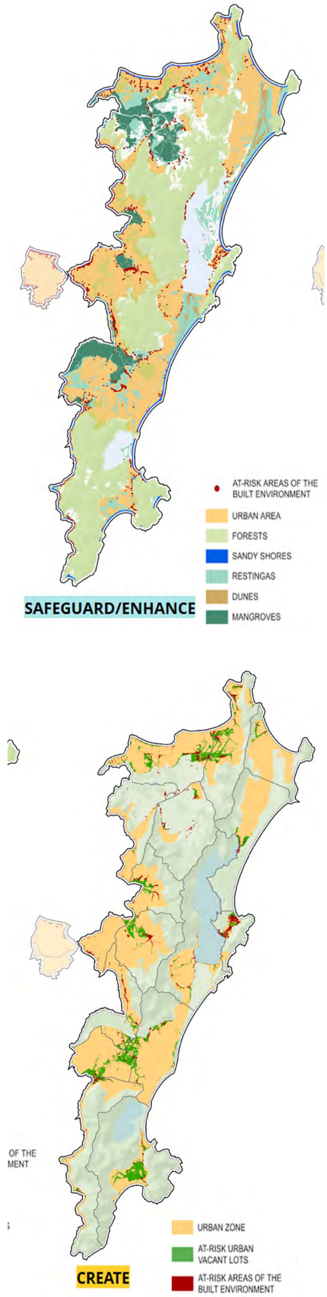


**Figure 4. Mapping of the spatialization of NbS areas to be safeguarded, enhanced and created. Elaborated by Author.**

The chosen Nature-based Solution (NbS), the coastal green corridor, primarily focuses on creation. In an optimistic scenario, vulnerable flood-prone areas within the urban perimeter, yet not developed, could serve as potential components for crafting coastal green corridors. These corridors would act as buffers safeguarding flood-vulnerable parts of the built environment from potential inundation by 2100. Consequently, the coastal green corridor would interlink various NbS proposed earlier. At-risk vacant zones suitable for inclusion in this corridor are depicted in Figure 32. Designing for these areas necessitates anticipating periodic flooding and, accordingly, allows for temporary activities and water-resistant structures. Planning and design must incorporate elements serving as barriers, including NbS and hybrid strategies like embankments, dikes, and coastal vegetation planting. These strategies should avoid rigid approaches, as they can intensify wave impact. For safeguarding against sea-level rise, the concept of living shorelines should underpin NbS development, gradually mitigating water's force and facilitating controlled dissipation (Yale Climate Connections 2023).

## 5 Discussions

Based on the case study contextualization, a bank of strategies was defined to adapt coastal cities to sea level rise projections: mangroves, sandy shores, urban forests and coastal green corridors. Then, the mapping of risk areas based on elevation provided an overview on priority areas in risk of coastal flooding, and the spatial distribution of the selected nature-based solutions in the city was mapped to identify opportunity for its implementation. Therefore, this chapter aims to discuss the outcomes of these methods.

The main challenges and barriers for the implementation of these large-scale NbS identified during this research are related to economics and governance, such as the lack of concern with climate change from key stakeholders, the political and regulatory uncertainty, and the influence that the real estate market has on the governmental sector.

**GOVERNANCE**

- Insufficient commitment of major stakeholders towards climate change
- Political and regulatory uncertainty
- Real estate market's impact on government decisions
- Fragmented sectors and lack of coherent strategies

**SOCIAL**

- Limited Understanding of coastal adaptation methods
- Partial lack of community supports

**PHYSICAL**

- Presence of vulnerable constructions in high-risk zones
- Presence of construction in areas needed to connect multiple strategies
- Proximity of built environments to coastal zones in numerous regions
- Scarcity of strategically located vacant lots

**Figure 5. Challenges and barriers identified according to the methods of this research. Elaborated by Author.**

Therefore, the following list presents a set of recommendations based on the results and discussions provided by the methods used in this research.

- Creation of a Coastal Management Plan, considering nature-based solutions and using the Coastal Green Corridors as a main protection strategy, including an adaptation pathway based on spatial distribution and scenarios.
- Plan for a responsible reallocation of communities living in risk areas, offering economic support with the creation of "green jobs", such as working in the enhancement and construction of the proposed nature-based solutions.
- Include safe routes for the community in case of unpredictable extreme events, using the coastal green corridors as main axes for escape.
- Consider complementary strategies according to monitoring and decision points to be defined in the adaptation pathway.

Therefore, coastal green corridors integrating marine, intertidal and land ecosystem have been shown to be a viable solution for coastal protection, and a network of NbS could be created to protect cities from SLR.

Finally, when strategies are chosen and priority areas are mapped, coastal cities can move to an adaptation pathway approach. There are different models of adaptation pathways, and this research proposes a diagram based on mapping and SLR scenarios, where spatial analysis is combined with time to allow cities to plan in phases, according to priority areas and long-term interventions. This can be a helpful tool to inform decision-making and revise adaptation plans for coastal cities, and instead of using years as decision points, it proposes that the strategies should be based on the rise of the sea and on high tide predictions.

# 6 Conclusions

The research investigates the application of nature-based solutions (NbS) in response to sea-level rise (SLR) predictions and coastal flooding. While current NbS strategies are effective against high tides and storm surges, they fall short in protecting cities from SLR. Managed retreat might become necessary with extreme SLR, but NbS can aid in planned retreat, minimizing negative impacts through community involvement. NbS remain a promising strategy for mitigating climate change effects. Converting natural areas into public spaces for recreation and tourism is proposed to safeguard these locations. Gradual transformation based on sustainable practices and community participation is recommended.

Various research methods were employed, including mapping methods offering a holistic view of opportunities, questionnaire surveys with experts, and flood map modeling based on elevation data. These methodologies aid in understanding risk areas and priority zones for coastal cities. However, providing adaptable frameworks and strategies based on local context is challenging yet crucial.

The case study of Florianopolis, Brazil, highlights its potential as a model city for coastal adaptation due to preserved natural surroundings and implemented protective measures. Overcoming governance challenges and improving citizen awareness of climate change are essential. Enhancing the existing Climate Action Plan with nature-based solutions and recent findings, such as a Coastal Management Plan, is vital for sustainable development.

Finally, the main outcomes of the research are limited to a context-specific picture of the case study, and not all the methods and results can be applied in a general coastal cities context. However, this work is a contribution to the ongoing exploration of mapping as a tool for sustainable planning of cities, and more knowledge could be built on that to transform the methodologies in replicable material for general coastal cities context.

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GEBRAN, LORENA

# The Exploration of Nature-Based Solutions as a Social Cohesion Tool

## A case study on the revitalisation of urban streams in the City of Dresden, Germany

*The Anthropocene era has dramatically reshaped river landscapes, posing a significant threat to these ecosystems. Nature-Based Solutions (NbS) emerge as a promising and multifaceted approach to address these challenges, particularly in urban river contexts. Beyond ecological restoration, NbS hold the potential to promote social cohesion, a dimension often overlooked in current literature. This knowledge gap impedes a comprehensive grasp of NbS benefits, hampering their effective implementation and full realization.*
*This study aims to investigate the potential of employing NbS for river restoration and seeks to explore the capacity of NbS to promote social cohesion within a community, a dimension that has not been fully explored in previous studies. Prohlis, an urban neighbourhood in Dresden, Germany is taken as a case study. The methodology involves data collection via surveys, interviews, and workshops, engaging both the local community and professionals. Initial findings indicate that collaborative NbS approaches effectively enhance community connections and shared responsibility. The study emphasizes the significance of considering local contexts, involving stakeholders, and highlighting co-benefits in NbS implementation. Ultimately, the research culminates in an integrated and practical framework that offers real-world guidance for leveraging the potential of NbS and fostering unity among diverse communities. Despite some limitations, this research contributes to a more profound understanding of the multifaceted benefits of NbS, paving the way for inclusive and sustainable approaches to contemporary environmental and social challenges.*

# 1 Introduction

The Anthropocene era has drastically altered rivers and streams worldwide, with human interventions leading to denaturalization and extensive modifications (Albert et al. 2021). These interventions include embankments, concrete channelling, and tributary filling, resulting in diminished wetlands and floodplains. Water resources face various other pressures, including pollution, droughts, floods, land use changes, soil erosion, and channelization. Effectively safeguarding these resources requires cost-effective measures to alleviate these pressures, benefiting both the aquatic environment and the community (Cohen-Schacham et al. 2019).

Conventional grey infrastructure, though instant in water management, has limitations and can exacerbate flooding. This has prompted interest in nature-based solutions (NbS) that utilize natural elements to enhance water quality and biodiversity (Charlesworth & Warwick 2020). The International Union for the Conservation of Nature (IUCN) defines NbS as actions that protect, manage, and restore ecosystems, addressing societal challenges while providing benefits for human well-being and biodiversity (IUCN 2020).

NbS is particularly relevant in urbanization's age, promoting green, resilient, and inclusive development. These solutions address pressing challenges through actions inspired by nature, providing multiple services including biodiversity development, and being highly effective and cost-efficient (Sowińska-Świerkosz & García 2022). The growing popularity of NbS is attributed to its co-benefits for the environment, society, and economy (Ommer et al. 2022). NbS are increasingly used to address biodiversity loss, climate change, public health, social justice, and green economic prospects (Dushkova & Dagmar 2020), making them crucial for river restoration and ecosystem services.

The 2018 UN World Water Report emphasizes the need for more NbS aplications, especially floodplain-based approaches like reconnecting rivers to floodplains and managing infiltration and overland flow (UNWWDR 2018). These solutions enhance hydrological connectivity, regulate water supply, and serve as biodiversity hotspots (Guerrero et al. 2018). They underscore the importance of community connections and integrated watershed management to address flood risks. While recent studies focus on ecosystem service provision for climate change adaptation through NbS, there is a research gap regarding social and cultural benefits aside the recreational and aesthetic dimensions. The aim of this thesis is to explore social cohesion provisions through participatory NbS projects for stream renaturation, using the case of Prohlis, an urban district of Dresden in Germany.

**The main research objectives are to:**

1. Contribute to the development of a knowledge base for different stakeholders interested in implementing participatory NbS for streams renaturation
2. Define the potential use of NbS as a social cohesion tool by evaluating people's responsiveness to NbS and participatory approaches
3. Co-design with the community of Prohlis conceptual NbS for the local stream
4. Investigate opportunities and limitations of participatory NbS as a social cohesion tool based on experts' knowledge and experience
5. Develop a practical framework for the implementation of participatory NbS as a social cohesion tool based on workshops' initial findings and professional experiences

The results of this study contribute to understanding the benefits and limitations of participatory NBS for social cohesion in urban river restoration and offer insights for scaling up and replicating these approaches in other urban contexts.

# 2 Background / Literature Review

The literature review critically examines existing research and scholarly discourse surrounding Natural Based Solutions and their role in strengthening urban resilience, particularly within river landscapes. It investigates NbS and the delivery of ecosystem services in rivers, participatory NbS, the definition and indicators of social cohesion, and the research gap identified in the implementation and assessment of NbS.

## 2.1 NbS and the delivery of ecosystem services in river landscapes

Natural Based Solutions integrate natural system processes into human environments to provide a wide range of ecosystem services (European Commission 2021). These services include provisioning, regulating, and cultural services, which encompass tangible and intangible benefits (Vejre et al. 2010). Understanding the interactions between ecosystem services and human activities is essential for effective ecosystem management (Gonzalez-Ollauri & Mickovski 2017). NbS, as part of green and blue infrastructure networks, can address urban challenges like climate change, enhance resilience, and contribute to Sustainable Development Goals (SDGs) (IUCN 2020).

River landscapes have historically provided numerous ecosystem services, but they are among the most threatened ecosystems globally (Böck et al. 2018). Implementing NbS in river landscapes can lead to benefits and co-benefits, contributing to SDGs and enhancing ecological conditions (Schmidt et al. 2022). In summary, NbS in river landscapes offer a comprehensive approach to improving urban ecosystems, aligning with SDGs, and addressing global challenges (Perini, 2022). However, NbS should be part of a broader strategy and not considered as a cure-all solution (Böck et al. 2018).

## 2.2 Participatory NbS

Participatory approaches are crucial for sustainable management of complex natural hazards and climate change challenges (Koutsovili et al. 2023; Zoumides et al. 2017). Engaging local stakeholders fosters understanding, ownership, and contextually relevant adaptation measures.

Social values associated with NbS include creating safe spaces, promoting social integration, and enhancing cultural vitality (Souliotis & Voulvoulis 2022). Moreover, successful NbS development requires cross-disciplinary collaboration, political support, community engagement, financing, and effective communication (Dushkova & Dagmar 2020), and given this interdisciplinary requirement, the participatory process becomes even more relevant. It serves as a platform for stakeholders with different areas of expertise, experiences, and insights to come together.

In addition, participatory NbS can enhance environmental quality in urban settings, empowers communities, and contributes to project decision-making (Puskás et al. 2021). Open dialogue platforms and active participation are imperative for equitable and sustainable outcomes (Puskás et al. 2021). Involving stakeholders early in project planning can garner support and resources. However, while understanding stakeholder influence and promoting inclusivity are essential aspects of NbS implementation, there is a lack pf practical framework for participatory NbS approaches.

In conclusion, public participation is vital for the long-term success of NbS in delivering ecosystem services (Puskás et al. 2021). However, there is an apparent lack of practical framework and research that explore the effectiveness and impact of public involvement in NbS initiatives.

## 2.3 Definition and Indicators of Social Cohesion

Social cohesion is seen as a positive trait of a social entity and is multi-dimensional, involving micro, meso, and macro-level events (Schiefer & van der Noll 2016). It encompasses aspects like social relations, identity, and orientation towards the common good.

Social relations involve maintaining group membership through social networks and trust, particularly between individuals and institutions (Schiefer & van der Noll 2016). It emphasizes the importance of mutual tolerance, especially for minority groups, in building a cohesive community.

Identity, attachment, and belonging signify the emotional connection individuals have with their community, fostering a sense of belonging and recognition (Schiefer & van der Noll 2016). This connection is rooted in shared values and socialization contexts.

The orientation towards the common good involves a sense of duty and adherence to societal rules, putting the community's well-being ahead of personal needs (Schiefer & van der Noll 2016). It creates a cohesive society and reinforces acceptance of social norms.

### 2.4 Research and Professional Knowledge Gap

Nature-based solutions (NbS) face challenges in adoption due to limited evidence and understanding of their performance, especially in river restoration (Cohen-Schacham et al. 2019). There's a need for frameworks guiding NbS implementation, focusing on site-specific contexts and community needs (Guerrero et al. 2018). Additionally, aligning NbS with standardized systems requires a more integrative perspective, encompassing social and human health aspects (Schmidt et al. 2022). To address these gaps, future research should focus on evaluating the social benefits of NbS in river restoration, beyond ecological, economic, and eathetical aspects (Basak et al. 2021). Qualitative studies, while relatively scarce within the existing literature on this subject, are essential for understanding stakeholder perceptions and experiences, informing effective decision-making (Basak et al. 2021). Tools for assessing social impacts, stakeholder engagement, and participation should also be developed to ensure ecological sustainability and social justice in NbS projects.

In summary, there is a need for more comprehensive research on the primary and co-benefits of NbS, practical implementation methods, and holistic assessment approaches. Understanding the social benefits and empowerment potential of NbS within communities, and especially in river restoration, is crucial for informed implementation and successful achievement of Sustainable Development Goals (SDGs).

## 3 Methodology

The methodology begins with a site analysis of the case study area, Prohlis, to inform the selection of suitable NbS for stream renaturation. This analysis leads to the creation of a knowledge base, comprising a catalog detailing different NbS options for river renaturation, encompassing their descriptions, objectives, implementation steps, ecosystem services, and costs. This catalog serves as a valuable resource for stakeholders, providing detailed insights into the benefits, challenges, and costs associated with each NbS, enabling informed decision-making based on specific needs and goals. Additionally, it fosters knowledge sharing and collaboration among stakeholders, promoting an integrated and holistic approach to river renaturation projects.

The next step involves conducting a workshop with Prohlis residents to facilitate open dialogue, raise awareness about NbS, and co-design NbS for the Geberbach stream. This participatory approach engages local communities and stakeholders, ensuring their perspectives are considered, enhancing the relevance and applicability of findings. It also builds trust, fosters collaboration, and strengthens a sense of belonging and involvement among stakeholders. The workshop serves as a platform for discourse, allowing participants to directly influence decisions about their neighborhood, potentially leading to more sustainable and resilient communities.

Furthermore, the workshop includes a site visit to three pre-identified locations along the Geberbach stream, where participants share their insights on belonging, familiarity, accessibility, aesthetic value, and social potential of the sites. The workshop concludes with an anonymous survey to assess changes in participants' social and spatial integration, NbS knowledge, and participatory experience.

The final phase involves consulting experts, in the fields of landscape architecture, water engineering, urban planning, and participatory researchers, through interviews. These professionals provide valuable insights on the limitations and opportunities of participatory NbS for social cohesion. They also contribute to the development of a practical framework for the implementation of NbS for social cohesion.

# 4 Results

## 4.1 Site Analysis and development of NbS Catalogue for Stream Renaturation

The Geberbach stream (local stream in Prohlis), is a water body in the municipality of Dresden. This stream exhibits morphological deficits, including bank and bed reinforcement, as well as a lack of depth and width variance, indicating significant alterations to its natural state (Stowasser Plan 2022). Additionally, its ecological potential, morphology, and patency are rated as "poor," "completely changed," and "worse than good," respectively. This state falls short of the environmental targets set by the European Water Framework Directive, and necessitates urgent renaturation measures (Stowasser Plan 2022).

In response to the stream's current condition, renaturation measures are proposed to improve its ecological potential and chemical status, with a management objective to achieve good ecological potential by 2027. Notably, the morphology and continuity quality components offer significant potential for optimization (Stowasser Plan 2022). Widening the water body within the minimum development corridor is recommended to enhance water body structure and ecological continuity (Stowasser Plan 2022). By involving community stakeholders in the design process, proposed natural-based solutions can be tailored to their expectations and priorities.

To provide a knowledge base for the diverse stakeholders engaged in stream renaturation, a comprehensive Nature-Based Solutions catalogue (figure 1) for stream renaturation has been developed. The catalogue is organized into four distinct primary sections: Stormwater Management, Riparian Zone Restoration, In-Stream Installation, and Bank Stabilization. Within each of these sections, the catalogue offers detailed insights, encompassing the definition, aims, ecosystem services, implementation complexity level, requisite resources, step-by-step implementation guidelines, potential constraints, and cost estimates per square meter for each NbS technique proposed.

The implementation of NbS on the Geberbach stream, as identified by Stowasser Plan (the consultancy firm in charge), in conjunction with the NbS catalogue and co-design ideas from the workshop participants, is expected to enhance the overall health and resilience of the stream ecosystems. These measures aim to improve water quality, increase biodiversity, and enhance habitat connectivity, while also providing co-benefits such as flood mitigation, carbon sequestration, and social opportunities.

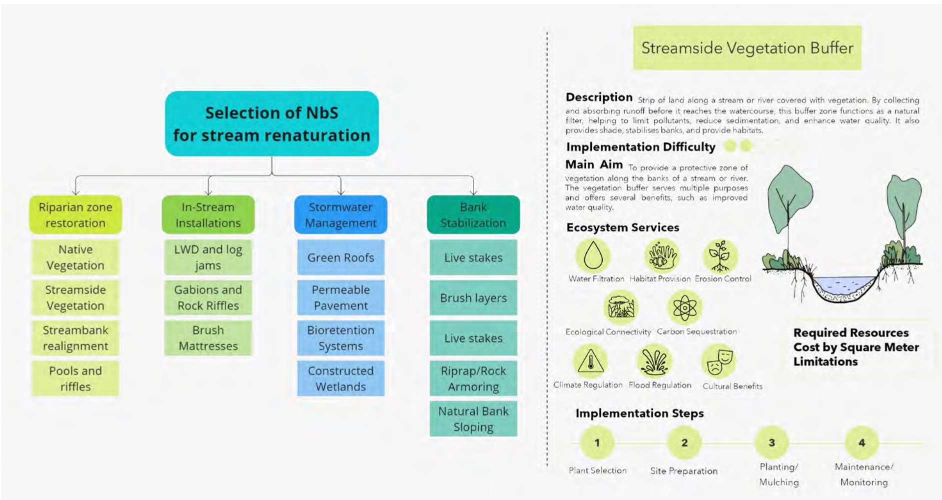


**Figure 1. Sample of NbS Catalogue Content**

## 4.2 Workshop Findings

The indicators used to evaluate social cohesion during the workshop are (1) the quality of social relations (including social networks, trust, acceptance of diversity, and participation), (2) identification with the social entity (sense of belonging and attachment), and (3) orientation towards the common good (sense of responsibility, solidarity, and compliance with social order) (Schiefer & van der Noll 2016).

In terms of social relations results, the workshop saw a diverse range of participants in terms of age, nationality, gender, ethnicity, education, and professional backgrounds, enriching the discussions with varied perspectives and experiences. Over two days, approximately 40 participants attended, with 36 opting to share their information. Survey results revealed participants originating from at least 11 different countries, with 6 distinct mother tongues, and a wide array of professional

backgrounds. Nearly half had prior participatory experience, while over half were new to the concept, creating a dynamic learning environment. The majority expressed a keen interest in future participatory experiences, highlighting the value gained through this workshop. Feedback indicated a strong endorsement for community involvement in decision-making processes. The overwhelmingly positive feedback of participants suggests that future workshops in Prohlis are likely to be well-received and continue to generate community interest. Regarding social networking, only 32% of participants knew each other before the workshop, emphasizing the event's success in bringing together individuals from diverse backgrounds. 50% of the participants reported a positive experience in forming new relationships during the workshop, while 41% anticipated possible future relationships. Evaluations of the workshop's success in terms of social cohesion revealed diverse perceptions, however, most participants rated the social cohesiveness of the workshop as satisfactory, with many middle range ratings, suggesting room for improvement in group dynamics for future workshops.
In terms of identification, sense of belonging, or attachment, the study reveals that initially, only a small percentage of participants felt fully integrated within their cultural community, despite half of them having lived in or visited Prohlis for more than 5 years. However, after attending the workshop, a significant shift occurred, with a majority reporting a stronger sense of identification and attachment to the community. This indicates that the workshop effectively addressed feelings of disconnection, fostering a stronger sense of belonging and social cohesion. Additionally, spatial integration and attachment to the physical environment improved, with 45% reporting strengthened integration. The study emphasizes the need for ongoing engagement and workshops to ensure continued progress in both spatial and social integration.

As per the orientation towards the common good indicator for social cohesion, the study found that participants' sense of responsibility towards the long term involvement in the stream renaturation needs further incentives. 26% expressed reluctance in committing, while others showed varying levels of willingness to contribute, from sharing ideas to active participation. Interestingly, during the site visit, reluctance decreased to 19%, indicating a positive impact of the visit on participants' engagement in restoration efforts. The diverse levels of willingness highlight the importance of a diverse group of volunteers with different skills and availability. Lack of active involvement may stem from a limited understanding of the benefits of NbS, underlining the need for targeted education and community outreach. Encouraging a sense of ownership and shared responsibility is crucial for active participation, and gathering feedback on participants' understanding and willingness to contribute would provide valuable insights into their sense of responsibility. Accordingly, ongoing educational programs and inclusive initiatives are instrumental in nurturing this orientation.

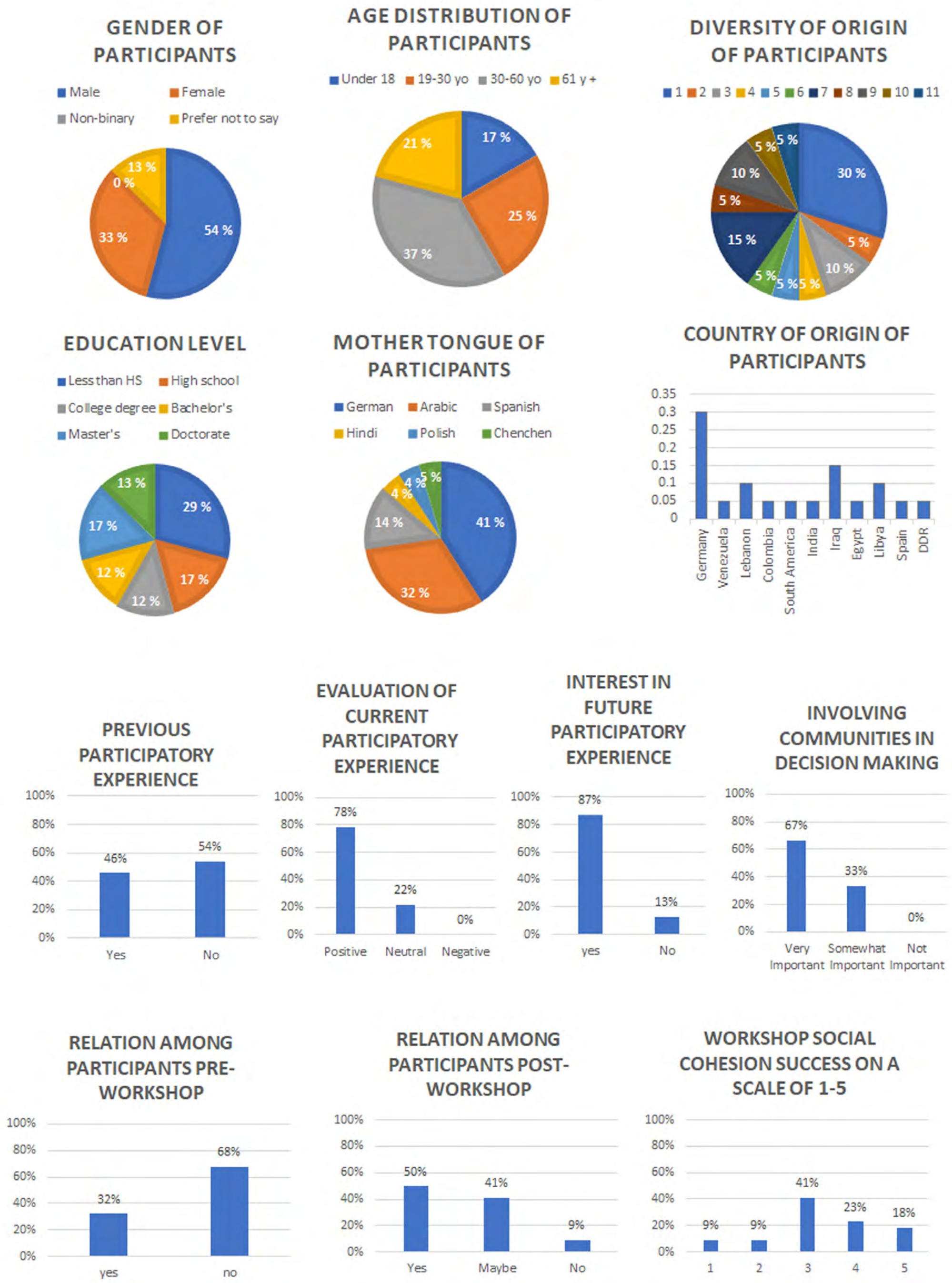


**Figure 2. Workshop Findings**

## 4.3 Site Visit

The site visit revealed important insights into residents' perspectives on the pre-selected sites. Approximately 44% of participants were acquainted with the site, with a similar percentage feeling a sense of belonging. 38% expressed personal willingness to engage in restoration efforts. Interestingly, only 63% believed that NbS could improve site conditions, while 38% were unsure or neutral. This finding is of particular interest as it suggests that there is a need for additional education and a longer period of exposure to the concept of NbS for individuals to gain a comprehensive understanding of their benefits. Furthermore, it indicates that the community may not yet fully appreciate the advantages associated with these solutions and their potential co-benefits to their well-being. In terms of aesthetic values, only 23% of participants were satisfied, indicating the significance of considering community preferences for visually appealing NbS projects. Accessibility received positive feedback from only 40% of participants, and 27% expressed strong concerns, suggesting room for improvement. Regarding social potential, only 17% had a positive perception, while 52% had a negative view, highlighting underlying social challenges. Correlation analysis (Table 1) showed strong links between familiarity, belongingness, willingness to restore, and accessibility. Notably, aesthetic value showed no significant correlation with other factors. Social potential displayed a negative correlation with familiarity, belongingness, and accessibility, highlighting that there might have been a misunderstanding among the participants relating to the terms used and explanation and underscoring the need to unsure a common understanding of key concepts among all participants. These findings highlight that further awareness and time is required for the community to commit to NbS projects and that their insights are of strong relevance when it comes to spatial design, as they have a strong understanding of their needs and requirements along the stream.

| | Familiarity | Sense of Belonging | Willingness to restore | Aesthetic | Accessibility | Social Potential |
|---|---|---|---|---|---|---|
| Familiarity | 1 | | | | | |
| Sense of Belonging | 0.970725343 | 1 | | | | |
| Willingness to restore | 0.970725343 | 0.884615385 | 1 | | | |
| Aesthetic | 0.155542754 | -0.086279596 | 0.388258183 | 1 | | |
| Accessibility | 0.866025404 | 0.960768923 | 0.720576692 | -0.359210604 | 1 | |
| Social Potential | -0.912245461 | -0.983933098 | -0.787146478 | 0.262765132 | -0.99484975 | 1 |

**Table 1. Correlation table as per the site visit assessment of Familiarity, Belonging, Willingness to Restore, Aesthetic, Accessibility, and Social Potential**

## 4.4 Co-design of NbS for the Geberbach Stream

The workshop and site visit facilitated a collaborative design process for proposing NbS implementation across the three selected Geberbach stream sites. While the designs are currently conceptual, they effectively capture residents' needs and aspirations, providing a robust foundation for further refinement. This inclusive

co-design approach ensures diverse perspectives are considered, meeting both community and ecosystem requirements. Involving participants in decision-making heightens ownership and dedication to implementing these NbS strategies.
The participants raised their opinions about stream aesthetics, water quality, and seating limitations. They proposed solutions such as using rocks or gabion boxes for water regulation and pollutant filtration, add meanders for a natural look, and enhance biodiversity. Accessibility and steep banks were also noted as challenges, especially for safe water access. Participants recommended to adjust the slope in site 3 to create child-friendly access to water.

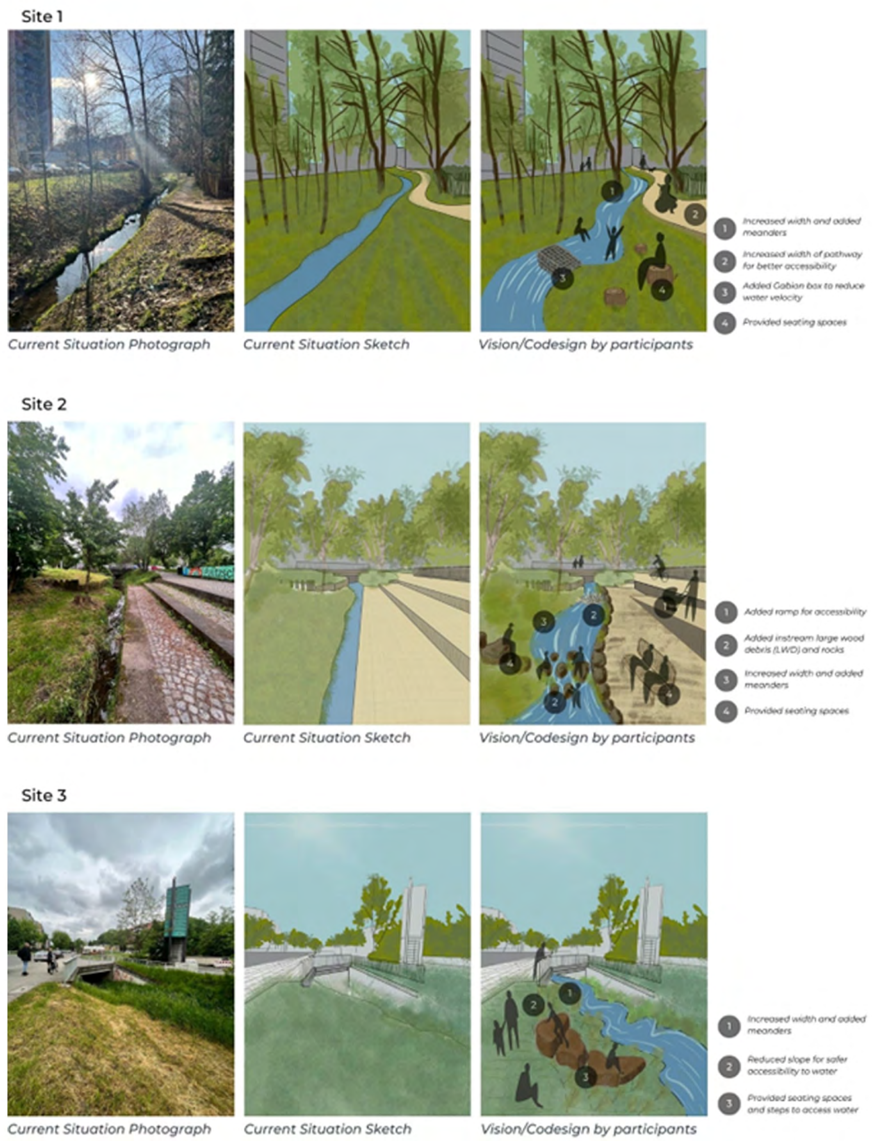


**Figure 3. Co-Designed Sites with the Workshop Participants**

## 4.5 Interviews with Professionals

The interviews conducted with the professionals centered around seven primary questions. The ensuing section is dedicated to the organization and presentation of recurring themes and common concepts that emerged from these interviews.

### The 7 questions asked and converged answers are as follows:

**Q1: Based on your expertise and opinion, how can Nature-Based Solutions promote social cohesion within communities? Can you share an example?**

A1: Experts generally agree that NbS are instrumental in fostering social cohesion, though they acknowledge it's not the sole determinant. NbS effectiveness lies in its capacity to confront shared environmental challenges, uniting communities in the face of climate change impacts. Given the interdisciplinary nature of NbS projects, a diverse range of skills such as science, creativity, and design are requisite. These undertakings further foster collaboration among stakeholders from diverse backgrounds, fostering dialogue, comprehension, and empathy.

**Q2: What are the key design principles or considerations that should be kept in mind when implementing NbS for social cohesion?**

A2: Experts emphasize the importance of participation and stakeholder involvement in implementing NbS for social cohesion. Spatial availability and the spatial dimension of certain NbS, such as in the case of rivers renaturation, can foster social relations compared to other types of NbS. Communication, trust, and understanding are other key pinciples to consider. Other factors include understanding the environmental context, prioritizing issues, exploring socio-ecological systems, addressing safety concerns, and considering the long-term implications of NbS processes whitin a community and space.

**Q3: What are the limitations encountered in such projects? Do demographics and cultural backgrounds play a role?**

A3: The implementation of NbS projects for social cohesion faces barriers including the need for evidence of their efficacy, limited funding and resources, as well as challenges related to sociopolitical acceptance and regulatory processes. Spatial and temporal considerations are crucial, emphasizing the need for long-term planning and understanding of ecosystem interconnectivity. Demographics and cultural backgrounds play a secondary role, with education and socio-economic factors taking precedence. Vulnerable communities may prioritize immediate needs over long-term initiatives, and certain cultural norms and gender dynamics can impact the participatory process. Socioeconomic factors like income levels and access to resources significantly influence NbS adoption and effectiveness, highlighting the importance of tailoring approaches to local values and financial capacities.

**Q4: What strategies or techniques can professionals employ to address potential challenges related to maintenance, long-term management, and community ownership of NBS projects?**

A4: Experts emphasize collaboration and early stakeholder involvement as crucial strategies for ensuring the long-term success and efficient management of NbS projects. Building trust, transparency, and inclusion into the process is essential. Community engagement and ownership play pivotal roles in fostering understanding and pride in the project. Additionally, linking the project to the liveability of the community, especially by involving children and providing educational opportunities, promotes a sense of attachment among residents. Organizing site visits to natural spaces further reinforces individuals' connection and sense of ownership.

**Q5: Are there any specific tools, technologies, or innovative approaches that can be utilized to enhance the effectiveness of NBS in fostering social cohesion?**

A5: Interviewees highlight citizen science applications for collaborative data collection, virtual reality for visualizing project goals, and digital media platforms and social networks for community engagement and feedback. Simplified approaches and gamification were also emphasized for broader participation. Additionally, experts stressed the relevance of traditional techniques that can be fitted to enhance the effectiveness of NbS.

**Q6: What are some effective ways to measure and evaluate the social cohesion outcomes and impacts of NbS? What are the indicators and factors that can showcase the success of participatory NBS for social cohesion?**

A6: Experts underline the importance of measuring community interaction levels during and after participatory NbS processes to assess social cohesion outcomes. Indicators like shared interests, common goals, mental and physical well-being, project safety, community engagement, and ongoing support are crucial. Additional indicators are the evaluation of space utilization, access, satisfaction, comfort, memory impact, and diversity representation.

**Q7: How can NbS be tailored to suit diverse cultural contexts and diverse communities? What are your insights of ethical considerations related to NBS implementation, particularly in terms of equity, inclusivity, and the protection of marginalized groups?**

A7: Experts mention the importance of tailoring NbS to diverse cultural contexts and communities through an inclusive and open approach that prioritizes equity and the protection of underprivileged groups. This involves conducting a preliminary study to understand specific community needs, avoiding generalizations, and promoting open dialogue and knowledge exchange. Ethical considerations, including clear expectations and transparency about potential positive, neutral, and negative impacts, are crucial for building trust. Simple and easily understood communication strategies, such as using plain language, visual aids, and specific tools, enhance engagement.

## 4.6 Framework Development for NbS implementation fostering Social Cohesion

The framework development was carried out through a series of iterations based on the seven frameworks developed by the interviewed professionals. These iterations allowed for the identification of common themes and the integration of diverse perspectives. The final framework incorporates the key overlaps among the individually developed frameworks, ensuring a comprehensive approach that optimizes the implementation of NbS for social cohesion. Ultimately, this approach ensures that the final framework is not only comprehensive, but also practical and feasible for implementation and upscaling in real-world scenarios.

Among the most notable theme overlaps identified can be noted, the design, selection of NbS, implementation, and management phases were often grouped together, with education or expert involvement as the basis for action. Consultation, knowledge sharing, empowerment, and participation are overarching principles that cut across multiple phases. Funding and policy integration are often mentioned as enablers for the successful implementation of NbS. Social cohesion is considered an end goal rather than a pre-requisite for its effectiveness. Stakeholder identification should precede a scoping exercise involving comprehensive landscape and planning assessment and social and spatial analysis. Monitoring, evaluation, communication, professional stakeholders, and a common understanding of key concepts are additional elements added to the final framework. This multi-stakeholder approach promotes transparency and inclusivity, aiming to enhance the overall impact and sustainability of nature-based solutions as a tool for social cohesion.

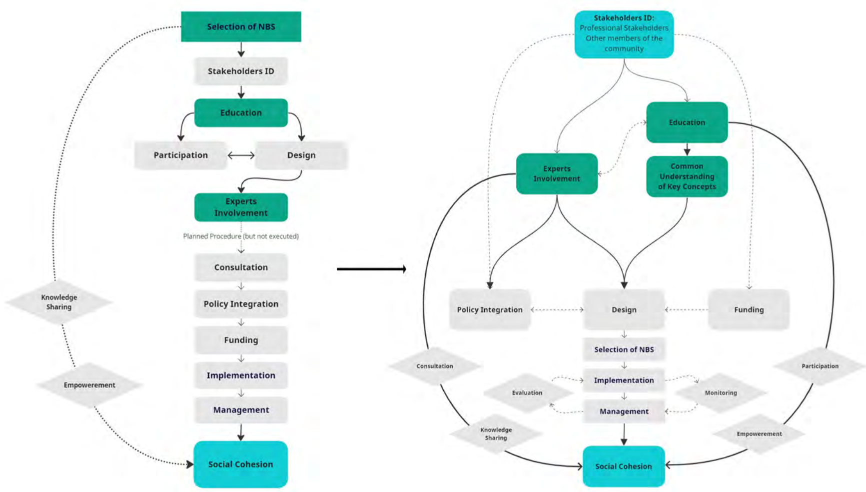


**Figure 4. Initial Framework used for the Workshop Planning (left) optimized through finding and interviews into Comprehensive Practical Framework (right)**

# 5 Conclusion

This thesis explores the potential of Nature-Based Solutions as a social cohesion tool within communities. The study used various methods, such as site analysis, workshops, site visits, surveys, and interviews, to assess the effectiveness of participatory NbS for social cohesion in urban river restoration and takes the Geberbach stream located in the urban neighbourhood of Prohlis, Germany, as a case study.

The findings derived from this study demonstrate that, in addition to the previously recognized social advantages and ecosystem services of NbS, participatory NbS can function as an instrument for enhancing social cohesion within communities. It is imperative to note that this research, constitutes a preliminary exploration of NbS as a catalyst for social cohesion. Nevertheless, it unequivocally showcases a heightened sense of community integration and improved social cohesion among the participants from the local community of Prohlis. However, to gain a more comprehensive understanding of the extent to which NbS can contribute to fostering social cohesion, further research is warranted. This should encompass continued educational workshops involving the community, coupled with an evaluation of social cohesion dynamics throughout the subsequent phases of NbS implementation, such as construction and maintenance. The expert interviews provided valuable insights into the potential and limitations of NbS in advancing social cohesion, drawing from their extensive professional expertise and observations. Furthermore, their input contributed to the development of a comprehensive pragmatic framework, which encapsulates the interdependence of various segments. This framework underscores the pivotal role of education, stakeholder engagement, and strategic design in facilitating the success of NbS initiatives.

There are several limitations to this study that warrant acknowledgment and consideration. The main limitations include the sample size, participant engagement, language barriers, concepts and misconceptions among the community, limited timeframe and its implications, and external factors related to power structures. Language barriers were partially solved by translating material through moderators fluent in multiple languages during the workshop and using visuals and icons to transcend language barriers and facilitate understanding among participants. Nevertheless, despite introducing the concept of NbS and presenting it to the participants, NbS was not equally understood by everyone, leading to a lack of knowledge and recommendations about the subject. To achieve social cohesion in participatory NbS, efforts should be made to provide adequate education and awareness about the concept of NbS, creating a supportive and inclusive environment where participants feel comfortable asking questions and sharing their perspectives. Moreover, the limited timeframe of the study was a major constraint as both NbS and fostering social cohesion are long-term processes.

Future research should take the temporal dimension into account and evaluate trends and changes in the community's responsiveness to NbS and the social cohesion aspect of Prohlis through the different phases of the NbS implementation project. Exploring the long-term effects of these initiatives on social cohesion could provide valuable insights into their overall effectiveness and potential for scalability in other communities facing similar challenges. Further research could also address the effect of the implemented NbS on the community beyond the planning phase, such as the interrelationships between NbS and other aspects such as biodiversity conservation, erosion control, flood control, and water quality improvement. This information could help identify potential synergies and trade-offs between social cohesion and the ecosystem services provided by the renatured stream.

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RAUT, PRAGYA

# Rethinking Suds - A Way Forward For Sustainable Urbanization

*The aim of this research is to critically reassess the potentiality of Sustainable Urban Drainage Systems (SuDS)and propose them as the reliable way forward for sustainable urbanization in a present context when urban areas everywhere are facing extreme climate events and surging flood risks due to disrupted natural hydrological cycles. The issues are likely to get worse in the coming years.*

*Considering UNSDG goals as the universally accepted benchmark of a sustainable world, the "more than meets the eye", suds' benefits are philosophically tallied against them while also zooming at some best practices. Advancing the research, it is identified that very limited awareness about SuDS prevails, and some effective strategies for unsealing are provided in a real-world scenario yielding general recommendations for SuDS implementation in the end.*
*The research reveals that SuDS align well with the UN SDGs demonstrating their potential to resolve modern urban challenges while catering to the sustainable way ahead.*

*This study underscores the necessity of re-embracing SuDS as a means to balance urbanization and environmental integrity and, this time as the centerpiece, for more-than just water managing solutions. It also urges that the very first thing to do is fill up the suds literacy gap. The research 'outputs' makes us rethink that SuDS have the capacity to rephrase the narratives of not only urban water management systems but whole urban systems in a broader framework.*

# 1 Introduction

It is estimated that by 2050, close to 72 percent of the global population will live in urban locales (Zhang 2016). This will increase the urban regions by six times compared to the present situation. This means that urban areas will continue to come under pressure, and existing multiple challenges related to resources, biodiversity, climate issues, air quality etc. will escalate. There is a crucial need to urgently find a way for sustainable urbanization and its effective management. Among several issues cities are facing worldwide, stormwater management tops the list. The replacement of natural lands with pavements and buildings disrupts the natural hydrological cycle in urban areas. As a result, rainwater accumulates on surfaces instead of being absorbed by the land, straining conventional drainage systems, and polluting nearby water bodies. Uncontrolled water accumulation on land leads to flooding. Consequently, pluvial flooding risk have become a crucial concern in the realm of management of urban water resources (Rosenzweig et al. 2018).

In this vicious scenario, Sustainable Urban Drainage Systems (SuDS) have emerged as the beacon of hope in so many cities. Also known as the sponge city concept, water sensitive urban design (WSUD) or 'green infrastructure integration', in these systems, more natural elements such as plants, soil, water, etc. are used (US EPA 2015). There have been several successful projects around the world time and again, proving that SuDS are an effective sustainable approach for stormwater management in urban areas and for flooding. But they are taking too long to be fully integrated into mainstream urban planning and development practices. In western Europe, the adoption of green infrastructure processes has encountered reservations and caution (Cettner et al. 2013).

SuDS encompass a wide array of technologies and strategies (Fletcher et al. 2015), and since they are based on nature, their benefits in cities are of a wide range too if properly implemented. They protect water bodies, provide aid to biodiversity, and improve livability in cities (Cotterill & Bracken 2020), and the list is long.
Hence, in this light, where it's imperative that cities today find solutions for solving a wide range of issues brought by unmanaged urbanization, this research intends to investigate and re-assess if SuDS properly implemented, can contribute to promoting overall sustainability in urban neighborhoods.

## Research questions

This study intends to find the answers to the following research questions, with a focus on the literature review and the neighborhood context of Prohlis, Dresden.

**Question 1:** How are SuDS and UN SDG goals aligned with each other? Can they come together to create sustainable neighborhoods?
**Question 2:** What is the state of SuDS literacy among people? Why is SuDS taking so long to become mainstream practice?
**Question 3:** How can we unseal the neighborhood of Prohlis while managing water for the creek Geberbach for its driest days?

### Aims and objectives

The main aim of this research project is to critically rethink and review Sustainable Urban Drainage Systems (SuDS) as the living system that could be the basis of sustainable urbanization.

The basis of this critical rethink is exploring the co-relation of SuDS and its benefits with 'UN SDG' goals, the universally accepted benchmark and shared dream of an ideal sustainable world. It also examines the effectiveness and advantages of integrating green infrastructure into flood management in a real-life problem scenario in Prohlis, Dresden, while making recommendations for a small neighbourhood context. The project aims to provide ideas for unsealing and the basic concept of rainwater storage to the city of Dresden.

**The objectives are to:**

a. Analyse the linkage between SuDS and UN SDG goals.

b. Evaluate the awareness of SuDS among the public.

c. Suggest different strategies for sustainable urban drainage systems, the concept of rainwater storage, and ideas for unsealing for effectiveness for the chosen case study of Prohlis.

d. Provide site-specific design recommendations for implementing suds.

e. Provide general recommendations for the universal implementation of SuDS.

## 2 Background

### 2.1 Sustainable Urban Drainage Systems

Sustainable drainage systems are drainage systems that mimic the natural drainage principle and follow patterns of the same (CIRIA 2015). The core idea of this micro level design approach is to re-connect urban areas with the underlying soil, making infiltration and storage of storm water possible (Irvine et al. 2021).
As water risks are projected to increase day by day, SuDS fit as solutions as they are based on the ideology of increasing the benefits and reducing the harms of surface water, especially runoff. Sustainable drainage systems offer various ways to manage water effectively while also making places more livable and valuable.
The multifarious advantages of SuDS are largely categorized under four broad categories: water quality, water quantity, amenity, and biodiversity (CIRIA 2015).
They are also known as the four pillars of SuDS, with each pillar having a specific design objective. The positive implications of proper implementation of SuDS are even greater, as shown in Fig. 1 below, as proposed by Charlesworth. It implies SuDs ultimately help mitigate climate change as they co-benefit by reducing urban heat stress, reducing energy usage, and contributing to carbon storage. It also contributes to positive human health.

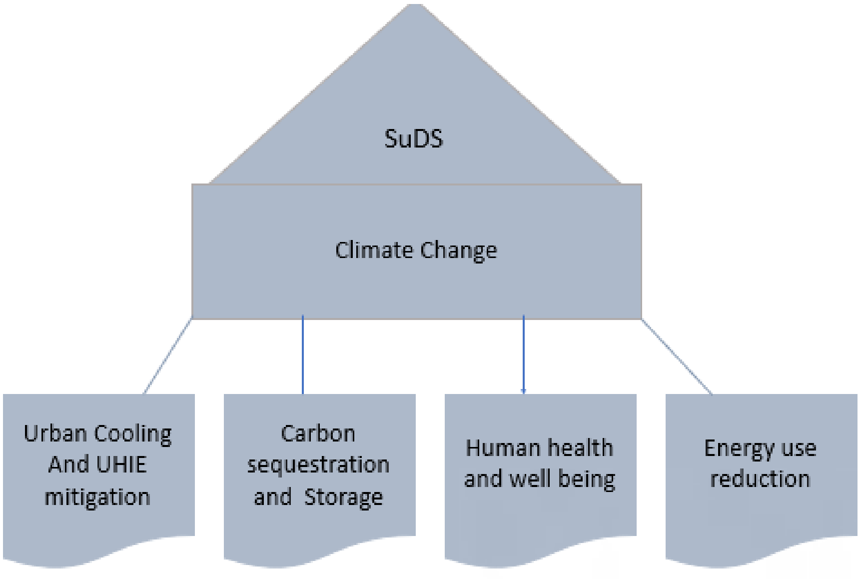


**Figure 1. SuDS Rocket re-illustrated by author (Source: Charlesworth 2010)**
**UNSDG – A vision for a sustainable world**

The United Nations General Assembly introduced the UN SDG goals in 2015. Representatives from 193 United Nations member countries came to a consensus on the 'Sustainable Development Goals', known as SDGs in short, which are a set of 17 goals with 169 specific targets (United Nations 2015).

The United Nations considers the UN SDG goals as the roadmap to a sustainable future that benefits everyone (United Nations 2015). By addressing a range of worldwide challenges in a sustainable manner (Jan et al. 2021), these 17 interconnected global goals serve as a framework or as the standards for an ideal sustainable society. At the same time, they can be used as practical benchmarks for assessing sustainability, development along and quality of life. The purpose behind formulating the UNSDG goals was to encourage organizations from all over the world to embrace sustainability, meet the demands of current and future stakeholders, and ultimately advance societal sustainable development (Fonseca & Carvalho 2019).

## 2.2 Knowledge gap

Though both the aims and objectives of UNSDG goals and SuDS is to create a sustainable world, ultimately, UNSDG goals have a wider focus to encompass social, economic, and environmental aspects of sustainability. Sustainable Urban Drainage Systems (SuDS) are considered micromanaging tools for urban runoff primarily to control urban floods and reduce water pollution. But the advantages of SuDS are even greater than that. The studies to analyze and critically review the linkage between UN SDG goals and Suds' philosophy and relationship to foster the common goals have been very limited or null. This research work attempts to address this gap.

# 3 Methodology

## 3.1 Approach & Research Methods

This is an explanatory literature review based on qualitative research. First literature review and site analysis was conducted parallelly. The literature review involved suds benefits analysis with UNSDG goals, best practices analysis with UNSDG goals and general literature review. Then engagement with stakeholders was done through participation in the NBS participatory workshop, direct surveys and interactions with residents of the neighborhood. From this, SuDS designs and recommendations were generated. Finally, SuDS rocket identified from the literature review was reproposed as the final and most important output of the whole research process. The detailed steps of the methodology is represented by the figure (2).

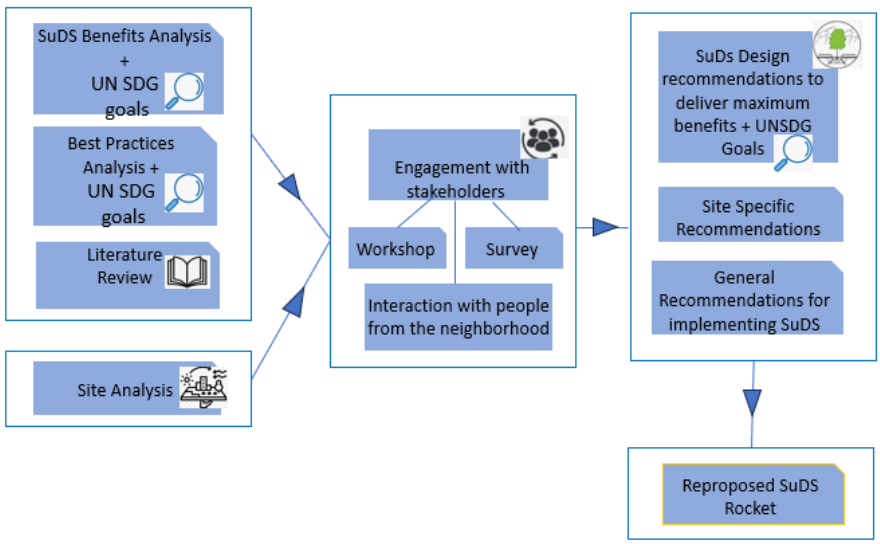


**Figure 2. Detailed Methodology of the research**

# 4 Results

## 4.1 SuDS benefits analysis with 'UN SDG' goals

Within this specific section, the various advantages associated with SuDS are philosophically aligned with the 17 UNSDG goals. In the following Table 1, the foremost and bold goal demonstrates the highest degree of alignment.

| SuDS benefit category | SuDS Benefits | 'UN SDG Goals' | 'UN Goal Target' |
|---|---|---|---|
| **Water quantity** | Help reduce flood risk by decreasing and slowing down the runoff | **'Goal 6: Clean Water and Sanitation'** | Target 6.6 |
| | Support groundwater recharging and assist in preventing low flow of rivers in summer | **'Goal 6: Clean Water and Sanitation'** | Target 6.4 |
| | Reduction in both pollution and erosion | **'Goal 14: Life Below water '** | Target 14.1 |
| | Collect Rainwater for domestic use | **'Goal 6: Clean Water and Sanitation'** | Target 6.3 |
| | Reduce pressure on sewer system leading to the less needs for their upgrades | **'Goal 6: Clean Water and Sanitation'** | Target 6.3 |
| **Water quality** | Decrease pollution in river by reducing the quantity of pollutants | **'Goal 6: Clean Water and Sanitation'** | Target 6.3 |
| | Decrease the quantity of sewage in urban area | **'Goal 6: Clean Water and Sanitation'**<br>'Goal 11: Sustainable cities and communities' | Target 6.3 |
| | Decrease erosion and reduce the quantity of suspended materials in water bodies | **'Goal 6: Clean Water and Sanitation'**<br>'Goal 14: Life below water' | Target 6.3 |
| | Decrease the frequency of improper connections to sewage systems | **'Goal 6: Clean Water and Sanitation'**<br>'Goal 11: Sustainable cities and communities' | Target 6.3 |
| | Lessen the use of chemicals for maintaining paved surfaces | **'Goal 11: Sustainable cities and communities'**<br>'Goal 12: Responsible consumption and production'<br>'Goal 3: Good health and well-being' | Target 11.6 |
| | Minimize sewage overflow pollution | **'Goal 6: Clean Water and Sanitation'**<br>'Goal 11: Sustainable cities and communities' | Target 6.3 |
| **Natural environment** | Help in keeping urban trees healthy | **'Goal 15: Life on Land'**<br>'Goal 11: Sustainable cities and communities'<br>'Goal 13: Climate Action' | Target 15.3 |
| | Aid in preserving and promoting biodiversity | **'Goal 15: Life on Land'**<br>'Goal 13: Climate Action' | Target 15.5 |
| | Aid in valuable species and recreational amenities | **'Goal 15: Life on Land'**<br>'Goal 11: Sustainable cities and communities'<br>'Goal 3: Good health and well-being' | Target 15.9 |
| | Aid in protecting river ecology | **'Goal 14: Life below water'**<br>'Goal 15: Life on land'<br>'Goal 6: Clean Water and Sanitation'<br>'Goal 11: Sustainable cities and communities' | Target 14.1<br>Target 15.1 |

| SuDS benefit category | SuDS Benefits | 'UN SDG Goals' | 'UN Goal Target' |
|---|---|---|---|
| | Aid in maintenance of natural morphology of rivers | **'Goal 6: Clean Water and Sanitation'** | Target 6.6 |
| | Aid in protecting natural resources | **'Goal 15: Life on land'**<br>'Goal 6: Clean Water and Sanitation'<br>'Goal 13: Climate Action'<br>'Goal 14: Life below water'<br>'Goal 12: Responsible consumption and production' | Target 15.3 |
| **Built environment** | Elevate the visual and recreational appeal of a developed area | **'Goal 11: Sustainable cities and communities'**<br>'Goal 3: Good health and well-being'<br>'Goal 5: Gender equality' | Target 11.7 |
| **Cost reductions** | Minimize the funds needed for drainage construction | **'Goal 9: Industry, Innovation, and Infrastructure'**<br>'Goal 6: Clean Water and Sanitation'<br>'Goal 11: Sustainable cities and communities' | Target 9.1 |
| | Assist in long term cost savings | **'Goal 12: Responsible consumption and production'**<br>'Goal 11: Sustainable cities and communities' | Target 12.8 |
| | Aid in cost savings through the use of simpler construction methods. | **'Goal 9: Industry, Innovation, and Infrastructure'**<br>'Goal 11: Sustainable cities and communities'<br>'Goal 12: Responsible consumption and production' | Target 9.1 |
| **Sustainability** | Superior in effectiveness compared to conventional sewage system | **'Goal 6: Clean Water and Sanitation'**<br>'Goal 11: Sustainable cities and communities'<br>'Goal 3: Good health and well-being' | Target 6.3 |
| | Aid in decreasing the environmental impact of a development. | **'Goal 13: Climate Action'**<br>'Goal 11: Sustainable cities and communities' | Target 13.2<br>Target 11.6 |

**Table 1: SuDS benefits aligned with UNSDGs, benefits adapted from (Charlesworth & Booth 2016), originally derived from (CIRIA 2001)**

As it is seen in the above Table (1), different SuDS benefits exhibit alignment with many SDGs and hence can be concluded that when implemented properly, SuDS can really act as the accelerator or catalyst of many UNSDG goals mainly Goal 6 (Clean water & Sanitation), Goal 11 (Sustainable Cities and Communities and Goal 13 (Climate Action). Also, since they are interlinked goals, they create ripple effect and bring along many other SDG benefits that address multiple contemporary urban issues.

## 4.2 Best Practices Analysis with UN SDG goals

### Cloudburst Management Plan (Copenhagen)

The Cloudburst Management plan 2012, with a budget of 1.3 billion euros, outlined 350 diverse interventions such as green roads and cloudburst tunnels, retention spaces and boulevards (Ziersen et al. 2017) based on the hydraulic modelling conducted for seven different catchment areas within the city. Roads are reprofiled and dry basins are constructed such that they enhance social values (Liu et al. 2019). Biodiversity has also been prioritized by planting native and drought resistant plants (Sørup et al. 2019). These all were complemented by other SUDS such as construction of green rooftops, gardens, bioswales etc. to slow down rainwater. Taking into account of UN SDG goals, it can be inferred that "Goal 6" of "clean water & Sanitation", "Goal 11" of "Sustainable cities and communities" and "goal 15" of "life on land" are directly realized.

### Rotterdam Water Square (Netherlands)

A public area 'Water Square' in Rotterdam functions as a GI measure for controlling stormwater runoff. It is based on the concept that it can be used as a square and basketball court, skating area etc. all for public during dry days but can store rainwater when it rains (Ilgen et al. 2019). Other suds like rain gardens and permeable pavement are also present.

Considering UN SDG goals, goal 6 "Clean water and sanitation" is directly addressed as the aim of treating wastewater is met while facilitating reuse and promoting water efficiency. Similarly, the effective strides in making cities and human settlements safe and resilient with inclusive public spaces caters goal 11 of "sustainable cities and communities." Equally significant is Goal 13 of "climate action" which encompasses climate adaptation strategies to mitigate the impacts of climate change.

### Bluegreenstreet , Hamburg (Germany)

This famous project of Hamburg is more about streetscapes (BlueGreenStreets n.d). It adds and maintains green on the streets while managing stormwater (Blue) through tree trench systems and hence the project is named Bluegreenstreets. As drought issues are also increasing in the cities as the effect of climate change, this project showcases how stormwater can be dealt with the help of street trees to slow them down.

Along with Goal 6, this project works in alignment to the UN SDG goals 11 and 13 as it is targeted for making cities sustainable while trying to cope with effects of climate change.

## 4.3 Workshop & Survey findings

Evident from the answers written by the participants of the workshop, it seems that people have noticed the changed patterns in Climate, and they know that there is some relationship between increasing rain intensity and drains systems, but they do not seem to be clearly aware about the role paved surfaces play in creating flood by disturbing the natural water balance. Only one response directly tapping on the keyword 'Too much sealed ground' was achieved by the researcher. A serious knowledge gap about hydrological cycle and paved surfaces among people has been identified and concluded by both survey and workshop.

Much hype and expectations around the techniques like green roof have been generated which is good but it would be better if people would also know that even though green roofs are effective way of adding green in urban built environment as they might have their own implications on water of nearby water bodies. Participants have not seen rainwater collected and converted to ponds/fountains, but they have positive attitude towards managing rainwater.

## 4.4 Case study of Geberbach & Prohlis, Dresden

Prohlis district lies to the southeast of Dresden, the German city of the arts and culture of the state of Saxony. It is approximately 7.4 km from Dresden's city centre. It is the new development area and is often regarded as the one necessitating focused developmental support (Diverse Neighbourhoods in Prohlis 2022).

### Masterplan Prohlis 2030

To improve the current social image of Prohlis while also managing the flood risk of Geber bach river, the Project Masterplan-Prohlis 2030 has been proposed by the city of Dresden. The project builds upon the ambitious green belt project called 'Blaus Band Geberbach' which means "Blue Ribbon Geberbach".

### Creek Geberbach & flood risk

As lots of surface runoff from the built environment enters to the Geberbach through the sewage systems of the municipality which are mainly different discharge points (Gewaessersteckbrief-Prohliser Landgraben/Geberbach 2011), Geberbach exhibits the flood risks in its proximity during heavy rainfall.

### The Site

The neighborhood opposite the Gamigstrasse-14 of Prohlis Nord at 51°00'28.9" N Longitude and 13°47'46.3" E Latitude has been taken as the site of this research. It is chosen because it is significant as the most immediate neighborhood, situated right next to the parking area across the street, which many experts consider suitable for long term rainwater storage for Geberbach from the Prohlis Neighborhood.

### Basic concept for rainwater storage

The creek Geberbach went dry for few weeks in 2022. To store rainwater for long term for the driest days of Geberbach, it's important to check the climate history and make a proper analysis of projected number of dry days in coming years. Then minimum flow requirement at that point of the creek intended for rainwater storage to feed the water should be determined. Here, for Geberbach, we are considering the minimum water required by the vegetations along the bank of the creek and the water required by fish.

Thus, for the size of rainwater storage, the following formula can be used if we are looking to feed the creek entire time:
Size of the Rainwater storage = minimum flow of the creek per minute × total minutes in dry season.
Both the role of evapotranspiration in microclimate and climate change allowances should also be considered.

This idea of rainwater collection and storage can be repeated over different points along the stretch of Geberbach and the proposed green belt can be kept alive even during its driest days.

### Identified SuDS Strategies for SuDS Treatment Train


**Figure 3. Approx. catchment division of Site and the identified suds strategies**

## 4.5 General recommendations for implementing SuDS

Thus, after analyzing the literature review, lessons from best practices and the site-specific recommendations, following recommendations can be derived for implementing SuDS as the basis for a sustainable neighborhood anywhere:
Inspire & Educate about SuDS

People should be educated on SuDS starting from the basic information to different types of SuDS and tell them it's possible to have a fun filled, water filled natural neighborhood.

### Vision and Planning

Detailed action plans and long-term visions that integrate SuDS as the cornerstone of neighborhood sustainability should be developed. Action plans to guide the implementation of sustainable drainage solutions aligning with neighborhood's overall sustainability goals should be formulated.

### Multifunctionality

SuDS element should be designed keeping multifunctionality in core addressing not only stormwater management but also social, ecological and aesthetic aspects.

### Green spaces and biodiversity

Rain gardens, native plants and wildflowers should be introduced and reinforced in the neighborhood while safeguarding and integrating existing trees.

### Resilience and adaptability

Suds should be designed to adapt to changing climatic patterns and future growth to provide effective stormwater management both in normal and extreme conditions.

### Retaining natural water bodies

In case any natural water bodies exist in the neighborhood, they should be preserved and made them the focal points of the neighborhood enhancing their visibility.

### Monitoring and evaluation

Monitoring systems should be implemented for assessing the efficacy of SuDS Elements to manage stormwater, improve water quality and enhance the community wellbeing.

### Living system approach

It should be emphasized that SuDS need continuous care for their effectiveness and longevity. A culture of taking pride for maintaining SuDS in their neighborhood should be developed. Recreational spaces, outdoor seating and sports facilities should be created out of SuDS elements so that it encourages physical activity while being an integral part of neighborhood people.

## 5 Conclusions and discussion

Thus, just as how urban challenges in cities are interconnected (Hoang and Fenner 2015), SuDS and UNSDGs are also directly linked due to their nature and objectives to work against these challenges. As seen from SuDS benefit analysis and best practices analysis above, it can be concluded that SuDS can be the accelerator of multifarious UN SDG goals that ultimately help to achieve what the United Nations (United Nations 2015) aspires to seek through UNSDG goals. It can be said that SuDS and UN SDG goals both align together in their nature and philosophy to build an ideal and sustainable world.

The idea can be better understood with figure 4, which is a newly proposed SuDS Rocket by Author. It says when SuDS is rethought and prioritized as beyond water managing solutions and adopted as way of living in society, it can accelerate so many other factors of sustainability which are also named by United Nations as UN SDG goals. The rocket has two tiers where the first tier has three clear benefits with 'Clean water & Sanitation' being the central benefits. The second tier has other added benefits that come eventually but surely in the long run.

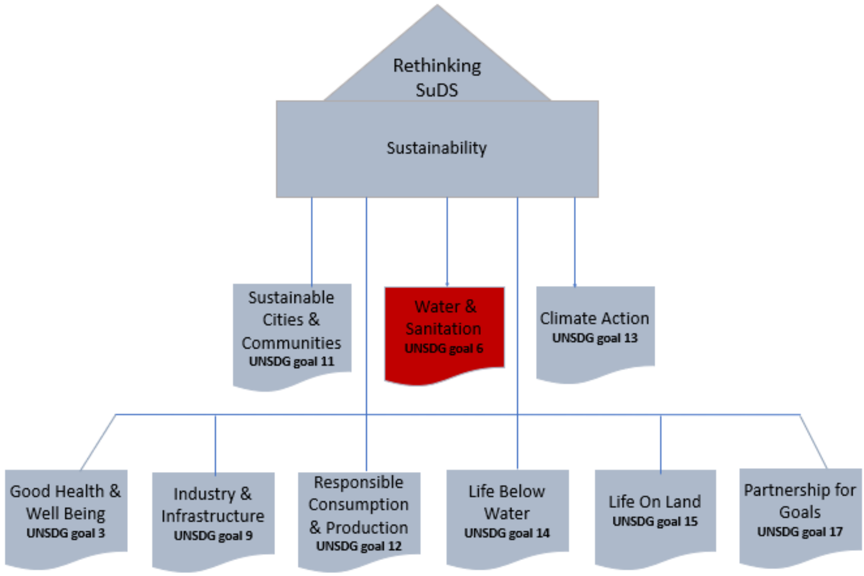


**Figure 4. Reproposed SuDS Rocket**

As of 2023, every time it rains in Hyderabad, India these days, schools, colleges, and institutions are closed to escape from the probable dangers of flood (The Times of India 2023). Till before 2020, Hyderabad never had this frequent flood in the city (The Times of India 2023a). Throughout the world, in our cities, the impacts of disturbing natural hydrological cycle knowingly/unknowingly are surreal and are evident with the extreme climate changes.

The destruction, effects, reasons, affected communities all could be of different range and level but everywhere the problem persists and will persist more & more unless we don't intervene with conscience & resilience.

Sustainable Drainage Systems (SuDS) are a set of best practices for managing stormwater runoff in a sustainable and environmentally friendly manner. Having their benefits wide and well aligned with UN SDG goals, SuDS provide us with the way forward to live in sustainable neighbourhoods having privileges of urbanization while naturally tackling the modern-day urban challenges. Thus, with suds, we can have the best of both worlds. With SuDS, we have the strong and undeniable chances to rewind our cities and develop them into green and sustainable. The fact that all SuDS benefits well align to UN SDG goals clearly says that SuDS are the fastest ways of achieving the ideal world that UN SDG has benchmarked.

But the interesting as well as complex aspect of stormwater management is that for the proper implementation, each individual house/building should install the stormwater attenuation system. Even with natural drainage, it's the same. We need all people committed to suds. This thesis research's finding proves that till date, only a handful of people, either professional or self-curious, know about SuDs. There has not been enough transfer of knowledge about SuDS worldwide. This makes seizing the benefits of SuDS in large scale impossible.

It's impressive that like in the city of Dresden, people in authorities are slowly understanding and they have included SuDS in their long-term vision but looks like they have left their main beneficiaries' 'people', behind in the process. Without people involved in the process enthusiastically, it will take forever, and we might have to learn unnecessary hard lessons. SuDS should embody the soul of democracy, of the people, by the people, for the people. Thus, SuDS not only brings people close to nature but also brings people close to people.

It's important that we bridge this huge gap of suds literacy, and it must start by creating awareness from basics of how paved surfaces interrupt in the water cycle and how this has serious implications like urban floods. Also, treating the commitment to SuDS' as moral or ethical behaviors could greatly contribute to this manifestation. In fact, SuDS clearly showcase a strong dedication for the preservation of the environment (Charlesworth and Booth 2016). People really need to know there are more ways other than green roofs and green façade for creating a sustainable city. SuDS should be a lifestyle, way of living rather than any alternative because SuDS might not be the whole solution, but they are the only way to the solutions.

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SHABNAM, MST MAHBUBA

# Exploring Opportunity Sites for Implementing Nature-Based Solutions against Flooding in Urban Vacant and Derelict Land

## - Case Study Area: Glasgow City

*Urban surface water flooding is getting severe due to rapid urban expansion and climate change, while urban environment is getting fragmented due to urban VDL accumulation. Implementing nature-based solutions (NbSs) in cities is also getting difficult due to space constraints. A balance between VDL regeneration and NbS implementation might assist flood mitigation and help interconnecting fragmented ecosystems. However, the success and effectiveness of NbSs heavily depend on the site characteristics. This study aims to explore the suitable site for NbS implementation by considering the interrelationship of NbS on different environmental criteria in the context of managing surface runoff in the Glasgow City. Relative importance of environmental criteria was carried out through the multi-criteria AHP analysis based on experts' opinion and the possible opportunity sites was mapped using Geographic Information System (GIS) software. The maximum portion of the VDL was found as moderately suitable for different types of NbSs implementations. The finding can contribute to planners, leaders, and decision-makers with a better understanding of site suitability analysis to pick the right places for NbSs to make the city more flood-resistant.*

# 1 Introduction

The number of total urban areas exposed to flooding is growing rapidly (Mensah & Ahadzie 2020), creating a tremendous problem in coping with flood disasters. Due to frequent and intense rainfall and other extreme weather events, in Europe, floods are becoming severe, which may have catastrophic effects on infrastructure and human life. On the other hand, the situation is getting worse due to the continued urban growth and the replacement of permeable surfaces with impermeable ones (Warner 2023). Moreover, the present drainage systems in many cities are not adequate to reduce surface flooding for increasing impermeable surfaces, which indicates that the difficulties brought on by flood hazards will become much more severe. The promotion of 'work with nature' is crucial to effectively address urban flood challenges through promoting water absorption and storage as well as for connecting habitat and other emergency needs. The concept of nature-based solutions (NbSs) in this context, can be a promising solution. NbSs are the actions aimed to manage, protect, restore or modify natural ecosystem sustainably and effectively address challenges like climate change and natural disasters while benefits biodiversity (Cohen-Shacham et al. 2018). However, NbSs are place-based solutions, to maximize their positive effects and reduce any possible negative effects, they must be adapted to the specific environmental context of the area (Cheng et al. 2017). Therefore, for their success and efficacy in offering multi-functional advantages, it is essential to conduct a site-specific evaluation and choose the proper NbSs type depending on the site's features and demands. But as cities are becoming more crowded, the need for urban space is growing, and the implementation of NbSs is often hindered by the lack of available space (Cousins 2017; Zhang et al. 2017). Use of vacant and derelict lands (VDLs) can be a promising solution with the co-benefit of utilizing unused land while addressing the issue of limited space for NbS (Qiao et al. 2018.) to mitigate and build resilience to flood events. In sealed urban areas with high runoff, these underutilized VDLs can provide potential opportunity sites for NbS implementation, which can hold and attenuate stormwater flow, increase infiltration, and recharge aquifers, hence lowering runoff and the danger of floods (Sanches et al. 2016).

Following the hypothesis that NbSs implementation in the right place can manage the flood risk, and taking the Glasgow City as a case study, with a comprehensive site selection approach, this study aimed on exploring potential opportunity sites in urban vacant and derelict land for the implementation of Nature-based Solutions (NbS) against flooding, to support urban resilience and flood risk reduction along with following Objectives

- To develop a comprehensive understanding on surface water flooding and aspects of NbS associated with floodwater management.
- To score the relative importance of individual environmental criteria with a multi-criteria decision analysis (MCA-AHP) approach.
- To evaluate the suitability of the sites for nature-based solutions implementation based on identified environmental criteria.
- Mapping the opportunity sites for NbS implementation in urban vacant and derelict areas using ArcGIS pro software.

# 2 Background

## 2.1 Surface Water Flooding and Necessity of Surface Flood Management

The term surface water flooding is often a combination of various sources, including both natural (like small watercourses) and artificial (like sewers) drainage systems, also direct inundation from surface water run-off (Flood risk management Act 2018). In Europe, floods already account for a considerable portion (33%) of recorded natural events spanning the period between 1900 and 2019 (Ferreira et al. 2021). The reports from the IPCC consistently emphasize the severity of the impacts and the projected increase in both frequency and intensity of flooding caused by climate change (Ferreira et al. 2021). Because, it typically affects natural water systems such as increasing rainfall runoff, decreasing infiltration, evapotranspiration, and groundwater recharge, thus intensifying surface runoff rate and volume (Zölch et al. 2017). Moreover, in the UK, over the last 20 years, nearly 14% of the population has increased and shortages of housing for population are leading urban areas to continue expansion (Flood risk management Act 2018). This ongoing urban expansion is converting the natural landscapes to residential, commercial, and industrial area with increased impervious surface and decreased vegetation; increases the likelihood of flooding (Warner, 2023). Consequently, since 2011, several major UK cities have faced severe flooding from surface water runoff (Lashford et al. 2019) and associated challenges (Ferreira et al. 2021).

## 2.2 Traditional Flood Management and Driving Source for Flood Risk

In the past, the management of floods primarily relied on engineering infrastructure solutions, commonly known as “grey solutions,” such as dikes and dams. However, there has been growing skepticism about the effectiveness of these solutions as they are designed to withstand floods with specific return periods; limiting their adaptability to cope with increasing flood hazards driven by climate and urbanization uncertainties (Kapetas & Fenner 2020). Moreover, the potential failure of these solutions can have severe consequences (Ferreira et al. 2021), which is making the situation worse. Although the focus remains largely on grey infrastructure, there has been a paradigm shift in Europe since the 1990s towards sustainable flood management that considers vulnerabilities (Ferreira et al. 2021). In sustainable flood risk management, to assess and understand the potential flood risks, and the vulnerabilities of environment and populations, we need to consider the presence of sources, a pathway that transports the floodwater to a receptor, and the vulnerability of the receptor to flooding (O’Donnell & Thorne 2020). This framework is known as the source-pathway-receptor model (Çoban 2021). The study by O’Donnell & Thorne (2020) also showed that Climate change-induced rainfall is the primary source driver for urban flood risk. Urbanization and deterioration of urban assets are the leading pathway drivers, resulting in various consequential flood risks. Because of the complexity of drivers and responses relationship, urban flooding needs multi-functional sustainable management approaches (Lennon et al. 2014), rather being dependent on traditional grey solution. The idea of sustainable management is to meet ongoing environmental, social, and economic challenges through use of nature which is referred to as 'Nature-based Solution (NbS)' (Chiu et al. 2021). Multi-functional approach can ensure that NbSs can manage run-off and surface water flooding through influencing each sector of source-pathway-receptor model while making the urban environment more adaptable to future changes.

## 2.3 Nature-based Solution (NbS)

According to Lennon et al. (2014), Nature-based solution (NbS) has a potential to deliver a comprehensive multi-functional service by managing all rainfall event and providing other socio-ecological benefits (e.g., using foot paths and cycle paths as routes for infiltrating and conveying water, contributing to 'green and blue networks') through emulating natural processes.The main processes associated in providing multifunctional benefits are

- Let the water seep through restoring permeable ground and let it infiltrate underground, feed the aquifers, and allow humidity exchange within air and soil.
- Do not let the water go from urban impervious ground and roof surfaces by capturing, harvesting, and storing rainwater for further use.
- Convey the run-off from the flood risk area to the safe zone or drainage system.

Nature-based solutions provide responses focused on the receptor of flooding and mimic the pathways taken under natural conditions by which stormwater reaches those receptors (Lennon et al. 2014). In terms of pathways, nature-based solutions influence floodwater movement and distribution by increasing water storage and reducing runoff. As for receptors, nature-based solutions can mitigate the impacts of flooding on communities and the environment by providing flood protection, improving water quality, and enhancing biodiversity.

## 2.4 Importance of Site Selection

The success and effectiveness of NbSs heavily depend on the specific characteristics of the site where they are implemented. According to Cheng et al. (2017), NbSs are place-based solutions; need to be tailored to the specific environmental and social context of the location to maximize their benefits and minimize negative impacts. For example, if a green infrastructure project is implemented in a location with inappropriate soil conditions, it may not be able to function properly or may even cause negative environmental impacts such as soil erosion.

For implementing NbSs in urban VDLs, a study by Nassauer et al. (2019) concluded that, without any NbSs, VDLs on their own are much less efficient for rainfall runoff capturing in compared to the VDLs with the NbSs interventions. Therefore, conducting a site-specific assessment in VDLs for finding appropriate location for different NbSs is crucial for their success and effectiveness in providing multi-functional benefits and to manage stormwater.

Based on local site condition of the VDLs, multiple environmental criteria must be combined for this assessment of finding suitable site. The Analytical Hierarchy Process (AHP), by Saaty (1980) is the most common Multi-Criteria Analysis (MCA) approach (Velasquez and Hester 2013), applied by planners and decision-maker for assessing heterogeneous factors and for scoring relative importance of each.

# 3 Methodology

With a combination of qualitative and quantitative method, framework of this study designed under context of two phases:

1) Understanding and conceptualization and
2) Contextualization and localization.

The objective of the first phase was to gather detailed on general classification of NbS for storm-water management and environmental criteria related to NbS implementation. Common approaches on these issues offered by a collection and review of different papers, literature, articles, and reports on the relative topic.

Following the general understanding, the second phase focused on:

a) study area, and
b) sampling and data analysis to visualize the result of this study.

## 3.1 Case study

Glasgow city was considered as case study based on factors including- Significant flooding issues, Availability of VDLs, Data accessibility, and Its urban setting. According to GCC (2021), about 68% of Glasgow city is at risk of surface water flooding which is responsible for the majority of damage caused by flooding, resulting in an estimated around £550,000 annual average damages. The challenge of mitigating the flood impacts becomes even more complex when considering climate change (UKCCRA 2017) effects. The Metropolitan Glasgow Strategic Drainage Partnership (MGSDP) has been promoting the use of Sustainable Drainage Systems (SuDS) and recommends SuDS measures that promote water infiltration, evapotranspiration, and stormwater reuse to manage surface water runoff. Glasgow has the largest area of vacant and derelict land (VDL) in Scotland. In Glasgow, there is 9.38 $km^2$ of VDL, accounting for 5.29% of the city's territory (Ordnance Survey, 2021a). Significantly, 55.5% of Glasgow's population resides within 500 meters of derelict land. Glasgow has made progress in re-purposing VDL focused on residential purposes (66.4%) with other transport and recreational uses (GCC 2018). This exemplifies the city's commitment to transforming unused land into functional spaces. Therefore, for sustainable urban extension, VDL needs to be assessed for effective stormwater management.

### 3.2 Sampling and data analysis

Environmental factors identified in the literature review and based on a number of variables (including ecological integrity and site-specific features) and data availability for a suitability analysis for NbS included: Land Cover, Percentage of impermeable area (PIMP), Proximity to existing drainage features, Proximity to flood prone area, Soil Texture, Topography, Proximity to urban green areas.

The method was subdivided into three phases:

1) collecting the primary data.
2) data processing and
3) data analysis.

The data analysis techniques for this research included content analysis, and spatial analysis.The results were explained as maps, table, and diagram.

**Collecting data:** For content Analysis, the research population were experts in nature-based solutions and urban flood management, including local government officials, planners, and environmental experts. The data collection methods were through original questionnaire surveys, sent anonymously by email. Out of a total of 32 experts invited, 5 responded, where through a pairwise comparison matrix, experts offered their assessments on the relative importance of one attribute to another for suitable sites selection for implementing NbSs. Data for spatial analysis were collected from various online sources, including EDINA Environment Digimap Service, SEPA's Flood Risk Management Scotland, Copernicus Land Monitoring Service, Glasgow Open Data Portal, Glasgow City Corporation etc.

**Data Processing and Analysis Techniques:** The content analysis was used to analyze the survey data. Based on understanding, identified environmental criteria were scored according to suitability. Following the Analytic Hierarchy Process (AHP) method, a spatial multi-criteria analysis (MCA) was then carried out to determine the relative importance of each environmental criterion, based on expert opinions. An eigenvector was obtained after the AHP had been applied to assign weights (i.e., relative priority to each environmental parameter). The total sum of the eigenvector components was one. The Consistency Index (CI) and Consistency Ratio (CR) were used to assess the consistency of the pairwise comparison matrix. To calculate the spatial suitability scores, these evaluations were then integrated using a simple additive weighting (SAW) methodology (e.g., Gonzalez-Ollauri, Thomson, and Mickovski, 2020). For Spatial Analysis, Geographic Information System (GIS) software ESRI ArcGIS Pro 2.8.0 was used to process and analyse the data and to map the potential sites. By summing the GIS layers that integrate selected attributes and their weights (from the MCA-AHP), Weighted Overlay Analysis generated a composite suitability map for implementing NbSs within the study area. The suitable site was categorized under the three classes, where 5 indicates optimal suitability, 3 indicates moderate suitability and 1 indicates low suitability.

# 4 Result and Analysis

## 4.1 Understanding and Conceptualization

This study conducted a thorough assessment on nature-based solutions (NbSs) based on the literature and case studies for managing stormwater and identified a number of NbSs. Based on the understanding and to facilitate the analysis, this study categorized the NbSs into three classes according to their basis functions of lowering storm-water runoff as following:

- **Retention-based NbS:** Designed to foster infiltration and prevent the discharge of a specified volume of stormwater into sewer networks or surface waters and does not therefore become runoff. Examples of water retention NbS include- green roofs, Rain Garden, Subsurface wetlands etc.
- **Storage-based NbS:** Focused on temporarily holding and storing stormwater, which is then either reused or released in a controlled manner to sewers or receiving channels after water levels recede following a storm event. Examples of water storage NbS include Created Wetlands, Underground storm-water detention area, Floodplains with storage ponds.
- **Conveyance-based NbS:** Designed to redirect excess stormwater away from vulnerable areas and minimize the risk of overflow.Examples of water conveying NbS may include- Permeable pavements, Live pole drain, Bioswales.

While considering the environmental factors, existing buildings and road data were analyzed as subdivisions of the land cover suitability analysis. Same as proximity to existing drainage system, where the proximity to existing culvert and a distance from natural watercourse (river) were considered with equal importance. The table 1 shows the scoring of each environmental criteria for the context of different types of nature-based solution implementation according to the framework for suitability classification discussed beforehand.

## 4.2 Contextualization and Localization

### 4.2.1 Content Analysis: Relative Weight of Environmental Criteria

Following table 4.2 shows the results from AHP analysis. For the Retention-based NbS and Storage-based NbS, Topography (Slope) was considered as the most significant environmental criteria (RW = 0.18 and 0.29 respectively). For the Conveyance-based NbS, proximity to flood prone area (RW = 0.20) was defined as the most important environmental criteria before Topography (Slope) (RW = 0.18). Proximity to urban green areas was counted as the least important environmental criterion. Since the values of consistency index (CI) and consistency ratio (CR) were below the standard values of 0.14 and 1.10 respectively, the results of the AHP were consistent (Table 2).

| Environmental Criteria | | Unit | Class | Retention | Storage | Conveyance |
|---|---|---|---|---|---|---|
| Land Cover | Land cover<br>Source: Ordnance Survey (2021)<br>EDINA Environment Digimap Service<br>Raw Data Type: Polygon | Level | Broadleaf woodland | 5 | 5 | 1 |
| | | | Built-up areas | 1 | 3 | 5 |
| | | | Coniferous woodland | 5 | 3 | 1 |
| | | | Arable | 1 | 1 | 3 |
| | | | Improved grassland | 3 | 3 | 1 |
| | | | Semi-natural | 5 | 3 | 3 |
| | | | Mountain, health | 1 | 1 | 1 |
| | | | Open Water body | R | R | R |
| | Proximity to Buildings<br>Source: Ordnance Survey (2021)<br>EDINA Environment Digimap Service<br>Raw Data Type: Polygon | m | 0-70 | 1 | 1 | 5 |
| | | | 70-200 | 1 | 3 | 3 |
| | | | 200-350 | 3 | 5 | 1 |
| | | | >350 | 5 | 3 | 1 |
| | Proximity to main Road<br>Source: Ordnance Survey (2021)<br>EDINA Environment Digimap Service<br>Raw Data Type: Polygon | m | 0-50 | 1 | 1 | 5 |
| | | | 50-200 | 3 | 1 | 3 |
| | | | 200-350 | 5 | 3 | 1 |
| | | | >350 | 3 | 5 | 1 |
| Percentage of impermeable area (PIMP)<br>Source: Copernicus Land Monitoring Service<br>Raw Data Type: Raster | | % | 0-35 | 5 | 1 | 1 |
| | | | 35-70 | 3 | 5 | 3 |
| | | | 70-100 | 1 | 3 | 5 |
| Proximity to surface flood prone area<br>Source: SEPA's Flood Risk Management Scotland<br>Raw Data Type: Polygon | | m | 0-100 | 1 | 1 | 5 |
| | | | 100-250 | 5 | 5 | 3 |
| | | | 250-400 | 5 | 3 | 3 |
| | | | 400-550 | 3 | 1 | 1 |
| | | | >550 | 1 | 1 | 1 |
| Proximity to existing Drainage features | Proximity to main watercourses<br>Source:Ordnance Survey (2021)<br>EDINA Environment Digimap Service<br>Raw Data Type: Polygon | m | 0-100 | 5 | 5 | 1 |
| | | | 100-300 | 5 | 5 | 3 |
| | | | 300-700 | 3 | 3 | 5 |
| | | | >700 | 1 | 1 | 3 |
| | Proximity to existing culverts<br>Source: Glasgow city council (2023)<br>Raw Data Type: Polygon | m | 0-100 | 1 | 1 | 5 |
| | | | 100-250 | 5 | 3 | 3 |
| | | | 250-700 | 5 | 3 | 3 |
| | | | >700 | 3 | 5 | 1 |
| Soil Texture<br>Source: Ordnance Survey (2021)<br>EDINA Geology Digimap Service<br>Raw Data Type: Polygon | | Level | Clay to loam | 3 | 1 | 1 |
| | | | Clay to sandy loam | 5 | 3 | 1 |
| | | | Clayey loam to sandy | 3 | 3 | 3 |
| | | | loam | 3 | 3 | 3 |
| | | | Clayey loam to silty loam | 5 | 5 | 1 |
| | | | Loam | 3 | 3 | 1 |
| | | | Loam to Clayey loam | 5 | 3 | 1 |
| | | | Loam to sandy loam | 5 | 3 | 3 |
| | | | Loam to silty loam | 5 | 5 | 1 |
| | | | Peat | 3 | 3 | 3 |
| | | | Sand to loam | 3 | 3 | 3 |
| | | | Sand to sandy loam | 5 | 3 | 1 |
| | | | Sandy loam | 5 | 3 | 1 |
| | | | Sandy loam to loam | 5 | 3 | 3 |
| | | | Sandy loam to silty loam | | | |
| Topography (Slope)<br>Source: Ordnance Survey (2021)<br>EDINA Geology Digimap Service<br>Raw Data Type: Raster | | Degree | 0-1° | 5 | 5 | 1 |
| | | | 1-5° | 5 | 5 | 5 |
| | | | 5-15° | 3 | 3 | 3 |
| | | | 15-35° | 1 | 1 | 3 |
| | | | >35° | 1 | 1 | 1 |
| Proximity to open green areas<br>Source: Ordnance Survey (2021)<br>EDINA Environment Digimap Service<br>Raw Data Type: Polygon | | m | 0-80m | 5 | 5 | 5 |
| | | | 80-200m | 5 | 3 | 3 |
| | | | 200-350m | 3 | 3 | 3 |
| | | | >350m | 1 | 1 | 1 |

**Table 1. Scoring of each environmental criteria for the context of different type of nature-based solution implementation and sources of data**

| Environmental Criteria | Relative Weight (RW) in context of - | | |
|---|---|---|---|
| | Retention based NbS | Storage based NbS | Conveyance based NbS |
| Land Cover | 0.16 | 0.13 | 0.12 |
| Percentage of impermeable area (PIMP) | 0.17 | 0.15 | 0.16 |
| Proximity to existing Drainage features | 0.12 | 0.10 | 0.17 |
| Proximity to flood prone area | 0.13 | 0.11 | 0.20 |
| Soil Texture | 0.17 | 0.16 | 0.11 |
| Topography (Slope) | 0.18 | 0.29 | 0.18 |
| Proximity to urban green areas | 0.07 | 0.06 | 0.06 |
| CI | 0.03 | 0.09 | 0.02 |
| CR | 0.02 | 0.07 | 0.02 |

**Table 2. Relative Weight of Environmental Criteria**

These relative weights from MCA-AHP were then used to compute the overall spatial suitability for each type of NbS implementation through equation of Simple Additive Weighting (SAW), where higher number will have higher impact and lower number will have lower influence on final output map.

### 4.2.2 Spatial Analysis: Opportunity site mapping for NbS implementation

#### Opportunity site mapping in Glasgow City

Using weighted overlay tools in ArcGIS software, the seven maps had been overlaid and weights of the environmental criteria achieved through SAW analysis were combined; thus suitable opportunity sites for three NbSs types in Glasgow were produced. 11% of the Glasgow city area was accounted as restricted area because of buildings, roads, and open water area. For implementing retention-based NbS, moderate suitability was found for most of the area (71%) while 18% of the area considered optimally suitable. While considering storage-based NbS , almost 85% of the area was of moderate suitability which is about 81% for conveyance-based NbS . Optimal site proportion for storage-based and conveyance based NbS were 4% and 5% respectively. Nearly 0% of Glasgow city was found to be least suitable for both Retention and

#### Opportunity site mapping in urban vacant and derelict area of Glasgow City

After finding the opportunity sites in Glasgow, VDLs were prioritized for further analysis. 5% of vacant and derelict land of Glasgow city area was accounted for restricted area for retention-based and conveyance-based NbS, where 4%

was for storage-based NbS. For all the NbSs, maximum portion of the VDLs was found as moderately suitable, which were 68% (1% of Glasgow city territory), 90% (2% of Glasgow city territory) and 89% (2% of Glasgow city territory) for retention-based (Figure1), storage- based (Figure 2), and conveyance-based NbS (Figure 3) respectively. Though the optimal suitability for NbS in compared to overall city territory was found nearly 0.1%, but of 9.38 km2 VDL, 5% was considered as optimally suitable for both storage-based (Figure 2) and conveyance-based NbS (Figure 3). The highest proportion (27%) of vacant and derelict areas (1% of total city territory) showed optimal suitability in context of implementing retention-based NbS (Figure 1) in VDLs, with no low suitability for NbS creation. It also found no unsuitable sites for retention and storage-based NbS in VDL of Glasgow, where only 1% land was of low suitability for conveyance-based NbSs implementation.

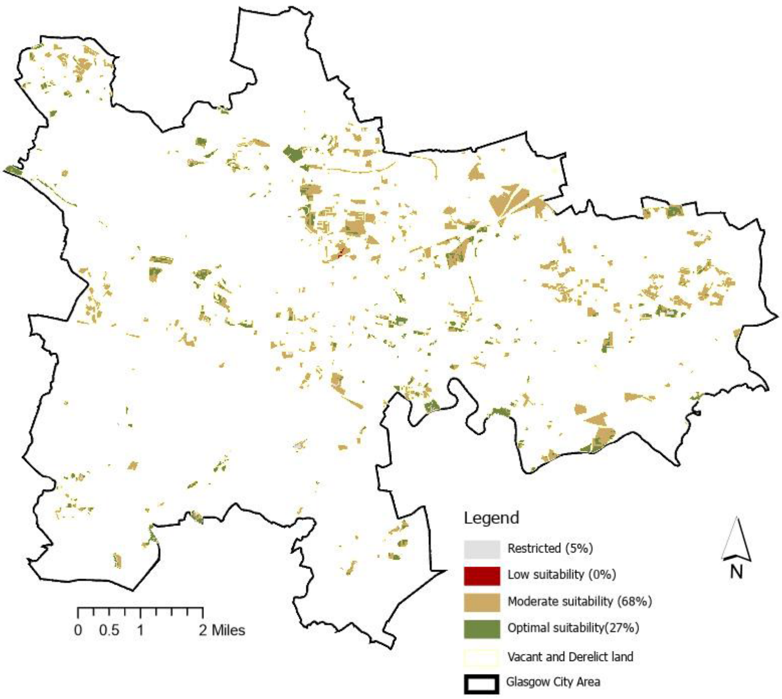


**Figure 1. Opportunity site suitability for retention based NbSs in VDLs of Glasgow city**

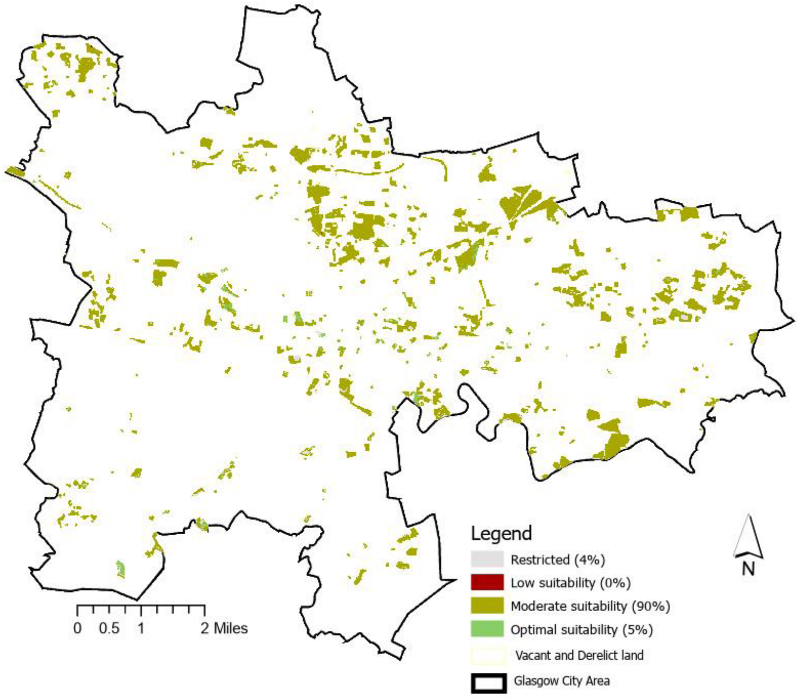


**Figure 2. Opportunity site suitability for storage based NbSs in VDLs of Glasgow city**

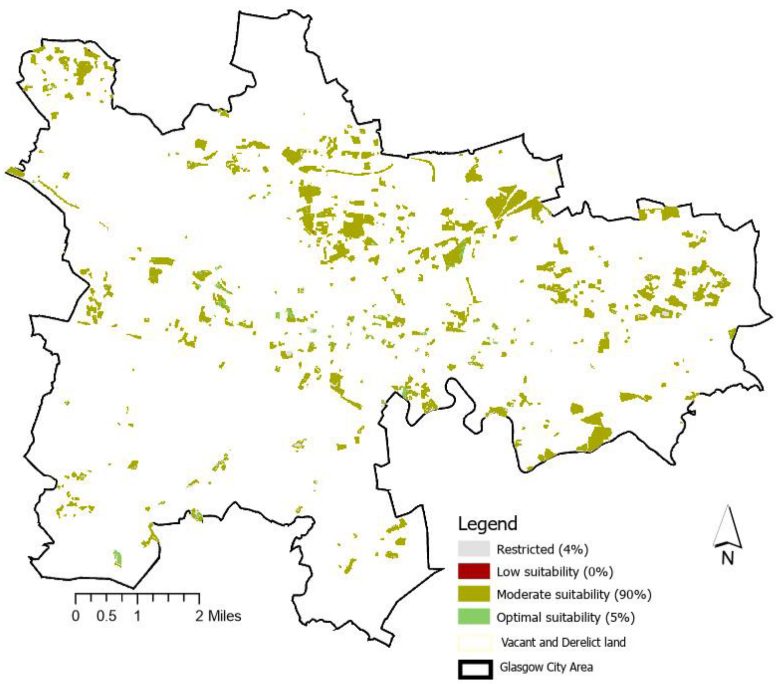


**Figure 3. Opportunity site suitability for conveyance based NbSs in VDLs of Glasgow city**

# 5 Conclusions and Discussion

Several studies have shown that NbS can contribute a significant role in buffering communities from urban flood risk (Debele et al. 2019). But NbS implementation is mostly hindered due to lack of suitable site. To investigate potential opportunity sites in urban vacant and derelict land (VDL) for NbSs, this research was done by collecting secondary data from literature review, official and open sources and primary information supported by experts' opinion. Relative importance of one attribute compared to another was carried out through AHP analysis. Data processing and analysis were done using Geographic Information System software to map the identified possible opportunity sites.

The Findings of this study demonstrate, Galsgow has a satisfactory suitability to accommodate all the three types of NbS. To accommodate storage and conveyance-based NbS, Glasgow City has shown only 4% and 5% optimal suitability respectively, whereas higher (18%) for retention-based NbSs, which is satisfactory. For instance, 7.1% of Florence city was found as completely suitable for retention-based NbS (Bioretention area and Rain garden) creation, whereas 1.7% - 2.5% for conveyance-based NbS (Tree box filter, infiltration trenches, bioswals and permeable pavement) and 0.3-0.9% for storage-based NbS (detention basin and ponds) in context of surface flood management (Pacetti et al. 2022).

While considering VDLs, about 27% showed optimal suitability for implementing retention-based NbS and 5% VDLs were found for both storage-based and conveyance-based NbS. When comparing with other study, utilizing VDLs in Glasgow city can present a significant chance to manage urban surface water flooding. For instant, Cheng et al. (2017) identified that about 0.87 $km^2$ (50% of analyzed vacant land) suitable land surface can have a potential of reducing 29%, 25% runoff for a 2-year and 5-year design storm respectively, where Glasgow found 5.05 $km^2$ (27% of VDLs) as optimal suitability of retention-based NbS.

However, Pacetti et al., (2022) suggested that the site suitability range can be varied or limited for the cities depending on the dense of urbanization and environmental attributes. From the MCA-AHP analysis, for retention-based and storage-based NbS, Topography (Slope) was found to have the most influenced environmental criterion, where it was second most important criterion for conveyance-based NbS (Table 2) . Experts assigned proximity to flood prone areas as the most important criterion for conveyance-based NbS. 'Proximity to urban green area' found as the least important environmental criterion for all the types of NbS (Table 2).

Even though these methods have been used in earlier research (e.g., Gonzalez-Olluari et al. 2020), the multi-criteria analysis process was based on only five responses from 32 invited experts, which indicates that, the relative importance on the criteria should be interpreted with cautious and further assessment is therefore advised, as the dependability and quality of input datasets, and the survey responses all had a direct influence on the final opportunity sites identification for NbS creation. Despite its structured approach, due to few engagement of

NbS experts, MCA-AHP may still be influenced by the judgment and preferences of experts involved, leading to potential bias in site selection. As a limitations, the question on how effective the selected VDLs could be at reducing volume of surface water runoff and the ownership authorization of the available land in Glasgow city was out of this work. However, to identify and quantify suitable location for any specific purpose, the methods considered showed fluency while considering multiple attributes at once at the city level. Also, Glasgow has free and ready access for the user like urban planners, sustainable decision-maker to all the data used here except the location of existing culverts, which made the method simple.

Finally, though some academic researchers are talking about the effectiveness of nature-based solutions (NbS) in flood control, overall study on their adoption in planning and practice has been limited (Grace et al. 2021; Moosavi et al. 2021), especially due to lack of knowledge on site specification. Despite few limitations, this research can contribute to the planners, sustainability decision-maker, environmental managers, and policy maker with the decision-making process in seeking opportunity site to manage urban surface water flood and to enhance urban resilience.

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# Critical evaluation of climate change

## mitigation plans and actions

KHODAYAR, MOHAMMAD

# Obstacles, Enablers, and the Role of City Networks in Climate Action from the local perspective

## - A case study of Glasgow (Scotland, UK), Dresden (Germany), and Lahti (Finland)

*This research investigates the effectiveness of climate action plans in Glasgow, Dresden, and Lahti, with a focus on the perspectives of local practitioners. The study employs a mixed-methods approach, including policy reviews, questionnaires, and interviews, to analyze the drivers and barriers and the role of city networks in climate action.*

*The research finds that many practitioners perceive climate mitigation plans as challenging to achieve. However, opinions on adaptation plans vary. Financial constraints, political hurdles, and the complexity of urban planning emerge as key obstacles. Collaborations with academia, political support, and public engagement are identified as crucial enablers of climate action. Peer-city collaborations and climate-tailored infrastructure investments are also considered essential.*

*City networks, which offer knowledge exchange and funding opportunities, are seen as valuable but face challenges such as communication gaps and stakeholder management. The study emphasizes the importance of a collaborative, multifaceted approach to achieve climate action goals. Overcoming obstacles and maximizing enablers, including academic alliances, public involvement, and city network collaborations, are crucial for successful climate action implementation.*

# 1 Introduction

The Intergovernmental Panel on Climate Change (2018) has highlighted the increased frequency, intensity, and duration of extreme weather events due to climate change, exacerbating existing stressors on natural systems and human societies and posing significant risks to human health, water availability, food security, and economic development. Cities, being major contributors to greenhouse gas emissions and highly vulnerable to the impacts of climate change, have been recognized as key actors in addressing these challenges (IPCC 2018; UNEP 2021). The Paris Agreement has acknowledged the importance of local actions in combating climate change (United Nations 2015). However, despite cities adopting and committing to climate adaptation and mitigation actions (Eurocities 2019), they are not currently on track to achieve the objectives of the Paris Agreement and need to significantly increase their ambitions and efforts (Salvia et al. 2021). There are also concerns regarding the capacity of cities to act as leaders in addressing climate change (UNEP 2021; Foss 2018). As (Foss 2018) argues, economic development priority of cities, competition and political controversies in cities prevent cities to incorporate climate change issues in their planning efforts. City climate networks have been identified as playing a crucial role in promoting the development of urban local climate plans (Reckien et al. 2018), fostering knowledge and methodologies for addressing climate change mitigation at the local level (Fünfgeld 2015), and enhancing local climate change strategies for cities that utilize their membership in these networks (Busch & Anderberg 2015). As local climate actions and plans have the potential to contribute to global climate change mitigation and adaptation efforts, by understanding the obstacles and enablers of such actions more effective local responses can be facilitated and models can be created for other cities to follow (Bai et al. 2018). Moreover, further investigations are needed to explore if city networking represent a disruptive urbanism or if they corrode or integrate with traditional planning tools and policies. For instance, networked urbanism tends to shift the focus of urban policies e.g., urban planning, land use regulations toward more project/solution based, experimental and ephemeral project related actions which completely differs with traditional planning methods that tends more toward comprehensive planning. (Davidson et al 2019)

This study aims to provide valuable insights into the factors influencing local climate action, as well as how city networks influence climate actions in different cities of Dresden, and Lahti and Glasgow from the perspective of local practitioners. The empirical approach, involving case study of Glasgow, Dresden, and Lahti, adds value to the research aim as it allows for the investigation of diverse urban contexts with varying political, socioeconomic, and environmental characteristics. By examining these three cities, the study can provide insights into the obstacles and enablers of local climate action across different contexts, which may yield more generalizable conclusions and recommendations for cities to enhance urban response toward urban climate actions.

# 2 Background

This background examines the complex link between climate change and cities, emphasizing cities' dual role as contributors to and sufferers of climate change. It also delves into climate governance, local climate initiatives, and the impact of city networks on promoting effective climate action. Finally, it addresses research gaps and their implications.

## 2.1 Climate change and cities

Climate change signifies persistent alterations in global climate parameters, notably temperature, precipitation, wind patterns, and other atmospheric conditions. These climatic shifts pose substantial and multifaceted risks encompassing human health, water resources, food security, and economic development (IPCC 2018). Cities hold a pivotal position within the climate change discourse, serving as both primary sources of GHG emissions and highly susceptible locales due to their high population density, concentration of assets, and intricate socio-economic networks (Hallegatte & Corfee-Morlot 2011). Their contribution to global CO2 emissions exceeds 70%, primarily stemming from energy consumption, transportation systems, and industrial activities (IPCC 2014).

The interplay between climate change and urban environments manifests in the vulnerability of cities to climate-related hazards, including heatwaves, floods, and extreme weather events (De Sario 2013). These hazards pose substantial threats to critical infrastructure and public health (Kumar, 2021). Furthermore, urban heat island (UHI) effects exacerbate local temperature anomalies, affecting human well-being, energy demand, and air quality (Grimm et al. 2008; Gago et al. 2013).

Mitigating these challenges necessitates cities to undertake prompt and sustained actions aimed at GHG emissions reduction and bolstering climate resilience. Strategies encompass investments in renewable energy sources (Owusu et al. 2016), green infrastructure (Demuzere et al. 2014), and sustainable transportation systems (Mashayekh et al. 2012). Moreover, urban planning and design principles, exemplified by compact and connected city models (Lee & Lim 2018), contribute to energy efficiency and emissions reduction. Policy interventions, including building codes, zoning regulations, and carbon pricing mechanisms, assume a pivotal role in curtailing vulnerability to climate change impacts and reinforcing urban resilience (McDonald 2011).

## 2.2 Climate Governance and Local Response to Climate Change

Climate governance has undergone significant evolution in recent decades, emphasizing the importance of local and international collaboration to combat climate change impacts. The United Nations Framework Convention on Climate Change (UNFCCC), established in 1992, responded to growing global warming concerns (Bodansky 2001). The 1997 Kyoto Protocol marked the first international accord setting legally binding emission reduction targets for developed nations and providing a flexible framework (Böhringer 2003). The more comprehensive and ambitious Paris Agreement in 2015 further solidified global climate action (Falkner 2016).

Cities have increasingly recognized their role in addressing climate change due to their direct control over crucial sectors like transportation, waste management and landuse planning (Gore & Robinson 2009). They develop climate action plans, emission reduction targets, and resilience measures. However, studies have questioned cities' capacity to lead climate initiatives. Economic priorities, inter-city competition, and political disputes often hinder climate integration in urban planning (Foss 2018). Institutional uncertainty in climate and sustainable development is a barrier (Bulkeley & Kern 2006). Bureaucratic structures, administrative capacity, and budget constraints limit climate protection (Pitt & Randolph 2009). Response capacity disparities among local authorities, internal coordination issues, and political opposition create governance barriers (Walker et al. 2014). Additionally, financial constraints, such as funding shortages, are a major obstacle for local climate action (Litt et al. 2022). These challenges impede effective climate strategies at the local level.

### Local Climate plans and transnational municipality networks

Local climate action is essential for addressing climate change, primarily through the development and implementation of climate action plans (CAPs). These plans encompass strategies, policies, and measures to reduce greenhouse gas emissions and adapt to climate change impacts (Boswell 2012). Cities worldwide are adopting ambitious emission reduction targets, aligning with national commitments like the Paris Agreement (Rosenzweig et al. 2018).

Studies have identified drivers and barriers in local climate planning. Factors such as climate network membership, population size, and economic prosperity drive mitigation and adaptation planning, while unemployment rates, proximity to the coast, and projected climate impacts hinder it (Reckien 2015). Internal community motivations, co-benefits recognition, and moral beliefs drive local climate action (Salon et al. 2014). Transnational municipal climate networks play a crucial role in fostering climate action. Membership in networks like ICLEI, C40, and the Global Covenant of Mayors enables cities to mobilize for climate action, set emission reduction goals, exchange knowledge, and access project support (Busch et al. 2018). These networks, with hundreds of signatory cities, facilitate collaboration and knowledge-sharing.

This research focuses on addressing a critical research gap related to climate change in cities. It highlights the dual role of cities as both contributors to greenhouse gas emissions and vulnerable to climate-related impacts. Cities worldwide have developed Local Climate Action Plans (CAPs) to combat these challenges and have often joined city networks for support. Two central aspects are identified for investigation: 1) the diverse factors influencing the success of CAPs, and 2) the varying efficacy of city networks.

The study underscores the importance of incorporating the perspective of local practitioners who bridge the gap between policy and action. The cities of Glasgow, Dresden, and Lahti are chosen as case studies due to their diverse geographical contexts and climate action efforts. Glasgow's active participation in climate conferences and transformation from industrial to services-based economy make it an ideal case study. Dresden's history of flooding and investment in sustainable urban flood management provides a Central European perspective, while Lahti, as a Nordic city, offers insights into colder climate cities' approaches to climate change. The research aims to explore challenges and enablers of climate action and the influence of city networks from a local practitioner's viewpoint, addressing this research gap.

**Sub-questions are posed to guide the investigation are to**

1. Investigate climate targets and plans in the selected cities.
2. Identify obstacles hindering climate action from local practitioners' perspectives.
3. Explore enablers promoting climate action from local practitioners' viewpoints.
4. Analyze the influence of city network membership on climate action.
5. Extract key lessons from the cities to enhance their climate transitions.

# 3 Methodology

This section presents the research methodology, employing a mixed methods approach that integrates quantitative analysis through questionnaires with qualitative insights derived from document analysis and interviews to accomplish the study's aim and objectives.

## 3.1 Research Design

This research adopts a pragmatic philosophy, allowing for a flexible mixed-methods approach. It employs an inductive method, starting with raw data to identify emerging themes. The study uses a sequential explanatory design, beginning with quantitative data collection and analysis, followed by qualitative data collection. The research operates on a cross-sectional time horizon, focusing on the current state of the subject.

**To address the research question, the study is conducted in three stages:**

1. **Policy Review:** Analyzing climate change policies and goals in Glasgow, Dresden, and Lahti.
2. **Local Practitioners' Insights:** using questionnaires to gauge policy implementation likelihood.
3. **Grounded Perspective:** Conducting open-ended interviews with local staff for thematic analysis on obstacles, opportunities, and city networks' roles in climate action.

### 3.1.1 Stage One: Policy Review
Primary climate action documents for Glasgow, Dresden, and Lahti, along with their national frameworks (UK, Germany, and Finland), were sourced from official governmental websites, policy documents, environmental reports, and relevant international publications.

Documents were reviewed, categorizing content to extract climate goals, strategies, and commitments related to climate adaptation and mitigation plans of each city.

### 3.1.2 Stage Two: Local Practitioners' Insight
A questionnaire capturing local experts' perceptions on climate policy implementation was developed, hosted on an online platform. It featured Likert scale questions and incorporated web links to climate plans identified in Stage One. Local staff from diverse city council departments in Glasgow, Dresden, and Lahti were selected for interviews. Despite initial outreach to 15 individuals/units, only five agreed to participate. Participants were chosen based on their roles, experience, and knowledge within city councils, with a focus on environmental roles to enrich data quality. Recruitment was facilitated through academic partners, online searches, and snowball sampling.

Participants remained anonymous, representing various city council units and differing levels of environmental experience. Anonymity was strictly maintained to foster open and candid sharing during interviews.

### 3.1.3 Stage Three: Grounded Perspective
The transition from Stage Two's questionnaire to Stage Three's interviews aimed to deepen our understanding. While the questionnaire provided broad insights, interviews explored climate action implementation challenges, opportunities, and city network influences in greater detail.

Semi-structured interviews were chosen to gain detailed insights into climate actions in the target cities, uncovering challenges, facilitators, and the impact of city networks.

Online interviews were conducted with local practitioners across various municipal sectors using Microsoft Teams. Sessions were recorded for accuracy (with participant consent) and lasted 20-45 minutes.

Thematic analysis was employed following Braun and Clarke's (2013) framework. Transcriptions were reviewed, codes generated, and themes formed. Themes were refined and named to reveal latent content.

Initially, nine interviews were planned, but logistical constraints led to five in-depth interviews. Qualitative research emphasizes data depth over quantity (Smith et al. 2009). Smaller samples allow deeper exploration of participant experiences, often leading to data saturation (Guest et al. 2006).

The research adheres to ethical guidelines, securing informed consent, maintaining confidentiality, and avoiding harm to participants.

# 4 Results

This section aims to present the primary findings of this research study based on the methodologies described in the previous chapter.

## 4.1 Cities Climate Action Plans and Targets

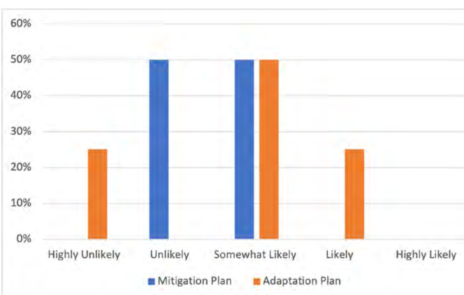
This section outlines cities' climate action plans and targets alongside national climate-related policies and legislation.

### 4.1.1 Glasgow City Climate Action Targets, the UK Context, and local practitioner's perspectives

The UK Parliament's Climate Change Act 2008 mandates regular risk assessments and climate adaptation objectives. Additionally, it requires the government to propose policies for meeting these objectives (UK Government 2008). In 2021, the UK government released the Net Zero Strategy, outlining a roadmap for achieving net-zero greenhouse gas emissions by 2050 (UK Government 2021). Scotland aims for net zero by 2045. (Net Zero Nation n.d.).

The Council of Glasgow declared a climate and ecological emergency on May 16, 2019, leading to the Local Climate Plan (Covenant of Mayors, n.d.). Developed by a diverse working group, this plan emphasizes climate neutrality by 2030 and includes 61 key recommendations (Glasgow City Council, n.d).
Glasgow City Council's Climate Adaptation Plan 2022-2030 aims for a climate-resilient city by addressing vulnerabilities in 13 key areas by 2030.

Local professionals assess Glasgow's likelihood of achieving its climate goals as follows:




| Scale | Mitigation Plan | Adaptation Plan |
|---|---|---|
| Highly Unlikely | 0% | 25% |
| Unlikely | 50% | 0% |
| Somewhat Likely | 50% | 50% |
| Likely | 0% | 25% |
| Highly Likely | 0% | 0% |

**Figure 1 and 2. Perceptions of Local Practitioners on the Implementation Potential of Climate Action Plans in Glasgow City.**

### 4.1.2 Dresden City Climate Action Targets, the Germany context, and the local practitioner's perspective

Germany sets ambitious goals, with the aim of achieving greenhouse gas neutrality by 2045 (Bundesregierung, 2021). In Dresden, climate change impacts various sectors, including water management, agriculture, viticulture, forestry, and the commercial economy (REGKLAM Consortium 2013). To address these challenges, Dresden's Lord Mayor established a "Central Climate Protection Strategies" office, with a goal of achieving climate neutrality by 2035 (Dresden City Council 2023). The city also introduced an Integrated Energy and Climate Protection Concept in 2020 (City of Dresden 2020). In response to these challenges and guided by the Integrated Urban Development Concept (INSEK) titled "Future Dresden 2035+," Dresden aims to address climate adaptation through initiatives like a flood-proof city and heat-resilient strategies (Office of Urban Planning and Mobility 2022).

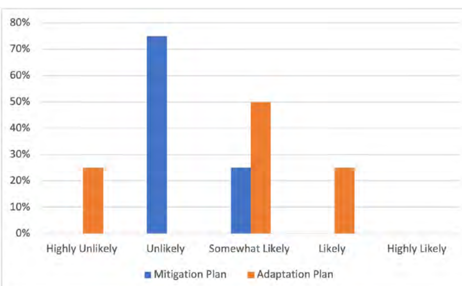
### 4.1.3 Lahti City Climate Action Targets, the Finland context, and the local practitioner's perspective

Finland's Climate Act sets ambitious national targets for emissions reduction and carbon neutrality, with the aim of achieving carbon neutrality by 2035 (Finnish Ministry of the Environment 2022). This Act also mandates municipalities, including Lahti, to create climate plans, with implementation starting by March 1, 2023 (Finnish Ministry of the Environment 2021).

Lahti, a signatory to the EU Covenant of Mayors for Climate & Energy, aspires to achieve carbon neutrality by 2025, a decade ahead of Finland's national target (Green Lahti 2021). The city has already achieved a remarkable 70% reduction in greenhouse gas emissions compared to 1990 levels.

Lahti's Climate Risks and Vulnerability Assessment, developed collaboratively with stakeholders, identifies climate threats such as temperature increases, precipitation changes, windstorms, heatwaves, and heavy rainfall. To address these risks, Lahti has devised a comprehensive Climate Action Plan comprising over 90 measures to mitigate and adapt to climate impacts.

Local professionals assess Lahti's likelihood of achieving its climate goals as follows:




| Scale | Mitigation Plan | Adaptation Plan |
|---|---|---|
| Highly Unlikely | 0% | 25% |
| Unlikely | 75% | 0% |
| Somewhat Likely | 25% | 50% |
| Likely | 0% | 25% |
| Highly Likely | 0% | 0% |

**Figure 3 and 4. Perceptions of Local Practitioners on the Implementation Potential of Climate Action Plans in Lahti City.**

## 4.2 Likelihood of Achieving City Climate Goals - Quantitative Results

In the assessment of the likelihood of Glasgow and Lahti achieving their climate adaptation and mitigation goals, respondents used a five-point Likert scale ranging from 1 ('Highly Unlikely') to 5 ('Highly Likely'). The summarized findings are as follows:

Climate Mitigation Plan: 67% of respondents believe it to be 'Unlikely,' while 33% consider it 'Somewhat Likely.'

Climate Adaptation Plan: In contrast, 50% of respondents find it 'Somewhat Likely,' 33% rate it as 'Likely,' and 17% perceive it as 'Highly Unlikely.'

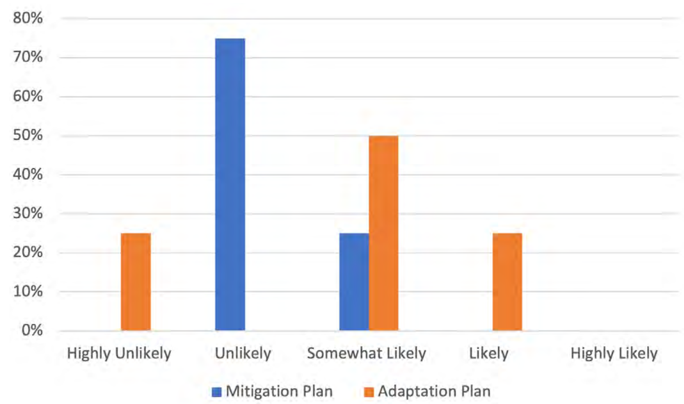



**Figure 5. Perceptions of Local Practitioners on the Implementation Potential of Climate Action Plans of case study cities.**

## 4.3 Obstacles and Challenges in Climate Action

Through a thorough thematic analysis, five primary themes have been identified that encapsulate these challenges:

1. Financial challenges: limited local financial resources for climate work at the local level, difficulty in quantifying budget allocation for specific climate action measures, and the risk of funding reduction due to policy changes.
2. Political and leadership challenges: conflicting political priorities, lack of collective leadership and collaboration, bureaucracy and decision-making hurdles, resistance from the private sector, ambitious targets and the risk of greenwashing and deficiency in green skills at the municipal level.
3. Challenges facing mitigation initiatives: avoiding reliance on emission offsetting, private sector engagement, difficulty in obtaining citizen commitment, legacy infrastructure constraints and infrastructure limitations.

4. Challenges facing adaptation initiatives: Unproven nature-based systems management, and Conjectural costs and maintenance of Adaptation Projects.
5. Urban planning challenges: balancing economic growth and climate objectives and managing urban expansion without losing green spaces.

## 4.4 Enablers in Climate action

Academic collaborations:

1. Access to scientific research and data.
2. Political factors: political will and support.
3. Public involvement: public awareness and support, and early and continuous engagement of local stakeholders,
4. Learn from peer-city collaboration: participation in city networks.
5. Investments: investment in climate measures infrastructures were identified as main themes of enablers and opportunities in climate action.

## 4.4 The Role of City Networks in Climate Action Implementation:

Advantages of participating in city networks from the local perspectives were identified as:

1. Knowledge Sharing and Learning: Sharing good practices, and Facilitated learning from other cities,
2. Influence and Impact: Inspirational role, Adaptation of successful measures, and Raising global awareness.
3. Collaboration and Funding: Opportunities for collaboration, and Project funding possibilities
4. Advocacy and Visibility: Increased visibility on climate efforts.

On the other hand, challenges and limitations of city networks were identified as:

1. Cities and City Networks Alignment Issues: Non-alignment with city business processes, and Objective misalignment.
2. Communication and Collaboration Barriers: Information flow bottlenecks
3. Authenticity Concerns: Greenwashing concerns.
4. Multiple Stakeholder Management: Balancing diverse interests.
5. Time and Resource Limitations: Workload pressures, and Practitioner engagement constraints.

# 5 Conclusion and Discussion

The findings resonate with global concerns, particularly in terms of financial constraints, leadership challenges, and the need for green skills. Additionally, the findings emphasize the role of city networks in climate action. however, it acknowledges challenges such as alignment issues, communication barriers, stakeholder management, and resource limitations within these networks. The data synthesized local perspectives on likelihood of successfully achieving climate targets highlights skepticism towards mitigation and adaptation targets.

## 5.1 Challenges

Financial and Budgetary Challenges: Cities grapple with limited resources, making it difficult to fund and prioritize climate initiatives.

- **Political and Leadership Challenges:** The misalignment between political targets and long-term city objectives and bureaucratic decision-making process, combined with a lack of collective leadership and efficient green skills capacity poses significant hurdles.
- **Mitigation and Adaptation Challenges:** The legacy of existing infrastructures and the challenges of adopting untested solutions and engaging private sectors and individuals in climate initiatives remains a considerable challenge.
- **Urban Planning Challenges:** A tension exists between economic growth and climate objectives.

## 5.2 Enablers

Academic Collaborations: Partnering with academic institutions offers cities access to the latest research and innovative solutions, enhancing the credibility of climate action plans.

- **Political Factors:** Strong political will can overcome many of the bureaucratic barriers, potentially accelerating the pace of climate initiatives.
- **Public Involvement:** A well-informed and engaged public can exert pressure on decision-makers, ensuring climate actions remain a priority.
- **Learning from Peer Cities:** The practice of sharing knowledge and experiences among cities offers a wealth of best practices.

## 5.3 City Networks

City networks emerge as platforms for knowledge sharing, inspiring actions, fostering collaboration, and increasing visibility of local climate efforts on larger platforms. However, the alignment between city networks and individual cities isn't always seamless. Communication barriers, potential greenwashing, diverse stakeholder management, and limited resources are identified as concerns that need addressing.

## 5.4 Recommendations

Based on the in-depth analysis of the challenges and enablers associated with climate actions at the city level, the following recommendations are proposed for other cities:

### Streamline Financial Framework:

1. Stable Funding Mechanism: Cities should explore alternative, stable funding sources.
2. Cost-Benefit Analysis: Rigorous economic evaluation of climate initiatives can help in prioritizing investments.

### Strengthen Political Will:

1. Align political agendas with climate action goals through legislation.
2. Capacity Building: Equip municipal bodies with necessary green skills.
3. Stakeholder Collaboration: Foster an environment where governmental institutions, the private sector, and the community collaboratively decide and act.

### Mitigation & Adaptation Strategy Refinement:

1. Promote Green Transition: Support the private sector with incentives to participate in sustainable projects.
2. Behavioral Change Campaigns: Implement public awareness campaigns to influence individual behaviors.
3. Infrastructure Retrofitting: Dedicate resources to upgrade legacy infrastructure in alignment with climate goals.
4. Research and Validation: Invest in research to validate the effectiveness and benefits and co-benefits of climate adaptation measures and NbS.

### Integrate Climate Action into Urban Planning:

1. Policy Integration: Embed climate objectives within city development plans to ensure economic growth doesn't come at an environmental cost and the climate targets align with cities' future vision.

**Maximize the Utility of City Networks:**

1. Early Practitioner Engagement: local practitioners should be involved from the outset of city network projects ideation and planning.
2. Open Channels of Communication: Establish regular dialogues between city networks and municipalities at different levels
3. Consistent monitoring framework: Develop a mechanism within city networks to ensure minimizing the risk of greenwashing.
4. Resource Optimization: Foster an environment where cities within a network can share resources for project implementations.

## 5.5 Limitation and further study

This study employed a small sample of five interviewees. While smaller samples can yield rich qualitative data, they may not fully represent the wider population or demographics, limiting generalizability. The study's timing during the aftermath of the COVID-19 pandemic may introduce unique challenges and enablers specific to this period. The research focused on cities with established climate action plans, offering valuable insights but lacking in context-specific recommendations. Tailored strategies may be needed to address individual city intricacies. Future studies should explore the challenges and enablers of climate action in specific cities with larger sample sizes, providing localized recommendations from local practitioners' perspectives. Policymakers and practitioners should adapt study recommendations to their unique local contexts.

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MODEKURTY, SRUTI

# Assessing the Systemic Impact of Solar Energy Projects for Low-Income Communities in the United States

*Equitable solutions are needed to address the climate crisis, as the impacts go beyond environmental challenges. Deploying solar in low-income communities addresses emissions mitigation, while providing co-benefits such as reducing energy costs, improving air quality and creating jobs. This research studied the potential impact of a new federal bonus tax credit (LITC) passed as part of the Inflation Reduction Act (IRA), focused on solar deployments in low-income communities in the United States. Existing datasets on technical solar potential, demographic, and economic data were combined at the census level to predict implementation feasibility and quantify possible benefits. Over the course of the program, the IRA LITC could result in at least 41.3 GW of added capacity, 119,770 new clean energy jobs, and 35 million metric tons of CO2 avoided emissions. However, significantly reducing energy burden is only possible if the cost of installation is reduced beyond the 40% tax credit. Without other incentives, households would be paying off the cost of the installation for 10-20 years. The work produced open, actionable datasets for stakeholders to evaluate target areas and complementary actions for optimal policy success.*

# 1 Introduction

Communities around the world are beginning to feel the effects of climate change – from increasing intensity and frequency of natural disasters to economic pressure to social changes. Efforts to mitigate greenhouse gas emissions have so far fallen short, and warming is likely to exceed 1.5°C. While the focus is on reducing emissions as quickly as possible, there is also an urgent need to support resiliency and strengthen communities to better handle the consequences of climate change which go beyond the environment (IPCC 2023). This is especially needed in the United States, where the gap between the rich and the poor is increasing (Horowitz et al. 2020).

As one of the highest emitters in the world, decarbonizing the grid is an important strategy for the United States. 25% of total emissions come from electricity production, the largest emitting sector after transportation (Energy Information Administration 2023). At the same time, many low-income households are struggling to pay their energy bills, with 16% paying 6% or more of their income on just their energy needs (Scheier & Kittner 2022).

A systems thinking approach reveals a mitigation solution which can also make socioeconomic improvements. Renewable energy projects for low-income communities such as rooftop solar reduce GHG emissions and energy burdens by cutting the cost of energy bills. Additional benefits can include job creation, air pollution reduction, and improved health outcomes (Millstein et al. 2017).

While solar has become more affordable in recent years due to technological advances, many barriers still remain for low-income communities to adopt solar energy. In 2022 US Congress passed the Inflation Reduction Act (IRA) which contains $369 billion in funding for clean energy projects, the largest in the nation's history (Vero Bourg-Meyer 2023). To increase affordability, it introduced a novel bonus income tax credit specifically for solar projects benefitting low-income communities, in addition to existing income tax credits on renewable energy projects (Internal Revenue Service 2023).

As a new incentive, the potential use and benefits are not widely understood. Beyond eligibility guidelines, a comprehensive database of qualifying buildings and communities does not exist, making implementation more difficult and ad-hoc, leaving states, municipalities, and community organizations the burden of understanding and applying for the benefit. With limited resources, it is not clear where this incentive could have the most benefit and where efforts should be focused. This research sets out to bridge the gap between policy, energy poverty, and renewable energy, to understand the potential systemic impact of the added solar income tax credit on urban, low-income communities.

### 1.1 Aim and Objectives

What potential systemic impact can solar projects subsidized by the low-income tax credit (LITC) have on urban, low-income communities in the United States?

The following objectives guided the research:

1. Develop a methodology based on previous work suitable for simple predictive policy analysis
2. Assess the feasibility and potential impact of solar projects in qualifying areas
3. Evaluate potential adoption scenarios influenced by the IRA low-income tax credit
4. Quantify potential systemic impacts (energy burden, emissions, jobs)

## 2 Background

### 2.1 Solar Energy Adoption

According to the Paris Agreement, the United States needs to reduce its greenhouse gas emissions to 50% below 2005 levels by 2030 (Plumer and Popovich 2021). Transitioning to renewable energy sources is an important strategy to reach this target but the United States is currently lagging in renewable energy production. In 2021, only 12% of energy was sourced from renewables, 12% of which was from solar, compared to 19% hydroelectric and 27% from wind (Energy Information Administration 2023).

Solar accounted for 46% of new generating capacity in 2021, with most coming from utility-scale PV, but a significant and growing portion comes from residential PV (Solar Energy Industries Association 2022). Residential PV is one of the most accessible ways for individuals to participate in the renewable energy transition but solar adopter demographics currently skew toward higher-income households (Darghouth et al. 2022).

The Rooftop Energy Potential of Low Income Communities in America (REPLICA) study by (Sigrin & Mooney 2018) established a baseline for the potential of solar in low-income communities in the US. Using LiDAR data and several demographic and building information datasets, the rooftop technical potential by income category, housing type and tenure, was calculated for all census tracts in the country, creating a first of its kind dataset. In total, 1000 TWh of generation potential exists for residential PV, enough to cover 75% of annual electricity consumption. 42% of that, or 416TWh, is on buildings occupied by low and moderate income households. Currently, installed residential potential is only at 30 GWh, leaving much room for improvement.

## 2.2 Barriers

In addition to financial challenges, low-income households encounter many barriers to solar adoption including regulatory, community engagement, and site suitability. One of the biggest barriers is the 'split-incentive' problem for renter-occupied buildings. Many low-income families lack the financial capital to own homes, or live in urban areas, making it more likely they rent. Renters may want solar panels on their building to reduce energy bills or for other benefits but lack the authority to install them. On the other hand, property owners are not incentivized to invest in installations because the utility bills are paid by the residents, so the owner does not necessarily see the benefits. This prevents many multi-family and renter-occupied buildings from participating in rooftop solar (Heeter et al. 2021).

Other barriers are due to local and state-specific policies. The Community Power Scorecard is a composite index of 11 factors which encourage or hinder clean energy choice and accessibility. For example, the state of Kentucky has a low score partly because it passed a bill which effectively reduces the value of excess solar production connected to the grid, reducing the cost benefits for the adopter (Institute for Local Self-Reliance 2022).

Building off the REPLICA research (Heeter et al. 2021) found despite high technical potential, low-income solar adoption is directly affected by many of these often compounding barriers. However, financial incentives for single-family and multi-family homes encourage greater adoption. Across different modeled scenarios with different levels of incentives, they found over 30 years a 51% increase in generation capacity for a partial incentive scenario and a 122% increase for a full incentive scenario. Incentives have long been used to encourage renewable energy adoption, though the beneficiaries tended to be high income, early adopters (Millstein et al. 2017). Targeted policies are therefore needed to address barriers and incentivize adoption to meaningfully increase income parity (O'Shaughnessy et al. 2020).

## 2.3 Inflation Reduction Act

Passed in 2022, the Inflation Reduction Act (IRA) has $369 billion allocated for clean energy incentives, with specific provisions for disadvantaged communities. In addition to a solar investment tax credit (ITC) available at 30% until 2033, a bonus ITC of 10-20% is available for projects in or benefitting low-income communities. The total cost reduction is therefore 40-50%. However, the incentive is only available for a limited number of projects, with a yearly allocation of 1.8 GW across four eligibility categories (Internal Revenue Service 2023). The focus of this project is eligibility Category 1, which is open to all projects located in low-income census tracts with poverty or median income exceeding certain thresholds.

In total, the clean energy provisions in the IRA are estimated to result in enough new solar and wind capacity to meet 85% of needed electricity generation. Resulting benefits would avoid up to 118,600 asthma attacks and 2900 to 4500 premature deaths, many in low-income and communities of color, due to improvements in air quality (Mahajan et al. 2022). However, these estimates are for all clean energy provisions, and do not focus specifically on low-income solar adoption and subsequent benefits. Feasibility of the incentive is also not considered. Because the program has a limited allocation of 1.8 GW per year, research is needed to understand where the incentive will generate the most value, particularly where and how much benefit it can provide to these communities.

### 2.4 Co-Benefits

When factoring in social costs of avoided emissions and co-benefits such as better air quality and improved health, solar energy incentives generally pay for themselves. Power generation is a major contributor for air pollution, from the extraction to processing to usage of fossil fuels (Jaramillo & Muller 2016). Prolonged exposure to high levels of PM2.5 and other pollutants has been linked to asthma, stroke, cardiovascular and pulmonary diseases, and even death. Low-income communities and communities of color are often disproportionately exposed to poorer air quality and consequently face more adverse health outcomes (US EPA 2022).

Beyond health benefits, solar installations can also provide direct financial benefits. Energy burden is the proportion of income spent on energy needs – including heating, cooking, electricity, and more. Despite having less per-capita consumption, low-income households spend a higher proportion of their income on energy compared to other income groups. A household is considered energy impoverished if their energy burden is 6% or above, which is the case for 16% of households in the United States. As a basic necessity for modern living, access to reliable energy is important for upward mobility and needs to be addressed for poverty alleviation and community resilience (Scheier & Kittner 2022).

Increased solar adoption may also bring new job opportunities to communities. A variety of jobs are needed for the solar industry including construction, manufacturing, utilities and professional services. In 2020, the United States had over 300,000 workers in the PV industry, with 55% focused on residential projects. According to current conditions, it is estimated each MW of added capacity creates 2.9 jobs (Truitt et al. 2022). Co-benefits increase the overall value and return on investment of solar, especially in disadvantaged communities, and therefore need to be assessed when considering policy potential and incentive outcomes.

## 3 Methodology

This research follows a data-driven methodology to answer the research question and achieve the objectives. The overall goal of the chosen methodology was not to make precise predictions, but to have a simple and replicable method for high-level policy analysis to identify areas of high impact, with data available at a granular, census-tract level.

All of the analysis and generation of plots was written in Python using libraries such as pandas, matplotlib, seaborn and scikitlearn. To facilitate transparency and replicability, all the code used for analysis and data outputs from the analysis are available on Github. Only open data and software was used to promote open science practices.

## 3.1 Datasets and Preparation

Various datasets from government, academic, community, and private industry sources were combined to identify target tracts eligible for the IRA low-income tax credit. Table 1 provides an overview of the datasets used. The data was filtered to keep only the IRA LITC Category 1 eligible census tracts, based on poverty percentage and median income. The data was also filtered to keep only the urban tracts because a majority of the population and most buildings are in urban areas. The final dataset had 23,400 census tracts, equivalent to 31.6% of all tracts.

| | REPLICA | Project Sunroof | Energy Equity Project | Climate and Economic Justice Screening Tool | Solar Demographics Tool |
|---|---|---|---|---|---|
| Data Year | 2015 | 2019 | Varies | Varies | 2021 |
| Main Entity | NREL (Gov, Academic) | Google (Private) | Energy Equity Lab, University of Michigan (Academic, NGO) | White House Council on Environmental Quality (Gov) | Lawrence Berkeley National Lab (Academic, Gov) |
| Short Description | Solar Potential of Residential Rooftops (focus on LMI) with other demographic information | Solar Potential of Building Rooftops | Demographic Data related to Equity & Energy Burdens compiled from mainly government sources | Demographic data about census tracts categorized by disadvantaged communities | Demographic Data of Solar Adoption |
| Geographic Level | Census tract | Census tract | Census tract | Census tract | Census tract |

**Table 1. List and details of datasets used**

## 3.2. MCDA for Feasibility and Impact

The first part of the analysis used Multi-Criteria Decision Analysis (MCDA) to separately examine feasibility and impact. Weighted scores were calculated for each tract based on selected criteria. The feasibility score considered barriers and opportunities which affect the implementation of projects, including total yearly solar generation based on available roof space, percentage of buildings owner-occupied, and the community power score. Criteria for impact include energy burden, poverty, air quality, and unemployment. The criteria were chosen and weighted based on relative importance, according to the literature review of mainly (Heeter et al. 2021) and (Brown et al. 2020). The scores provide decision-ready data for stakeholders to identify areas where the incentive is most likely to be successful and provide the most value for residents, and areas that need extra help. It also provides baseline values for comparison of subsequent analysis.

### 3.3 Adoption Scenarios

The second part of the analysis calculated generation capacity based on different adoption scenarios. Scenarios were constructed to model various adoption outcomes: Business As Usual (BAU), IRA Only (IRA), and IRA + Other Incentives (IRA+). The BAU scenario followed current trends, and the yearly adoption rate increased by 0.75% per year. The IRA scenario considered the existing incentive with a 40% reduction in installation cost, and increased adoption rates by 2% per year. The IRA + scenario considered the inclusion of other incentives so installation cost was reduced by 100%, or eliminated. This scenario was modeled to increase adoption rates by 4%. Future adoption rates were extrapolated until 2033, a year after the program is set to end. Once the future adoption rates were calculated for each scenario, capacity and annual generation were then calculated for each tract. This was an important intermediate step for the next part of the analysis to quantify benefits.

### 3.4 Benefits Calculation

Under each scenario, benefits were calculated for all the tracts. Reductions in emissions and air pollution were calculated using the 2022 EPA AVERT emissions factors. For renewable energy generation, $CO_2$ is 1451 lb/MWh and for $PM_{2.5}$ it is 0.09 lb/MWh (US EPA 2023). The number of new energy-related jobs were calculated using the multiplier 2.9 jobs/MW (Truitt et al. 2022).

Calculating the energy burden reduction involved several steps. First, the generation potential was calculated for each tract, based on available sunlight for that location and an installation size of 6 KW. This was the median residential installation size for low-income installers in 2020 (Barbose et al. 2021). Given the calculated generation potential and median energy consumption for the tract, the new energy cost was calculated. The new energy cost included the cost of any energy not covered by the solar panels. For the IRA scenario, the new energy cost also incorporated the cost of the 6 KW installation after the 40% incentive while the IRA+ scenario did not include the installation cost. This new energy cost was used to calculate changes in energy burden.

For another meaningful metric of financial benefit or strain due to the installation, the number of 'payoff years' was calculated. Given an installation size large enough to cover consumption, 'payoff years' is the number of years needed to pay off the cost of the installation if the energy burden were to stay the same. This was calculated for the BAU scenario, where the installation cost has no reduction, and the IRA scenario where the installation cost reduction is 40%.

# 4 Results

## 4.1 Feasibility and Impact

Feasibility and impact scores were calculated for each census tract, but also aggregated to a state level to find regional trends. Figure 1 plots the feasibility versus impact scores for all the states.

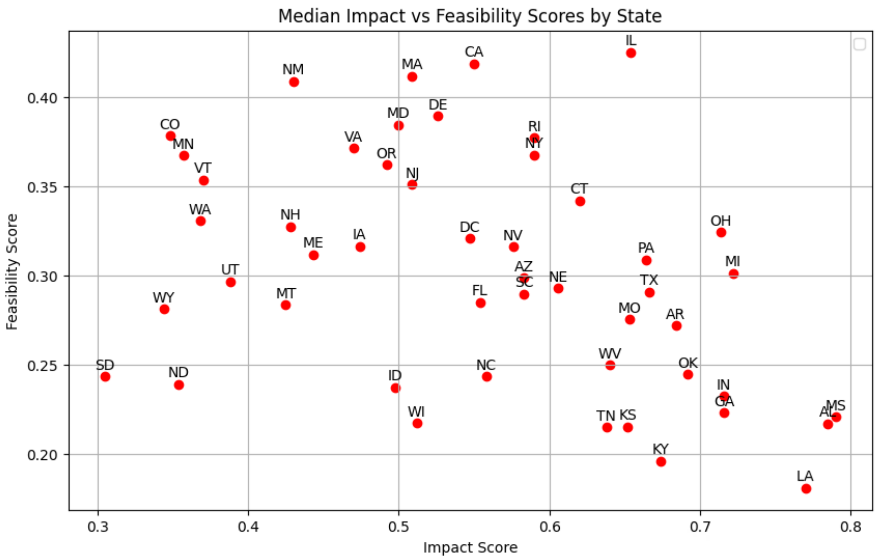


**Figure 1. Median feasibility versus impact scores for all states (Figure: Modekurty 2023)**

Several clusters are apparent in the scores. Illinois (IL), California (CA), and Massachusetts (MA) have the highest feasibility scores. Illinois stands out with high feasibility and impact. As a northern state, Illinois does not have very high technical generation potential, which must mean it has higher levels of roof space available. States like IL and MA also have high ratings for clean energy policies. Considering its high feasibility and impact scores, but current low levels of deployment, IL seems to be a prime location to promote the LITC. On the other hand, Mississippi (MS), Alabama (AL) and Louisiana (LA) form a cluster to the bottom right as they all have very high impact scores and very low feasibility scores. This is because they have unfavorable community energy policies, despite having high technical potential. Because they have such high scores for impact, local governments and utilities should strongly investigate adopting friendlier policies to encourage and at the very least not inhibit solar adoption. The scores help triage different areas for policy implementation and create a baseline to check potential benefits against.

## 4.2 Co-Benefits: Energy Burden

A main motivator for this research was the potential for residential solar projects to reduce the energy burden for low-income households. In the results, energy burden reduction varied highly across regions and depended on the scenario and subsequent installation cost.

To understand the impact of a solar installation on typical household consumption, the change in energy burden was calculated only for the IRA + Other Incentives scenario, so the installation cost is not considered. The average energy burden reduction across tracts was 80.3%. 25% of tracts had an energy burden reduction of 100% or higher, and 75% achieved an energy burden reduction of at least 38.3%. These numbers are higher than previous research by (Heeter et al. 2021), which found the average reduction to be 26.3%, with a range from 8.6% to 81.2%. They used modelled installation capacity, ranging from 3.6 KW to 4.9 KW, whereas this research was based on a fixed capacity of 6KW. Analysis on a more local scale would be beneficial as energy burdens vary widely between households, within cities, and across the US (Scheier and Kittner 2022).

To evaluate the impact of the policy to encourage installation for low-income households, "payoff years" were calculated. The capacity needed to cover yearly consumption and resulting installation cost were first calculated for each tract. Assuming the energy burden stays the same, the years needed to pay off the installation cost, given either no incentive (BAU scenario) or the 40% incentive (IRA scenario) were calculated next. This means normal consumption would be covered by the solar installation, but the energy burden would now comprise of installation cost. The results are shown in Figure 2.

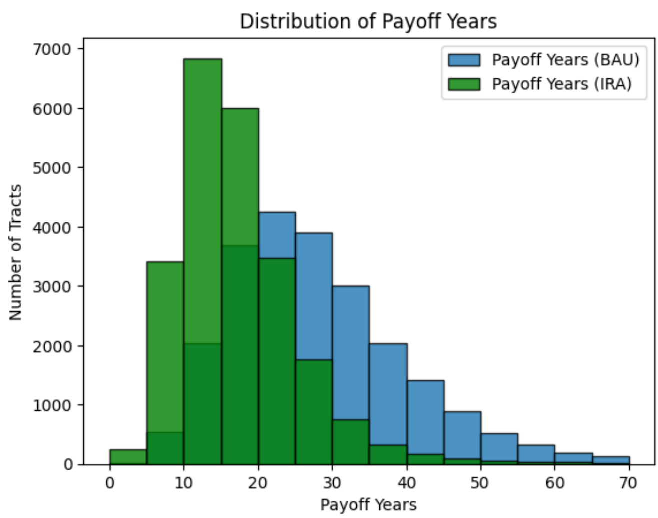


**Figure 2. Payoff Years for BAU and IRA scenarios (Figure: Modekurty 2023)**

For this calculation, the average capacity needed to cover energy consumption was 7.8KW. For the BAU scenario, the average payoff time for all tracts was 30 years, with a majority needing 4 to 35 years. In the IRA scenario, with the installation cost reduced by 40%, households in most census tracts needed 10-20 years, with the average at 18 years. This calculation clearly illustrates the 40% incentive is still not enough for most low-income households to afford solar, let alone households with incomes below the median in these areas. Further incentives and financing options are needed for the policy to truly help the communities it targets.

### 4.3 Co-Benefits: Emissions, Jobs

The possible benefits of the incentive were calculated for the IRA Allocation cap for the LITC in 1 year, the total capacity for the IRA incentive according to the model in 1 year, and the cumulative added capacity for the whole program. Table 2 presents these benefits.

| | IRA Allocation Limit (2023) | IRA Incentive Only (2023) | IRA Incentive Only Cumulative (2033) |
|---|---|---|---|
| Capacity | 1.8 GW (Additional Capacity) | 3.4 GW (Total) | 41.3 GW (Total) |
| $CO_2$ Emissions Reduction | 2,621 Mt | 2,942 Mt | 35,369 Mt |
| $PM_{2.5}$ Emissions Reduction | 0.163 Mt | 0.182 Mt | 2.193 Mt |
| Jobs Created | 5220 | 9963 | 119,770 |

**Table 2. Summary of Benefits for IRA Incentive**

The potential added capacity for 2023 under the modeled IRA scenario is 3.4 GW in total, compared to the allocation limit of 1.8 GW. The cumulative impact of the IRA incentive, if trends continue, are calculated until 2033, the year the incentive is set to phase out. With 41.3 GW added over the 10 years 119,770 clean energy jobs would be added and 35.369 MMt of CO2 emissions would be avoided. It should be noted the calculated results are only for the 21,563 target tracts (52% of all eligible tracts in Category 1), so the results are only a fraction of the likely impact of the policy if all eligible categories are considered.

## 4.4 Focus Area: Chicago

Because the data is available at a granular level, insights can be found within cities such as Chicago, which has several of the highest scoring census tracts for feasibility and impact. Figure 3 presents various tract-level maps of Chicago, comparing the impact and feasibility scores, the generation capacity for 2024, and the potential for energy burden reduction.

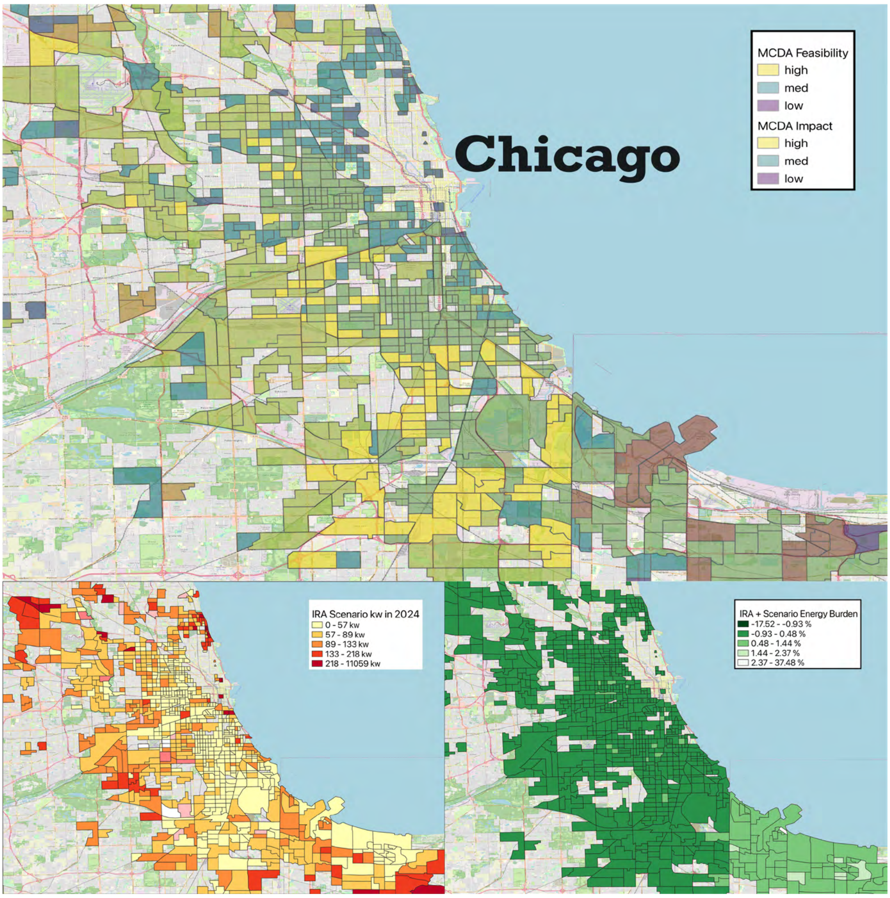


**Figure 3. Maps of Chicago at census tract-level showing impact and feasibility scores (top), generation capacity for 2024 in IRA scenario (bottom left) and energy burden reduction in IRA+ scenario (bottom right) (Figure: Modekurty 2023)**

In the first map with the feasibility and impact scores, the bright yellow tracts have the highest scores and should be focus areas. Areas in red have low feasibility but high potential for positive impact. In combination with the information in the maps showing potential generation capacity, targeted efforts could increase the feasibility of these areas. In terms of benefits, the last map shows nearly all tracts in the Chicago area would have an energy burden below 1.4% or even generate excess capacity, if the installation cost were eliminated. These detailed datasets allow decision-makers to prioritize resources and outreach within cities.

## 5 Conclusion

The goal of the research was to understand the potential impact of a new policy and where implementation should be focused. An open source and replicable methodology was developed to answer this question at a granular level. The results present a new, fine-grained nationwide dataset specific to the policy which help with current assessment and prioritization and serve as a baseline for future work. Despite limitations, several insights were found which can help inform policy implementation and further research.

Results show the possibilities of different areas, regionally across the US and within a city. High feasibility and high impact areas can be "low-hanging fruit" or give the highest return on investment. Areas with high technical potential, high impact scores, but low feasibility scores could also provide tremendous value once feasibility challenges are addressed. This can motivate local governments to encourage adoption in those communities while enacting policies making financing and grid connectivity easier.

Rooftop solar does have the possibility to reduce energy burdens, with most consumption covered by an average installation of 6-8 KW. However, many low-income families cannot afford the upfront cost of installation. The IRA tax credit alone is not enough to make solar energy affordable for most low-income households and other incentives or financing models are needed for the policy to have its intended impact.

Beyond energy burden reduction, co-benefits results at a census tract level are quite small, so residents may not feel or see the direct benefits. They are more significant at larger scale, such as at a county or state level and over the course of the program, the effects compound and will have a substantial impact.

The research had several limitations including the availability of adoption data and older data in some cases. State and local incentives were not considered but could be explored in further research to understand the true affordability of the installation costs, and where local measures can supplement the federal tax credits in high impact areas. Additionally, community solar can be explored as an attractive option for renters and those who can't afford the upfront costs of a solar installation.

Overall, this policy targeted at low-income communities is predicted to have a significant impact adding solar capacity, reducing pollution, creating jobs, and reducing energy burdens. However, efforts need to be prioritized to ensure this does not become a lost opportunity. A systematic method to continuously monitor the deployment and impact is needed to ensure limited resources go to the areas that will get the most value. The outcome of this research can be turned into interactive tools for governments to support and supplement the policy implementation while encouraging communities to assess the suitability of applying for the incentive. This research combines efforts from various agencies and previous research to attempt such an evaluation system.

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RATHNAYAKE, NAVODA

# Evaluating the implementation potential of nature-based solutions for heat and flood hazard mitigation in Lahti, Finland.

*Extreme weather events triggered by climate change is affecting urban populations of Europe on multiple forms. Strategies for mitigating heat and flood hazard and facilitating adaptation to inevitable impacts of climate change are therefore being increasingly explored for urban areas. Although relatively new, implementation of nature-based solutions (NbS) is slowly gaining traction as their co-benefits and ecosystem services are being valued alongside their capacity to mitigate heat and flood risks, as well as to build adaptive capacity. However, NbS implementation depends on the mitigation needs, as well as various socio-ecological implications. Therefore, this study focuses on exploring the parameters affecting NbS in urban areas, for heat and flood hazard mitigation though a case-study based approach, focusing on Lahti, Finland.*

*While Lahti may not currently face imminent risks, the assessment reveals a need to combat urban heat island effects and urban floods while preparing for anticipated climate change impacts. The study identifies key parameters influencing NbS implementation while enhancing knowledge and technical capacity among key stakeholders, involving citizens in co-creation processes, and integrating NbS into the city's planning strategy. The study concludes that NbS can be effectively incorporated into Lahti's urban fabric as complementary infrastructure and emphasizes the benefits of integrating green and blue infrastructure as a network for dual functionality and synergy.*

# 1 Introduction

With rising trends in extreme heat and flood events in urban areas, cities are increasingly adopting nature-based solutions (NbS) as an ecosystem-based approach for mitigating climate change risks and for adaptation (Voskamp et al. 2021). However NbS implementation in urban areas is still low, being limited to experimental interventions and in need of contextualised research to identify their applicability. Hence this study explores the potential of integrating NbS to manage two frequent hazards affecting European cities: increasing heat and flood events (Guerreiro et al. 2018). The study is based on the case study city Lahti, which represents a medium sized European city (Giffinger et al. 2017) in a continental climate, to assess the factors affecting NbS implementation for mitigating these dual challenges.

Lahti city is considered as a pioneer in environmental work and climate action in Finland, and is predicted to experience significant increases in air temperature and precipitation levels caused by climate change (SECAP 2018). The city's environmental policy: 'Lahti- a bold environmental city' helps to build the image of the city and to continue attracting projects and funds for projects that support the city's vision (Lahti city council 2022) and its status as the European Green Capital of 2021 and one of the 100 carbon neutral and smart cities of the European Commission in 2022 creates additional incentive for experimentation and climate action. This study therefore considers Lahti as a model city to explore a planning-oriented approach for identifying the impact of heat and flood hazard on urban areas, and to identify applicable NbS to address these dual challenges.

Thus, the aim of this research is to explore the potential of implementing nature-based solutions in urban areas for heat and flood risk mitigation, by evaluating Lahti city as a case study. This will be achieved through four primary objectives: evaluating the impact of heat hazard and UHI effect, evaluating the impact of urban flood events, identifying the socio ecological barriers and opportunities to implement NbS, and developing a criteria for implementing NbS to mitigate heat and flood risk in urban areas. The research findings were used to develop a NbS implementation criteria suitable for urban areas in continental climates, and to develop a conceptual framework to promote NbS uptake as part of the sustainable development and environmental work in Lahti.

# 2 Background

Extreme weather events affect cities globally, which are predicted to increase in frequency and intensity (IPCC 2022). European cities are especially susceptible to climate change impacts, with predictions of increased occurrences of extreme heat, rainfall events, heatwaves, droughts, and flash floods (Guerreiro et al. 2018). According to the world bank, 75% of European population is living in urban areas, which increases the exposure of populations to these climate change hazards (The State of European Cities 2016). These impacts are felt at neighbourhood scale in the microclimate, and even create health risks, threatening human mortality and ecosystems (Europa.eu 2018).

The urbanization and land use changes in Europe have led to the emergence of urban heat islands (UHI) and urban flooding, which have local-scale impacts on populations (Pfleiderer et al. 2019, as cited in Kuoppamäki 2021). The risk triangle model proposed by Chrichton (1999) underscores the interplay of hazard, exposure, and vulnerability in determining the severity of a risk, emphasizing that extreme weather effects are not solely dictated by weather conditions but also by the exposure and vulnerability of affected populations (Ma et al. 2023). Therefore, it is imperative to reduce urban populations' exposure to heat and flood risks, prevent exacerbation of vulnerability, and build adaptive capacity to address the inevitable changes in urban climates.

## 2.1 Implementation of nature-based solutions in cities

The European Commission defines nature-based solutions (NbS) as a strategy for developing long-term resilience for future effects of climate change, with a potential to generate multiple short-term benefits (Wickenberg et al. 2021). Debele et al. (2019) categorises NbS into four groups:

1. blue (water-based),
2. green (vegetation-based),
3. mixed (green and blue) and
4. hybrid (green-blue-grey) infrastructure.

These various ecosystem-based strategies grouped as NbS enhance biodiversity, ecosystem services and liveability in urban areas (Anderson et al. 2022; Nesshover et al. 2017; Wickenberg et al. 2021). Thus, NbS can be defined as an umbrella term that incorporates a wider range of established concepts in literature such as green and blue infrastructure (BGI) and ecosystem-based adaptations (Albert et al. 2017; Seddon et al. 2020, Han & Kuhlicke, 2021). The co-design practices with community participation, ecosystem services including improvement of wellbeing, habitat provision to enhance biodiversity and increased resilience through adaptive capacity (Irvine et al. 2023; De Vreese 2021) are among the widely acknowledged benefits of NBS. Thus, NbS provides a holistic approach towards climate change risk mitigation and adaptation.

## 2.2 Green and blue infrastructure for heat and flood risk mitigation in urban areas

Under the broader title of NbS, blue-green or green-blue infrastructure (BGI) is a recent development of terminology (Gledhill & James 2008; Selman 2008; Lamond & Everett 2019) that is used interchangeably, which refers to an integrated, systems-based approach for managing green and blue infrastructure. Multiple research works have identified BGI as an effective mitigation solution for UHI (Lehmann 2014; Lin et at. 2016; Livesley et at. 2016; Norton et at. 2015; Antoszewski et al. 2020), and an effective flood mitigation strategy while deriving multiple ecosystem services (Lamond & Everett 2019; Han & Kuhlicke 2021; Kuoppamäki, 2021). Integrated systems of BGI such as sponge city concept, sustainable urban drainage systems (SUDS), water sensitive urban design and low-impact developments are also gaining popularity in various geo-political contexts for managing urban stormwater, for flood prevention in cities (Wong, 2006; Chang et al. 2018; Xie et al. 2022). Research indicates that NbS assists managing stormwater in urban areas and thereby the flood hazard, while improving shade and thermal insulation for mitigating UHI impacts with the heat hazard.

### 2.3. Applicability of NbS in the Finnish context

Finland, including Lahti, experiences a Dfc Nordic climate but is influenced by the nearby Dfb region, resulting in cold winters and hot summers with significant temperature fluctuations (Duckson 1987). Thus, research on specific NbS that are aimed at improving thermal comfort and stormwater management in cities in similar contexts were studied to determine the applicability of urban GBI, which is insightful for this study.

Research reveals that the effectiveness of green roofs in winter insulation depends on vegetation and material properties (Kuoppamäki 2021; Moody & Sailor 2013; Sailor 2008; Ascione et al. 2013; Collins 2017). According to Xie et al. (2022), green walls' efficiency in stormwater management is influenced by substrate moisture, temperature, and precipitation. Urban parks, especially with grassy areas, help mitigate Urban Heat Island (UHI) effects, while greenery's shape and volume are crucial (Wu 2019; Vaz Monteiro 2016; Antoszewski et al. 2020). Research by Suomi and Käyhkö (2012) shows that land-use changes affect daily urban temperatures, particularly at night, with seasonal impacts from water bodies, which is also reflected in a similar study in Lahti, Finland by Suomi (2018). Additionally, urban green spaces and nearby forests have mental health benefits (Fagerholm et al. 2021; Korpilo et al. 2021), and scalable green infrastructure in domestic gardens can manage stormwater and vegetation effectively, resulting in cost savings (Tahvonen 2018; Silvennoinen et al. 2017).

## 3 Methodology

This study aims to explore the potential of implementing nature-based solutions (NbS) in urban areas for heat and flood risk mitigation, by evaluating Lahti city as a case study. The four primary objectives (numbered below) were achieved through a mixed-method approach as follows:

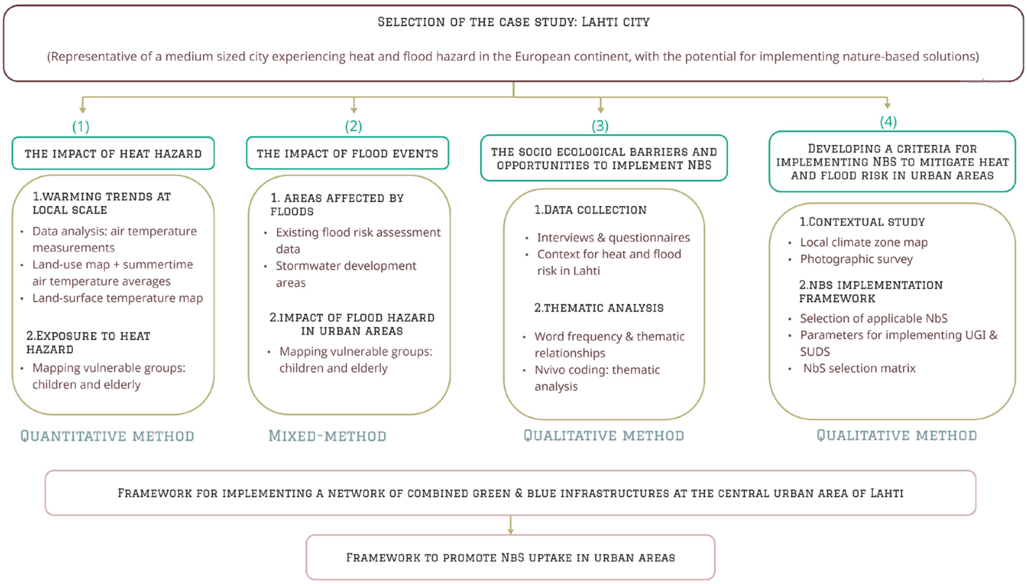


**Figure 1. Research methodology**

Thus, a thorough research on heat hazard was conducted using the city's climate and environmental action plans, air temperature data from 8 measuring stations for 6 years and land surface temperature data (Landsat 8- level 2, band 10 data for 18 July 2020: the warmest month of the recent year with highest air temperature anomaly, at 09.22 and cloud cover < 10%; source: United States Geological Survey (USGS) Earth Explorer). To identify the flood hazard, the 2018 flood risk assessment report, storm water development areas and GIS-based maps were used. This information was complemented by conducting interviews and questionnaires by 8 professionals related to Lahti municipality (6 participants from planning, administrative and water management departments of the municipality, and 2 participants from academia and RDI sectors). The questions were framed under 3 themes, from which 2/3 were repeated for all participants and 1/3 was customized to suite their professional expertise. Nvivo codes were interpreted under 4 main themes to further explore implications from thematic relationships identified. Finally, the data collected was complemented by a literature survey, contextual study on land-use and a photographic survey compiling existing NbS to develop an implementation criteria that is suitable for Lahti, and a framework to promote the uptake of NbS in urban areas.

# 4 Results

## 4.1 Heat and flood risk analysis

### 4.1.1 Assessment of heat impact

Lahti city is already experiencing a 2 0C rise in air temperature from 1960 levels, which is predicted to ncrease by 2.9– 8.2 0C, depending on the scenario (SECAP 2019). Furthermore, the Finnish meteorological institute 1960-2020 normal period data confirms city-scale rising air temperature trends, where the warmest anomaly is in year 2020. Thus, air temperature data analysis from 8 measuring stations in Lahti were analysed for year 2020, which complements research findings by Suomi (2018) based on 2014-2016 data, identifying a UHI effect at 2 stations: Vesijarvenkatu and Aleksanterinkatu sites. This confirms the impact of topography, surface cover and land-use on air temperature variations, and the highest average summertime air temperatures observed at the city centre. Furthermore, data analysis to identify air temperature variation trends for 6 years (2016-2021) from these 2 warmest sites (Vesijarvenkatu and Aleksanterinkatu sites) show a warming trend at the neighbourhood scale, complementing existing research indications in the SECAP 2030 report and by Suomi (2018). To visualise the impact of summertime temperatures at city-scale, a land surface temperature (LST) map for July 2020, which reveals the hotspots for heat hazard in urban areas. Extreme temperatures exceeding 41 0C is observed at the city centre and other urban areas with highly impervious surfaces such as built-up areas with large parking spaces or industrial areas.

### 4.1.2 Assessment of flood Hazard

Precipitation and storms are predicted to increase 10-30% by 2071 (SECAP 2019) & Lahti city centre is prone to flooding during heavy rainfall if the drainage capacity exceeds. The 2018 City of Lahti and Lahti Aqua Oy flood risk assessment report states that rain events lasting between 5 and 60 minutes have highest impact on stormwater drainage. It also identifies flood-prone areas with limited infiltration capacity due to clayey soil and flood-prone streams connecting to the Porvoonjoki River. As identified by the stormwater development areas by Lahti municipality, the urban areas fall within the areas that need increased stormwater management efforts. Thus, these areas can integrate NbS to complement grey infrastructure by increasing infiltration, detention and retention capacity.

### 4.1.3 Exposure of populations for heat & flood hazard

According to statistics Finland, the child population under 15 years is approximately 13%, and elderly population over 65 years is approximately 25% from the total population. These two groups were identified as potentially vulnerable (Chrichton 1999; Ma et al. 2023, Fagerholm et al. 2021), to heat and flood hazard. Exposure was determined by locations of daycare centres and schools, and concentrations of elderly population in 250m x 250m Squares, that overlapped with the land surface temperature (LST) map and generalized flood hazard map from the of Finnish environmental institute. Figure 2 reveals high exposure of vulnerable populations to heat (especially the elderly), while exposure to flood hazard is considerably limited. The risk assessment based on exposure emphasizes the need for integrating demographic data in planning and decision-making, since the city needs to mitigate the urban heat island effect and urban flood events, while building adaptive capacity for predicted increases in impact due to climate change impacts.

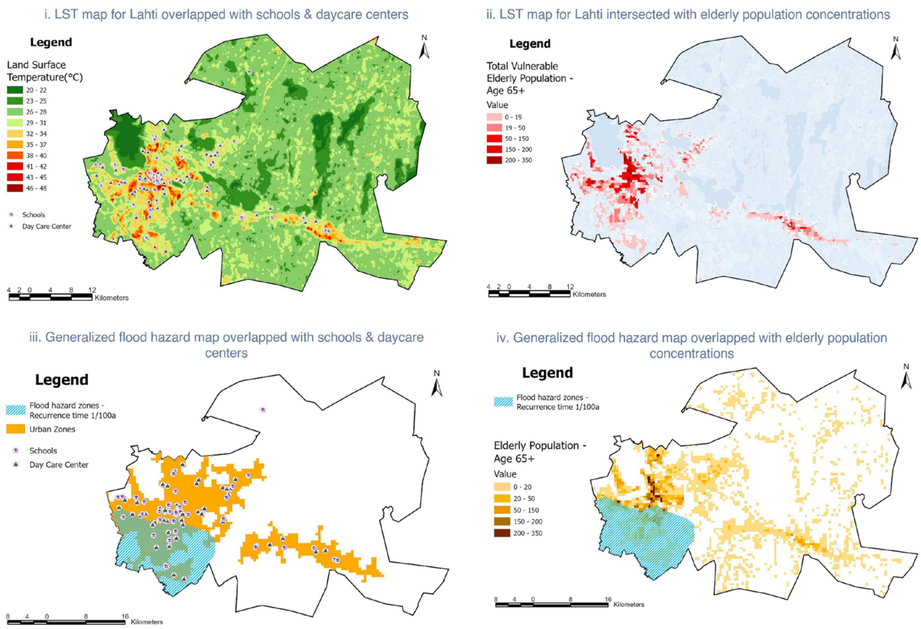


**Figure 2. Exposure of child (left) and elderly (right) populations for heat & flood hazard in Lahti**

## 4.2 Socio-ecological barriers and opportunities to implement NbS

A key aspect of the study was to identify the barriers and opportunities for promoting NbS as a suitable strategy to help mitigate heat and flood risk in urban areas, while facilitating adaptation to climate change. All direct and indirect statements from the 8 participants were coded to interpret the barriers and opportunities and the weightage given to each.

In terms of the barriers for Lahti, high cost for land acquisition and implementation, attitudinal barriers and lack of knowledge on implementation techniques (which also contributes increased cost for implementation and maintenance) were highlighted by the 8 participants. These complement research findings by Han & Kuhlicke 2013; Tafel et al. 2022; Anderson et al. 2022 & Wickenberg 2022.) Furthermore, selection of plants that can withstand seasonal weather changes (extreme winters and climate) should be prioritised. The old building stock also limits vegetation growth for green walls and green roofs due to the lack of integrity in the structures and surface properties to support additional weight and irrigation systems.

The analysis also reveals significant opportunities to promote the uptake of NbS, which can foster gradual change against attitudinal and knowledge barriers, as well as to support the implement of Lahti's development strategies. Alignment with city goals, incremental change, image of the city and co-implementation with the public scored highest among opportunities for the city to overcome barriers with cost, space availability and to bridge knowledge gaps.


**Figure 3. Socio-ecological barriers and opportunities to implement NbS in urban areas**

The results from the thematic analysis was used to develop a conceptual planning and policy framework to promote NbS uptake in urban areas that combines socio-ecological factors to foster stewardship for climate action and NbS adoption. It should be an iterative process of implementing pilot projects, monitoring and improving knowledge gaps between stakeholders.

## 4.3 Criteria for implementing NbS

Based on the literature survey and photographic survey, 12 Green and blue infrastructure (6 UGI and 6 SUDS) were identified as suitable for heat and flood hazard mitigation in urban areas of Lahti. Complementing these findings with the thematic analysis allowed to determine the decision-making themes, performance indicators and desirable ecosystem services for these NbS. The contextual study using local climate zones (LCZ) classification identified that a majority of built areas are in class 5 (open mid-rise buildings), 6 (open low-rise) and 8 (large low-rise buildings/ industrial and warehouse complexes), which implies a potential to allocate space for NbS. Furthermore, Finland's green area maintenance classification: RAMS (Viherympäristöliitto ry 2020) was also referred to determine its applicability for the 12 NbS selected.

### 4.3.1 Green & blue infrastructure selection matrix

This matrix grades the selected NbS under six key considerations from high (green) to low (red): limited space, low maintenance requirements, cost-effective implementation, speed of maturity, co-benefits (aesthetics, biodiversity, improved water quality, health benefits, and carbon sequestration) and resistance to seasonality, to determine the suitability of each NbS for the contextual requirements. In addition implementation of NbS should consider climatic conditions, suitable vegetation, topography and soil conditions, the suitability of a selected NbS for mitigating the hazard(s), as well as demographic factors.


**Figure 4. GBI selection matrix**

### 4.3.2 Criteria for selection and implementation of NbS in urban areas

The literature survey, complemented by the thematic analysis of interviews and questionnaires, highlighted the need for integrating combined blue-green infrastructure (BGI), to facilitate dual functionality for mitigating the heat and flood hazard and to ensure synergy between the systems. Thus, the study proposes a framework for implementing a network of BGI at the central urban area of the city, where extreme heat and flood events are more critical. It identifies 7 interventions that can be retrofitted to the built areas by adopting a sponge-city concept that combines UGI and SUDS to facilitate this dual functionality while providing multiple ecosystem services.

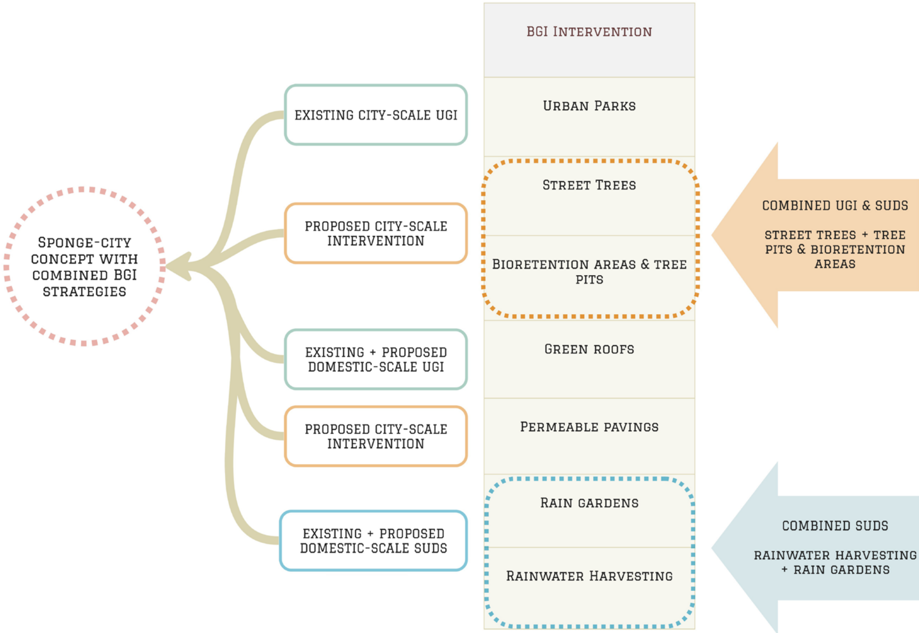


**Figure 5. Framework for implementing a network of BGI at the central area of the city**

# 5 Conclusions and discussion

This study selected heat and flood risk as prominent dual challenges facing European cities and Lahti was selected as a model city, to study the impact of these hazards and to evaluate the potential to implement NbS as a mitigation strategy. As the research reveals, Lahti city has a strong potential to implement NbS as an ecosystem-based approach for planning solutions aiming to mitigate heat and flood risk. The city has the capacity and resources to improve the ongoing environmental work, and there is a positive attitude towards to NbS and desirable co-benefits.

The research reveals that Lahti does not face an imminent flood risk, due to low probability of the hazard, preparedness of the city to avoid vulnerabilities and ongoing stormwater management work with risk assessments. Awareness on need for managing stormwater and flood prevention, as well as the focus on environmental work and green infrastructure were reflected in the word frequency analysis and thematic analysis. However, the identified stormwater management areas and flood hazard areas should be further studied to determine which areas could be improved with NbS for flood mitigation and optimum ecosystem services. The LST map (figure 2) shows the effect of UHI in the city centre which is characterised by impervious surfaces and limited vegetation. Based on the interviews, the heat hazard remains undetected and gains intensity with air temperature warming trends. Elderly population is more vulnerable to heat-related related risks, and therefore implementing shaded resting areas should be prioritized alongside other mitigation and adaptation strategies including BGI.

Proposing NbS as a strategy to improve the built environment should have several considerations including the microclimate, funding, functionality & users, ownership-liability, needs for adaptation to climate change, perceptions & biases, risk mitigation potential of the selected NbS, climate action goals of the city, vulnerability of populations & accessibility, timeline for the interventions to become effective, topography and technical criteria to calculate the capacity or effectiveness of the intervention. The type of vegetation and how they are planned for installation should be key parameters for NbS since most vegetated interventions rely on the capacity of the plant for evaporative cooling, shading, pollution dispersion, soil infiltration and to act in synergy with other natural areas for optimized functionality and for delivering multiple ecosystem services. When implementing SUDS, especially for water retention, it is crucial to do a hydrological assessment to assess its performance. In addition, for Lahti, the location of the interventions should be checked against the valuable groundwater area maps to ensure that the BGI do not create pathways to contaminate the groundwater. Several SUDS also allow to be adapted to limited space availability and to be implemented with a liner to prevent pollutants that are being trapped from contaminating the groundwater.

The thematic analysis reveals that educating citizens and getting private land-owners involved is a significant opportunity for the city to promote NbS uptake at the domestic level. Promoting grass-root level organizations that engage with related objectives such as urban farming is another opportunity to promote NbS in a more decentralized approach. This benefits the municipality as well, since it reduces the effort and cost for implementation and maintenance for the city council. Experimentation and pilot projects are also a major opportunity that also helps to shift biases and to resolve conflicts of interest, especially for implementing NbS as a supportive infrastructure for the city’s sustainable urban mobility plan. There should also be more efforts for building knowledge and capacity among stakeholders such as property developers to promote BGI in the built environment. This also helps to tackle the biases arising against NbS due to the tendencies for risk aversion by developers and investors.

Thus, there is no one specific NbS that can mitigate effects of heat and, or flood hazards. However, a combined network of green and blue infrastructure can improve permeability and reduce heat gain, especially in urban areas, while providing multiple ecosystem services. The study concludes that NbS can be integrated into Lahti’s built fabric as complementary infrastructure, to help mitigate these dual challenges. Co-creation with citizens, decentralizing NbS implementation measures and combining green and blue interventions with the city’s planning strategy are identified as the most favourable approaches to facilitate NbS uptake.

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# Sustainable Development Planning in the Built Environment: Towards a Circular Economy A Case Study in Lahti, Finland

*Increasing human environmental impacts, particularly from surging material consumption, necessitate transformative solutions. The resource-intensive built environment sector requires transitioning from linear models towards circularity. Circular economy (CE) principles offer substantial sustainability potential through waste minimisation and resource efficiency enhancement.*
*This research examines Lahti, Finland as a case study amidst the city's Carbon Neutrality 2025 and Zero-Waste CE 2050 goals. Using literature reviews, GIS mapping, and stakeholder engagement, the three-phased methodology involves: spatio-temporal analysis of Lahti's building stock (Phase I); focus on residential buildings (Phase II); and identifying key themes from interviews and seminars (Phase III).*

*Results indicate a substantial existing building stock with qualitative improvement potential over quantitative expansion. Materials analysis showed a concrete construction shift, but opportunities exist to restore bio-based materials like wood. Stakeholder perspectives reflected balancing sustainability, economics, and regulations while highlighting collaboration, innovation, and digitalisation as key enablers necessitating cross-sectoral efforts. The research underscores the influence of urban development on environmental strain and offers recommendations for asset revitalisation, policy optimisation, digital solutions, and inclusivity.*

# 1 Introduction

In recent years, the escalating impact of human activities on the environment has underscored the urgency for transformative solutions. The continuous growth of the global population and rising income levels have triggered a surge in material resource consumption, posing formidable challenges to sustainable development (Goudie 2018; Behrens et al. 2007).

Amidst this context, the Circular Economy (CE) approach emerges as a promising paradigm. By prioritising waste minimisation and resource efficiency, CE principles offer a pathway to harmonise economic progress with environmental preservation, particularly within the built environment sector (Barros et al. 2021; Ellen MacArthur Foundation 2015; Ghisellini et al. 2016).

Effectively integrating CE principles into current and future built environment planning requires a comprehensive assessment of their present state of implementation. This encompasses identifying prevailing trends, challenges, barriers, and prospects for enhancement. Recognising that the application of CE principles is profoundly shaped by distinct local factors, a nuanced understanding of specific urban circumstances and complexities is imperative (City Loops 2020; Kooter et al. 2021).

Guided by these considerations, this research delves into the built environment of Lahti, Finland, to scrutinise its spatial and temporal dynamics, appraise prevailing industry practices, and pinpoint opportunities for the integration of CE principles. Additionally, Lahti has set ambitious sustainability objectives, aiming for Carbon Neutrality by 2025 and a Zero-Waste Circular Economy by 2050 (European Commission 2020; Lahden kaupunki 2022). This research endeavors to provide practical insights to aid Lahti in achieving these aspirations, thus contributing to broader discussions on sustainable development and the CE.

This research's objectives encompass the examination of Lahti's built environment through analysis of its spatial-temporal patterns, along with an assessment of current industry practices related to CE. Comprehending the practical implementation of CE concepts is vital for informing long-term sustainable planning and policy development. This research aligns with Lahti's Carbon Neutrality and Zero-Waste CE targets, offering insights into fulfilling these goals and the consequent implications for future sustainability planning.

# 2 Background

## 2.1 The Built Environment and Its Planetary Impact

The resource-intensive built environment sector requires profound change. Construction represents 9% of EU GDP and 18 million jobs (Winch 2010; European Commission 2023a) but has an unsustainable 'take-make-waste' model needing alternative approaches (Adams et al. 2017). The linear extract-transform-dispose paradigm causes downcycling, demolition of functional buildings, inflexible designs, and material inefficiency (Thelen et al. 2018; Smedlund 2019). Construction and demolition waste (CDW) is an EU priority stream due to its recycling potential, though policies have focused more on waste management than value retention (European Commission 2023b; Zhang et al. 2022).

With projected doubling of global building floor area by 2050 (Thelen et al. 2018), systemic innovation is imperative. Sustainable models aligning with 'Planetary Boundaries' are needed in this vast, high-impact sector.

## 2.2 Circular Economy as a Sustainability Tool

CE principles emerge as a powerful tool to combat climate change and sustainable development by minimising waste and extending lifespans through recycling and reuse, maintaining optimal resource utility (Material Economics 2018; Ghisellini et al. 2016). Recognising this potential, the EU aims to transition towards circularity through its Circular Economy Action Plan, ensuring long-term value retention (European Commission Directorate-General for Environment 2020). Recognising CE's potential, the EU Circular Economy Action Plan aims to ensure long-term value retention (ibid). Moreover, CE aligns closely with UN Sustainable Development Goals, significantly contributing to their achievement as a viable business model (Kruchten & Eijk 2020).

## 2.3 Systemic Challenges

### The Layered Complexity of the Built Environment

Understanding buildings through a CE lens requires envisioning buildings as compositions of layers with distinct lifespans (Thelen et al. 2018). Stewart Brand's "Shearing Layers" categorises buildings into site, structure, skin, services, space plan, and stuff (Brand 1994). For existing buildings, inner layer renovations can optimise services, space, and materials. New constructions can prioritise circular design of fundamental outer layers (Thelen et al. 2018). Further, the 'layers' thinking reveals diverse lifecycle stakeholders. Architects and engineers affect structure, while users and owners influence circularity during use (ibid). This multilayered approach showcases complex material management, demanding stakeholder coordination.

### Urban mining and Estimating Materials for Secondary Markets

Urban mining recovers materials from end-of-life buildings, providing secondary construction resources (Zhang et al. 2020). However, long lifecycles and inconsistent data challenge urban mining and secondary markets (Deloitte 2017). Accurately quantifying material stocks and flows is crucial to inform strategies and establish efficient markets (Lanau & Liu 2020). Material Intensity Coefficients help estimate accumulations over time and space (Tanikawa et al. 2021; Gontia et al. 2018). But materiality is site-specific, impacted by climate, geology, history, and other local factors (Gontia et al. 2018). Hence floor area or monetary values often proxy for inventories (Heeren & Hellweg 2019).

### The Need for Transformative Change

Profound systemic change is imperative for the built environment sector to transition from linear models to circular ones that regenerate resources and enable significant emissions and waste reductions (Giorgi et al. 2022). EU policies such as the Waste Framework Directive and European Green Deal provide momentum, directing the sector to align with Paris Agreement targets and principles prioritising prevention, reuse, and recycling (Circular Buildings Coalition 2023; European Council 2023). The EU's Circular Economy Action Plan introduces measures targeting the building lifecycle to extend resource value through redesign (European Commission Directorate-General for Environment 2020). However, linear practices persist in construction, with focus on waste management rather than reuse or efficiency. Despite legislation, business ecosystems enabling cooperation and circular flows across the value chain are lacking (Giorgi et al. 2022). Extending repairable building lifecycles is the most effective way to avoid waste generation (Huuhka & Kolkwitz 2021). Fundamental shifts in policies, business models, public procurement, and supply chains are vital to translate policy momentum into on-ground circularity across the construction lifecycle.

## 2.4 Cities as Accelerators of the Circular Economy

According to a joint report by ICLEI Europe and Ellen MacArthur Foundation (2022), cities play an integral role in advancing CE principles, particularly in construction and the bioeconomy. Urban centres, with their dense populations and resource flows, offer ideal grounds for circular interventions, benefiting from scale and agility (Byström 2018). City governments can define a CE vision and strategy, embedding principles through roadmaps, public procurement, and stakeholder collaboration. Key success factors include political support, dedicated teams, measurable targets, and overcoming value chain barriers (Tátrai & Diófási-Kovács 2021).
The transition implies stakeholder role changes, requiring collaboration across interlinked built environment interests (Thelen et al. 2018). As experts collaborate across the built environment, a circular city becomes a crucible for transformation, utilising governance tools to catalyse circular change (Byström 2018). It's not merely about activities, but about recognising a city's potential to be a cradle of circular development.

## 2.5 Lahti as Case Study

Lahti's evolution from industrial town to 2021 European Green Capital awarded for sustainability commitment provides an interesting case study. Originally a 1445 village, Lahti grew rapidly in the late 19th century with the railway, becoming a city by 1905 (Lahti Guide 2017). 20th century industrialisation and urbanisation severely degraded Lake Vesijärvi, catalysing Lahti's sustainability journey. The 1987 Lake Vesijärvi Project marked the first restoration step, uniting stakeholders to improve water quality (Mäntysalo et al. 2019). Alongside the European Green Capital recognition in 2021, Lahti aims for Carbon Neutrality by 2025 and a Zero-Waste Circular Economy by 2050 (European Commission 2020).

### 2.6 Lahti's Circular Economy Journey

Lahti introduced a Circular Economy roadmap in 2017, emphasising resource efficiency and sustainability. Furthermore, initiatives launched in 2011 to enhance energy efficiency in buildings have proven successful in both cost savings and CO2 reduction (European Commission Directorate-General for Environment 2020). As a case study, analysing Lahti's developmental patterns and sustainability strategies provides insights on urban green planning, specifically governance, policies, and frameworks enabling the transition. Lahti's experience balancing growth and environmental stewardship can exemplify sustainable development for other cities.

## 3 Methodology

This research is motivated by the author's internship experience at the ELY Centre in Häme, Finland. The ELY Centres are governmental agencies responsible for regional implementation and development, tasked with promoting sustainability and curbing climate change (ELY-keskus 2022). The internship involved analysing CE potential across sectors in the Kanta- and Päijät-Häme region, where Lahti is located. It provided insights into company distribution differences between municipalities and access to stakeholder interviews about their CE strategies. Further, the research integrates an architectural perspective with sustainable development planning, influenced by the author's background. As with any research, the disciplinary background shapes the approach, often guiding research questions.

**The study follows a three-phased methodology:**

- Phase I employs a descriptive approach with spatial-temporal analysis using quantitative and qualitative techniques to examine the entire city-level built environment stock and answer "what, where, and when" questions.
- Phase II narrows the focus to detailed analysis of residential buildings, which comprise a major portion of the overall building stock in both quantity and floor area.
- Phase III takes a qualitative approach, utilising literature reviews, seminar attendance, and interviews to provide an overview of current practices, analyse policies and governance, and identify key themes.

### 3.1 Research Materials

Phases I and II employ geographic information systems (GIS) building data from the Lahti city government. Contained within the GIS dataset are attributes of the buildings registered which include geospatial coordinates, the purpose of the building according to the Classification of Buildings 2018, the year of its construction, the current state of the building, the total gross floor area, the supporting or structural material used, and the facade material. The GIS dataset cover 88 classified building types, simplified into 13 groups in Phase I and residential subgroups in Phase II. Spatial-temporal trends are mapped considering location, usage, size, and materials. The units examined are building counts and gross floor areas ($m^2$). As Material Intensity Coefficients (MICs) for Finnish building stocks are unavailable, the primary supporting material (load-bearing frame), which has been documented and is accessible to the author, is examined. Here, the gross floor area serves as a proxy indicator for estimating material stock using QGIS software.

**Phase III interviews maintain coherence by focusing on 4 key points that can guide the discussion. These points include, but are not limited to:**

1. **Current practices in the industry/sector:** Examining the stakeholder's existing strategies and approaches that align with the principles of the CE.
2. **The roles of public and private entities:** Exploring the responsibilities and contributions of public and private entities in promoting and implementing CE initiatives within the Lahti and/or at the national level.
3. **Challenges and opportunities:** Identifying the barriers and opportunities encountered in the implementation of CE practices.
4. **Future goals/developments:** Delving into the anticipated developments and potential advancements in the CE within the City of Lahti, including long-term goals and aspirations.

Further, to gain a broader perspective on the current events relating to CE, the author attended seminars and sessions available. Some sessions presented findings on a macro scale, i.e., EU, while some sessions focused on planning, construction, building or even material scale.

# 4 Results

## Phase I: Overview of Lahti's Built Environment

Phase I aims to characterise Lahti's urban building stock through spatial-temporal distribution and proportion analysis.

Lahti's stock is predominantly young, with ~95% of floor area constructed post-1940, reflective of Finland's later urbanisation (Huuhka 2016). With 0.18 buildings and ~94m² per resident, Lahti has a higher ratio than Helsinki, Tampere, and Turku. This large per capita area likely stems from industrialisation's warehouses and factories. While enabling growth, maintaining this extensive stock could prove challenging amidst changing economies, necessitating reuse.

Trend analysis shows residential buildings have consistently dominated in count, with peaks in the 1940-1959 and 1980-1989 periods. Commercial and industrial buildings exhibit upward count trends, particularly in the 1980-1890s expansion. In terms of floor area, residential area grew steadily until the 1970s then declined, while industrial area surged in the 1960s before tapering. From 2000-2019, Lahti added 5,242 buildings totalling 118,491m² annually.

Regarding proportion, residential buildings account for 87.21% of count and 60% of floor area, while industrial buildings comprise 2.66% of count yet 15% of area due to their larger individual size.

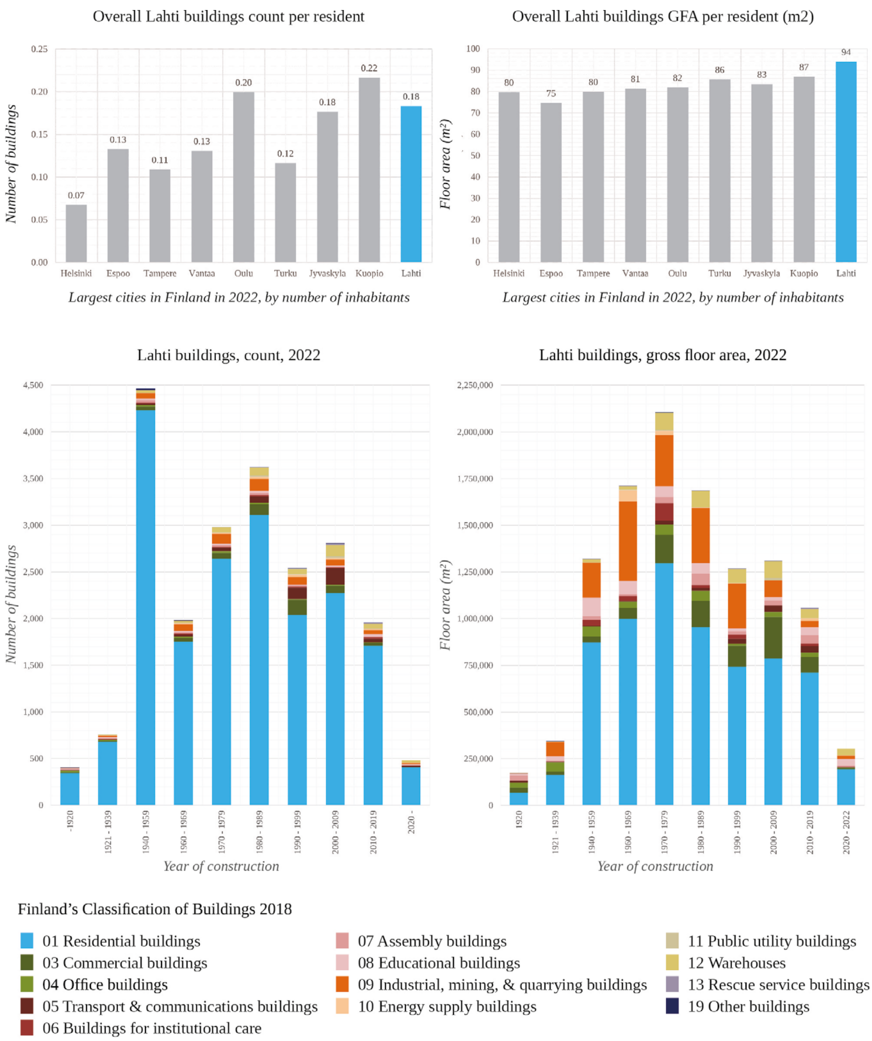


**Figure 1. (Top) Building stock share per resident in major Finnish cities. (Bottom) Basic composition of the Lahti building stock as of 2022. Source: Statistics Finland (2023).**

## Phase II: Examining Lahti's Residential Buildings (Distribution, Development, and Materiality)

Phase II focuses on Lahti's residential buildings, which shape the urban landscape and present CE opportunities through their scale. As the largest building type, residential structures embody significant embodied energy and generate substantial construction waste, necessitating circular approaches to materials and waste. Their scale also enables impactful energy efficiency improvements.

Residential buildings are classified as detached, terraced, blocks of flats, and others. Detached houses constitute 90% of count but only 45% of residential floor area, while blocks of flats comprise 10% of count but 53% of area. Lahti has more living space per resident (~56m²) than major Finnish cities. This context poses unique sustainability and planning challenges.

Urban densification concentrated compact housing near lakes are observed in the city centre as well as infill development from 1940-1959. A 1960-1979 construction boom produced 35% of blocks of flats, now requiring repairs (Cronhjort 2015; Hietala et al. 2015).

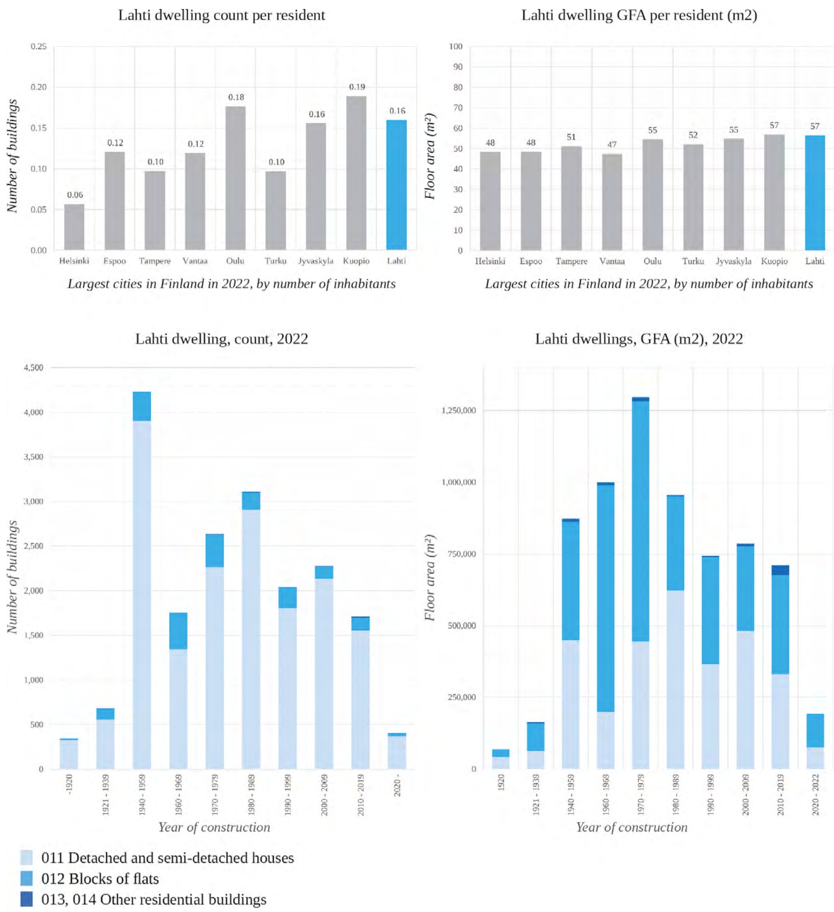


**Figure 2. (Top) Dwelling stock share per resident in major Finnish cities. (Bottom) Basic composition of the Lahti dwelling stock as of 2022. Source: Statistics Finland (2023).**

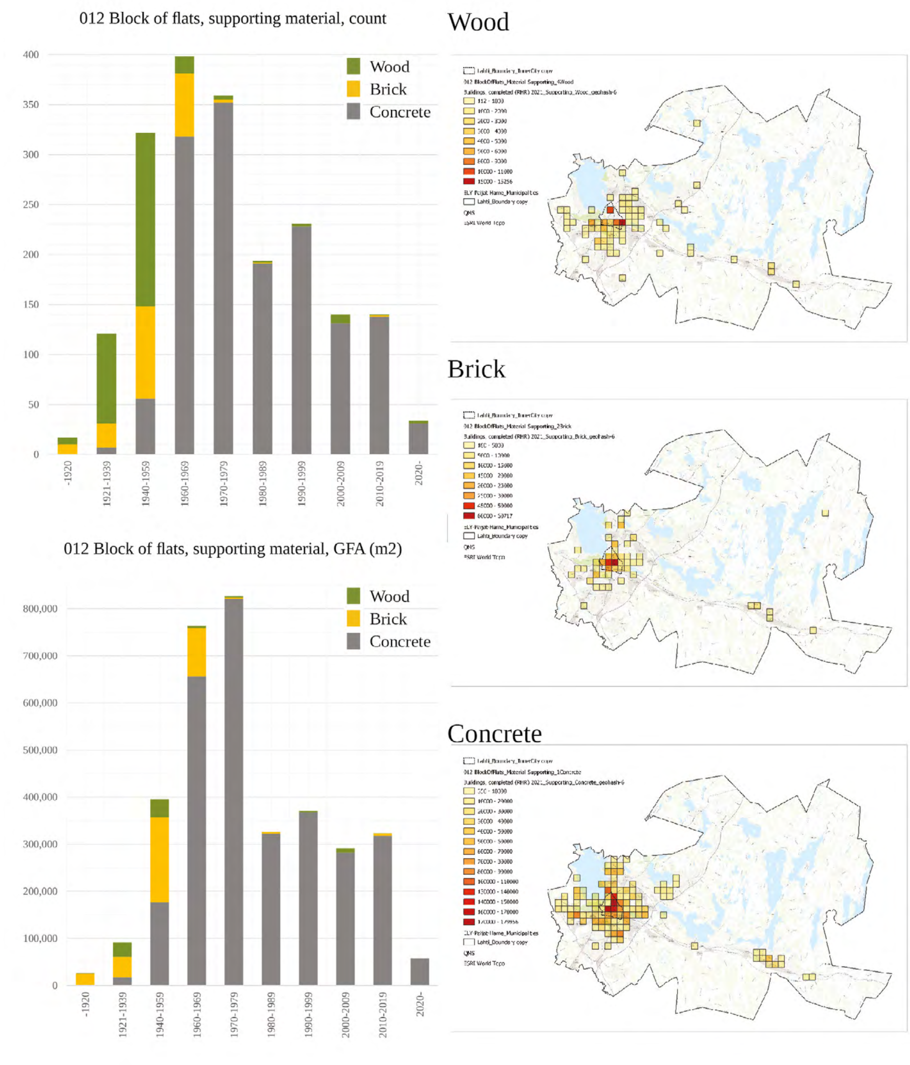


**Figure 3. (Left) 'Supporting material' overview for Lahti's residential typology '012 Block of Flats' (Right) Spatial distribution of 'supporting material' used for '012 Block of Flats' using QGIS.**

Regarding materials, Concrete, Brick, and Wood support '012 Blocks of flats'. Concrete usage rose from the 1940s, peaking in 1970-1979 at 99% of constructed area, while Brick and Wood declined. Spatially, Wood structures concentrate southeast of the centre, brick in the centre, and concrete throughout Lahti. Concrete's rise is attributed to modernist industrialised systems like the BES (Betonielementtisystemi or concrete element system) that enabled affordable housing (Hytönen & Seppänen 2009). However, extensive concrete now requires renovations (Smedlund 2019). Meanwhile, wooden structures hold potential to meet sustainability goals through renewable or bio-based materials and industrial prefabrication (Mäkelä 2022; Emre Ilgın & Karjalainen 2023). Overall, Lahti's residential scale presents opportunities to redirect material flows and energy usage through circular strategies.

## Phase III: Circular Urban Practice

Phase III assesses circular practices across Lahti's built environment, extending to the national and EU levels. Insights from interviews and seminars explore practices, challenges, opportunities, and stakeholder roles to understand the scale of challenges, impact of policies, and alignment with Lahti's sustainability targets.

### Stakeholders in the Built Environment

Overall, the study collected 13 expert interviews across the building lifecycle phases—Design, Construction, Use, and End-of-life. Word frequency analysis of the interviews suggests that while there are common themes across all stakeholders, each group has its unique focus areas. City governments concentrated on construction's carbon impact and economic feasibility. Private companies emphasised waste management and recycling, likely driven by landfill costs. Academia focused on sustainable economic systems, EU environmental initiatives, and Lahti's sustainability goals. Non-profits highlighted legal frameworks, circular construction, and digital transformation.

## Interviews

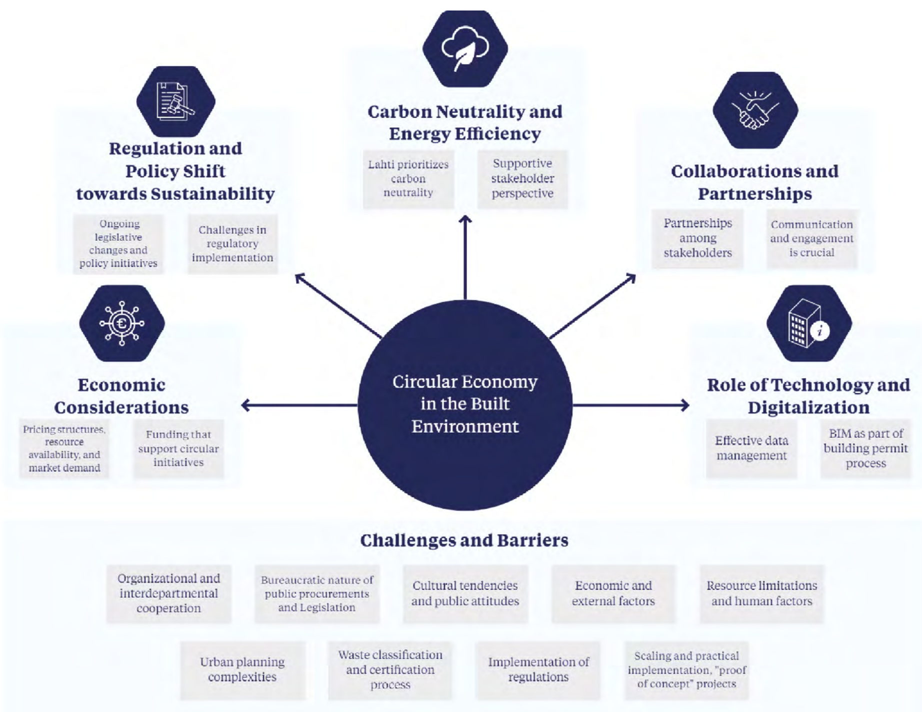


**Figure 4. Five recurrent themes identified from the interview transcripts.**

**Interviews highlighted five key themes.**

1. **Carbon Neutrality and Energy Efficiency:** Lahti emphasises carbon neutrality and energy efficiency evident through projects like 'Carbon Neutral Construction Development Centre' and 'Innovation Network for Carbon Neutral Construction'. However, slow adoption due to high costs and resistance to new technology presents challenges, while pilot projects demonstrate viable solutions.
2. **Regulation and Policy Shift:** Evolving legislation like the EU Green Deal, new Finnish Building Act, and city roadmaps provide impetus for circularity and sustainability. However, stakeholders express mixed sentiments regarding policy efficiency, citing waste certification processes and social factors as challenges.
3. **Technology and Digitalisation:** Technology modernises building renovation while preserving heritage value. Finland's digital reforms will provide standardised building data to streamline processes and support circularity. Digital tools also enable circular business models. However, successful adoption hinges on usability, integration, and data standardisation.
4. **Economic Considerations:** Economic factors influence sustainability transition, with public-private cost perception disparities. While governments often fund sustainability initiatives, private companies take on risks developing new technologies, recognising value despite higher costs. Integrating economic feasibility is key for organisations driving change.
5. **Stakeholder Engagement:** Collaboration is critical to advance sustainability but requires better implementation strategies between entities. Internal cooperation, communication, and bridging organisational silos are vital, with organisations playing mediating roles.

## Seminars

Seminar attendance offered broader perspectives on advancing circularity. Several sessions discussed and highlighted the built environment's importance and continuous CE progress. Sessions concluded that despite complexities, integrating the sector's innovation capacity can maximise circular gains through optimising resources, reducing impacts, and enabling enduring value that eclipse transition challenges.

### Key takeaways include:

- CE is critical for sustainability, transforming resource use and reducing environmental impacts. The built environment is a prime sector for application.
- Data and digitalisation are vital to track materials, improve efficiencies, monitor policies, and understand interconnected systems.

- The built environment plays a crucial role in the CE transition; however, circularity lacks systemic scope and scale. Urban planning and revitalising underused assets can align with CE goals.
- Collaboration, communication, and shared understanding are fundamental, enabled by tools like the EU taxonomy. Long-term cross-sectoral projects can overcome and scale circular initiatives.
- Innovative business models and policy reforms are interdependent for successful transition. Cities act as pivotal policymakers and material consumers.

# 5 Conclusions and discussion

## 5.1 Implications

### Theoretical implications

This research makes several key theoretical contributions to knowledge on sustainable urban development and the CE. Firstly, the spatial, temporal, and material analysis of Lahti's building stock provided novel insights into aligning the city's resource profile with circular principles of reducing, reusing, and recycling, highlighting the value of evidence-based research in informing asset management (Kohler et al. 2009).

Secondly, examining diverse stakeholder perspectives reinforced the complex, multi-layered systems view required for the circular transition, emphasising the need for cross-sectoral collaboration (Karhu & Linkola 2019).
Finally, the research underlined the importance of contextual factors in sustainability planning, endorsing tailored solutions aligned with local conditions rather than a one-size-fits-all approach. Overall, the research theoretically contributed to utilising stocks sustainably, recognising complexity, and contextualising the shift to circularity.

### Practical implications

The research provides practical implications for informing city planning and decision-making towards sustainable asset management in Lahti. Systematically analysing the building stock highlights opportunities to advance the CE transition:

- **Urban Planning Strategies:** Prioritising adaptive reuse of underutilised assets, piloting circular models, and community co-creation can optimise resource use. Mainstreaming flexibility, efficiency, and lifecycle thinking through policies, standards, and showcasing innovations can enact systemic change.
- **Digital Materials Registry:** A city-level registry tracking material flows can forecast waste volumes and reveal circularity potential through transparency. Developing this infrastructure collaboratively can catalyse circular material markets.
- **Circular/Bio-based Materials:** Transitioning to renewable bio-based materials like wood can reduce impacts while nurturing the local

bioeconomy and creating green jobs. Multi-stakeholder efforts and demonstrations can mainstream solutions.

- **Social Dimensions:** Public-private collaborations can demonstrate and scale innovations; inclusion and empowerment initiatives can build capabilities; and cross-sector partnerships can drive systemic change through cooperation. Ultimately, a just transition requires socio-cultural transformation across society.

By spatialising assets, strategically guiding development, mapping materials digitally, harnessing circular resources, and cultivating collaborative social ecosystems, Lahti can enact a restorative systemic transition towards a circular built environment.

## 5.2 Conclusion

This research provided multi-faceted empirical insights into Lahti's built environment, arguing cities significantly impact environmental strain based on development approaches. The CE aligns with sustainability objectives through specialised resource efficiency focus.

Initial quantitative inquiry of 'Does Lahti need to build more?' revealed substantial existing assets with higher per resident floor area compared to other Finnish cities, indicating qualitative improvement potential over quantitative expansion. Materials analysis showed a concrete construction shift, though opportunities exist to restore renewable materials like wood. Stakeholders reflected sustainability inclination with economic viability and regulatory efficiency. Collaboration, innovation, and digitalisation were recognised as key enablers requiring cross-sectoral efforts. As the research evolved, the question became 'How can Lahti build better?' Given versatile space needs and economic uncertainties, cities require resilience through revitalising underused assets via adaptive reuse incentives, optimised policies, and public-private partnerships. A digital materials registry can optimise stocks by tracing recovered materials into circular construction cycles instead of landfills. Renewing bio-based materials offers environmental gains while catalysing the local bioeconomy. Fostering inclusion, education, and cooperation is vital for systemic transformation. However, slowing population growth raises concerns about external factors affecting development. Reevaluating substantial existing assets through reuse, aligned with frameworks like Planetary Boundaries, is vital for sustainability.

The query ultimately expanded into 'How can Lahti plan, develop, and manage its built environment for circularity and sustainability?' This encapsulates assessing stocks, reuse opportunities, and adaptable new buildings while balancing growth and improvement. The study provided empirical analysis revealing the sector's extent, complexity, and interconnectedness. While initial questions were quantitative, qualitative improvement opportunities emerged by leveraging assets. Holistic management requires aligning with sustainability frameworks. Transitioning stocks through adaptive reuse, optimised policies, and digital solutions is crucial, alongside fostering inclusion and cooperation for systemic change.

In conclusion, through evidence-based planning and circular policies, Lahti can continue leading in environmental stewardship. The mixed-methods research provides transferable insights for enabling circular transitions through spatial, statistical, and social data. While geographically focused, it highlighted the built environment's central role in resource efficiency, resilience, and prosperity.

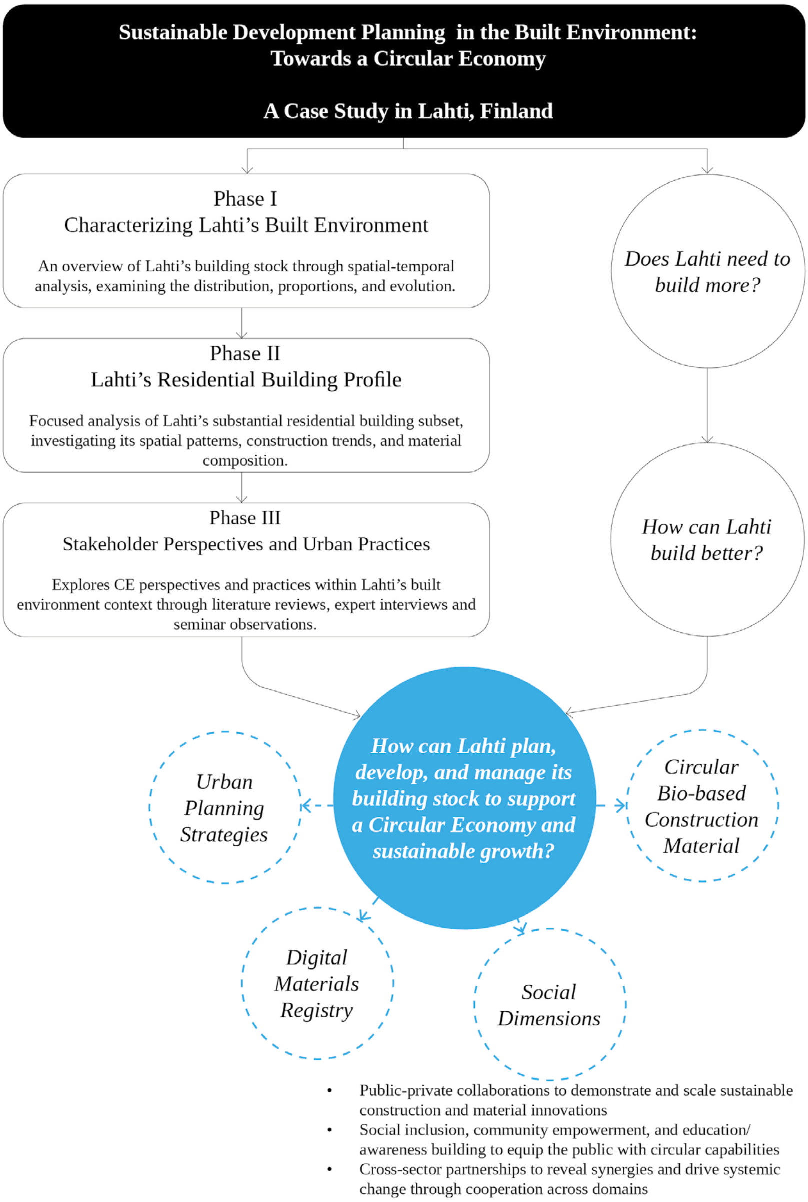


**Figure 5. Overview of research and results on sustainable building practices in Lahti.**

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# Sustainable mobility – air quality and active travel perspectives

BERNAL REINO, MARIA ELISA

# Assessing Sustainable Mobility Scenarios and their Influence on Street Level Air Pollution: A Comparative Analysis in Kesselsdorfer Street in Dresden, Germany

*Considering that transportation highly contributes to air pollution, sustainable mobility strategies are presented as a solution not only for reducing air pollution, but also for promoting a better quality of life. Nonetheless, different operational limitations to assess air pollution from municipalities, and the lack of a citizen's perspective within pollution analysis, have limited the understanding of the real benefits/impacts of street-level mobility projects. Through the use ADMS-Roads dispersion model and surveys on people's experiences as a dual approach, this study has provided a detailed assessment for mobility scenarios that aim to reduce air pollution in Kesselsdorfer street in Dresden. Particularly, showing that shifting from cars towards more sustainable transportation methods contributes to further reduction of emissions. This study considered different exploratory scenarios, where a radical scenario has the potential to cut NO2, PM10, and PM2.5 emissions by 91.6%, 66.26%, and 67.61% respectively, compared to the current situation. The results from combining quantitative and qualitative methods resonate with current research that emphasizes that residents' daily experiences cannot be overlooked, as well as other elements of the streetscape. Planners must assess air pollution in a holistic way including local communities' perspectives for more informed decisions and better local and beyond regulations.*

# 1 Introduction

Urbanisation is replacing the natural and green land with pavement, which brings several consequences for the environment and for people's health and quality of life. In this sense, car-centred mobility, and its grey infrastructure, like highways and roads, significantly impact cities' sustainability and quality of life (Brůhová et al. 2020). Moreover, emissions and pollution significantly impact air quality (Gireesh et al. 2021), contributing to global climate change. Pollutants represent a major threat to human health, affecting the respiratory system, the mucous membranes, and the cardiovascular system (Maas 2022). This situation calls for a more human-centred mobility, including sustainability principles in transportation planning. In this sense, various cities are promoting sustainable mobility actions and plans to reduce the pollution generated by the excessive use of internal combustion vehicles. Among others, these actions include traffic restrictions, prioritizing active means of transportation, increasing the pedestrian areas, switching to more sustainable means of transportation, and encouraging public policies towards sustainable mobility (TUMI 2019).

In the context of Germany, cities are aligned to reduce emissions, providing programs and measures against increased air pollution (IQAir 2022). The main causes for air pollution in Germany are "road traffic, emissions from power stations, industrial processes (including solvent emissions), heating with fossil fuels, agriculture and waste treatment" (IQAir 2022). Dresden, the capital of the Saxony state in Germany, is similar to other intermediate cities with targets towards sustainability and the reduction of traffic-related air emissions. For 2035, Dresden aims to achieve climate protection and ensure safe mobility for everyone (Dresden 2023a). However, urban plans are designed to operate at city level and the translation of sustainability targets, particularly those aimed at reducing pollution, remains unclear for street level interventions. By the scale of this interventions, the community has greater strength and commitment (Ramos 2022). So, it is necessary to involve people's perspectives in order to go beyond the phrasing of emissions within the goals and objectives of urban plans; integrating complementary measures that allow not only to improve air quality, but also the quality of life. Several cities focus on analysing the effects of interventions once they are implemented, rather than having a predictive vision (Sanchez et al. 2021). The most significant challenges that municipalities face are an absence of instruments, methodologies, and professional capacities necessary to conduct assessments of mobility interventions toward air pollution reduction or control (Mohlala 2020). This, along with the fact that pollution has a negative impact on health and that individuals' views are rarely included in pollution assessments, raises the need of a comprehensive methodology that will allow a holistic assessment of air pollution for street-level projects. In light of this, the research aims to assess street air pollution, through the application of a hybrid methodology, within different street scenarios based on sustainable mobility strategies.

## 2 Background

As some highlights from the literature review, it is possible to mention:
Air pollution in poorly ventilated street canyons creates health risks for people in the street. The street obstacles, the morphology and the behaviours play a significant role in increasing or reducing the air pollution in the street (Cepeda et al. 2017; Adams et al. 2001; Fischer et al. 2023; Vardoulakis 2003; Qiu et al. 2019). Therefore, strategies to mitigate and adapt to future changes are required.

Mitigation strategies outnumber adaptation strategies in the field of sustainable mobility. The mobility strategies analysed (IPCC 2014; Jaramillo et al. 2022; Sims et al. 2014) focus on environmental concerns and policy instruments, it is possible to highlight the ASI mode, modal shift, electromobility, travel distance reduction and zoning restrictions.

Among different methods to assess air pollution, dispersion models like ADMS-Roads are highly used to experiment with different scenarios before the implementation of the projects (IPCC 2022). They provide flexibility to predict potential futures for the streets, providing inputs for reports and analysing the impact of public policies. According to the case studies (Szopinska et al. 2022; CERC 2021; Sánchez et al. 2021; Steinberga et al. 2019), the interventions are envisioned, allowing the possibility of multiple changes during the planning process.

Although the applicability of various scenarios based on dispersion models is demonstrated for assessing air pollution, these mainly contemplate the analysis of the sources, leaving behind a holistic analysis of people's behaviours or street obstacles. This has necessitated the application of a mixed method by undertaking additional studies. Complementary methodologies mainly analyse the source and the behaviours (Gehl 2021; Szopinshka et al. 2022; Sanchez et al. 2021; Fischer et al. 2023; Marquart et al. 2022), where interviews and surveys were the most common to complement the software analysis. As a result, there is a dual approach that employs both quantitative and qualitative methodologies.

### Case study overview

Dresden is an intermediate city, capital of the Saxony area at the east of Germany. It has around 561,002 inhabitants (Dresden 2021). Today, Dresden is reaping the benefits of its commitment to an intermodal mobility concept. Since 2018, more than 60 multimodal points (MOBIPoints) have been established within the city, comprising trams, buses, rental bicycles, and rental automobiles (car-sharing) (Dresden 2023b). This has resulted in a significant demand for people to choose more sustainable transport solutions for travel more efficiently. Furthermore, Dresden complements its mobility concept by implementing Tempo 30 zones for traffic calming in several neighbourhoods (Hanewinkel & Sgibnev 2023). Additionally, Dresden includes bicycle and pedestrian concepts linked to its Sustainable Urban Mobility Plan (SUMP), paving the path for active modes of transportation to be prioritized not just in infrastructure but also in road safety (Mourey 2019). On the other hand, Dresden (2018) refers to the levels and targets of air pollution. For NO2, considering an annual average of 40 µg/m3, the annual average is still above the permitted limit. In the case of PM, the values for PM10 remain under the limits but there is no information regarding PM2.5 which is smaller and more dangerous. Finally, the SUMP reduction target for noise pollution has been met to date but population does not perceive it as such.

# 3 Methodology

Understanding from literature review that an approach based mainly on the source doesn´t give a clear picture of the effects of air pollution, the necessity of a more complete methodology arises. This research will focus on a hybrid methodology, combining the dispersion model analysis with people experience data (Gehl 2021); resulting in the analysis of the source and the behaviours conditioned by the urban design of the street. By taking into consideration the source and the behaviours, this hybrid methodology will approximate the holistic perspective of air pollution assessing. To address the aim, the research will use quantitative and qualitative methods following a deductive approach.

This research is divided into four phases. First phase refers to background processes like the literature review, a brief and general context about Dresden as case study, and the learning of the main principles of the dispersion software ADMS-Roads. Phase 2 involves the baseline, the definition of the area, the data collection, cleaning and processing, and the selection of the street for analysis. The selected methods for this phase are data collection via secondary sources, direct communication with key stakeholders, primary data collection for the selected street(s) based on photography analysis and observations. The main outcomes of this phase are the street profile or urban analysis of the selected street, a canyon analysis, and the current scenario modelling with ADMS-Roads.

Phase 3 includes the scenario ideation and prioritization based on selection matrices between stakeholders' inputs, city goals in urban plans, future projects for the area and SMPRS from the literature case studies. The expected outcome is a matrix with the scenarios' specifications and street sections. From this, the hybrid methodology is introduced, with two paths, one related to the modelling and simulation of the scenarios using the dispersion model ADMS-Roads; and the second one, a qualitative approach by using online surveys to collect perspectives of the current situation and the scenarios. At the end of Phase 3, the expected outcome is a comparative assessment among scenarios, and the outline of a framework for assessing air pollution. Finally, Phase 4 involves the discussion of the results with connections with literature and the current mobility situation in the city, the implications of using a hybrid approach, and recommendations for urban planners and for future research.

### Site selection

Kesselsdorfer Street is a 1000-meter-long axis located in the district of Löbtau, in south-west Dresden. This street (between Tharandter St. and Saalhausener St.) not only hosts a large number of trips from the west of Dresden, but also considers a future project to redesign part of its length for public transport circulation only. This sparked the interest for this research because of the possibility to simulate real future projects and understand their impacts.

### ADMS-Roads specifications

The inputs for ADMS-Roads include the meteorological data, traffic flows, canyons specifications, roughness factor and emissions data. The latter could be calculated automatically by the software, so this type of information was not gathered. Five receptor points were identified in each intersection, these were assessed at a height of 1.65 metres, or the height of an adult. For the outcomes, the software was instructed to simulate NO2, PM10, and PM2.5 levels for each scenario. The basic outputs are values per hour and point for the selected year in text format; in addition, pollution maps may be obtained using the Mapper and the text files can be opened in Excel. For more details about ADMS-Roads inputs please contact the author.

### Surveys

A 17-question questionnaire was developed, consisting of three sections: general information, views of the street current condition, and perceptions of possible futures. The survey was conducted in English to residents and people who circulate in the area. It was decided to use social media in order to disseminate the survey and have a wider reach, in addition to sending it directly to residents and municipality officers; hence, Google Forms was used to design the form. The Likert scale was chosen to assess respondents' perceptions of pollution, traffic, and noise in each scenario. In addition, a question was included to determine which things may enhance the street's existing status. The questionnaire was concluded with a vote for their favourite scenario.

## 4 Results

Kesselsdorfer Street is located in Löbtau district which has a population of 11,662 people, with 51.6% males and 48.4% females (Dresden 2021). According to the mobility analysis, peak hours for cars are 9 am and 4 pm, with a number of 805 vehicles per hour, while the majority of cyclists circulate at 8 am and 4 pm with 90 bicycles per hour (Dresden 2023c). The street configuration comprises mainly deep canyons, with the exception of the stretch in front of the cemetery that is an open road. Additionally, based on the observation of the urban dynamics the street presents greater activity on the first two stretches towards east; whereas the blocks to the west present less ac¬tivity and a small number of neighbourhood-scale businesses. All this information provides an overview of the street's dynamics and serves as a foundation for constructing scenarios.

Based on SMPRS from case studies, goals from urban plans, future urban projects for the area, and conversations with stakeholders, four scenarios were developed, the current scenario (CS) that represents the status quo, and three explorations (Figure 1). The optimistic scenario (OPT) with an 11.8% increase in traffic; a radical scenario (RAD) with a redesign of one section of the street in favour of only public transport circulation (and a lane for residents and emergencies), with 11.8% (x3) decrease in traffic plus a 3.5% increase for public transport. Finally, a setback scenario (SB) with more car-centre policies that includes two more lanes for cars and an 11.8% (x3) increase in traffic circulation. The 11.8% traffic variance was calculated considering traffic growth percentages and the modal split, and it represents 100 cars per hour.

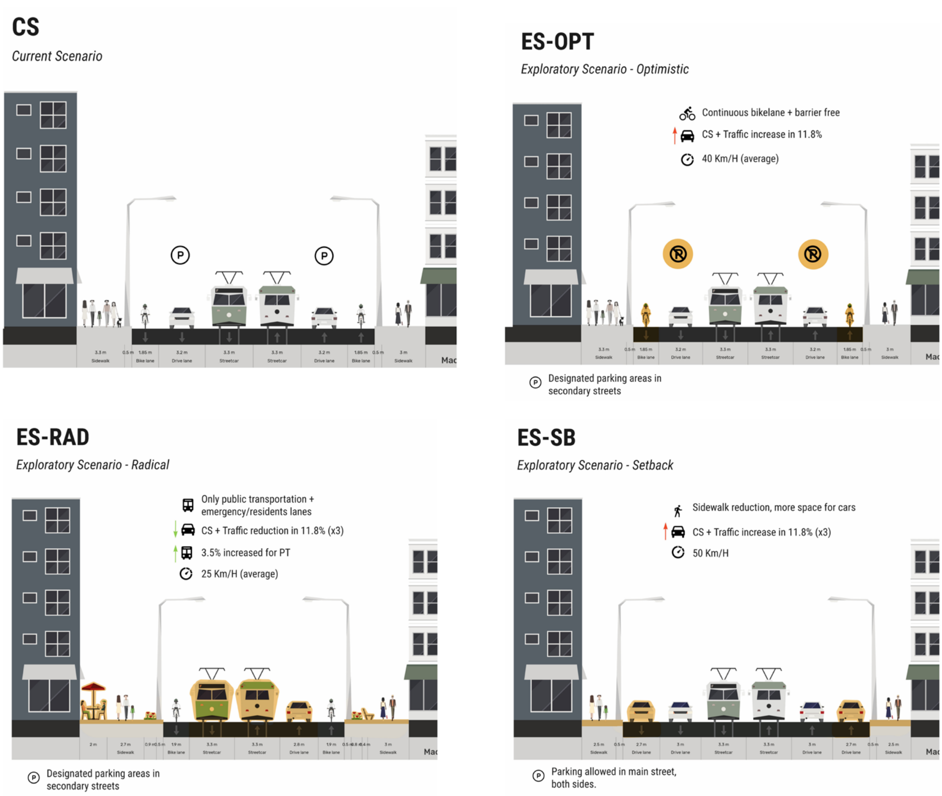


**Figure 1. Scenarios' sections with descriptions.**

## ADMS-Roads results

In all scenarios, the maximum average values for NO2 concentrations do not exceed the EU-regulated hourly maximum value of 200 µg/m3 (European Union 2008); contrarily, PM10 values surpass the daily threshold (50 µg/m3) by 19% in all the scenarios. No scenario exceeded the daily WHO (2021) thresholds for PM2.5 (15 µg/m3). The variation percentages passing from CS to the SB scenario reported that RAD poses the major emission reduction, with the values of 91.60% for NO2, 66.26% for PM10 and 67.61% for PM2.5. On the other hand, the maximum emission increase was with PM2.5 with 38.03% for SB, followed by PM10 with 35.37% for the same scenario.

Figure 2 depicts the NO2, PM10 and PM2.5 concentration for each scenario where it is possible to identify emissions hotspots on sections 2 and 4. In the RAD scenario, the hotspot in Section 2 disappears due to the projected car restrictions except for emergency and residents' vehicles. Moreover, Section 3 in all scenarios has fewer emissions compared to the rest of the street since it is an open road with better and quicker dispersion. The impact of particulate matter (PM) can be appreciated in RAD and SB, as they are smaller in diameter (10 and 2.5 micrometres) and can be dispersed over greater distances (DEFRA 2023); in this case, reaching up to one and a half blocks away.

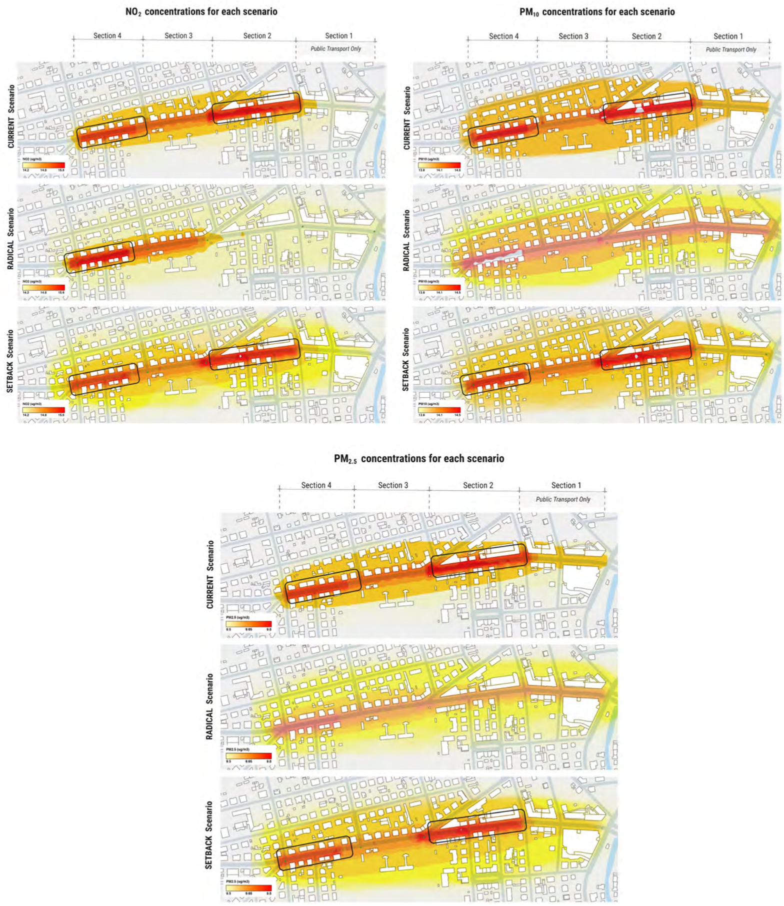


**Figure 2. Pollution maps and hotspots for all the scenarios for NO2, PM10 and PM2.5.**

## Perspectives of people

The online questionnaire collected 20 responses from residents, workers from the area and commuters. Because the survey was distributed via social media, it was decided to generate target images of the scenarios, modifying the number of vehicles and vegetation to depict a street with more and less pollution. The majority of these were replied by women (76.5%) and by people aged between 25-34 years (58.8%). In Figure 3, participants assessed that both OPT and SB present heavy traffic, with 76.4% and 94.2% respectively. For the CS, 41.2% of the respondents stated that traffic is noticeable but manageable. In terms of pollution perception, 53% of participants believe that CS has high levels of pollution. Furthermore, most participants (94.2%) estimated a high level of pollution for SB, but only 11.8% reported pollution for RAD. Regarding noise, all scenarios had substantial percentages of high noise levels, including the current situation of the street (70.5%); SB had the largest percentage (94.1%), where participants reported excessive noise levels. Finally, 94.1% of participants indicated that RAD best depicts their image of a street with less air pollution, and suggested that strategies like more trees, less traffic and more urban furniture will enhance the present circumstances of the street. This last part, evidence that respondents identify that more efforts beyond sustainable mobility are necessary to achieve a healthier street.

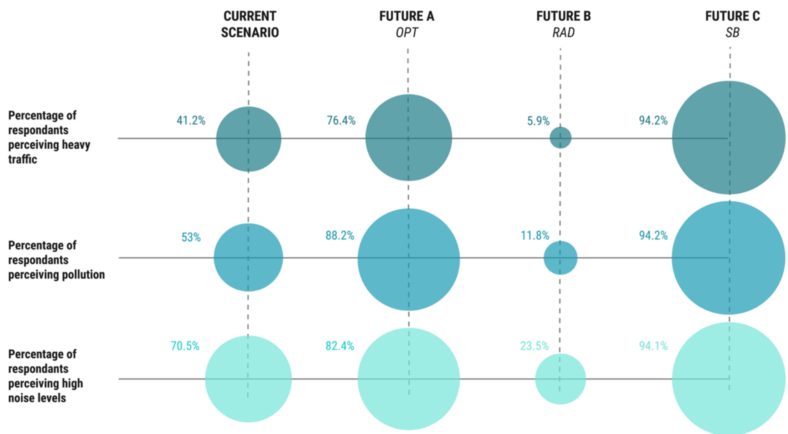


**Figure 3. Participants responses for perception of pollution, traffic, and noise for all the scenarios.**

## Comparative assessment and framework

The comparison of the two approaches (qualitative and quantitative) included the major findings of both analyses. From the results and findings, the software indicates that yearly and daily average pollution thresholds are not exceeded, so everything appears to be in order. However, respondents indicate that they experience high levels of noise and pollution and while they believe traffic is still manageable, they would prefer less traffic and more trees on their street. The relation between methods can be observed in Figure 4, where the two approaches follow the same pattern, which indicates that as the amount of pollution and traffic grows, so does the sense of excessive pollution and a congested street. However, in the radical scenario, as pollution and traffic levels drop, so does the number of participants who perceived high levels of pollution and traffic.

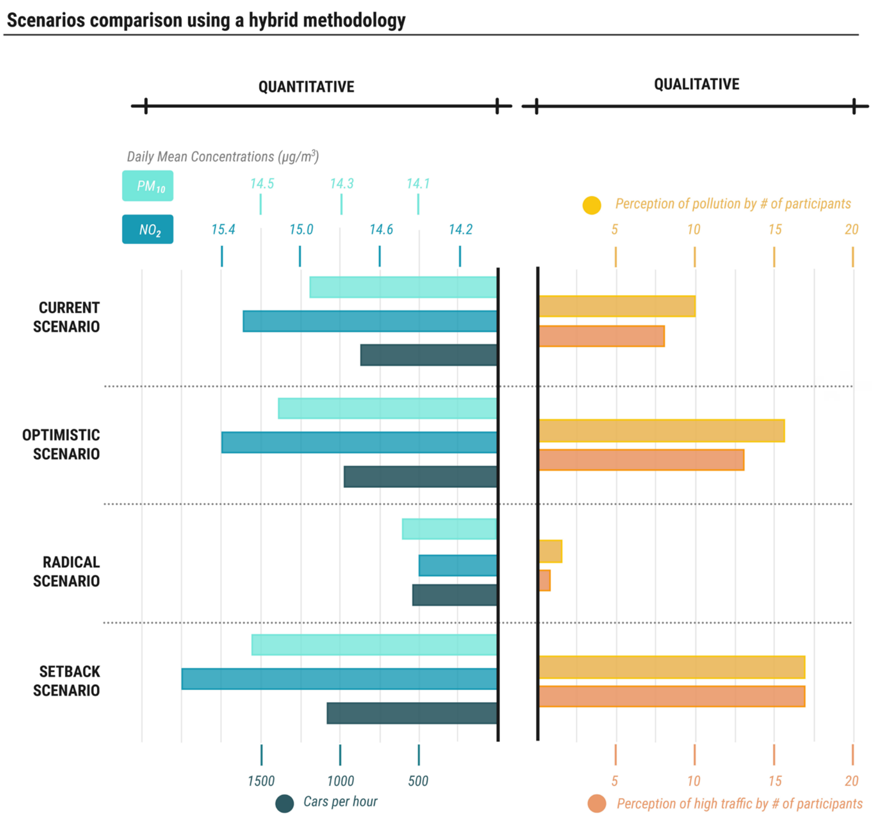


**Figure 4. Comparative assessment of the quantitative and qualitative data per scenario.**

This research has also highlighted the need for a framework for assessing air pollution for urban planners (Figure 5). It summarises the main operations and steps of the research methodology and includes the main results and empirical findings. The framework comprises 3 phases (contextualisation, dual approach and refinement and divulgation) and it was designed to be utilized in different streets or cities. It also includes the main methods, tools, indicators and suggestions of key stakeholders that could be involved in every phase, in order to make its application more user friendly.

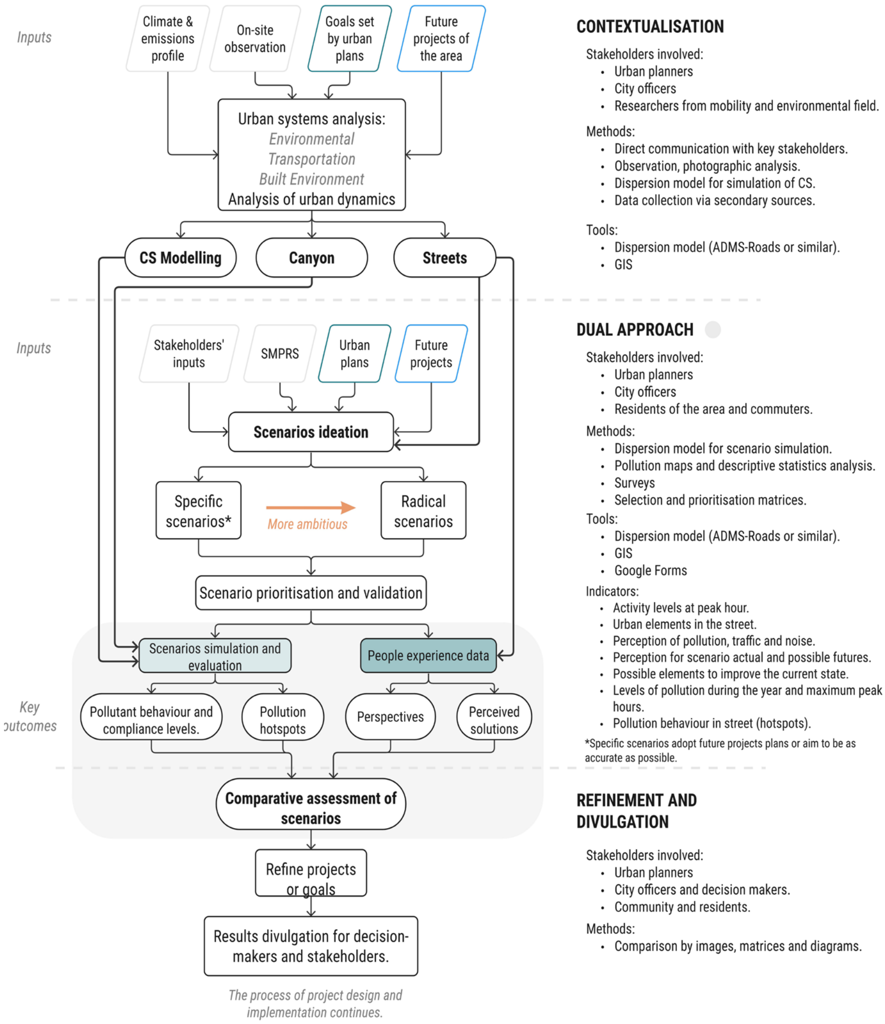


**Figure 5. Framework for air pollution assessment. Based on methodological framework and findings.**

# 5 Conclusions

Through the use of the ADMS Roads dispersion model, this research has identified that current air pollution levels in Kesselsdorfer Street are below the maximum permissible limits posed by ongoing regulations and recommendations from the EU and WHO, respectively. Moreover, emissions from potential scenarios that gradually shift towards more sustainable transportation methods contribute to further reduction of emissions. Compared to the current scenario, a radical scenario that shifts to less private cars and more use of public transport has the potential to cut NO2, PM10, and PM2.5 emissions by 91.6%, 66.26%, and 67.61%, respectively.

This research implemented a dual approach that revealed that dispersion models and people's perceptions go hand in hand, meaning that while pollution and traffic increases in the simulations, so does citizens' perception of high levels of pollution. Around 80% of respondents preferred fewer cars (RAD scenario) and more urban greenery, thus even radical mobility improvements need to be accompanied by complementing strategies in the streetscape. To provide clarity regarding the dual methodology for proper application by planners, an implementation framework was developed.

Dresden has the potential for boosting its mobility planning towards a more radical future, mainly due to its predilection for sustainable modes that will allow implementation of more ambitious projects with the residents' support. This study suggests that the most suitable strategy for Kesselsdorfer Street is the reduction of car use in favour of public transportation. This strategy can complement the mobility concept of the Löbtau area in Dresden (MOBIPoints and Tempo 30), to generate both a safer neighbourhood and improved air quality.

All the assessed scenarios presented two constant hotspots located in the street sections 2 and 4 that correspond to deep street canyons (with aspect ratios near 1.5). Thus, it is corroborated that the planning of deep canyons in cities prevents the dispersion of particles and concentrates pollutants. The hotspots' locations coincide with street areas of high commercial activity, thus justifying specific interventions for reducing pollution levels and protecting users. As previously mentioned, such interventions do not necessarily need to be around mobility but can be part of the street design, such as vegetation, barriers or distance.

Although some findings might or might not be translated into actions in Kesselsdorfer Street, they provide insights for considering citizens' perspectives that can trigger other actions or interventions. This study suggests that tackling car-related emissions do not require to go as far as to implement a completely radical mobility scenario (that could be hindered by social or economic factors) but aiming in that direction can contribute a significant change in pollution levels.

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EKUNDAYO, OLUTAYO

# Optimizing bike-sharing in Glasgow using a multi-criteria Analysis approach

*Promoting bike-sharing and sustainable urban mobility is crucial in modern urban planning. With escalating urbanization, addressing congestion and environmental issues is imperative. Bike-sharing offers a sustainable solution that improves urban living standards. This research optimizes Glasgow's bike-sharing system through rigorous analysis, including a literature review, expert interviews, surveys, and stakeholder engagement. Key findings underscore the urgency of optimization. There is a concentration of stations in the city centre, highlighting the need for a more dispersed network. Also, disparities in bike-sharing access across sub-neighbourhoods call for equitable distribution. Furthermore, first/last-mile connections and bike lane infrastructure improvements are essential. The study, utilizing Geographic Information Systems (GIS) and the Analytical Hierarchy Process (AHP), recommends the addition of 22 strategically located new bike stations to enhance accessibility and coverage. These stations address community needs while promoting sustainability. This research, shaped by stakeholder engagement, interviews, and surveys, aids urban planners, policymakers, and transportation authorities in promoting sustainable mobility and urban development. It also offers a versatile framework for similar cities, emphasizing equitable access and community involvement.*

# 1 Introduction

Bike-sharing schemes have seen a significant increase in popularity over the past decade, although they have been in existence for nearly 50 years (Nieuwenhuijsen & Rojas-Rueda 2020). More than 1900 bike-sharing schemes are now available in over 1,500 cities, with a global fleet of more than 8 million bikes (Meddin Bike-sharing World Map Report 2022). Currently, China boasts the largest bike-sharing programs globally in terms of bike availability. Conversely, the United States holds the record for the highest number of bike-sharing programs in total (O'Brien 2020). Various bike-sharing schemes have been implemented across cities within the UK and they have experienced varying degrees of success and faced unique challenges.

Glasgow, boasting a population exceeding 1.1 million according to the National Records of Scotland (2022), introduced a Mass Automated Cycle Hire (MACH) scheme in 2014. This initiative, operated by NextBike, was launched following the Commonwealth Games. The program has gained popularity, with close to 200,000 trips recorded in the first two years of operation (McPherson 2017). However, the scheme faces challenges such as the absence of dedicated cycle lanes, inadequate road infrastructure, limited docking station space, safety concerns, and bike theft (Glasgow City Council 2020; Glasgow Times 2020; Garnham & Whyte 2023). Additionally, funding and operational costs pose ongoing difficulties for the scheme. Further, the Glasgow City Council conducted a public engagement exercise called "Connecting Communities" to gather feedback and identify concerns related to the bike-sharing system (Glasgow City Council 2020). The study highlighted issues such as limited infrastructure, safety concerns, health inequalities, and limited community involvement. The problem of theft and vandalism has also been a significant challenge for the scheme (Glasgow Times 2020).

This research focuses on optimizing Nextbike Glasgow, through strategies, methodologies, and recommendations related to station placement, demand analysis, infrastructure assessment, and operational efficiency. The aim is to optimize the bike-sharing system in Glasgow by leveraging Geographic Information System (GIS) analysis techniques and considering multiple criteria. The goal is to achieve an enhanced and efficient bike-sharing program that meets the diverse needs of Glasgow's residents and visitors. To achieve this aim, the following specific objectives will be pursued:

1. To conduct a comprehensive literature review on bike-sharing programs, providing a contextual understanding of the subject and identifying key findings and gaps for further research and improvement.
2. To identify the current state of bike-sharing in Glasgow and the challenges faced by the existing system.
3. To conduct a SWOT analysis of the Glasgow bike-sharing scheme, identifying strengths, weaknesses, opportunities, and threats to adoption and usage.

4. To optimize the bike-sharing program in Glasgow for enhanced efficiency and effectiveness.
5. To identify potential new locations for Nextbike stations in Glasgow with high demand and good infrastructure.

This research intends to contribute new insights to the existing knowledge base on bike-sharing programs and provide valuable information for decision-makers, urban planners, and bike-sharing providers not only in Glasgow but also in other cities worldwide.

# 2 Background

## 2.1 History and Evolution

Bike-sharing schemes have evolved through five generations, each marked by distinct advancements (Parkes et al. 2013; Shaheen et al. 2013). The first generation, exemplified by Amsterdam's "White Bike programme," was rudimentary and lacked payment or security features. The second generation introduced coin deposit systems to deter theft but faced challenges due to anonymity (Guo et al. 2017). The third generation, IT-based systems, brought docking stations, automated payments, and smart card technology, significantly improving efficiency and expanding globally (Chen et al. 2018). The fourth generation, demand-responsive and multimodal systems, introduced dockless options, e-bikes, integrated cards, and advanced technology for enhanced user convenience and seamless mobility. The fifth-generation bike-sharing systems are characterized by extensive use of big data technologies, including free-floating (dockless) models implemented through various operator partnerships (ibid). Users can rent bicycles for short-term use, facilitated by smart cards or keys using radio-frequency identification technology. Stations provide information, network maps, customer service, and payment options via kiosks. Real-time monitoring through technologies like GPRS and GPS enables efficient management, with most schemes offering the first 30 minutes of use free, followed by increased rental fees. Users must provide their credit or debit card details and a deposit for registration and usage fees (Chen et al. 2018; Ricci 2015). These fifth-generation systems are poised to revolutionize urban mobility and accessibility.

Extensive research has explored the factors influencing bicycle usage, with Heinen et al. (2009) categorizing them into the natural environment, built environment, price, distance, effort, socioeconomic factors, and psychology. Fishman et al. (2014), and Eren & Uz (2020) identified specific factors affecting bike-sharing systems, including fares, infrastructure (integration with public transportation, bike quality, cycle lanes), system functioning (customer support, ease of registration and use), cycle lane extension, and the convenience of not owning a bicycle.

## 2.2 Bike sharing in the UK

Bike-sharing systems in the UK exhibit varying degrees of success and unique challenges. London's Santander Cycles, launched in 2010, stands out as one of Europe's largest and most successful schemes, significantly reducing congestion and air pollution (Heydari et al. 2021). Exeter's Co-bikes, introduced in 2016, innovatively offers a city-wide network of electric bikes for self-service hire and ranks well among UK local authorities (Macauley 2016). Bournemouth and Poole's Beryl bikes excel through data science methods, utilizing AI and machine learning to optimize bike positioning and maintenance (City, University of London 2020). Cardiff's Nextbike scheme, with over 10,000 weekly cycle hires, promotes cycling as a sustainable mode of transportation but faces challenges like safety concerns and theft (Sustrans 2019). In contrast, Belfast Bikes, Mobike in Manchester, Liverpool City Bike, Just Eat Cycles in Edinburgh, and Yobikes in Bristol have encountered usage declines or challenges like vandalism and theft, prompting changes or withdrawals (The Irish News 2022; Cycling Weekly 2021; Thorp 2022; Dalton 2021; Booth 2021).

## 2.3 Bike sharing in Glasgow

Glasgow's bike-sharing scheme, operated by Nextbike in collaboration with TIER and maintained by Bike4Good, strategically positions docking stations near major transportation hubs, tourist attractions, and business districts, ensuring easy accessibility for users and integrating seamlessly into the city's transportation network (Garnham & Whyte 2023). This placement enhances convenience and promotes sustainable transportation. Commendable progress in bolstering Glasgow's cycling infrastructure includes dedicated cycle lanes, shared-use paths, and the implementation of 20mph zones, supported by initiatives like Go Cycle Glasgow and Sustrans Places for Everyone (Glasgow City Council 2016a; Sustrans 2022). While the council's Cycling Friendly Programme offers grants for cycling amenities, challenges persist, including safety concerns, inadequate infrastructure, and weather-related barriers (Clark & Curl 2016). Nonetheless, the scheme has exhibited significant growth, offering a diverse range of bikes, including e-bikes, with 1,159 bikes and 104 bike hire stations, attracting a substantial customer base, including corporate memberships.

The analysis of bike-sharing scheme usage in Glasgow reveals various motivations for users, including enjoyment, convenience, physical activity, and an alternative to public transportation (CoMoUK 2020). Demographics indicate that 55% of users are male, 36% are female, and 9% are unidentified, with most rentals lasting less than half an hour. Garnham and Whyte (2023) observed distinct usage patterns throughout the day and week, with roundtrip hires evenly distributed on weekdays and peak one-way hires during rush hours. Weekends showed a gradual increase in mid-afternoon and a slower decline in the late evening and early morning. Seasonal variations included higher hires in summer and lower hires in winter months. Proximity to rental locations influenced usage, with limited stations in outer Glasgow affecting adoption. The introduction of e-bikes is seen as a significant advancement, enhancing accessibility, and potentially reducing car use. However, the scheme faces challenges related to safety, security, limited infrastructure, station availability, financial costs, health inequalities, community involvement, theft, and vandalism (Glasgow City Council 2022a). Furthermore, nearly half of Glasgow's neighbourhoods lack bike hire stations (Glasgow City Council 2022a; Herald Scotland 2022; Garnham & Whyte 2023)

### 2.4 Benefits of Bike-Sharing Systems

Bike-sharing systems in urban areas offer numerous benefits as sustainable transportation options. They provide cost-effective, eco-friendly, and convenient travel, with the Glasgow scheme alone potentially saving around 650 tonnes of CO2 emissions over eight years (Garnham & Whyte 2023). These systems effectively reduce car usage, address the "first/last mile" problem, and integrate seamlessly with public transportation, enhancing accessibility and convenience (Fishman et al. 2014; Shaheen et al. 2014). Additionally, they contribute to tourism, economic growth, and flexible transportation options (Buehler & Hamre 2014; Schoner et al. 2012). They also promote physical activity, with users engaging in significant hours of exercise and improving well-being, including mental health benefits (Garnham & Whyte 2023; Morley 2021). During the pandemic, these schemes provided a socially distanced and environmentally friendly alternative to traditional transportation, offering the convenience of not owning a personal bike (Glasgow City Council 2022b).

## 3 Methodology

This study adopts an interpretive research philosophy to delve into the subjective meanings and social constructions surrounding bike-sharing. The methodology employed is comprehensive, combining both quantitative and qualitative methods, such as surveys, Multi-Criteria Analysis (MCA), interviews, and geospatial data analysis. The data collection process encompasses a literature review that explores the strengths, weaknesses, opportunities, and threats of the bike-sharing scheme. Additionally, surveys and interviews are conducted with various stakeholders, including transportation experts, users, and non-users of the bike-sharing scheme. Geospatial data analysis utilized shapefiles from reputable sources to understand the city's cycling infrastructure, potential bike-sharing locations, and their relationships with amenities and demographics. Glasgow Open Data provided information on bike-sharing trips, including trip durations, start and end locations, and other relevant variables from 01-05-2022 to 01-05-2023. This data facilitated a comprehensive analysis of bike-sharing patterns and trends. The Nextbike rental and trip summaries were analysed to gain insights into rental patterns, popular stations, trip routes, trip durations, and associated costs. The use of Python programming and ArcGIS facilitated data extraction, transformation, and analysis tasks. In addition, the Scottish Index of Multiple Deprivation (SIMD) data was also used to assess the socio-economic context of different areas.

To optimize bike-share station locations in Glasgow, this study applies the Analytic Hierarchy Process (AHP). Fifteen criteria are meticulously selected through an exhaustive approach, which includes a literature review and takes into account local guidelines from Transport Scotland (2021a) regarding Cycle

Infrastructure Design. These criteria were ranked by a diverse group of stakeholders, including users, non-users, and experts interviewed during the research. The AHP methodology constructs a hierarchical model and conducts pairwise comparisons to assign weights to these criteria based on the rankings, revealing critical factors that impact the bike-sharing system's success. This approach blends GIS and AHP, considering geographic factors, population density, transportation infrastructure, and existing bike routes. The selected criteria for this study shown in Figure 1 encompass crucial aspects of an effective bike-sharing program, covering cycle network proximity, slope levels, transport infrastructure accessibility (including train and bus stations), user motivation factors (such as green areas, seaside, sports centres, recreational centres, schools, universities, and shopping malls), and demand patterns across residential, commercial, and administrative/public areas. This meticulous selection aims to ensure fair access and facilitate the seamless integration of bike-sharing with other transportation modes, ultimately enhancing the overall efficiency and effectiveness of Glasgow's bike-sharing system.

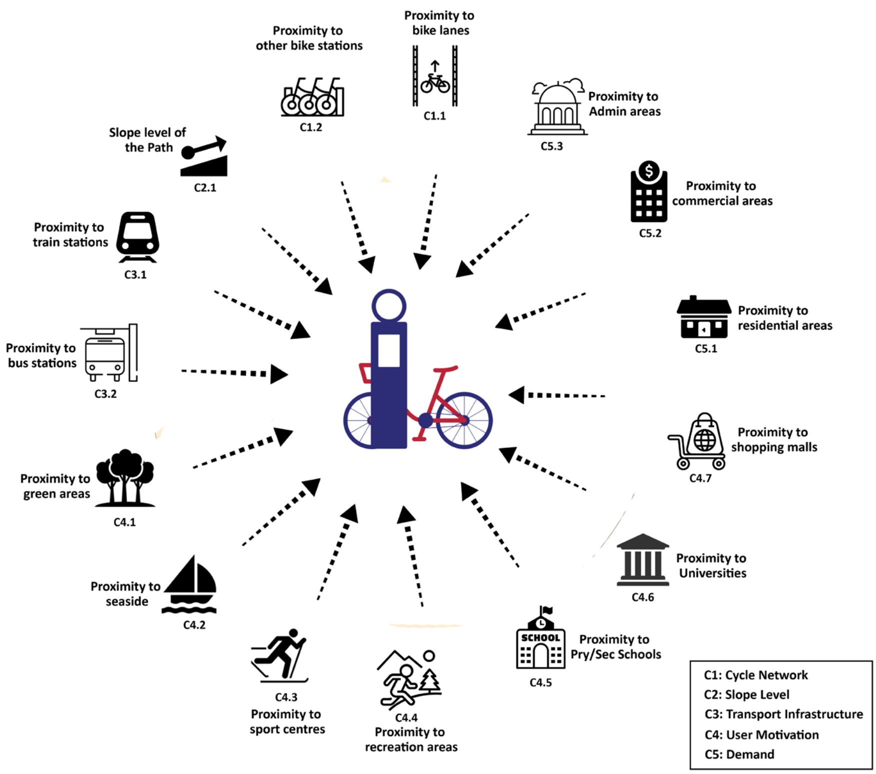



**Figure 1. Evaluation criteria for the study.**

To gather insights from various stakeholders, including transportation experts, users, and non-users of the Nextbike scheme, a structured approach was employed. Stratified sampling was utilized to ensure the representation of bike-sharing stations across four distinct geographical regions: North-east, North-west, South, and the city centre. From the pool of 104 stations, a total of 20 were selected for interviews. Within each of these stations, 4 users and 4 non-users were interviewed, resulting in 160 respondents in total. These respondents were actively engaged in ranking the selected criteria based on their perceived attractiveness for using the bike-sharing scheme. Furthermore, as part of stakeholder engagement, 10 transportation experts were purposefully selected. These experts played a vital role in the ranking analysis and were interviewed to gain valuable insights into various aspects, including infrastructure, policies, and potential enhancements related to the bike-sharing scheme.

GIS played a pivotal role in this analysis, allowing for the integration of diverse geographic datasets related to the chosen criteria, including bike stations, cycle paths, and points of interest. This integration enabled the identification of spatial patterns and relationships, providing valuable insights into the distribution of bike-sharing infrastructure, user behaviour, and areas requiring enhancements. To assess the suitability of different locations and propose potential new locations, the vector points representing the criteria were transformed into a raster format. This conversion facilitated distance accumulation analysis and reclassification on a scale of 1 to 10, where higher values indicated greater suitability. This assessment aligned with established guidelines from ITDP (2013) and Transport Scotland (2021a), emphasizing factors like integration with existing transportation infrastructure, proximity to bike lanes, and areas with high demand.

# 4 Results

## 4.1 Stakeholder's Engagement

The feedback from both users and non-users of Glasgow's bike-sharing system provides a nuanced perspective on its performance. While most users rated the system positively, it's essential to address the concerns of the 47% who rated it as "Fair," "Poor," or "Very Poor," indicating room for improvement. Transportation experts and stakeholders similarly rated the system predominantly as "Good," aligning with user feedback. Notably, none of them rated the system as "Excellent," further underscoring the room for enhancement.

In the area of proximity ranking analysis, both users and non-users were asked to rank criteria to inform the MCA analysis. In terms of location preferences, users and non-users consistently ranked "Proximity to Universities" as the most attractive criterion under 'User motivation', aligning with stakeholders' emphasis on this aspect. Additionally, both groups highlighted the importance of "Administrative/Public" and "Commercial" areas, as well as "Proximity to tourism/recreation areas" and "Proximity to green areas" for station locations. The significance of well-connected and safe cycling infrastructure, especially "Proximity to bike lanes/cycle networks" and "Proximity to train stations," was underscored as crucial for attracting users. This emphasis on train stations aligns with the preferences of potential users and underscores the significance of seamless intermodal transfers.

Furthermore, the challenges identified, primarily related to infrastructure and safety concerns, emphasize the need for comprehensive solutions to enhance the efficiency and appeal of Glasgow's bike-sharing system for all potential users. These insights from users, non-users, and transportation experts and stakeholders, are summarized in Figure 2.

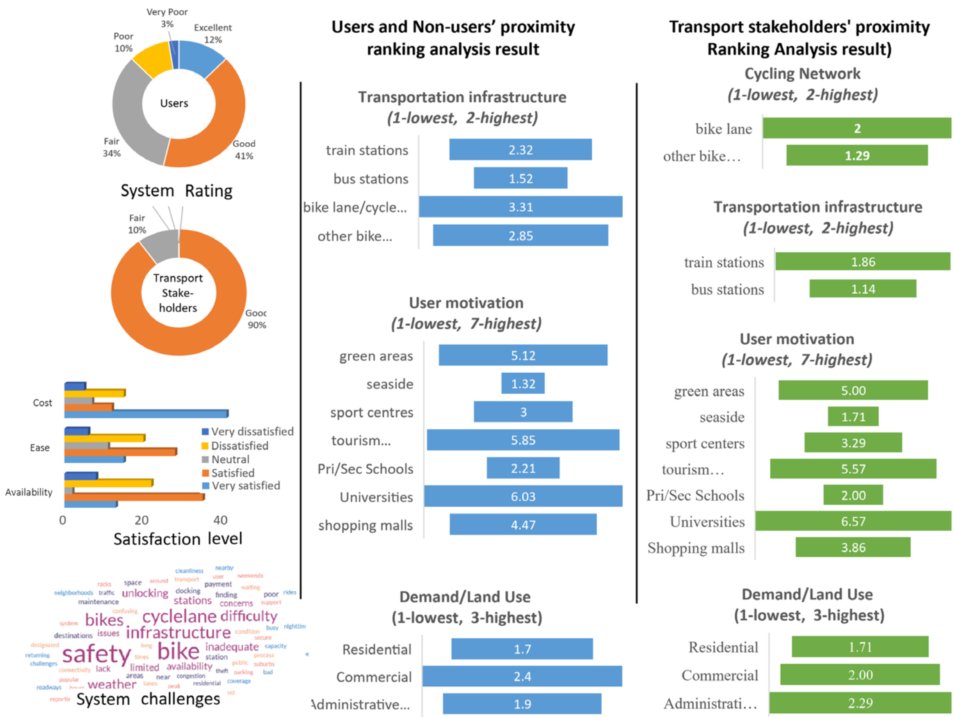



**Figure 2. Stakeholders' engagement result.**

## 4.2 MCA – Analytic Hierarchy Process result

Following the stakeholders' engagement and the collection of responses from users, non-users, and transportation stakeholders, the criteria were subjected to a pairwise comparison and weight assignment process. The analysis involved a total of 105 pairwise comparisons, and the resulting weights were determined based on the principal eigenvector of the decision matrix. This process yielded a consistency ratio (CR) of 9.6%. A lower CR value indicates a higher level of consistency in the pairwise comparisons made throughout the analysis. In this case, the CR value of 9.6% reaffirms the overall consistency of the analysis. These weights shown in Figure 3 were further normalized to ensure a comprehensive and consistent assessment of the criteria.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 4.00 | 9.00 | 3.00 | 9.00 | 6.00 | 9.00 | 8.00 | 4.00 | 9.00 | 3.00 | 7.00 | 8.00 | 6.00 | 3.00 |
| 2 | 0.25 | 1 | 7.00 | 1.00 | 6.00 | 5.00 | 9.00 | 7.00 | 4.00 | 9.00 | 0.25 | 5.00 | 7.00 | 1.00 | 0.50 |
| 3 | 0.11 | 0.14 | 1 | 0.14 | 0.50 | 0.25 | 2.00 | 0.20 | 0.12 | 4.00 | 0.11 | 0.33 | 0.33 | 0.20 | 0.12 |
| 4 | 0.33 | 1.00 | 7.00 | 1 | 7.00 | 6.00 | 9.00 | 5.00 | 3.00 | 8.00 | 1.00 | 4.00 | 2.00 | 1.00 | 0.25 |
| 5 | 0.11 | 0.17 | 2.00 | 0.14 | 1 | 0.25 | 2.00 | 0.17 | 0.11 | 2.00 | 0.11 | 0.25 | 0.20 | 0.14 | 0.11 |
| 6 | 0.17 | 0.20 | 4.00 | 0.17 | 4.00 | 1 | 9.00 | 1.00 | 0.50 | 8.00 | 0.17 | 3.00 | 3.00 | 0.20 | 0.17 |
| 7 | 0.11 | 0.11 | 0.50 | 0.11 | 0.50 | 0.11 | 1 | 0.17 | 0.14 | 0.50 | 0.11 | 0.14 | 0.17 | 0.14 | 0.11 |
| 8 | 0.12 | 0.14 | 5.00 | 0.20 | 6.00 | 1.00 | 6.00 | 1 | 0.50 | 6.00 | 0.14 | 1.00 | 2.00 | 0.25 | 0.25 |
| 9 | 0.25 | 0.25 | 8.00 | 0.33 | 9.00 | 2.00 | 7.00 | 2.00 | 1 | 7.00 | 0.25 | 2.00 | 2.00 | 0.50 | 0.17 |
| 10 | 0.11 | 0.11 | 0.25 | 0.12 | 0.50 | 0.12 | 2.00 | 0.17 | 0.14 | 1 | 0.11 | 0.17 | 0.20 | 0.11 | 0.11 |
| 11 | 0.33 | 4.00 | 9.00 | 1.00 | 9.00 | 6.00 | 9.00 | 7.00 | 4.00 | 9.00 | 1 | 9.00 | 7.00 | 5.00 | 1.00 |
| 12 | 0.14 | 0.20 | 3.00 | 0.25 | 4.00 | 0.33 | 7.00 | 1.00 | 0.50 | 6.00 | 0.11 | 1 | 3.00 | 0.17 | 0.14 |
| 13 | 0.12 | 0.14 | 3.00 | 0.50 | 5.00 | 0.33 | 6.00 | 0.50 | 0.50 | 5.00 | 0.14 | 0.33 | 1 | 0.20 | 0.12 |
| 14 | 0.17 | 1.00 | 5.00 | 1.00 | 7.00 | 5.00 | 7.00 | 4.00 | 2.00 | 9.00 | 0.20 | 6.00 | 5.00 | 1 | 0.25 |
| 15 | 0.33 | 2.00 | 8.00 | 4.00 | 9.00 | 6.00 | 9.00 | 4.00 | 6.00 | 9.00 | 1.00 | 7.00 | 8.00 | 4.00 | 1 |

Number of comparisons = 105
**Consistency Ratio CR** = 9.6%

Principal eigen value = 17.123
Eigenvector solution: 7 iterations, delta = 2.2E-8

| Cat | | Priority | Rank | (+) | (-) |
|---|---|---|---|---|---|
| 1 | (C1.1) Proximity to bike lane | 19.3% | 1 | 14.4% | 14.4% |
| 2 | (C1.2) Proximity to other bike-sharing statio | 7.4% | 6 | 5.4% | 5.4% |
| 3 | (C2.1) Slope level of the path | 1.3% | 12 | 0.9% | 0.9% |
| 4 | (C3.1) Proximity to train stations | 8.5% | 5 | 6.0% | 6.0% |
| 5 | (C3.2) Proximity to bus stations | 1.2% | 13 | 0.7% | 0.7% |
| 6 | (C4.1) Proximity to green areas | 3.7% | 8 | 3.0% | 3.0% |
| 7 | (C4.2) Proximity to seaside | 0.7% | 15 | 0.5% | 0.5% |
| 8 | (C4.3) Proximity sport centers | 2.8% | 9 | 1.8% | 1.8% |
| 9 | (C4.4) Proximity to tourism/recreation areas | 6.3% | 7 | 5.5% | 5.5% |
| 10 | (C4.5) Proximity to Pri/Sec Schools | 0.8% | 14 | 0.5% | 0.5% |
| 11 | (C4.6) Proximity to Universities | 16.6% | 2 | 13.7% | 13.7% |
| 12 | (C4.7) Proximity to shopping malls | 2.2% | 10 | 1.3% | 1.3% |
| 13 | (C5.1) Residential | 2.1% | 11 | 1.1% | 1.1% |
| 14 | (C5.2) Commercial | 11.9% | 4 | 12.3% | 12.3% |
| 15 | (C5.3) Administrative/Public | 15.4% | 3 | 12.2% | 12.2% |

**Figure 3. Priorities weighting and decision matrix.**

## 4.3 Spatial Analysis Result

The analysis of existing bike-sharing stations in Glasgow yielded several key results. First, the slope analysis indicated that most stations are strategically located in areas with favourable cycling conditions, characterized by flat or near-level terrain to ensure a smoother cycling experience. Stations situated on slopes exceeding 4 degrees were limited, as steeper slopes are generally less attractive for cycling. The presence of e-bikes also helps mitigate the challenges posed by hilly terrain. Secondly, the spatial analysis revealed a concentration of bike-sharing stations in the city centre, reflecting a deliberate focus on serving this densely populated urban area. While this concentration aligns with the demand for sustainable transportation options in the city centre, it raises concerns about the accessibility and coverage of the bike-sharing program in other parts of Glasgow. To ensure equitable access and broader adoption, expansion into other neighbourhoods with potential demand is crucial. Thirdly, the equity analysis indicated a correlation between station availability and population density, with efforts to improve accessibility and connectivity in densely populated areas. However, disparities in access were observed in some moderately populated areas and higher deprivation areas, where station availability did not align with population density. Targeted interventions are needed to address these disparities and provide equitable access to bike-sharing services.

Furthermore, the network connectivity analysis reveals significant spatial disparities in the proximity of bike-sharing stations to key transportation modes in Glasgow. Approximately 53% of train stations are located more than 400 meters away from the nearest bike-sharing stations, indicating a need for improvement in train station connectivity. In terms of bus stations, the median distance between bike stations and bus stops is approximately 67 meters, with some stations situated significantly farther away, like The Burrell Collection with a distance of 676.64 meters. Furthermore, the analysis highlights that bike-sharing stations, on average, are situated approximately 142 meters from the nearest bike lane.

Finally, the safety and security assessment identified accident hotspots, primarily concentrated in the city centre, suggesting areas with a higher risk of accidents. The analysis also considered the proximity of accidents to bike-sharing stations, highlighting areas where individuals accessing or using these stations may face elevated accident risks. Targeted safety measures, infrastructure improvements, and education campaigns are essential for accident prevention in these areas. The results of this spatial analysis are visually presented in Figure 4.

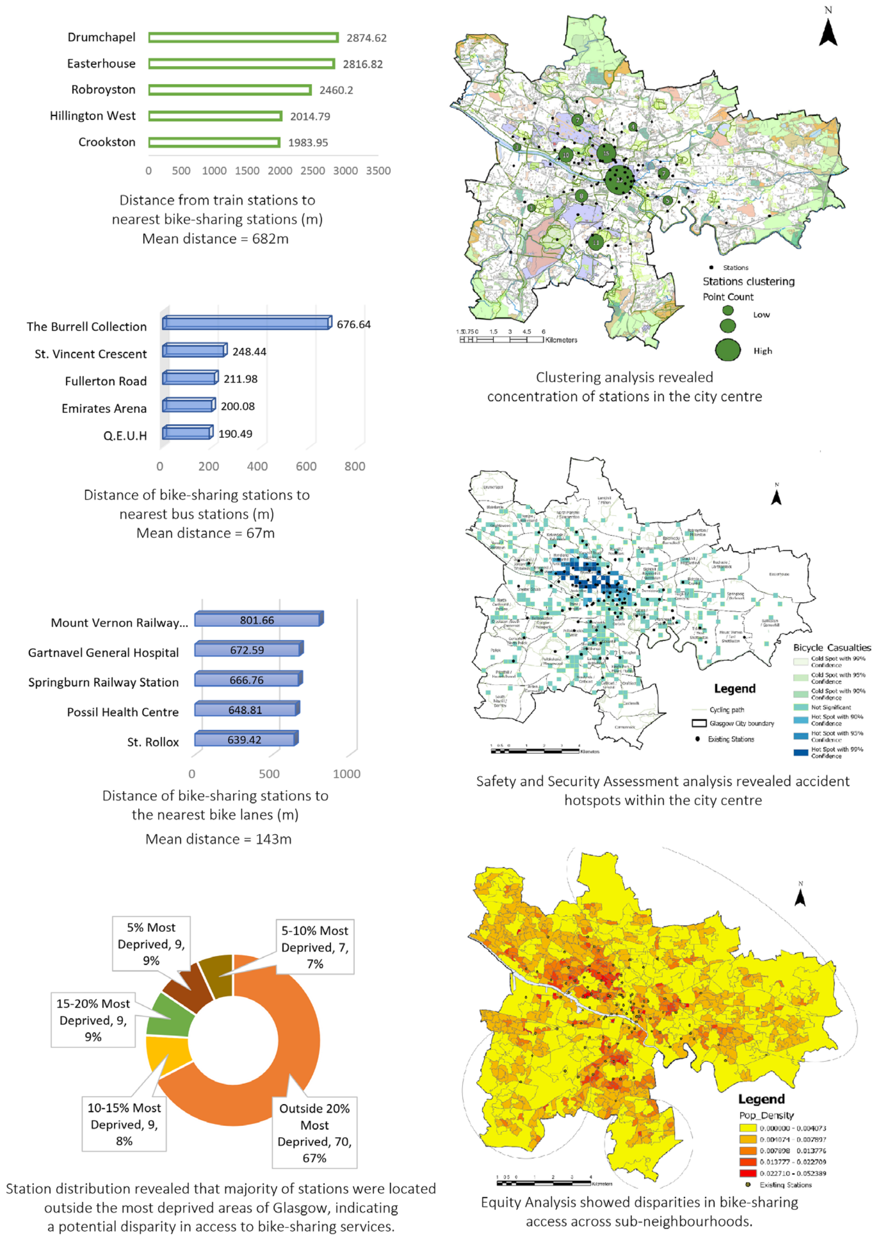



**Figure 4. Spatial Analysis Result.**

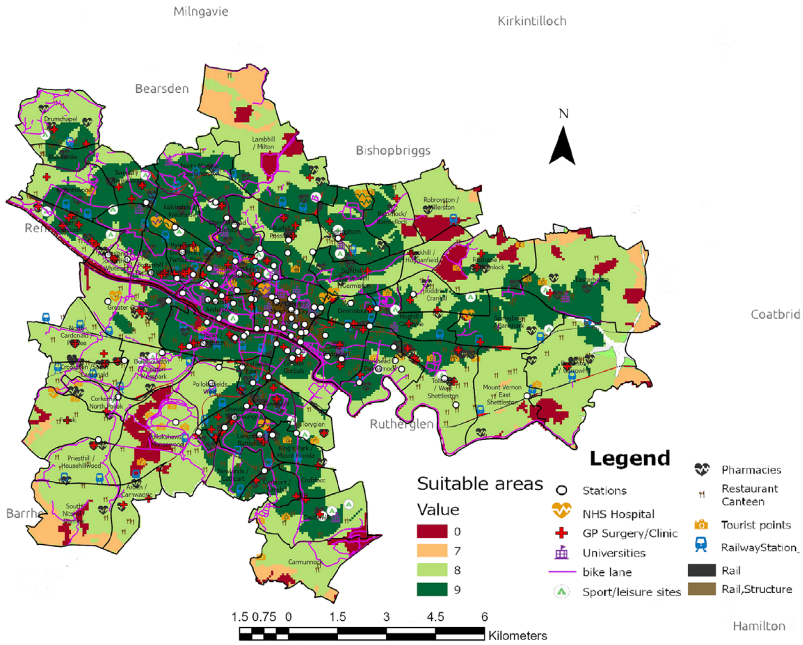
### 4.4 Suitability Analysis Result

The analysis aimed to identify suitable areas and optimal expansion locations for Glasgow's bike-sharing program, considering factors like demand, infrastructure, land use, and proximity to key destinations. Essential criteria were overlaid using ArcGIS to generate the most suitable areas. The Northwest, Glasgow Centre, parts of the Northeast, and some Southeast areas were identified as most suitable for program expansion. The optimized bike station placement map considered guidelines from ITDP and NACTO, along with population distribution and transportation demand. Specific areas like the city centre, deprived neighbourhoods, trip generators, and regions with active travel infrastructure improvements were chosen for twenty-two new bike station locations. Targeted input from stakeholders and the consideration of SIMD (Scottish Index of Multiple Deprivation) were included in the analysis to expand stations into deprived areas, addressing transport poverty as part of the factors considered. The suitability map and the optimized bike placement map are shown in Figure 5 on the next page.

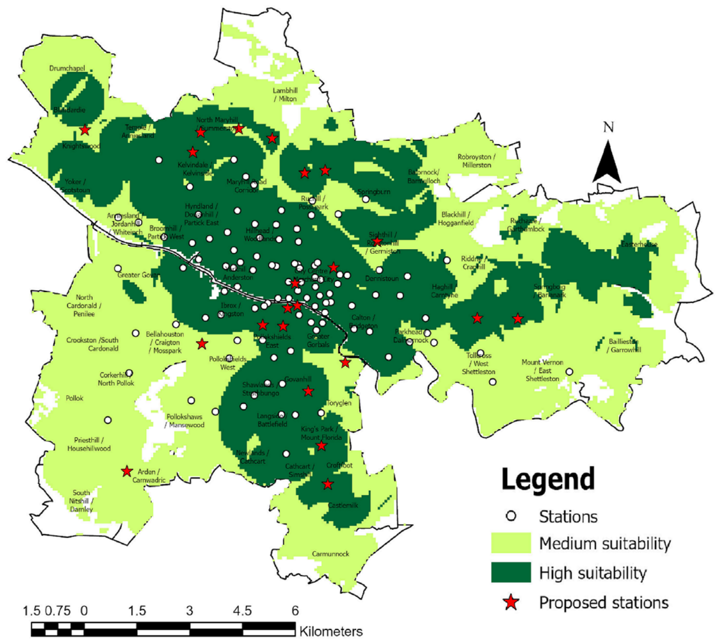
## 5 Conclusions and discussion

The findings of this comprehensive analysis of Glasgow's bike-sharing program highlight the potential for transformative improvements in the city's transportation landscape. The multifaceted assessment, which encompassed network connectivity analysis, security and safety evaluation, clustering analysis, and slope considerations, provides valuable insights that can shape the future of cycling in Glasgow.

One of the key takeaways from the network connectivity analysis is the need to bring bike-sharing stations closer to train stations. Currently, over half of the train stations are situated more than the recommended 400 meters away from the nearest bike-sharing station according to Shaheen et al. (2013). However, by reducing the mean distance to 395 meters through this study, Glasgow can enhance the intermodal experience for commuters, making it more convenient to seamlessly transition between trains and bikes. This aligns with the preferences of potential users and supports the broader goal of promoting sustainable transportation options. Additionally, approximately 69% of the bike-sharing stations are conveniently located within just 160 meters of a bike lane, demonstrating a certain level of integration that holds potential for improvement. These disparities emphasize the importance of targeted interventions to enhance connectivity and promote seamless multimodal transportation options for users across Glasgow. Furthermore, safety remains a paramount concern for cyclists, and the safety and security assessment analysis rightly identify accident hotspots that require targeted safety measures. As we move away from the city centre, the clustering effect diminishes, but proactive accident prevention measures should still be maintained. Allocating additional resources for accident prevention in the city centre and implementing targeted interventions like enhanced infrastructure, improved signage, and education campaigns in identified hotspots outside the




Suitability map




Optimized bike station placement map

**Figure 5. Suitability analysis result and optimized bike placement map.**

city centre can enhance the safety of cyclists and pedestrians across Glasgow. Improving the security and safety of bike-sharing users is not only a practical necessity but also a critical factor in encouraging more residents to embrace cycling as a viable mode of transport.

The clustering analysis further accentuates the imperative of achieving a more equitable distribution of bike-sharing stations, with a particular focus on underserved neighbourhoods, as a strategic step in mitigating transport poverty and stimulating social and economic development. It aligns seamlessly with established international guidelines, such as those outlined by the ITDP (2013), Karki and Tao (2016), and NATCO (2015), which advocate for a more balanced station spacing, ideally averaging around 300 meters. Nevertheless, the analysis also unveils disconcerting disparities in access, notably that bike-sharing stations tend to be predominantly located outside the most deprived areas. This circumstance significantly restricts the availability of sustainable transportation alternatives for residents in these marginalized communities. Through the insights gained from this study, there has been a tangible enhancement in the accessibility of bike-sharing services, notably in underserved areas. The number of bike-sharing stations has seen a commendable increase, rising from 33 (31%) to 47 (37%) in regions characterized by higher deprivation levels. This remarkable development represents a significant stride towards fostering a more equitable and accessible transportation landscape within Glasgow, with the potential to alleviate transport poverty and stimulate broader social and economic advancement.

Beyond the technical aspects discussed, the conversation extends to encompass broader themes of sustainability and community engagement. The significant reduction of 650 tonnes in greenhouse gas emissions as a result of the scheme over eight years underscores the positive environmental influence of cycling and reinforces the program's commitment to sustainability. By expanding the program following the insights gleaned from this study, even more substantial reductions in greenhouse gas emissions can be achieved, further enhancing the city's environmental sustainability efforts.

To ensure the successful expansion, collaborative efforts among various stakeholders, including the Glasgow City Council, Nextbike (the bike-sharing operator), and transportation experts and organizations, are crucial. These recommendations encompass expanding the system into underserved areas, enhancing cycling infrastructure, improving bike availability information, implementing affordable pricing packages, and advocating for integration with existing transportation infrastructure. Additionally, continuous research and community engagement are essential. Collectively, these measures aim to establish a sustainable and environmentally friendly bike-sharing system that transforms transportation habits, enhances urban mobility, and elevates the overall quality of life for Glasgow's residents, positioning the city as a model for sustainable transportation and active mobility.

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PICONE, NATASHA

# Air Quality in Different Local Climates Zones of Brindisi, Italy

## The Impact of Green Infrastructure

*Cities comprise more than half the world's population, and most are exposed to poor air quality. To improve it different approaches can be implemented: direct (tackling the source) or complementary ones (reducing the population's exposure, like GI). This article will center the analysis in Brindisi (Italy), an intermediate city with poor air quality related to NO2. The objective is to "assess how different green infrastructures impact the urban air quality (NOx) in different Local Climate Zones of Brindisi, Italy".*

*The methodology consists in GI intervention selection based on the literature, Local Climate Zone (LCZ) maps for Brindisi generated using the GIS methodology, and then two sites were selected (LCZ2 and LCZ6). Simulations in ENVI-MET were run to get the effects of the GI interventions on air quality and thermal comfort. Finally, the evaluation of the results was done in ArcGIS-Pro.*

*The LCZ maps showed that the main zones are LCZ2 and LCZ6. Concerning the effects of GI intervention, the results showed that combining aspect ratio, vegetation characteristics, and local meteorology can change the results. It has a better effect with green walls for high aspect ratios, though more discussion about the typology of streets should be addressed. At the same time, trees and hedges generate improvements with low aspect ratios.*

# 1 Introduction

Nowadays, half of the world's population lives in cities, and is expected to increase to over 65 % by 2050 (National Institute of Environmental Health Science 2023). More than 80 % of the urban population is exposed to air quality exceeding World Health Organization guidelines (United Nations 2016). In this sense, the air quality in cities is one of the main concerns in urban health, as it directly impacts the population's quality of life. Air pollution contributes to the development of respiratory (asthma and lung cancer) and neurological diseases (Alzheimer's and Parkinson's) as it gnerate heart diseases, fetal growth, autism, retinopathy, and low birth weight (National Institute of Environmental Health Science 2023).

In Europe, the urban population exceeded 70 %. According to the European Environment Agency (2022), "air pollution is the single largest environmental health risk in Europe", as it not only generates premature death but also affects the health quality (European Commission 2022). According to the last Air Quality in Europe 2022 report, though the pandemic lockdown temporarily improved air quality, the current conditions are not much better than pre-pandemic ones.

Improving the air quality can be achieved with different interventions; the direct one is to reduce pollution emissions, which sometimes is difficult as the sources are diffuse, or the implementation of the decisions is complicated. There are complementary methods to reduce the population's exposure to pollution, and currently, urban planners are looking to increase such methods (Hewitt et al. 2020). One of the proposed methods is the usage of Green Infrastructure (GI) to capture the air pollutants from the urban atmosphere, as it remarkably increasing the deposition surfaces.

In Italy, 71 % of its population lives in cities (United Nations Population Division and World Bank 2018), and 94.8 % is exposed to PM2.5, higher than the WHO guidelines (World Bank 2018). Most existing studies focus on the country's main cities (Manes et al. 2016; Piersanti et al. 2021; Tomassetti et al. 2020), and generally, intermediate cities are only analyzed for general purposes (Minutolo et al. 2023). This work will focus on Brindisi, located in Southeast Italy. The total population is 83317 (Istituto Nazionale di Statistica 2017), and has homogeneous neighborhoods. According to a report about the air quality of cities in Italy, Brindisi presents high values of pollution, especially nitrogen dioxide (NO2) (Minutolo et al. 2023). In this sense, the objective of the work is to "Assess how different green infrastructures impact the urban air quality (NOx) and thermal comfort (UTCI) in different Local Climate Zones of Brindisi, Italy".

# 2 Background

Air quality is assessed considering the concentration of air pollutants present in the atmosphere. In cities, human activities generate higher emissions of air pollutants than in other environments. The concentration of pollutants modifies the composition of urban atmospheres, generating harmful conditions for human, animal, plant, and microbial health or damaging infrastructure and ecosystems. Different agents (mainly winds) transport air pollutants in urban areas, generating a dispersion of the compounds from the sources and a varying concentration in the urban atmosphere. After being transported, the air pollutants are deposited by dry or wet processes (Oke et al. 2017).

Kumar et al. (2019) studied the interactions between the urban GI, the air quality, and the population health impact. The implementation of GI has the potential to reduce exposure to air pollutants and improve general well-being. On the other side, there is an ongoing debate about the limitations of using urban GI for air quality improvement; there are some studies that have demonstrated that depending on the way that the GI is implemented, it can have either opposite results to the expected ones or little effects (Grundström & Pleijel 2014; Nemitz et al. 2020; Vos et al. 2013). This is why it is essential to pay attention to the design of the GI and its interaction with the microclimatic characteristics (Pugh et al. 2012). This is one of the main reasons to test different GI designs in models before implementation.

Moreover, Tomson et al. (2021) present the implementation of the GI to improve the air quality at the street canyon level. They stated that it "depends on street canyon geometry (configuration and aspect ratio), local meteorological conditions (especially wind flow conditions) and vegetation characteristics (tree spacing or stand density, cross-sectional area covered by trees, LAD, etc.), making GI design in street canyons complex and context-specific" (Tomson et al. 2021, 8).

Different GI interventions have been proven to generate a positive effect on air quality. At the same time, it is essential to remember that not all of them can be implemented on every site. In this sense, Abhijith et al. (2017) present how different GI and road characteristics are related. Hedges and green walls have positive implications in both typologies of roads (street canyons and open roads), while green roofs positively affect street canyons. At the same time, trees deteriorate the air quality in street canyons but generate positive impacts on open roads.

To analyze cities and the characteristics of each site, to implement GI is essential to have a good classification of local areas. In this sense, the Local Climate Zone (LCZ) classification became a powerful tool for identifying neighborhoods and how urban climate design can be implemented. LCZ is a methodology where the urban environment is classified into ten build-up types and seven land cover types, representing "regions of uniform surface cover, structure, material, and human activity" (Stewart & Oke 2012, 1884). Though in its origin, this classification was developed to help describe the location of meteorological instruments in cities, today, it is used in urban morphology analysis and to describe areas in cities for a diversity of studies, particularly for urban design and urban planning. In general, the studies that examined the different LCZs related to variations in thermal comfort and energy footprint can be used for climate change adaptations and urban climate design (Aslam & Rana 2022). Most of the studies are related to the mitigation of heat exposure and how the urban climate design using the LCZ methodology can improve the population’s quality of life (Grundström & Pleijel 2014; Nemitz et al. 2020; Vos et al. 2013; Middel et al. 2014; Perera & Emmanuel 2018). There are almost no studies that relate the LCZ scheme and urban air quality characteristics.

The main implementation purposes for GI in urban areas are to reduce heat exposure and generate better runoff (Kabisch et al. 2017; Lafortezza et al. 2018). Generally, there is no analysis of the combined effects of the implementations in other aspects of the urban environment, which can become a problem, particularly for urban planners. Considering this, this work focuses on the double effect of GI on thermal comfort and air pollution. Several indexes are used to define thermal comfort, and one of the most relevant is the UTCI (Universal Thermal Climate Index), which represents the equivalent temperature for the environment derived from a reference environment (Zare et al. 2018).

On the other hand, always communicating research results is a challenge, the LCZ scheme became of great help as it presents a good way to show urban morphology, but at the same time, in this work, it is combined with the results of GI interventions regarding air quality and thermal comfort, so the communication can be simple and improved.

## 3 Methodology

The methodology has several parts as the work progresses over the previous results. Regarding the LCZ maps, there are several methodologies. For this work, the GIS approach was used, which implies the generation of more detailed maps than others, like Level 0 data from the WUDAPT project (Ching et al. 2018; Bechtel et al. 2019). Several parameters were calculated using the Territorial Data Consortium of Puglia database (Condivisione della Conoscenza per il Governo del Territorio 2023): Built-up Surface Factor (area occupied by buildings over the total area), Permeable Surface Factor (green surfaces over the total surface), Permeable Surface Factor (it was generated by subtracting green and built-up surfaces from the total area), Average Building Height (using the difference between the base points of each building and the height value); the Sky View Factor (the UMEP - Sky View Factor add-on tool was used, with the building and height data) and finally, using the last product, the Aspect Ratio (relationship between the height of the buildings and the width of the street). Each parameter value was imported in a 10 km x 10 km mesh with cells of 100 x 100 meters. Using a Phyton Code for QGIS that includes the original ranges of LCZ (Stewart & Oke 2012), the map was generated, after three iterations (Buccolieri et al. 2022; Esposito et al. 2023). It is essential to note that this classification focuses on the built-up classes; therefore, the natural cover classes are only presented as an extra-urban area.

With this map, the main LCZs were selected to study how the city structure influences the air quality and the effects of GI. The ENVI-MET software was used to simulate the current conditions and the effects of GI implementation. This software is a 3D model for microclimate focused on cities, which considers buildings (materials and morphology), vegetation (surfaces and 3D trees), sources of pollution, surface characteristics, and meteorological conditions. This approach has been used several times to analyze urban microclimates, the effects of vegetation, and its relationship with air quality (Jing & Liang 2021; Liu et al. 2021; Rui et al. 2019; Tsoka et al. 2018). To determine the meteorological conditions for summer and winter typical days and the pollution in the area, the ARPA database (Agenzia Regionale per la Prevenzione e la Protezione dell'Ambiente 2023) was used. All the urban morphology information and GI implementation were generated in QGIS and imported using the Mode Module – ENVI-MET (Esposito et al. 2023). The pollutant concentration was distributed in the area using the pollution sources tool in the ENVI-MET database. After all this preparation, 14 simulations were carried out: 8 for LCZ 2 (Base case and 3 different cases of GI implementation during summer and winter conditions) and 6 for LCZ 6 (Base case and 2 cases of GI implementation in summer and winter).

The data variation from the Base Case to each implementation case was done in Excel and then imported into ArcGIS Pro to generate the spatial analysis of NOx concentration and thermal comfort. Finally, a detailed urban canyon analysis was done, using Excel and Illustrator.

# 4 Results

The resulting map (Figure 1) shows that the study area presents mostly natural cover areas, including agricultural production surrounding the city, mainly fruit trees. As for the LCZ built-up, the lack of LCZ 1 and 4 is noteworthy, representing areas of very tall buildings (more than ten floors). Regarding the densely built areas, LCZ 2 occupies 9.7 %, and LCZ 3 only 2.7 %, and both are in the city center. On the other hand, the open or less densely built-up areas, which are the most crucial segment of the city, are LCZ 5 (17. 8 %,) LCZ 6 (37.6 %) and LCZ 9 (12 %). Finally, LCZ 8 (warehouses) is 20.4 %, and LCZ 10 (industries) occupies only 0.9 %. The selected sites to be modeled on are also shown in Figure 1. LCZ 2 and LCZ 6 are the two LCZs most frequent in each segment of built-up. At the same time, we will focus on areas where the population is higher and is exposed to poor air quality. In the figure also appear all the weather stations of the area.

### LCZ 2

The LCZ 2 selected site is in the city center of Brindisi. The area has commercial and residential uses. As can be seen in Figure 2 (Base Case), it has three main roads with heavier traffic. Buildings are between 9 and 25 meters high, and for the proposed model, the materials are the Defaults from the ENVI-MET database. Regarding the vegetation in the roundabout, there are olive and magnolia trees;

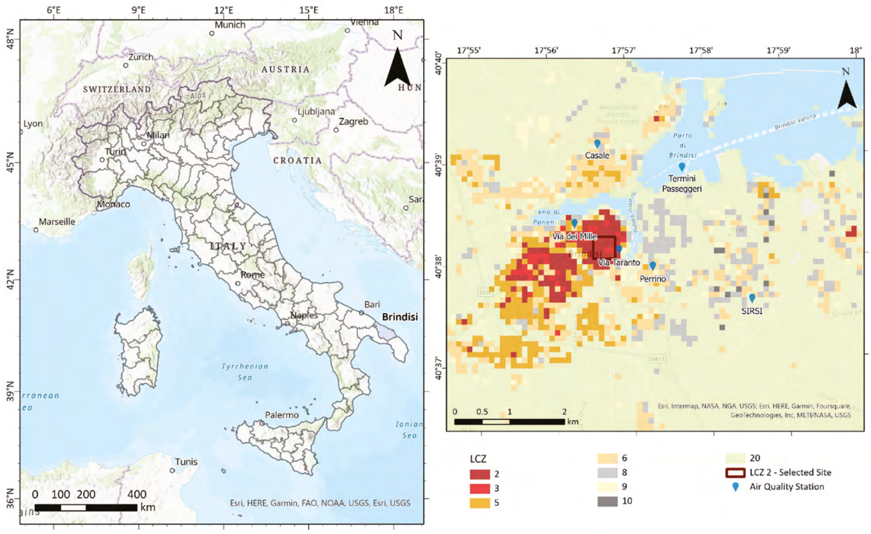


**Figure 1. Location of Brindisi, LCZ of the city, selected sites, and weather stations.**

in the southern part of the area, there are several giant cypresses and pines; and in the main avenues, there are palm trees. Case 1 presents several buildings with green walls. In Case 2, a combination of hedges in the middle of the roads, as boulevards, and increased trees were implemented. Finally, Case 3 only considers more evergreen trees to evaluate their impact in both seasons (Summer and Winter).

Summer and winter NOx concentrations at 5 p.m. from the Base Case are almost the same, with high concentrations near the roundabout and toads east of the site. In both cases, the values are over the WHO regulations. Regarding the variations from the cases, the best conditions are in Case 1 (green walls), but although some areas have improvements, the area affected in the Base Case presents a deterioration. Case 2 (hedges and trees) and Case 3 (evergreen trees) present a worse situation with an increase in NOx of over 10 %, reaching some intersections in Case 3 values of over 50 %. Regarding thermal comfort, the area presents Hot thermal sensations, especially in some courtyards, and general Warm conditions are present in the rest of the area. All the cases show an improvement of over 10 %. Case 2 has better conditions, primarily related to the hedges in the avenues. While Cases 1 and 3 show almost the same spatial distribution.

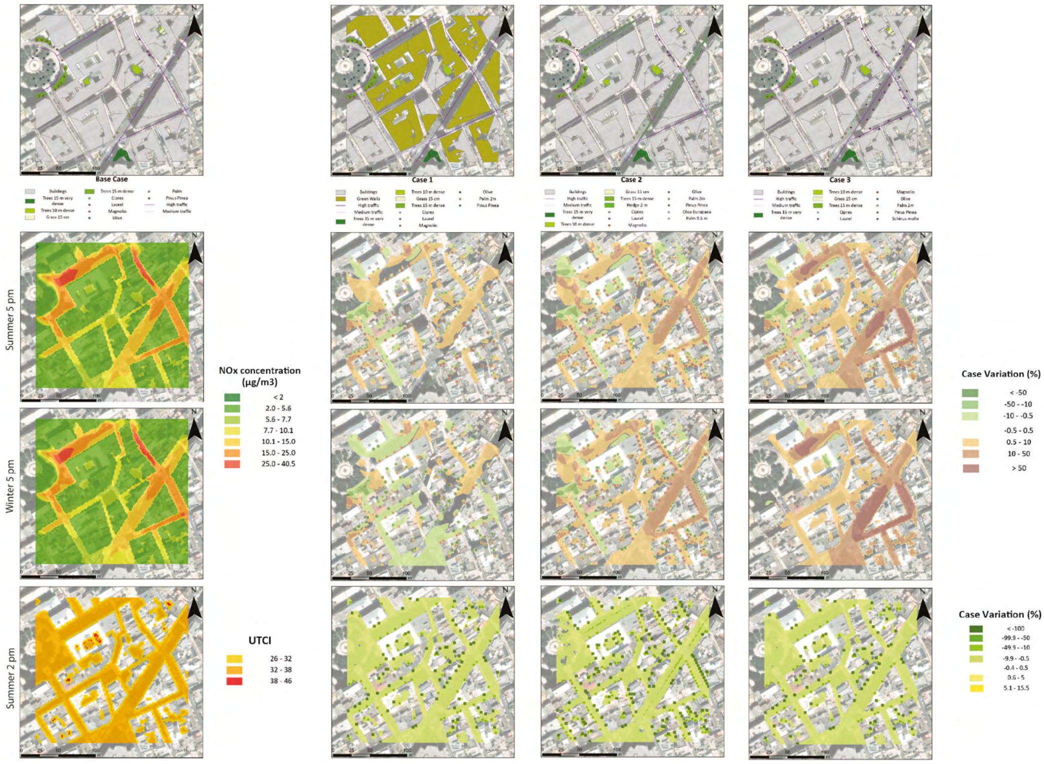


**Figure 2. LCZ 2 cases, NOx concentration, and UTCI spatial distribution and case variation**

To generate a better understanding of the interaction of urban morphology and GI implementations, an urban canyon in the area near the roundabout was selected. Figure 3 shows the selected site that has an Aspect Ratio of 1.22. The three parameters (UTCI, NOx concentration for summer and winter afternoon) are represented for the canyon. As the lower building is the south-facing one, the maximum UTCI is higher near the façade, with the lower values in the center of the canyon as a combination of the wind turbulence and the building shading.

Regarding the NOx concentrations, both seasons show a similar patron with higher values in the central area of the canyon. In contrast, the value is generally higher in summer (25 to 31 µm/m3) than in winter (21 to 27 µm/m3). In relation to the thermal comfort in all three cases, vegetation reduced more than 1 ºC the sensation, while the hedges made a more significant difference as boulevards with a decrease of 4 ºC. Concerning the NOx concentrations, Case 1 (green walls) is the only one that improves the situation in winter and almost does not generate any impact during the summer. On the other hand, Case 2 worsens the situation, increasing the values by 2 µm/m3. Finally, Case 3 generates the worst-case scenario, where more than 8 µm/m3 are added to the atmosphere in each meter. At the same time, the effects are larger in winter than in summer (pay attention to the scale change needed to correctly fit the values).

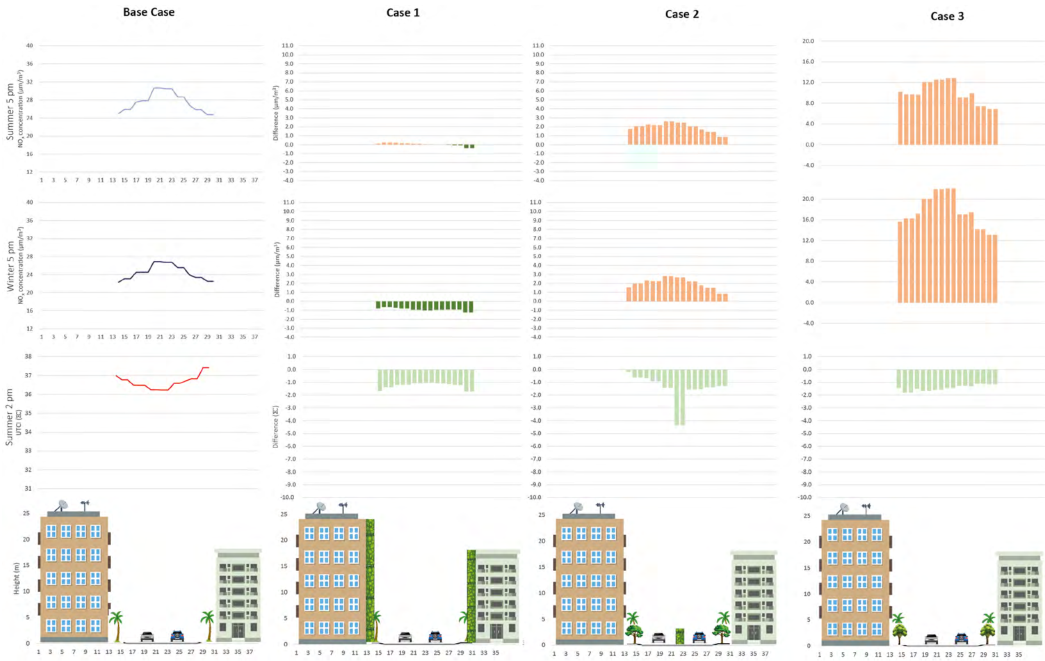


**Figure 3. Urban canyon in LCZ 2. Source: Picone (2023)**

## LCZ 6

The most common LCZ in the area is LCZ 6 (Figure 1); the site selected is located north of Brindisi, near the bay. It is primarily for residential use, and the traffic has been composed of suburban roads. The area presents a fair amount of vegetation (hedges, and trees of different heights). The main tree species are pines and palm trees (Figure 4). Two different GI implementations were tested. In summer conditions, both cases showed an improvement of over 10 % in the center and southeast of the area, while a slight deterioration was captured in the northwest; this correlates with the wind region from the Southeast. On the other hand, winter shows a general improvement of the conditions in both cases and a good synergy with higher velocities in regional winds. Finally, the thermal comfort, in the area is between Warm and Hot sensations. The cases showed a general improvement in the comfort condition with a reduction of almost 10 % in all the areas, while some trees generated even better UTCI values, with a slightly warm sensation.

In this case, the results demonstrate a better impact of the GI than in LCZ 2. This can be traced back to lower traffic levels (half the cars on the main roads of LCZ 2) and broader urban canyons, which allow for a better circulation of local dominant winds. This is especially true considering hedges.

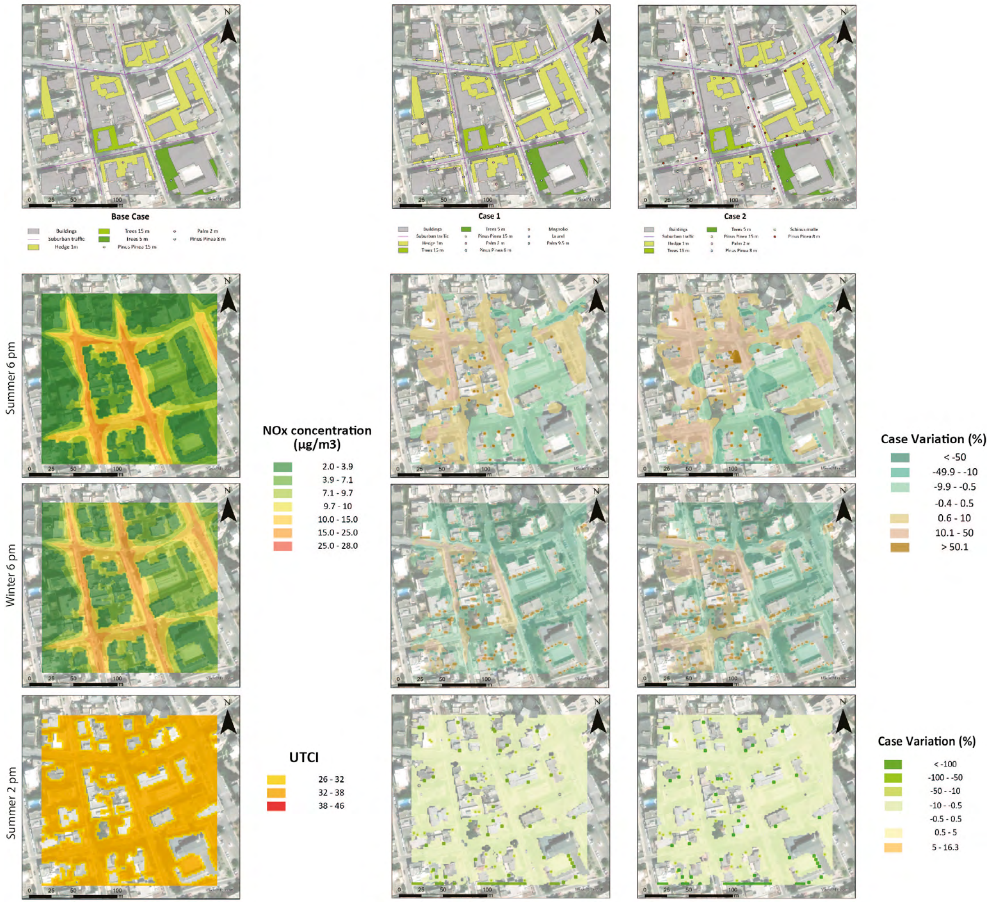


**Figure 4. LCZ 6 cases, NOx concentration, and UTCI spatial distribution and case variation**

The microclimatic analysis was done in a north intersection urban canyon. It has an aspect ratio of 0.25. The UTCI presents high variability, at almost 3 °C, with lower values in the street center and higher ones near the buildings, especially the south-facing ones. Regarding the NOx concentrations, it present low values but with high variability (16 µm/m3). As regards the effects generated by the considered cases, UTCI shows a general improvement that varies from 0.5 °C to more than 1 °C and is more homogeneous in Case 2 than in Case 1. Regarding the NOx concentrations, each case presents particularities. Case 1 generates an improvement during winter, with a reduction from 2 to 5 µm/m3, except where traffic runs. At the same time, in summer, there is an increase in the concentrations (1 to 3 µm/m3), except on the north sidewalks, which present a light reduction. Finally, Case 2 shows that in both seasons, the NOx concentration increased (from 2 to 4 µm/m3) with a focus on the street center and the south of the intersection.


**Figure 5. Urban canyon in LCZ 6. Source: Picone (2023)**

# 5 Conclusions and Discussion

The obtained results correlate well with the existing literature on the trees' negative impact on air quality, particularly in areas with narrow urban canyons (Grundström & Pleijel 2014; Nemitz et al. 2020; Vos et al. 2013). As presented by Abhijith et al. (2017) and Tomson et al. (2021), trees are not a promising intervention for street canyons, and in general, before any GI intervention, the canyon geometry, the local meteorological conditions, and the vegetation characteristics should be carefully considered. As Hewitt et al. (2020) presented, it is crucial to model the implementation of GI and study the possible impacts in the urban environment. In this sense, this study has shown that not all GI interventions will positively impact air quality, but some of them do. For example, in LCZ 2, green walls prevent trapping the pollutants in the canyon and improve the air quality conditions, while in LCZ 6, the hedges and some trees improve local wind circulations and generate more positive effects.

As a general conclusion, when implementing GI, it is recommended to evaluate all its interactions with the urban morphology, traffic patterns, and the climatic conditions of the areas. These three factors became vital to seeing the positive or negative effects of the GI. Moreover, they help to select which of the available GI can be implemented in each condition. After the results obtained in this work, the discussion about how we can improve air quality is back to the basic discussion about which type of street we design: one focuses on cars or one for people. In this sense, this work has shown that though GI implementation can have positive impacts in some cases, they do not have good outcomes in areas with high amounts of pollutants and narrow urban canyons.

The findings in this thesis show that though GI is essential in urban planning, it is only enough to improve the air quality if other plans are implemented, particularly traffic reduction. This is especially important in city centers, where there is often a high concentration of traffic, which implies a high exposure to pollutants, combined with urban morphology that does not allow the GI intervention to improve the air quality.

Finally, the combination of the LCZ scheme, GI interventions, air quality analysis, and comfort impacts, have shown a good interaction between the urban morphology characteristics of each LCZ and which GI can have a positive or negative impact on air quality. This can become a powerful tool to communicate researchers' results about this topic with urban planners, as it helps the association of urban characteristics and other environmental parameters.

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ISBN 978-951-827-475-2 (PDF)
ISBN 978-951-827-476-9 (painettu)

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Co-funded by the Erasmus+ Programme of the European Union