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MUrCS Proceedings 2021

LAB University of Applied Sciences

Technical reviewers: Eeva Aarrevaara, Alexandra Maksheeva & Shammi Keya
Layout: Oona Rouhiainen

ISBN 978-951-827-400-4 (PDF)

Lahti, 2021

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MUrCS

Proceedings
2021

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

GCU Glasgow Caledonian University
LAB University of Applied Sciences
uhu.es Universidad de Huelva

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Abinet has received his B. ED Degree in Geography as well as his M.A Degree in Urban Development and Management from Debub and Addis Ababa Universities in his native Ethiopia. Prior to commencing MUrCS he was a lecturer in the field of Urban Governance and Management in Hawassa University-Ethiopia. His thesis is focused on local climate adaptation in the unique case of high-altitude cities and has particular interest in circular economy solutions to cutting emissions to mitigating climate change.

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Graduated with MSc in Environmental Protection from the National University of Kyiv-Mohyla Academy, Ukraine. Before joining MUrCS, Oksana worked as a researcher at O.M. Marzieiev Institute for Public Health focusing on air quality and environmental health issues and was involved in industry consultancy projects. During MUrCS internship, Oksana contributed to development of the climate adaptation plan for the Päijät-Häme region, Finland. Her research interests encompass climate-proofing the cities, climate-sensitive policies and decarbonization. Oksana's MUrCS thesis evaluated the cooling potential of green infrastructure to mitigate rising temperatures in cities and provided guidance on green interventions to respond to the UHI effect.

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After attaining B.Sc. in Environmental Science from Asian University for Women with a fully funded scholarship, Rabeya Begum joined H&M Group as an intern and worked as a Sustainable Developer (Environment) for 3.5 years in Bangladesh. She served as a master trainer and completed numerous auditing and training on environmental topics like energy, water, waste and chemical management, and wastewater treatment. To promote sustainable urban environment, her master's thesis focused on different methods of urban heat risk mapping of Glasgow city during the MUrCS program, which has provided practical insights to Glasgow City Council on priority intervention areas for climate-sensitive planning.

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Civil Servant

Sonam has been working as an Environment Officer with the Royal Government of Bhutan for over a decade. He has led the formulation of various policies and strategies with regard to climate change in Bhutan. In addition, he also led and conducted numerous studies to assess the vulnerability to a changing climatic system, means of adapting to adverse impacts and also on ways to reduce greenhouse gas emissions. His field of expertise includes policy formulation and technical studies related to climate change.

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Environmental Engineer

Obtained her B.Sc. in Environmental Engineering from Marmara University, Turkey. As an environmental engineer, she specialized in water and wastewater treatment, and worked as a process engineer in private sector. She was responsible delivering the most feasible design solution for water and wastewater management tailored to clients' needs. After joining MurCS she had the opportunity to link her background with sustainability and climate change, that unveiled her interests in climate resilience and sustainability in water management. Her thesis explored water scarcity management in the context of urban climate resilience through a benchmarking study between London, UK and Istanbul, Turkey.

Keya, Shammi Akter

Architect

Shammi has a bachelor's degree in architecture from Bangladesh University of Engineering & Technology, has working experience of over 5 years as an architect, and as a lecturer in the Rajshahi University of Engineering & Technology, Bangladesh (Govt). She worked as a trainee in HYPE project during her master's studies in MUrCS Programme. Her field of interest includes Contextual Architecture, Climate Responsive Urban Planning, and recently Environmental Education for Urban Green Management in Cities- which she researched during her master's thesis. After graduation, she joined the LAB University of Applied Sciences, Lahti, as a project worker.

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Environmental Engineer/Bid Manager

Irmak Özkan has a bachelor's degree in environmental engineering and worked in wastewater and waste to energy sectors which later lead to a broader practice in environmental consultancy with a focus on international donor funded projects in developing countries. She followed the EMJMD MUrCS (Master's in Urban Climate and Sustainability) programme and received her degree in 2021 and studied green infrastructure applications in stormwater management in her master's thesis. Irmak continues working on water/wastewater, circular economy and sustainable development in consultancy sector.

Popal, Abuzar

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Abuzar Popal holds a Bachelor of Science (B.Sc.) in Geomatics from Carleton University and a Master of Science (M.Sc.) in Geospatial Technologies. He is a seasoned geographic information systems analyst with a demonstrated history of working in the environmental/ engineering/retail industries. His recent work includes utilizing GIS solutions to analyze the impacts of natural disasters, the effectiveness of mitigation strategies, and the assessment of environmental policies based on social media data. He has a keen interest in employing machine learning algorithms to analyze/decipher environmental challenges.

Rattanakijanant, Nichamon

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Obtained B.A in Landscape Architecture from Chulalongkorn University in Bangkok. She has five years of experience in the private sector, contributing to the design projects of lake restoration, regenerative mixed-use, roof gardens, urban farms, eco-tourism hospitalities, and environmental impact assessment in Asian cities. As part of MUrCS' collaboration with the Regional Council of Päijät-Häme, she prepared a study report on green infrastructure guiding plan in supportive of the city sustainable development strategy. Her research focuses on the provisioning of climate change adaptation capability through a healthy ecosystem.

Saloma Pacheco, Milagros Guadalupe

Architect

Received her Architecture degree from the Pontificia Universidad Catolica del Peru. Before MUrCS, she worked in airports design and HVAC projects in Peru and Mexico. Furthermore, she participated in a congress about Cultural Landscapes (Peru). During her master studies, she got an internship in Ramboll (Finland) for developing an interactive sustainability map for the City of Lahti (European Green Capital 2021). After completing her studies with distinction, she joined NatureScot for Natural Capital Accounting in urban Nature-based Solutions. Her master thesis focused on temporary interventions and their impact on microclimate, thermal comfort and the livability of Lahti´s Market Square.

Sethupatu Bala, Raju

Architect and Urbanist

With a Bachelor of Architecture from Sathyabama University, India and a Master of Architecture (majors in urban design) from CEPT University, India, Raju was practising Architecture and was involved in academia for four years before joining MUrCS. During MUrCS, he worked as a summer intern for the municipality of Hollola and identified quiet places in Hollola, Finland, using a decibel meter. In his MUrCS dissertation, in collaboration with the CNRS & LISST at Toulouse, France, he identified complementary spatialized indicators to support the urban climatic mapping approach for better urban planning and urban design climatic responsive decisions.

Simath, Shifana

Chartered Architect

Shifana graduated from the University of Moratuwa, Sri Lanka. Having served one of the top architectural consultancy firms for five years, she gained hands-on experience in architectural and urban design projects. She worked as an intern for the Regional Council of Päijät-Häme, Finland. Having exposure in planning, her MUrCS thesis focused on one of the imminent threats in developing countries - urban overheating. She elaborated on Sri Lanka as a case study and explored practical ways of incorporating climate actions in the local planning landscape. Her future work will focus on urban climate actions and climate-sensitive policy in developing countries

Stohmann Aguirre, Roberto Enrique

Civil Engineer

Graduated in Civil Engineering from Universidad Privada del Valle and obtained a master’s degree in public policy and Management from Universidad Católica Boliviana. He started his professional career as a project engineer consultant in Chile. Since 2013, Roberto has transitioned to the public sector in Bolivia, acquiring solid expertise in water utilities regulation, technical advisory, and policies development for national and municipal institutions. He is keenly interested in blue-green infrastructures, circular economy and climate-focused urban policies. His MUrCS thesis delved into the impacts of urbanisation and climate change on drainage performance while simulating its enhancement through sustainable solutions.

Suher Carthy, Banu Melis

Urban Planner

Graduated with an Urban Planning degree from METU, Ankara, she obtained her MSc in Urban Policy. As an urban professional in the private sector, she took part in various projects from urban conservation to development for several Turkish cities. Through geospatial projects she assisted the development of web and desktop based spatial applications for local authorities. During MUrCS she turned her focus towards urban climate data management. Her thesis was founded on the analysis of 47 French cities’ urban climate data in collaboration with LISST Toulouse & CNRS where she provided case-based recommendations to mitigate urban heat island impact.

Valdez, Murielle Aira A.

Architect

She worked as a professional architect in the Philippines for four years before taking her master’s degree in Europe and the UK under an Erasmus+ scholarship programme. Her academic achievements include graduating with honours during her bachelor’s degree in Architecture and MSc in Sustainable Urban Environments. As a self-determined individual, she believes that there should be a proper balance between built and natural environment, leading her to her ultimate goal of providing a much more liveable place without disrupting mother nature and the people’s way of living.

Summary

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The Master of Urban Climate and Sustainability (MUrCS) Project (www.murcs.eu) is pleased to bring out the second in our series of "summary for practitioners" arising from Student Thesis projects. The successful continuation of the Project is underpinned by the Thesis work by our students and it highlights the practical relevance of their work in addressing climate change adaptation in general and urban climate change in particular. 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 change in our time.

Two key themes are highlighted in the present volume. On the one hand, approaches to climate change adaptation in different urban contexts and addressing different hydro-meteorological risks is a key strand of work reported in the present volume. On the other, the specific issue of urban heat island / urban overheating mitigation continues to play a dominant role in the research activities of our students. There are additional cross-cutting work that straddle the two as well as expand the MUrCS approach into new areas.

The first section showcases practical relevance of student work in climate change adaptation in specific context and/or addressing specific climate risks. **Adela** discusses the case of twelve high altitude cities around the world. This work highlights the need for external intervention, but also the specific risks facing high altitude cities (in particular flood protection as well as drought/water scarcity and forest fire). The need for local expertise and capacity building is also highlighted, a role close to the ethos of MUrCS. **Iskenderoglu-Atahan** explores the management of water scarcity as an urban climate resilience action. The concept of urban resilience is contextualized in a framework, followed by a set of indicators, and a quantitative assessment tool tailored to water scarcity management is developed based on this framework. The next two studies tackle urban resilience in the face of flooding within the framework of sustainable urban drainage systems (SUDS) but from two diametrically opposed climatic contexts. **Ozkan** showcases the runoff reduction performance of green roofs under climate change scenarios for a wet, flood prone city (Dublin, Ireland) whereas **Stohmann Aguirre** highlights the case of a high altitude dry-zone city (La Paz, Bolivia). Both studies highlight the central role of SUDS even in the face of opposing trends in rainfall and promote ways to integrate this into the urban planning process. **Rattanakijanant** takes an ecosystem health and ecosystem services/disservice mismatch approach to highlight the role of green networks in local climate change adaptation. Given the paucity of focus on ecosystem health when highlighting the role of green networks in climate change adaptation, this study contributes new knowledge to minimise ecosystem disservices so as to promote the integrity of the green network.

The largest collection of studies falls under the specific theme of urban heat island / urban overheating mitigation. Given the focus of MUrCS (i.e. urban climate and sustainability) it is no surprise that this continues to be the case as in the previous year, but the coverage has expanded from maritime temperate climate of Glasgow to cold, temperate climate of Lahti, continental, temperate cities in France and hot, humid Colombo, Sri Lanka. **Ananyeva** highlights the urban heat island (UHI) intensity in Glasgow and its significant spatial clustering effect that has policy implications for local climate adaptation. Together with **Valdez**, Ananyeva studied the role of the Glasgow Avenues Project in mitigating the expected local warming by the use of green cover (Ananyeva) and urban form and building materials (Valdez). These studies found that the Avenues Project could be very useful to address the growing UHI problem that is likely to worsen with climate change, but also suggest ways to improve the performance of the local interventions. **Begum** highlights the role of urban climate mapping as a planning decision-making tool in Glasgow and shows that the decision to map green infrastructure as an indicator climate risk or adaptive opportunity or even climate vulnerability could lead to very different recommendations for local actions. This has implication for UHI mitigation not only in Glasgow. **Saloma-Pacheco** studied the role of temporary interventions in a cold climate city (Lahti, Finland) in enhancing the usability of the outdoors. The study found that temporary interventions could create more comfortable environments at specific hours, that could contribute to positive place-making in this cold climate city. **Sethupathu Bala** develops spatialized indicators for Toulouse, France, to aid climate-responsive planning decision making. The significance of urban parameters to the UHI problem changes according to the location and this knowledge could be important for a more nuanced approach to climate sensitive design. **Suher-Carthy** develops a methodology to conduct microclimatic analysis and deliver recommendations for 47 French cities, using the chorematic technique – a visualisation technique popularised in France to make sense of the increasingly large and complex geospatial data1. The workflow created in this study could simplify the communication of urban climate information to city planners in an efficient manner. Finally, **Simath** takes a pragmatic approach in identifying the barriers and opportunities to implement urban climate knowledge through planning action in the context of a warm, humid city (Colombo, Sri Lanka). Given the urgency of the need for climate-sensitive planning, especially in warm climate cities, this study could chart a practical course of action to improve local thermal comfort in developing cities.

There are three further 'cross-cutting' studies that have the potential to push the MUrCS approach towards new and exciting directions. **Dagay** develops a roadmap to decarbonise the fleet vehicles of the largest Health Authority in Scotland (National Health Service – Greater Glasgow and Clyde [NHS GG&C] Health Board). The study identifies and analyses the key factors affecting the decarbonisation of transport and backcast to assess the implications of achieving "net zero emission" fleet. **Keya** explores the potential of Environmental Education Practice (EEP) as an Urban Green (UG) management tool in cities with contrasting socio-economic settings and attitudes to the outdoors (Lahti, Finland and Dhaka, Bangladesh). This work enhances our understanding of contextual differences, even within a given city to promote or hinder pro-environmental behaviours and willingness to participate in outdoor educational activities. Another very different work by **Popal** attempts to use machine learning algorithms to identify the most vulnerable areas in a heatwave-affected region, with a view to aid disaster risk reduction. It creates a workflow to combine city-scale analysis with neighborhood-scale explorations to highlight the most severely affected areas in greater detail, and explore mitigation options to reduce the risk. These two studies are harbinger to new directions that MUrCS research could take in the coming years.

These actionable research is a small snapshot of the kind of possibilities that the 'new' professionals engendered by the MUrCS approach are able to achieve. Our hope is that urban practitioners and policy makers find these practical investigations to be of value in their quest to address climate change in cities.

Climate change adaptation in different urban contexts

ADELA, ABINET ASSEFA

1

Local Climate Adaptation in High Altitude Cities:

The Case of Twelve High Altitude Cities

This paper tries to find out the factors that determine local climate adaptation in high altitude cities by statistically testing thirty potentially influencing independent variables against the existence of a climate adaptation plan which is the dependent variable. Furthermore, it investigated the most pronounced climate change hazards and adaptation strategies. The results indicate that membership of ICLEI, donor agency support, proportion of green spaces, level of CO_2 *emission, existence of a climate expert body and existence of a climate concerned civil society act as drivers for formulating a climate adaptation plan. However, there are no significantly correlated negative factors. Based on analysis of the result, Cities are more likely to develop climate action plan with donor support than by their own initiative. Institutional and socioeconomic factors are more important than climate risk factors, Locational/geographic factors are not influential in driving the development of climate action plan. The evaluation matrix analysis shows Surface flooding is the most pronounced climate vulnerability in high altitude cities followed by drought/ water scarcity and forest fire. The most common adaptation strategy carried out belong to the engineering and built environment. Overall, the results indicate that Cities that are at high risk of climate change need external intervention in terms of donor support to formulate a climate action plan, High altitude cities should invest more on flood protection, drought/water scarcity and forest fire, local governments has to formulate a way of effectively engaging public participation in the process of developing a climate adaptation plan, Cities need to act in a pro-active manner by instituting a city-level climate expert body that also deals with donors in the process of developing a climate adaptation plan. Finally, this study could have relevance in terms of strengthening local climate adaptation planning in the specific case of high-altitude cities.*

1 Introduction

When it comes to adaptation, cities are particularly important for three reasons. First the future of the world depends much on cities. Much of the world population is set to live in cities (World Bank n.d.). Coupled with the growing global urbanization trend, cities are emerging as a dominant and powerful governance structures that challenge the nation states (Curtis 2018). Therefore, the growing importance of cities coupled with already happening extreme climate events makes the agenda of adaptation in cities a pressing need. Secondly, cities occupy a unique micro-climate that affect the elements of climate particularly temperature and wind, with resulting effect of mainly urban heat island (UHI) (Hebbert & Mackillop 2011). And climate change further exacerbates the UHI, the flood risk and other climate risks. Thirdly the concentration of people and infrastructures and the fact that these all are interconnected make cities a sensitive place for climate change. In addition, cities are in a better position in terms of, for instance enhancing the resilience to climate change using such municipality operation tools as land-use policies and zoning regulations (Araos et al. 2016). The decision to develop a city-wide climate adaptation plan is a symbol of the commitment from the side of the city government to dealing with climate risks at a local level (Tang et al. 2010). Most often climate change adaptation plans contain lesser binding principles but numerous goals and strategies. The detail among cities differs greatly. Some cities give emphasis and provide a detailed and time bound goals or objectives, other put in a general statement (Beaulieu et al. 2016). Adaptation, therefore, along with mitigation is one of the important tools by which cities can deal with climate change.

Although research in the field of local/urban climate change adaptation is growing, there is still a lot unknown about the issue of adaptation. For instance, there is a breadth of research and rich knowledge regarding adaptation options and about impacts of adaptation and adaptive capacity (Klein et al. 2014). There is no limit of knowledge about how to adapt, but there is limitation in knowledge about the factors that influence the implementation of adaptation options. This is a particularly important point because cities can adapt does not mean they will. There is a wide gap in implementing adaptation actions and knowing the capacity to adapt. Throughout the previous decade institutional responses to the impacts of climate change has been growing, but with much emphasis on mitigation efforts. And recently there has been a growing activity in adaptation response too both in the academic research line and in development of adaptation policies among city governments (Ford & King 2013)

There are so many cities that are in areas vulnerable to climate change. Cities located at high altitude are some of these that are prone to the risks of climate change. Cities located at high altitude are more exposed to such climate risks as frequent and intense hydrometeorological events including flooding. Additionally, the variability in the rainfall amount makes these cities more vulnerable to droughts (Torres et al. 2021). Studies so far emphasize on the evaluation of climate action plans (Reckien 2018, Stevens & Senbel 2017, Baker et al. 2012, Hardoy & Lankarao 2011). Few studies conducted to investigate the factors that influence the adoption or formulation of climate action plans (Reckien et al. 2015, Hyejung & Grafakos 2019). Cities depending on their altitude, latitudinal location, and proximity to the coast experience different climate, hence different or contextual challenges when it comes to adapting to the impacts of climate change. Therefore, studying the local adaptation situation of cities in their contexts helps to formulate an appropriate climate adaptation strategy. This study is focused on investigating the determinants of local climate adaptation among high altitude cities. Altitude is one of the determinants of climate and weather. Therefore, cities located at high altitude experience different weather and climate than their counter parts of low-altitude or mid-altitude (Vuille 2014). The condition of climate change adaptation might differ as well. To my knowledge, there is no study conducted on this topic. Therefore, this study tries to find out the determinants of climate change adaptation and climate change risks and strategies in the context of high-altitude cities.

1.1 Aims and Objectives

The aim is to advance the understanding of local climate adaptation in the unique case of high-altitude cities.

Objectives

- To find out the factors that determine local climate adaptation in the context to high altitude cities
- To investigate the most pronounced/most common climate change impacts to which the case study cities are adapting, and the adaptation measures they are undertaking
- To present a comparative analysis of this study's results with other similar studies
- To suggest recommendations for local climate adaptation planning in high altitude cities

2 Background

Cities are the most important entities when it comes to combating climate change. Cities consume a significant majority of resources, energy, and material resources, hence are significant polluters of the atmosphere particularly GHGs. Cities produce more than 70% of global anthropogenic GHG emissions and consume 75% of the total energy demand. Climate change already happening. Cities in different parts of the world and in different geographic locations are experiencing extreme weather events including high variability in climate elements and associated climate risks such as surface flooding, heat waves, landslides, drought, etc. Therefore, it is a crucial time city must figure out how to adapt to the changing climate situations and associated risks and vulnerabilities (IPCC 2014).

The degree of sensitivity to the risks of climate change depends on the geographical location of cities. Cities located on low laying landscapes are more sensitive than others. Equally high-altitude areas are more sensitive to climate change (Arsiso et al. 2018, Vuille 2014). Therefore, it becomes even an urgent matter for cities located in such geographies to develop a climate action plan. One of the measures for reducing the risk of climate change is by shifting towards a system where it can adapt to the changing climate. Therefore, developing a city-specific climate adaptation plan is a necessity. However, it seems mitigation gained more emphasis than adaptation when it comes to dealing with climate change (Carter et al. 2015). But climate change is already happening (IPCC 2014). Therefore, in addition to the efforts being made to cut GHGs, there must be a system of adapting the already happening climate risk. However, not all cities are showing an effort to adaptation (IPCC 2014). Therefore, it is necessary that research in this area be conducted to generate more scientific knowledge that helps the smooth transformation towards developing a system that adapts to the risks of climate change. The good news, however, is the level of academic research in this field is growing, with many publications coming out (IPCC 2014).

Traditionally adaptation activity has been dealt at national level by formulating national adaptation strategies (Agrawal & Perrin 2010). However, in recent years local climate adaptation is gaining attention due to different reasons. Firstly, the thinking adaptation is local that several adaptation literatures argue is gaining acceptance. It is true that even though climate change is a global phenomenon, the impact is felt at local level. There is also variability of climate impact in different places that necessitate specific place based adaptation strategies (B.L.Turner et al. 2003). Moreover, in terms of governance, local governments are the legitimate entities to deal with adaptation by structuring responses, mobilizing resources, and governing the delivery (Agrawal & Perrin 2010). Secondly so far international effort to deal with climate change bears little fruit and progress in achieving international collaboration is terribly slow. Therefore, local climate adaptation is viewed as a way out from such international barriers (Measham et al. 2011). Although local climate adaptation is more relevant with local level governments, eventually factors beyond the local government level influence the process of local climate adaptation planning (Agrawal & Perrin 2010)

Revi (2014) and Klein (2014) state that studies have identified several drivers and barriers to climate change adaptation. According to Moser and Ekstron (2010), barriers are defined as obstacles that can be overcome with concerted effort, creative management, change of thinking, prioritization, and related shifts in resources and institutions. Such barriers can be summarized into three groups as biophysical, locational, and socio economic. Drivers on the other hand are conditions that enable climate change adaptation through the process of developing and successfully implementing a climate action plan. These factors can also be socio economic, institutional, and physical (Reckien et al. 2015). Moreover, IPCC (2014) was able to identify the factors that influence climate change adaptation. These factors included, population age structure, income, technology, relative prices, lifestyle, regulation, governance structure, scientific information, and knowledge, local governance capacity, multilevel governance, networks and partnerships, community engagement, and education. It also adds that factors that influence adaptation are not well understood. Overall, the factors identified as barriers and enablers in the previous mentioned studies can be categorized as institutional, socio-economic, and environmental.

3 Methodology

3.1 Data Source, Data Collection and Sample Selection

This study is based on web-based content analysis of twelve high elevation cities (see table 1). The study focuses on local climate adaptation in the context of high elevation cities. The criterion to select the sample cities is elevation >1593m above sea level (Statista 2021). It is a proven fact that altitude modifies the local climate (Vuille 2014) Hence, the objective of this study is to see if that has something to do with the local climate adaptation and if the high-altitude cities have unique situation when it comes to local climate adaptation. The study adopted the (Statista 2021) cutoff point of high elevation cities. And the list of cities above 1593m is obtained from the same site (Statista 2021) that classified 20 high altitude cities in the world. However, it must be noted that some literatures classify an area as high altitude which is above 2500m above sea level. But for this research purpose the classification of the site (Statista 2021) is taken as a criterion. From among the twenty high altitude cities twelve of them are selected purposively.

Country	City	Title of the Document	Year of Publication	Source
USA	Denver	City and County of Denver Climate Adaptation Plan	2014	Denver Open Data Catalog Search (denvergov.org)
Ecuador	Quito	Resilience Strategy: Metropolitan District of Quito	2017	Quito is taking action on climate change | Global Covenant of Mayors
Mexico	Mexico City	CDMX (Mexico City) Resilience Strategy	2016	http://www.data.sedema.cdmx.gob.mx/.
	Toluca	Municipal Climate Action Plan, Toluca	2013	Climate Action Plans for Cities | Urban Climate Change Research Network, North America (uccrnna.org)
South Africa	Johannesburg	City of Johannesburg: Climate Action Plan, 2021	2015	https://www.globalcovenantofmayors.org/.
Colombia	Bogota	District Disaster Risk Management Plan and Climate Change for Bogota D.C: 2018-2030	2018	¡Bogotá, más cerca de la gente! | Bogota.gov.co.
Ethiopia	Addis Abeba	Has a consultation document		
Bolivia	La Paz	No climate action plan		
	Cochabamba			
Kenya	Nairobi	No climate action plan		
Mexico	Puebla			
Colombia	Medellin	Has mitigation plan without integrating adaptation		

Table 1. List of Sample Cities (Table: Adela 2021)

For the twelve sample cities a database of one dependent variable, existence of a published adaptation plan for the city, which could also be integrated with the city's mitigation plan and thirty independent variables was prepared. These variables are considered either potential drivers or barriers for the development of a local climate adaptation plan. The variables are obtained from (Reckien et al. 2015, Hyejung & Grafakos 2019) and are believed to be exhaustive of enabling factors and barriers for the formulation and execution of local climate adaptation plan.

Category	Variables
Institutional	C40 Member
	Covenant of Mayors Member
	Member of ICLEI
	Covenant of Mayors Plan Submitted
	City Level Expert Body or Commission
	Donor Agency Contribution to the Development of City Level Climate Change Adaptation Strategy
	Common National Institutional Arrangement
Socio-Economic	GDP
	Population Size
	GDP Per Capita
	Unemployment rate
	Population Growth Rate
	Gini-Coefficient
	City Level environmentally concerned Body
	Smart-City Index
	CO_2 Emissions
	Proportion of Green Space
Physical/ Environmental	Total Amount of RF
	Average Temp.
	Flood Risk/Surface
	Rainstorm
	Landslides
	Forest Fire
	Heatwave
	Drought
	Public Health
	Urban Fire
	Mass Removal
	River flood
	Wind
	Fresh Water Supply Risk

Table 2. Institutional, Socio economic and Environmental Variables (Table: Adela 2021)

For content analysis of climate action plans the documents are obtained from the websites of the municipalities of each cities and through Search the website of the city authority for availability of published climate change adaptation planning documents or with the following string of words (obtained from related literatures) is used to search the web: [city name] Climate Change Strategy, Climate Change Action Programme; Sustainable Development Action Plan; Climate Change and Energy Security Framework, Climate Change and Environmental Protection, Climate Change Adaptation plan, Climate Change Adaptation Strategy, etc.

3.2 Data Analysis

The independent variables are associated statistically with the existence of a standalone climate adaptation plan or a plan that integrates both mitigation and adaptation which is the case for most of the cities. To do this correlation and regression statistical analysis is found to be appropriate. But before conducting the correlation and regression analysis the data for each variable is coded to change into numeric, so it will allow to run statistical analysis on MS Excel.

The dependent variable is a dichotomous categorical variable (i.e., existence of a climate action plan, if yes (1), if no (0) and some of the independent variables are categorical with dichotomous and the rest are ordinal variables with more than 2 ranks or categories. To do statistical association between a categorical variable with a dichotomous option and an ordinal variable, Spearman rank correlation coefficient is found to be appropriate (Tzani-Pepelasi 2017). A correlation statistical analysis is conducted on MS Excel where the positive significant variables($r>+0.5$) are identified as potential drivers and variables with ($r<-0.5$) are identified as barriers for the formulation and execution of an adaptation plan which is the dependent variable. The significant factors are further analyzed using regression analysis to determine the actual causal relationship that existed between the independent and dependent variable.

For conducting content analysis of the climate action plans an evaluation matrix is prepared based on (Hurlimann et al. 2021) where codes are developed to represent different contents.

Variables	Code
Existence of A stand-alone or integrated Climate Adaptation Plan	Yes=1, No=0
Member of Climate Alliance	Yes=1, No=0
C40 Member	Yes=1, No=0
Covenant of Mayors Member	Yes=1, No=0
Member of ICLEI	Yes=1, No=0
Covenant of Mayors Plan Submitted	Yes=1, No=0
Climate Related Governing Structure	Yes=1, No=0
City Level Expert Body or Commission	Yes=1, No=0
Donor Agency Contribution to the Development of City Level Climate Change Adaptation Strategy	Donor Supported=1, Not Supported=0
Common National Institutional Arrangement	Yes=1, No=0
Population Size	>1.5 mill. =3, 500,000-1.5mill. =2, <500,000=1
Population Density	>1,500p/km2=3(h), 150
GDP	High Income=4, Upper Middle Income=3, Lower Middle Income=2, Low Income=1
GDP Per Capita	High Income=4, Upper Middle Income=3, Lower Middle Income=2, Low Income=1
Unemployment rate	High Rate of Unemployment=2, Low Rate of Unemployment=1
Population Growth Rate	High=3, Medium=2, Low=1
Gini-Coefficient	High Gini-Index=2, Low Gini Index=1
City Level environmentally concerned Body	Yes=1, No=0
Smart-City Index	Ranked=1, Non-existent on the Index=0
Altitude	High Altitude, yes=1, No=0
Total Amount of RF, mass removal	High=3, Medium=2, Low=1
CO_2 Emissions, river flood	High=3, Medium=2, Low=1
Average Temp., wind	High=3, Medium=2, Low=1
Proportion of Green Space	High=3, Medium=2, Low=1
Availability of Green Space	High=3, Medium=2, Low=1
Exposure to Weather Extremes	High=3, Medium=2, Low=1
Surface Flood Risk, Public health	High=3, Medium=2, Low=1
Rainstorm, fresh water supply risk	High=3, Medium=2, Low=1
Landslides, Urban fire	High=3, Medium=2, Low=1
Forest Fire, heat wave, drought	High=3, Medium=2, Low=1

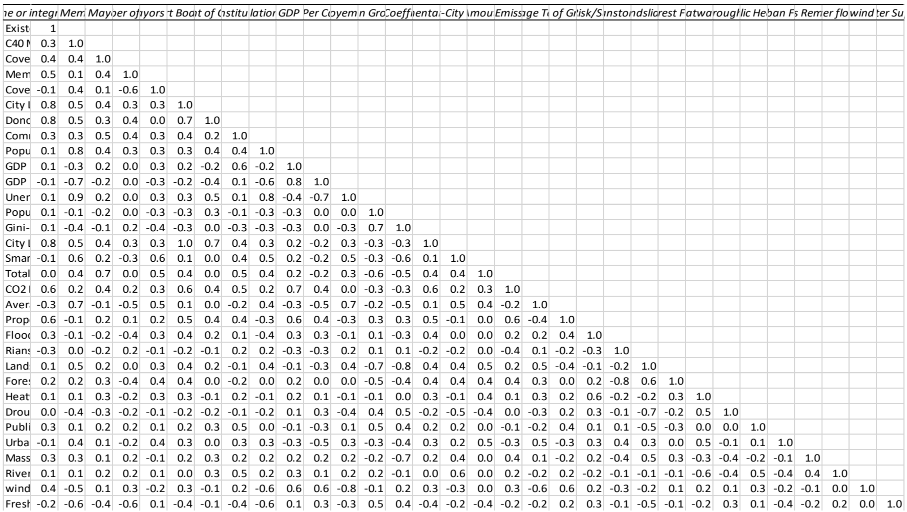
Table 3. Code Book (Table: Adela 2021)

4 Results

4.1 Correlation Coefficient Analysis

A correlation coefficient analysis was conducted on MS Excel with thirty independent factors and one dependent factor. The independent factors are considered potentially influencing (either driving and constraining) the formulation and successful implementation of an adaptation plan. At confidence level ($p<0.05$) 6 factors are found to be significantly correlated. Any correlation coefficient result with (r) > + 0.5 is considered significant. All the significantly correlated factors are driving factors with positive sign, and these are: membership of ICLEI, existence of city level climate expert body, existence of climate change concerned body in the city, donor agency contribution to the development of a climate adaptation plan, CO_2 emission level of the city, and proportion of green space the city possess.

From the correlation significant negative results could not be obtained. Therefore, the statistical analysis did not yield significant negative variables which means barriers to the formulation and implementation of a plan could not be identified.



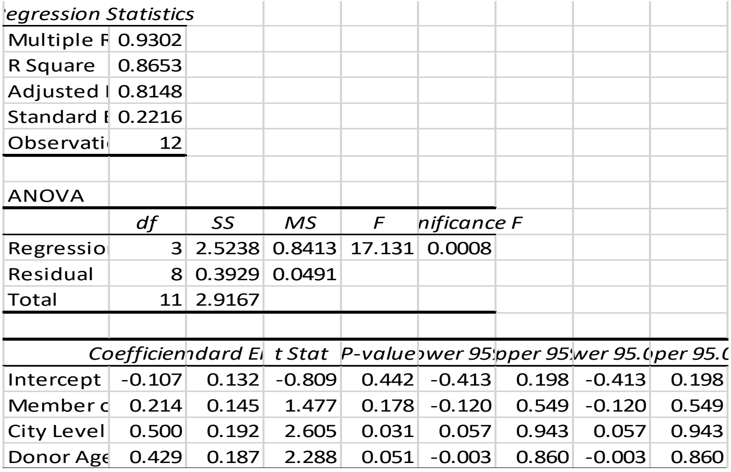
e or	integr	Mem	May	er of	yors	t Boa	t of (	stitu	latior	GDP	Per C	yem	n Gro	Coeff	enta	-City	mou	Emiss	ge T	of Gr	isk/S	nsto	ndsli	rest F	atwa	roug	lic He	ban F	Rem	er flo	wind	ter Su
Exist	1																															
C40 N	0.3	1.0																														
Cove	0.4	0.4	1.0																													
Mem	0.5	0.1	0.4	1.0																												
Cove	-0.1	0.4	0.1	-0.6	1.0																											
City l	0.8	0.5	0.4	0.3	0.3	1.0																										
Donc	0.8	0.5	0.3	0.4	0.0	0.7	1.0																									
Comi	0.3	0.3	0.5	0.4	0.3	0.4	0.2	1.0																								
Popu	0.1	0.8	0.4	0.3	0.3	0.3	0.4	0.4	1.0																							
GDP	0.1	-0.3	0.2	0.0	0.3	0.2	-0.2	0.6	-0.2	1.0																						
GDP	-0.1	-0.7	-0.2	0.0	-0.3	-0.2	-0.4	0.1	-0.6	0.8	1.0																					
Uner	0.1	0.9	0.2	0.0	0.3	0.3	0.5	0.1	0.8	-0.4	-0.7	1.0																				
Popu	0.1	-0.1	-0.2	0.0	-0.3	-0.3	0.3	-0.1	-0.3	-0.3	0.0	0.0	1.0																			
Gini-	0.1	-0.4	-0.1	0.2	-0.4	-0.3	0.0	-0.3	-0.3	-0.3	0.0	-0.3	0.7	1.0																		
City l	0.8	0.5	0.4	0.3	0.3	1.0	0.7	0.4	0.3	0.2	-0.2	0.3	-0.3	-0.3	1.0																	
Smar	-0.1	0.6	0.2	-0.3	0.6	0.1	0.0	0.4	0.5	0.2	-0.2	0.5	-0.3	-0.6	0.1	1.0																
Total	0.0	0.4	0.7	0.0	0.5	0.4	0.0	0.5	0.4	0.2	-0.2	0.3	-0.6	-0.5	0.4	0.4	1.0															
CO2 I	0.6	0.2	0.4	0.2	0.3	0.6	0.4	0.5	0.2	0.7	0.4	0.0	-0.3	-0.3	0.6	0.2	0.3	1.0														
Aver	-0.3	0.7	-0.1	-0.5	0.5	0.1	0.0	-0.2	0.4	-0.3	-0.5	0.7	-0.2	-0.5	0.1	0.5	0.4	-0.2	1.0													
Prop	0.6	-0.1	0.2	0.1	0.2	0.5	0.4	0.4	-0.3	0.6	0.4	-0.3	0.3	0.3	0.5	-0.1	0.0	0.6	-0.4	1.0												
Flooc	0.3	-0.1	-0.2	-0.4	0.3	0.4	0.2	0.1	-0.4	0.3	0.3	-0.1	0.1	-0.3	0.4	0.0	0.0	0.2	0.2	0.4	1.0											
Rians	-0.3	0.0	-0.2	0.2	-0.1	-0.2	-0.1	0.2	0.2	-0.3	-0.3	0.2	0.1	0.1	-0.2	-0.2	0.0	-0.4	0.1	-0.2	-0.3	1.0										
Land	0.1	0.5	0.2	0.0	0.3	0.4	0.2	-0.1	0.4	-0.1	-0.3	0.4	-0.7	-0.8	0.4	0.4	0.5	0.2	0.5	-0.4	-0.1	-0.2	1.0									
Fores	0.2	0.2	0.3	-0.4	0.4	0.4	0.0	-0.2	0.0	0.2	0.0	0.0	-0.5	-0.4	0.4	0.4	0.4	0.4	0.3	0.0	0.2	-0.8	0.6	1.0								
Heat	0.1	0.1	0.3	-0.2	0.3	0.3	-0.1	0.2	-0.1	0.2	0.1	-0.1	-0.1	0.0	0.3	-0.1	0.4	0.1	0.3	0.2	0.6	-0.2	-0.2	0.3	1.0							
Drou	0.0	-0.4	-0.3	-0.2	-0.1	-0.2	-0.2	-0.1	-0.2	0.1	0.3	-0.4	0.4	0.5	-0.2	-0.5	-0.4	0.0	-0.3	0.2	0.3	-0.1	-0.7	-0.2	0.5	1.0						
Publi	0.3	0.1	0.2	0.2	0.1	0.2	0.3	0.5	0.0	-0.1	-0.3	0.1	0.5	0.4	0.2	0.2	0.0	-0.1	-0.2	0.4	0.1	0.1	-0.5	-0.3	0.0	0.0	1.0					
Urba	-0.1	0.4	0.1	-0.2	0.4	0.3	0.0	0.3	0.3	-0.3	-0.5	0.3	-0.3	-0.4	0.3	0.2	0.5	-0.3	0.5	-0.3	0.3	0.4	0.3	0.0	0.5	-0.1	0.1	1.0				
Mass	0.3	0.3	0.1	0.2	-0.1	0.2	0.3	0.2	0.2	0.2	0.2	0.2	-0.2	-0.7	0.2	0.4	0.0	0.4	0.1	-0.2	0.2	-0.4	0.5	0.3	-0.3	-0.4	-0.2	-0.1	1.0			
River	0.1	0.1	0.2	0.2	0.1	0.0	0.3	0.5	0.2	0.3	0.1	0.2	0.2	-0.1	0.0	0.6	0.0	0.2	-0.2	0.2	-0.2	-0.1	-0.1	-0.1	-0.6	-0.4	0.5	-0.4	0.4	1.0		
wind	0.4	-0.5	0.1	0.3	-0.2	0.3	-0.1	0.2	-0.6	0.6	0.6	-0.8	-0.1	0.2	0.3	-0.3	0.0	0.3	-0.6	0.6	0.2	-0.3	-0.2	0.1	0.2	0.1	0.3	-0.2	-0.1	0.0	1.0	
Fresh	-0.2	-0.6	-0.4	-0.6	0.1	-0.4	-0.1	-0.4	-0.6	0.1	0.3	-0.3	0.5	0.4	-0.4	-0.2	-0.4	-0.2	-0.2	0.2	0.3	-0.1	-0.5	-0.1	-0.2	0.3	0.1	-0.4	-0.2	0.2	0.0	1.0

Figure 1. Correlation Matrix (Figure: Adela 2021)

4.2 Regression Analysis

The six significantly associated factors are selected for further regression analysis to determine whether they are actual causal factors and the degree of influence. The factors are membership of ICLEI, existence of city level climate expert body, donor agency support, existence of environmentally concerned body, level of CO_2 emission and proportion of green spaces the city possess. Before the regression operation is run two variables i.e., level of CO_2 emission and proportion of green space must be rejected from the regression analysis since they are ordinal, variables. The regression interpretation shown on Figure 2 with a coefficient of determination R^2=0.86/86% which is strong and indicates 86% of change in the existence of adaptation planning is explained, existence of city level climate expert body and donor agency support. 1-R^2 which explains the proportion of unexplained variance on the existence of an adaptation plan is 0.14/14% which is small percentage of change in the existence of an adaptation plan is explained by factors other than existence of city level expert body and donor agency support. The implication here is that donor agency support and existence of an independent climate expert body strongly determines climate adaptation planning and by extension it determines the existence of adaptation plans in the sample cities. The p-value for the factor, membership of ICLEI is 0.214, which is well above the standard p-value of 0.05, this makes it statistically insignificant, hence this variable is rejected as a cause for the existence of an adaptation plan. The regression coefficient for the variable existence of an independent climate expert body in the city is 0.5, with p-value of 0.03. This variable is stronger than donor agency support in predicting change in the existence of an adaptation planning. The regression coefficient value also has a positive sign which means existence in an independent climate expert body in the city has direct relationship and cause change in the existence of adaptation planning. It can also be explained that the chance of having an adaptation plan in the cities itself increases by almost 5% with 0.5 unit increase in the existence of an independent climate expert body or in other words when the city has an independent climate expert body the likelihood of having an adaptation plan increases by 5%. The variable donor agency support has a regression coefficient of 0.42 with a p-value of 0.05 which is statistically significant. The chance of having an adaptation plan among the sample cities increases by 4.2% for every 0.42 increase in the support gained from donor agencies. It can be said that city level expert body, donor agency support are significant predictors for an adaptation planning.

Summary output



egression Statistics	
Multiple F	0.9302
R Square	0.8653
Adjusted I	0.8148
Standard E	0.2216
Observati	12

ANOVA

	df	*SS*	*MS*	*F*	*nificance F*
Regressio	3	2.5238	0.8413	17.131	0.0008
Residual	8	0.3929	0.0491		
Total	11	2.9167			

	Coefficien	*ndard E*	*t Stat*	*P-value*	*ower 95*	*pper 95*	*wer 95.*	*per 95.*
Intercept	-0.107	0.132	-0.809	0.442	-0.413	0.198	-0.413	0.198
Member c	0.214	0.145	1.477	0.178	-0.120	0.549	-0.120	0.549
City Level	0.500	0.192	2.605	0.031	0.057	0.943	0.057	0.943
Donor Age	0.429	0.187	2.288	0.051	-0.003	0.860	-0.003	0.860

Figure 2. Regression Result (Figure: Adela 2021)

4.3 Content Evaluation of the Planning Documents

The results of the climate action plan evaluation of which adaptation measures are cities opting is presented in table 4. The evaluation is conducted by searching in the plans for the presence of adaptation measures. A content analysis was conducted by reading through the adaptation plans of the cities.

Based on the categorization of urban adaptation options adopted from (Klein et al. 2014) and which categorizes climate adaptation measures into 10 categories (see table). According to the coding system if an adaptation measure is not mentioned in the plan, it receives code 0, while if it is mentioned it receives code 1. To make the evaluation the climate adaptation plans easy all adaptation options identified are classified into 9 major categories based on (Klein et al. 2014). Individual adaptation options within the climate action plans were then evaluated to this classification. This classification comprised of three major categories which are:

A. structural/physical under which 4 sub-categories are included: engineering and built environment, technological and eco-system based,

B. Social: with sub-categories included educational, informative, and behavioral and

C. Institutional which includes sub-categories of economic, laws and regulations and government policies and programs.

However, it must be noted that these adaptation options are overlapping by their very nature hence in some plans they might not be mentioned separately but could be addressed generally as part of an adaptation plan. But it should also be noted that a plan that explicitly addresses each of these adaptation options along with the sectors they must be implemented gives an indication of the weight and emphasis the plan gave to the issue of adaptation and the desire for implementation. Such plans could be regarded or evaluated as good plans.

5 Conclusion

The finding of this study indicated that six factors from among the potential thirty factors are found to be strongly associated with the formulation of a climate adaptation strategy. The correlation analysis shows that membership of ICLEI, existence of a climate expert body, presence of a climate concerned body, proportion of green spaces, donor agency support and level of CO_2 emission from the cities to be significant drivers affecting the adoption of a climate adaptation plan. In this study potential barriers that acts as constraints for climate adaptation are not found to be significantly correlated. Hence, notable barriers do not exist. Generally institutional and socio-economic factors are found to be important drivers than physical/environmental factors. The regression analysis indicated that two of the strongly correlated factors are causally related with the dependent variable with strong coefficient of determination and one factor was rejected with a p-value well above 0.05. Vulnerable cities to the risks of climate change are less likely to develop adaptation plan by their own initiative. This indicates that developing adaptation strategy is not a proactive action, rather influenced by external support. It is also indicated that the likelihood of developing an adaptation plan increases significantly with increase in the proportion of green spaces the city has and the level of CO_2 emission from the cities. More importantly institutional and socio-economic factors are found to be important drivers than climate risk. Cities are more likely to develop adaptation plan with donor support than by their own initiative and climate risk is not a driver of an adaptation plan. The evaluation of the climate action plans found that much emphasis is provided for mitigation than adaptation with more of the pages of the planning documents dedicated to mitigation efforts. This could be because these plans are developed with the support from external sources hence their interests might have been prioritized. Most of the cities integrate both mitigation and adaptation, except the city of Denver that has developed its adaptation plan without external support or donor and which this factor might have played a role for having a separate stand-alone adaptation plan.

When evaluating the adaptation plans for the type of most prioritized adaptation strategies they are undertaking and the most pronounced climate risks the cities face, it was found that an adaptation strategy that focuses on engineering and built environment is the most common one. In fact, adaptation strategies should emerge from the specific climate risk the cities are facing and the most pronounced climate risk the cities face is surface flooding, followed by drought/water scarcity and forest fire. Hence, it makes sense that engineering and built environment Is the appropriate strategy to deal with surface flooding which is the common climate risk for the cities.

The findings of this study support local governments of high-altitude cities in planning for adaptation of the impacts of climate change. It identifies the most pronounced climate risks that are common to high altitude cities and the frequently addressed adaptation strategies. It also stresses the importance of locally driven planning of adaptation strategy and urges city governments to institute a climate expert body for this purpose.

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ISKENDEROGLU ATAHAN, NADIN

2

Water Scarcity Management in the Context of Urban Climate Resilience:

Benchmarking the Case Studies of Istanbul and London

In recent years, the exacerbated impacts of climate change have brought the "climate resilience" concept to the agenda in cities and its importance has been increasingly recognized to cope with the gradual effects. Water is one of the vital assets triggered in cities and needs strategic management to establish a solid infrastructure and provide uninterrupted service. In this context, climate resilience offers many opportunities, especially in water scarcity prone areas, by contributing in various ways to the cities' assets, infrastructures, and utility management. This is where this research steps in with a benchmarking between two case studies; London in United Kingdom and Istanbul in Turkey, aiming to verify the contribution of urban climate resilience to water scarcity management. This study not only provides insights into the benefits of climate resilience, but also proposes actions to vulnerabilities identified in case studies. In order to conduct the benchmarking study, the concept of urban resilience was contextualized in a framework with its qualities and dimensions, followed by a set of indicators, and a quantitative assessment tool tailored to water scarcity management was developed based on this framework.

1 Introduction

Climate change and its implications threaten cities to a great extent, by resulting in various failures and disruptions in urban systems. Water-related assets, infrastructures and utilities are critical components of urban developments and are already confronting challenges due to rapid population growth and its increasing demands. Encountered challenges will be exacerbated by the extreme events of climate change (Bichai & Flamini 2018), as water is highly vulnerable to climate change and its impacts.

The increase in unpredictable climate events in recent years brought the concept of "urban resilience" to the fore and led to its wide adoption in urban strategies as a key to climate adaptation in cities. "Urban climate resilience" refers to quickly respond and recover from shocks and stresses emerged by climate change. Therefore, building urban resilience in cities is crucial for society and is a need, especially in risk-prone zones (Tumini et al. 2017). Albeit the growing importance of climate resilience, there are still gaps in integrated frameworks, tools, and methods to comprehensively assess urban resilience in cities (Ribeiro & Gonçalves 2019).

Returning to the subject of water, scarcity management is critical to build urban resilience, especially in drought prone cities. Therefore, a comprehensive assessment of water scarcity management is vital in these cities to ensure robust water assets and infrastructures and build a resilient city. However, it has been determined that there is a gap in the assessment of the water-related consequences of climate policies (IPCC 2008) and that a quantitative assessment tool is needed for water problems triggered by climate change.

The main aim of this research, that set off from the highlighted gaps in the literature, is to shed light on the link between water scarcity management and climate resilience concept and to reveal whether the climate resilience approach contributes to the management of water scarcity problem sustainably and develops robust water assets, infrastructures, and services.

To accomplish this aim in a straightforward manner, the London and Istanbul case studies were strategically chosen. These case studies have a great potential to discover the interconnection between climate resilience and water scarcity management, as London offers a best-practice with its urban climate resilience strategy, while Istanbul stands vulnerable due to a lack of city-level resilience policies, strategies.

The overall objective of this research is to contribute to the concept of urban climate resilience by developing a framework for urban resilience and to design an assessment tool for water scarcity management that will fill the gaps in the literature and lead to a comprehensive benchmarking analysis among the selected case studies.

The assessment tool will enable to analyse the strengths and weaknesses of each city and ultimately the proposed actions towards water scarcity management will move the vulnerable city closer to the climate resilience concept.

The adopted “mixed method” for the research will provide a hybrid structure that combines qualitative interpretation, numerical evaluation and comparative analysis, giving the subject a multifaceted view.

2 Background

2.1 The Concept of Urban Climate Resilience

The “urban climate resilience” which will be extensively used in this study will refer to “the ability of cities to give a quick response to extreme climatic events and bounce back from potential hazards”. The increasing studies in practice and academia have brought various dimensions and qualities of resilience as well as different definitions.

2.1.1 Understanding the Dimensions

The study conducted by Tyler and Moench, (2012) links resilience with urban climate and describes the “urban climate resilience” under three key components: systems, agents, and institutions. Accordingly, a resilient system must be flexible to be able to cope with shocks without cascading failures and remain functional under these conditions. Agents should be responsive to the shocks, disruptions and failures quickly in an organizational context, should be resourceful to provide the necessary financial resources and assets, and should have the capacity to learn from past experiences to improve performance. Institutions interconnect two components: agents and systems, and they provide authorizations for critical urban systems, perform accountable and transparent decision-making, provide the necessary information to identify the risks as well as the required adaptation actions, contribute to application of new knowledges to improve the urban resilience (Tyler & Moench 2012).

On the other hand, the systematic review conducted by Assarkhaniki et al. (2020) conceptualized resilience dimensions in the view of sustainability and classified resilience under; social, environmental, economic, institutional, and infrastructural dimensions. The key dimensions used in this research follow the five dimensions proposed by Assarkhaniki et al. (2020).

2.1.2 Understanding the Qualities

There are several researches in the literature that defines the resilience concept, the qualities, and conceives a framework to evaluate resilience in cities.

One of the pioneering examples is the “City Resilience Index” (CRI), developed by Arup in collaboration with the Rockefeller Foundation to comprehensively assess cities’ urban resilience performance, both qualitatively and quantitatively, highlighting seven key qualities of resilience; flexibility, robustness, redundancy, integrated, reflective, resourceful, inclusivity (Rockefeller Foundation - ARUP 2015).

In addition to the CRI, various studies in the literature acknowledge different qualities for the same concept, such as; diversity, efficiency, autonomy, independence, collaboration (Godschalk 2003), modularity, foresighting, stabilizing and buffering (Kim & Lim 2016), innovation and variability (Allan et al. 2013).

The resilience qualities most commonly cited in the literature are: "redundancy, diversity, effciency, robustness, connectivity, adaptation, resources, independence, innovation, inclusion and integration" (Ribeiro & Gonçalves 2019).

In line with the literature review, nine qualities of resilience were determined to shape the assessment tool in this research; **flexibility**, **robustness**, **redundancy**, **resourceful**, **reflective**, **independence**, **inclusive**, **integrated** and **innovation**.

The definition of each resilience dimension and quality considered in this study is given in Table 1 on the next page.

2.2 Case Studies

2.2.1 Case Study No 1: City of London

Rapid urban growth in Greater London puts a large pressure on services, infrastructure and the built environment. In addition to urbanization, climate change is one of the factors that is expected to further exacerbate the strains on urban systems in London, especially on water resources and assets.

Although London is known for its rainy weather throughout the year, it is drier than Istanbul in terms of rainfall per capita. London is expected to face serious water shortages in the future due to its growing population, climate change and increasing drought periods.

There are developed several frameworks and policies to tackle with drought and associated water scarcity in London. The "Drought Response Framework" conceived by the London Resilience Partnership promotes the reduction in water consumption, increases drought awareness and strengthens resilience against the impacts, while minimizing negative impacts at both organizational and individual levels (London Resilience Partnership 2019).

Another strategy developed is the "London Environment Strategy", which promotes urban resilience to the long-term effects of climate change such as extreme weather events.

In addition, "London City Resilience Strategy 2020" by Greater London Authority (GLA) ensures a long-term resilience by providing notable insights into building community resilience, sustainable use of environmental resources, and building robust infrastructures and environments, as well as good governance in terms of policy and strategy in London (Greater London Authority 2020).

No	Dimension & Quality	Description
Dimensions		
1	Social	Indicates the features related with the population and demographics, community, collective life, and its features
2	Economic	Refers the financial capacity of people and government
3	Institutional	Reveals the performance of govenment and the governance, preparedness to stresses, capacity to response and recovery features as well as measuring the effectivity of mitigation actions.
4	Infrastructural	Consists of the functionality, effiiency accessibility, emergency response features of urban critica infrastructures and its related services.
5	Environmental	Identifies the impacts on environment, measures the performance of services related with environment/human/ecosystem and their functionality.
Qualities		
1	Flexibility	Flexible systems imply to the ability to easily evolve nd adapt to changing coditions. Flexibility can be archieved by innovation that brings new technologies and knowledge into practice.
2	Robustness	Robust systems refer to strong, resistant, well-managed and planned assets, developments, services and infrastructure that can cope with external shocks, stresses or hazards.
3	Redundancy	Redundant implies to cost-effective spare capacity designed to support the system in the event of component failure, so that the system does not fail and maintains its functionality by the replaced spare.
4	Resourceful	Resourceful means having sufficient resources in present to fulfil the needs under shocks or stresses, to be able to respond to any level of disruption quickly.
5	Reflective	Reflective systems enable constant learning from past experiences and inform the future decision-making.
6	Independence	The independent system maintains its operation functionality regardless of external forces and control bodies.
7	Inclusive	Inclusivity promotes involving communities and all groups of people especiallu vulnerable one's for the consultation process during planning and visioning resilience in cities.
8	Integrated	Integration promotes the interconnection between all urban components that contribute to a common purpose, support each other and ensures collective functioning of systems as well as consistent decision-making in shortet period of time.
9	Innovation	Innovation refers to the ability to find different alternates and new technologies to fulfil the needs and continue the operation during shocks, stresses or hazards.

Table 1. Dimensions and Qualities Determined for Urban Resilience Concept (Table: Iskenderoglu Atahan 2021)

2.2.2 Case Study No 2: City of Istanbul

Turkey is located in the Mediterranean Basin, which is identified as one of the regions most affected by the impacts of climate change and will face intensifying dry periods and severe water scarcity problems in the near future (IPCC 2014).

Besides, rapidly developing Istanbul witnesses many problems similar to other megacities, such as overpopulation, urbanization, fast growing economy, and these put more pressure on urban systems and natural assets of the city and aggravates water scarcity.

In recent years, Istanbul has been frequently confronting drought problems due to climate change. To provide climate resilience, "National Drought Management Strategy Document and Action Plan" at the country level and "Istanbul Climate Change Action Plan" at city level have been developed.

With respect to the water problem, Melen Dam Project was one of the non-conventional solution approaches implemented by transferring water from adjacent basin after a huge water scarcity encountered in Istanbul. It was a large and expensive project as it included approximately 180 km-long water transmission line from Melen watershed. In this way, the water problem of Istanbul was postponed. In fact, from past to present, no sustainable solution has been found to the water scarcity problem other than the instant solution approaches. The need for a sustainable water supply solution still possesses great importance and urgency, as one of the major impacts of climate change is water scarcity in the Mediterranean Region (Cuceloglu et al. 2017).

On the other hand, with the EU accession initiatives, great progress has been made in the environmental sector and climate change in Turkey. Investments in the country were supported by the EU in order to improve the environmental quality, promote climate adaptation and ensure sustainable environmental management (Delegation of the European Union to Turkey 2019). As a matter of fact, water infrastructure investments in Istanbul have been increased, albeit mostly grey infrastructure. Similar to the country's investment approaches, Istanbul tends to adopt predominantly grey infrastructure rather than sustainable options as nature-based solutions (NBS).

3. Methodology

This research follows a pragmatic philosophy internalizing mixed method, to enhance the study by allowing the selection of the most suitable method, either qualitative or quantitative. In order to make an in-depth exploration on the subject and acquire a solid understanding on the dynamics, "case study approach" was adopted as a research strategy. In this regard, two cities from the C40 Cities Network: the city of London in the United Kingdom and the city of Istanbul in Turkey were selected based on their common water scarcity risks, large populations and megacity profiles to provide a solid basis for benchmarking.

This research not only conducts a benchmarking study, but also provides a framework for urban climate resilience based on dimensions and qualities determined from the literature, further promoting the development of an assessment tool for benchmarking. Accordingly, the research consists of the following three phases.

3.1 Phase-A: Understanding Urban Climate Resilience

The first phase of this research focuses on collecting data on urban climate resilience and its definitions, dimensions and qualities, and synthesizing the collected information. Thus, this phase provides a thorough understanding of the concept and principles of resilience and forms the backbone of the assessment tool (i.e., Phase-B), by gathering the dimensions and qualities of resilience under a single framework shown in Figure 1.

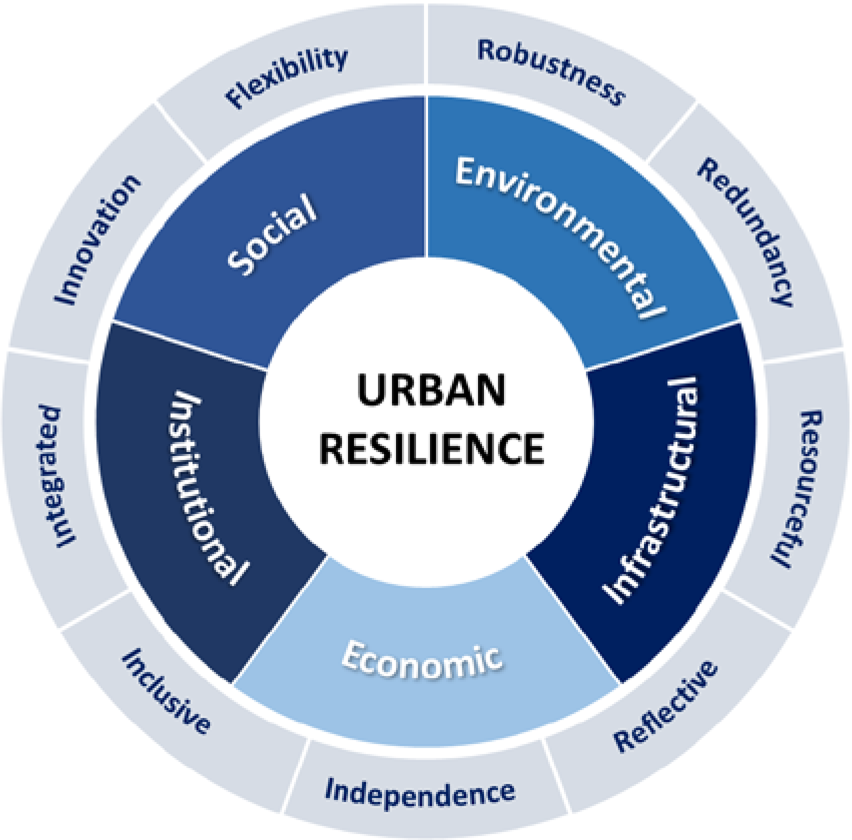


Figure 1. Designed Urban Resilience Framework (Figure: Iskenderoglu Atahan 2021)

The inner five parts of the designed framework (Figure 1) illustrate the dimensions and the outer nine notions present the qualities of urban resilience.

The five “dimensions” inferred from the study of Assarkhaniki et al. (2020) conceptualize urban resilience under the sustainability pillars. Thus, the adoption of these dimensions in the research leads to promote sustainability while building resilience in the city.

On the other hand, through the adopted relational content analysis method; the “qualities” those have dynamic interactions with sustainable urban water management strategies and those closely related to water-related services, assets and administrative aspects, were primarily considered.

In this sense, the synergy between dimensions and qualities acknowledged within this framework not only represents a vision for sustainable urban water management, but also contributes to achieve sustainable development.

3.2 Phase-B: Developing an Assessment Tool

The resilience qualities presented in the framework (Figure 1) act as a pillar for the assessment tool. The qualities are linked to various indicators to create this tool, and ultimately, evaluate the performance of water scarcity management in the context of urban climate resilience.

Since the nature of climate resilience and water management present conceptual and numerical features, both qualitative and quantitative indicators were selected according to the framework established in Phase-A. For each resilience dimension shown in the framework (Figure 1), 10 key performance indicators (KPIs) were selected to evaluate the water scarcity management performance of the case studies. Thus, a total of 50 KPIs formed the assessment tool.

In the assessment tool, the numerical range from 1 to 5 was used for scoring indicators, where 1 referred to the “highly undesirable” level and 5 implied to “highly desirable” level. Each score description was individually tailored to each indicator to provide unambiguous statement and accurate scoring. If there was a quantitative data available for the indicator, the description was quantified based on the data in the tool.

For the overall scoring, the weight of each indicator was selected equally in order to provide an uncomplicated and straightforward justification.

3.3 Phase C: Benchmarking & Proposing Actions

The final phase of this research consists of conducting literature review for each case study, evaluating the indicators and quantifying each by developed scoring scheme, obtaining an overall score for each case and comparing the results.

The city with the lowest overall score referred to "vulnerable city", while the highest referred to "best practice". The performance level of each city was evaluated in line with a theoretical background, by qualitative interpretation and quantitative analysis methods. The measured results also addressed the strengths and vulnerabilities of each city in terms of water scarcity management.

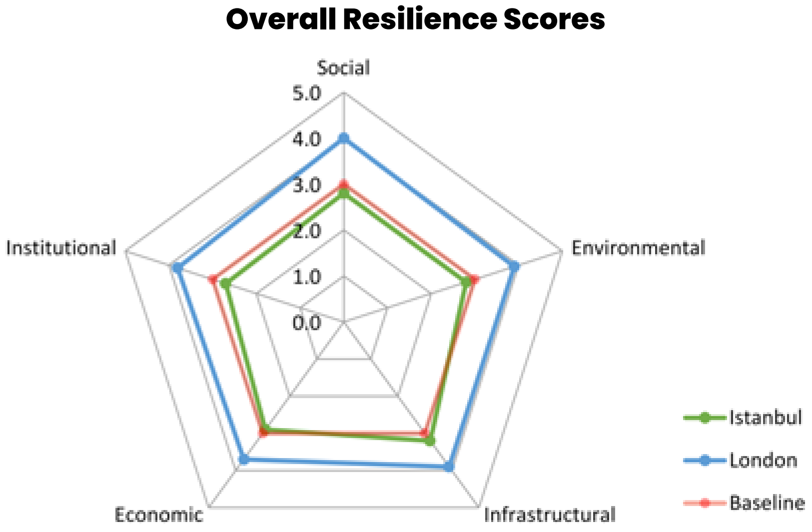
Ultimately, this phase proposed actions towards the vulnerable case study, in the lights of the best practice revealed.

4 Results and Discussion

4.1 Results

The overall scores calculated for each case study are summarized in Figure 2 to observe the dynamics of each resilience dimension comparatively.

In the radar type graph illustrated in Figure 2; the green line represents the overall scores of the Istanbul case study, the blue line refers to the results of the London case study, and the red line implies to the baseline for benchmarking, denoting the "neutral" level (score 3).



Case Studies	Dimensions					Overall
	Social	Environmental	Infrastructural	Economic	Institutional	
Istanbul	2.80	2.80	3.20	2.90	2.70	2.88
London	4.00	3.90	3.90	3.70	3.80	3.86

Figure 2. Overall Water Scarcity Management Performances of the Case Studies (Figure: Iskenderoglu Atahan 2021)

4.2 Discussion

Considering the overall results of the two case studies, it was confirmed that Istanbul was the “vulnerable city” of this research with the lowest overall score with 2.88 out of 5, and London was the “best practice” with the highest score of 3.86 out of 5.

Analysing the results, it was observed that all five resilience dimensions for London were above the baseline indicating good performance in water scarcity management. On the contrary, for Istanbul, all resilience dimensions except the infrastructural dimension were below the baseline, indicating a vulnerability, that is a ”risk” situation in water scarcity management.

Referring to the results in Figure 2, the following key conclusions were drawn based on the literature review.

4.2.1 Social Resilience

The biggest difference between the case studies was determined in the social resilience dimension.

Based on the literature review, the large difference between the dimensions of social resilience can be strongly associated with the lack of public awareness on the concepts of sustainable water use, climate change and urban resilience in Istanbul, due to insufficient programs to raise awareness. On the other hand, the lack of awareness brings another vulnerability in Istanbul; insufficient adaptive capacity and unpreparedness for extreme climatic events.

In contrast to Istanbul, the strongest aspect for London was observed in social resilience with various awareness-raising programs on climate change, climate resilience and water minimization across the city, steps to improve adaptation capacity (Greater London Authority 2020), and a city-level drought response framework that supports preparedness for extreme events.

4.2.2 Environmental Resilience

The difference observed between the two cities points to a major deficiency for Istanbul in this dimension.

One of the vulnerabilities observed in Istanbul is the high water consumption per capita with 189 LCD, that can be strongly associated with the lack of environmental awareness in the city. In this sense, London does not set the best example in water consumption with 149 LCD, but the way both cities address the problem, and their management strategies make a significant difference in their overall environmental resilience scores.

In London, various water efficiency and climate change awareness campaigns, a step change in regulations and in city plans to embrace water efficiency in new developments and developed comprehensive national drought monitoring and early warning systems pose the important values for the city in terms of environmental resilience.

These aspects specified for London set a precedent for Istanbul for water scarcity management in terms of environmental resilience.

4.2.3 Infrastructural Resilience

The least difference between the two case studies was found in the infrastructural resilience dimension.

As stated in the Background in Chapter 2, the driving force behind Istanbul's infrastructural resilience is the EU Accession Programme. However, the city majorly relies on grey infrastructure and new investments also follow the same mindset. Similar to the other results of Istanbul in the assessment, climate resilience in infrastructure was also found weak relative to London. The poor emphasis on NBS in urban policies and in urban planning, inadequate integration of GI in the city, as well as lack of retrofit programs for the existing infrastructure to switch into GI, were the major barriers found through the assessment.

Contrary to Istanbul, significant progress has been made in climate resilience, with concrete steps taken to integrate and implement GI in London. The "Green City Fund", "SuDS in London", "Greening the Business Improvement Districts", "Green Roofs and Walls" and "Grey to Green" are some of the programs identified in the London Plan (2021) and the London Environmental Strategy (2018). All these initiatives demonstrate GLA's willingness to implement GI widely in the city and its great efforts in this direction.

4.2.4 Economic Resilience

The most striking difference between the case studies on economic resilience is the insufficient budget allocation to climate resilience in Istanbul. The "Performance Programme" of Istanbul Metropolitan Municipality (IBB) reveals that only £80k (967k TL) is allocated to adaptation and combating climate change (Istanbul Metropolitan Municipality 2021).

In contrary, London poses a major strength in recognizing the climate resilience and various investments equivalent to around £5,799k is made to build adaptive capacity in the city to address climate change (Greater London Authority 2021), demonstrating GLA's solid steps towards a climate resilient city.

Considering the large population, urbanization levels and grey infrastructure tendency in Istanbul, the budget allocated to climate adaptation was found inadequate compared to London. In fact, it is worth noting that, other economic conditions and factors of the two cities should also be taken into account at this point, since investments are directly associated with the financial powers.

4.2.5 Institutional Resilience

One of the largest gaps between case studies was observed in institutional resilience. In fact, this can be strongly attributed to Turkey's relatively poor policymaking compared to the UK, particularly in terms of water efficiency, NBS and climate resilience. The importance given to climate change and environmental issues in public authorities in Turkey is insufficient.

In addition, although institutional fragmentation is a major problem in water management for both countries, the way they handle the problem led to a significant difference in the overall institutional resilience score.

The UK widely acknowledges and confronts coordination and cooperation issues in the water sector. The developed "National Framework for Water Resources" by the Environment Agency makes a step change in strategic and regional cooperation and promotes a better management by connecting water companies under separate regional groups. Unlike the UK, this issue was not fully internalized by the authorities in Turkey and the problem was remained in the background due to different priorities.

5 Conclusions and Recommendations

5.1 Conclusion

As a result of the assessment, it was clearly demonstrated that the climate resilience approaches adopted in cities and the policies followed in this direction contribute positively to the management of water scarcity, as evidenced by the high overall resilience score (3.86) in London, in contrast to the low score (2.88) in Istanbul.

This research clearly showed that the climate resilience concept embraced in urban planning and the built environment supports sustainable water scarcity management through different dimensions such as social, environmental, infrastructural, economic and institutional.

The results of London underpinned the argument specified in research aim and demonstrated the essential role of climate resilience in a city, revealing several strengths associated with water assets, infrastructures and services across each resilience dimension assessed.

According to the research results, the contributions of climate resilience to water scarcity management are determined for each dimension as follows:

- **In social dimension:**
  Stakeholder engagement and collaborations in the decision-making process; major efforts to raise awareness on water minimization and climate change; firm steps towards water saving culture; providing equally accessible water; built adaptive capacity in the city to shocks, stresses

or extreme events; city level drought response frameworks that promote preparedness; high quality of life and public health and safety achieved through an advanced supply network; socially strong water tariff taking into account all social groups, namely the vulnerable.

- **In environmental dimension:**
  Hydrological modelling and impact mapping leading to build robust water assets; widespread adoption of water efficient technologies; continuous monitoring of water resources; sustainable water management and resource conservation; attaching importance to sustainability in urban policies; integrated water resources management (IWRM) adopted in policies; drought monitoring and early warning systems; sound environmental management that ensures safe water.

- **In infrastructural dimension:**
  Continuous monitoring systems, smart water leak detection and water metering in the water supply infrastructure; widespread adoption of feedback systems in infrastructure to prevent cascading or persistent failures; spare capacity for non-conventional water resources (NCWR) and great emphasis placed on NCWR in urban policies; integration of green infrastructure (GI) into urban planning and its wide adoption across the city; solid steps to replace grey infrastructure with GI, e.g. retrofit programs; regular maintenance and repair for water-related infrastructure; integration of "climate resilience" into water-related infrastructure, services and assets; advanced water supply network.

- **In economic dimension:**
  Incorporating awareness campaigns into financial plans; incentive programs for agriculture sector to boost sustainable production and water savings; funding opportunities by successful international cooperation and partnerships on climate change; budgets allocated to build spare capacity for water-related infrastructure, assets and services; investments in water resources management, water reclamation and reuse; significant budgets allocated to improve climate resilience in the urban water systems; effective water tariffs to manage the supply-demand gap.

- **In institutional dimension:**
  Capacity building programs for non-conventional water resources (NCWR); wide recognition of water scarcity in policies; monitoring and assessment to ascertain progress on climate resilience; urban plans and policymaking on water efficiency for new developments; city-level climate resilience policies and strategies; "water vulnerability" recognized in urban policies; integration of NBS into urban policies; effective targets for reducing water losses and leaks.

In conclusion, climate resilience strategies followed in cities provide multiple benefits to cities, as listed above, especially in terms of sustainable management of water scarcity.

5.2 Recommendations

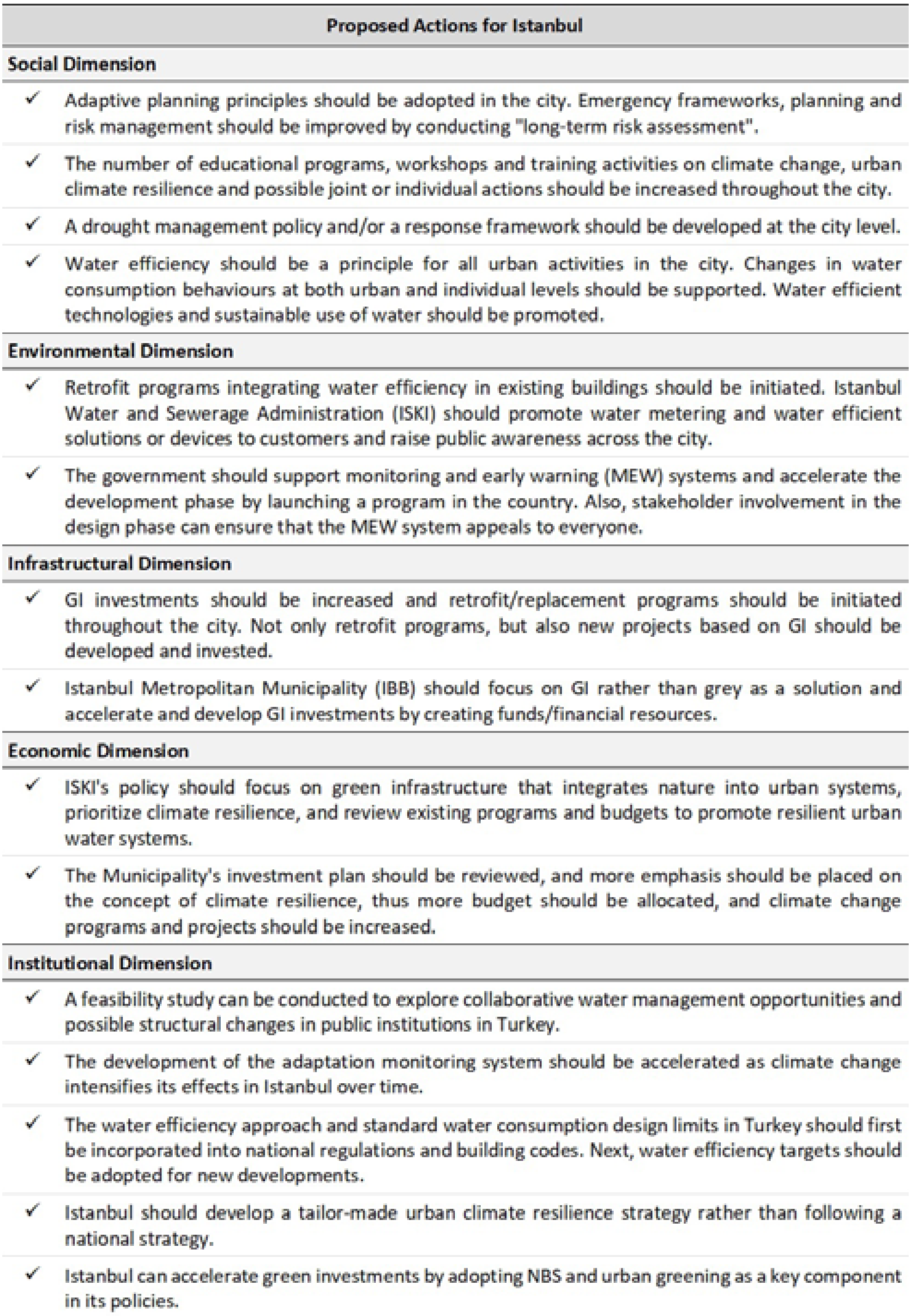
This research not only focused on revealing the benefits of the concept of climate resilience in cities, but also aimed to improve water scarcity management performances in both cities by presenting action plans.

5.2.1 Actions Proposed for Istanbul Case Study

London set a good example for Istanbul in this research and an action plan for Istanbul is proposed in Table 2 (on the next page), in line with the strengths observed in London. The proposed actions will not only improve Istanbul's water scarcity management, but also ensure its progress towards a climate resilient city, if implemented by Istanbul Water and Sewerage Administration.

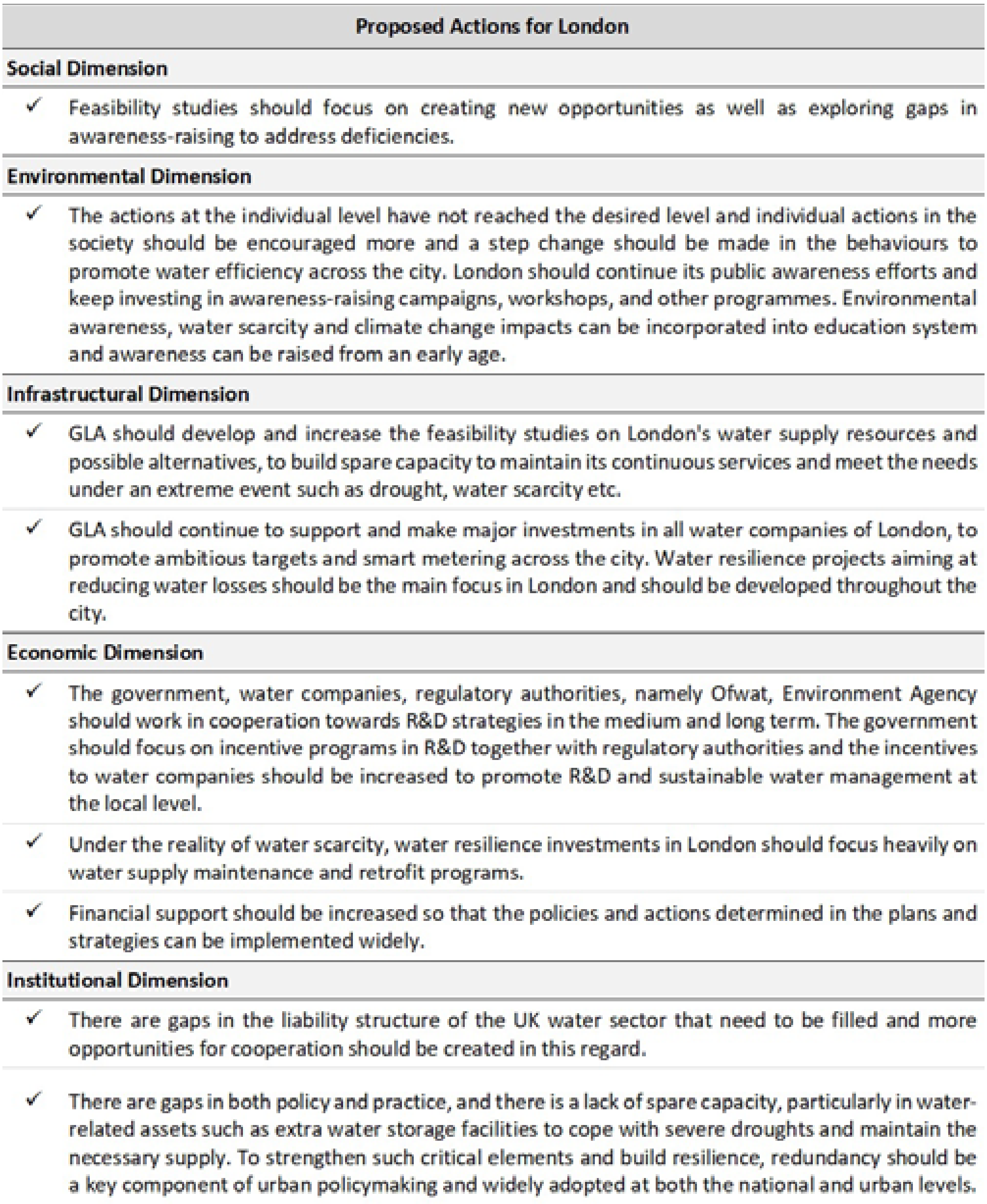
5.2.2 Actions Proposed for London Case Study

Despite London set a good example in this study, some "medium risks" (i.e., score 3) were also observed regarding water scarcity management. To improve those vulnerabilities and strengthen management performance, this research also proposes risk-related actions for London in Table 3 (next page).



Proposed Actions for Istanbul
Social Dimension
✓ Adaptive planning principles should be adopted in the city. Emergency frameworks, planning and risk management should be improved by conducting "long-term risk assessment".
✓ The number of educational programs, workshops and training activities on climate change, urban climate resilience and possible joint or individual actions should be increased throughout the city.
✓ A drought management policy and/or a response framework should be developed at the city level.
✓ Water efficiency should be a principle for all urban activities in the city. Changes in water consumption behaviours at both urban and individual levels should be supported. Water efficient technologies and sustainable use of water should be promoted.
Environmental Dimension
✓ Retrofit programs integrating water efficiency in existing buildings should be initiated. Istanbul Water and Sewerage Administration (ISKI) should promote water metering and water efficient solutions or devices to customers and raise public awareness across the city.
✓ The government should support monitoring and early warning (MEW) systems and accelerate the development phase by launching a program in the country. Also, stakeholder involvement in the design phase can ensure that the MEW system appeals to everyone.
Infrastructural Dimension
✓ GI investments should be increased and retrofit/replacement programs should be initiated throughout the city. Not only retrofit programs, but also new projects based on GI should be developed and invested.
✓ Istanbul Metropolitan Municipality (IBB) should focus on GI rather than grey as a solution and accelerate and develop GI investments by creating funds/financial resources.
Economic Dimension
✓ ISKI's policy should focus on green infrastructure that integrates nature into urban systems, prioritize climate resilience, and review existing programs and budgets to promote resilient urban water systems.
✓ The Municipality's investment plan should be reviewed, and more emphasis should be placed on the concept of climate resilience, thus more budget should be allocated, and climate change programs and projects should be increased.
Institutional Dimension
✓ A feasibility study can be conducted to explore collaborative water management opportunities and possible structural changes in public institutions in Turkey.
✓ The development of the adaptation monitoring system should be accelerated as climate change intensifies its effects in Istanbul over time.
✓ The water efficiency approach and standard water consumption design limits in Turkey should first be incorporated into national regulations and building codes. Next, water efficiency targets should be adopted for new developments.
✓ Istanbul should develop a tailor-made urban climate resilience strategy rather than following a national strategy.
✓ Istanbul can accelerate green investments by adopting NBS and urban greening as a key component in its policies.

Table 2. Actions Proposed for Istanbul Case Study (Table: Iskenderoglu Atahan 2021)



Proposed Actions for London
Social Dimension
✓ Feasibility studies should focus on creating new opportunities as well as exploring gaps in awareness-raising to address deficiencies.
Environmental Dimension
✓ The actions at the individual level have not reached the desired level and individual actions in the society should be encouraged more and a step change should be made in the behaviours to promote water efficiency across the city. London should continue its public awareness efforts and keep investing in awareness-raising campaigns, workshops, and other programmes. Environmental awareness, water scarcity and climate change impacts can be incorporated into education system and awareness can be raised from an early age.
Infrastructural Dimension
✓ GLA should develop and increase the feasibility studies on London's water supply resources and possible alternatives, to build spare capacity to maintain its continuous services and meet the needs under an extreme event such as drought, water scarcity etc.
✓ GLA should continue to support and make major investments in all water companies of London, to promote ambitious targets and smart metering across the city. Water resilience projects aiming at reducing water losses should be the main focus in London and should be developed throughout the city.
Economic Dimension
✓ The government, water companies, regulatory authorities, namely Ofwat, Environment Agency should work in cooperation towards R&D strategies in the medium and long term. The government should focus on incentive programs in R&D together with regulatory authorities and the incentives to water companies should be increased to promote R&D and sustainable water management at the local level.
✓ Under the reality of water scarcity, water resilience investments in London should focus heavily on water supply maintenance and retrofit programs.
✓ Financial support should be increased so that the policies and actions determined in the plans and strategies can be implemented widely.
Institutional Dimension
✓ There are gaps in the liability structure of the UK water sector that need to be filled and more opportunities for cooperation should be created in this regard.
✓ There are gaps in both policy and practice, and there is a lack of spare capacity, particularly in water-related assets such as extra water storage facilities to cope with severe droughts and maintain the necessary supply. To strengthen such critical elements and build resilience, redundancy should be a key component of urban policymaking and widely adopted at both the national and urban levels.

Table 3. Actions Proposed for London Case Study (Table: Iskenderoglu Atahan 2021)

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3

GR Runoff Modelling in Dublin for Climate Resilience:

Runoff Reduction Performance of a Single GR for Stormwater Management Using Hydrological Modelling with Climate Change Projections

This thesis aims to show runoff reduction performance of green roofs (GR) based on climate change projection scenarios using hydrological simulation for adapting to flooding events in a flood prone city, Dublin.

The study is based on a model validated with real life data and uses climate change projection model to assess the future implications of climate change and the impact of a GR could have. The model is created using SWAT and calibrated with a GR in Dublin. The model is later used with a climate change projection model. The runoff obtained from this model is bias corrected. Further analysis of urbanization trends in Dublin is also conducted.

Main findings show the GR is able to reduce %26-%55 of the runoff while the performance drops in more frequent and intense rain events. It is observed that climate change models are subjected to significant biases, especially for precipitation and bias correction on input variables or outputs is strongly advised. The urbanization trend shows Dublin will be more impervious in the future. Multiple GRs together with other sustainable drainage systems (SUDS) can create a cascading effect on overall runoff of the city, alleviating risk of flooding.

1 Introduction

Climate change and urbanization are two drivers shaping the view towards city development. The observed land surface air temperature has risen by 1.53 oC since the industrialization. It is suggested the rainfall events will increase 7% per degree of warming so, IPCC anticipates an increase in the frequency of flash floods, heavy precipitation, and extreme sea levels (Jia et al. 2019).

IPCC states approximately a quarter of the Earth's accessible lands are deteriorated due to anthropological reasons (Jia et al. 2019). Cities which are part of this deterioration, are growing fast as UN predicted almost 70% of the world's population will be living in cities by 2050 (UN 2018). Integrated environmental, social and economic issues arise in conventionally built cities, loss of natural cycles being one of them (Haase et al. 2014). Built-up area in a conventional sense means impervious land cover which tears the natural hydrological cycle where rainfall run off loses its ability to infiltrate and balance the groundwater supply and quality (Shafique 2018).

There are many studies on the usage of grey solutions can be optimized for better resilience to flooding and the effects of climate change (Balsells et al. 2015: Jia et al. 2012). Many conclude that in extreme storm events, the grey systems including pipes, underground retention basins and infiltration structures fail to discharge or remove the runoff when the annual recurrence interval is exceeded (Valizadeh et al. 2019).

Considering the benefits and trade-offs in favour of green stormwater solutions, more case studies should be conducted to understand and streamline the incorporation of green solutions to the modern stormwater management systems.

This study aims to show the impact of GRs in Dublin, on stormwater management and resilience to flooding using simulation techniques. Hydrological performance of a GR in terms of runoff reduction is recorded to be used in a simulation model to examine the runoff reduction that can be achieved with the GR in the future with climate change. Model simulations developed and validated according to the real runoff and meteorological data are produced to observe the impact of the GR on runoff by comparisons with and without the GR in a building scale. Finally, future runoff models are developed with different climate change scenarios to observe the impact of the GR in the study area under the implications of climate change.

The methodology builds upon the previous work undertaken by Bidroha Basu based on an existing GR in Dublin, deployed in February 2021. This real-life setup, helps to validate the simulation model and assess its accuracy. The simulation is developed using Soil and Water Assessment Tool (SWAT) for first, the observed weather for a historical time period; second, for the projected future data under two climate change scenarios, RCP4.5 and RCP8.5 (Representative Concentration Pathway) to observe the impact of the GR run off in line with climate change implications. In addition, a GIS analysis of land use maps of Dublin is carried out to examine the land use changes and evaluate the rate of urbanization.

2 Background

GRs are vegetated surfaces composed by substrate, drainage, water proofing and structural base layers. They operate to intercept and store rainfall with their vegetation and substrate layer, to achieve infiltration and evapotranspiration which can reduce the amount of water (Kasmin 2010). Many studies proved GRs can reduce the volume of the runoff and the intensity of the peak flow while delaying it as well (Bengtsson 2005; Stovin et al. 2012; Getter et al. 2007; Mentens et al. 2006). Also, several studies showed GRs can contribute to stormwater management in a catchment scale together with other sustainable drainage and nature-based solutions (Carter et al. 2007; Versini et al. 2015; Zahmatkesh et al. 2014). Shafique catalogued the performance of GRs in run off retention and stated the studies vary between 50 to 80% with an average of 67% (Shafique 2018). Overall, Mentens suggested a catchment scale runoff reduction of 2.7% if 10% of rooftops in Brussels were to be retrofitted with GRs (Mentens et al. 2006).

2.1 GR Design

2.1.1 Types of GRs

GRs are considered as a plant bed on a rooftop in a most basic sense, but their wide adoption and usages created more diverse designs. So, in order to standardize and create uniformity with the design parameters, a categorization based on the multilayer structure of GRs is adopted in which the categories are identified mainly as extensive and intensive GRs (FLL 2008). The structure differences in substrate depth, construction methods and vegetation types separate these types (Van Lennep et al. 2008).

2.1.1.1 Extensive GRs

Extensive GRs have typically a shallow substrate which is less than 100 mm, low organic content, furnished with low maintenance plants like succulents, sedum and grasses. They don’t typically require maintenance apart from during their installation and they don’t need to be irrigated (GRO 2011). They can be built as inaccessible by the public. They are seen as the cheaper and easier to install and maintain than other types of GRs (Van Lennep 2008).

2.1.1.2 Intensive GRs

Usually referred as a roof garden, intensive GRs have thicker substrate layer which is typically higher than 200 mm, usually require irrigation and maintenance due to their higher canopy and complexity vegetation (GRO 2011). Dublin’s policy guide identifies substrate depth for intensive roofs as 150-500 mm which partly coincides with extensive substrate depth, creating confusion Kotze mentioned (Van Lennep 2008; Kotze et al. 2020).

2.1.2 Properties and Maintenance of GRs

Adoption and acceptance of GRs highly depend on the accessibility of structural properties. These parameters either facilitate or hinder incorporation of GRs for projects involving environmental, social and/or economic benefits. They are also determinants of GR performance which can vary from stormwater management, thermal and energetic performance enhancement, biodiversity improvement and social wellbeing (Bengtsson et al. 2005; Kasmin et al. 2010; Stovin et al. 2012; Morau et al. 2012; Getter et al. 2011; Gaffin et al. 2009; Nagase et al. 2014; MacIvor et al. 2014; Braaker et al. 2014; Mesimaki et al. 2018).

2.2. Hydrological Performance of GRs

Hydrological performance refers to runoff reduction and peak discharge delay (Bengtsson et al. 2005). This is done by water uptake by the plant layer, infiltration, hence the delay in substrate layer and storage in the drainage layer in the roofs (Kasmin et al. 2010). Driscoll showed GRs are capable of 73.2% runoff reduction and are the second-best stormwater technology type after bioretention basins (Driscoll et Al. 2015). Stovin, clearly showed GRs can reduce runoff and delay discharge more than conventional roofs (Stovin 2012).

2.2.1 Hydraulic Performance Based on GR Type and Design

Intensive roofs have higher retention performance than extensive roofs as they have more robust vegetation that can take up more water and enhance evapotranspiration more, thicker substrate layer in which infiltration takes more time and higher water storage is possible (Beecham et al. 2014).

GRs having larger drainage storage can retain more water and delay discharge but being only a mechanical delaying mechanism, the performance should be enhanced by careful design of substrate and vegetation. (Carbone et al. 2014; Vijayaraghavan 2014).

2.2.2 Hydraulic Performance Based on Vegetation

When antecedent dry period is longer, vegetation gains more importance than the substrate as plants increases retention capacity by water uptake and evapotranspiration after being subjected to a long dry period (Beecham et al. 2015). Vegetated roofs are better in delaying and reducing runoff than plain substrate ones (Vijayaraghavan et al. 2014). Plants can be chosen for their root depth to enable access to deeper moisture levels and leaf succulence to avoid rotting in wet climates and wilting in dry climates (Rayner et al. 2016; Feng et al. 2018).

2.2.3 Hydraulic Performance Based on Climate Conditions

Rainfall frequency and intensity highly affects the hydrological performance. When rainfall is frequent, the moisture level in the substrate remains high which reduces the retention capacity (Carpenter et al. 2016). Water content in the substrate slowly reduces after the end of the rain event but the drop is a slow process so long antecedent dry period is necessary to regenerate the retention potential of the roof (Carbone et al. 2014).

2.3 Climate Change and Urbanization Implications for Dublin

Dublin is in a significant development trend since 1990s (Ellis et al. 2001). Rapid urbanization followed big economic development, but traditional urban development approach made the city more impervious in time. The traditional system favours that the collected stormwater bypasses the natural environment to the treatment plant and discharge to a usually far away waterbody. Dublin was also subjected to this like many cities in Europe until the Greater Dublin Strategic Drainage Study in 2005, which mandates the use of SUDS (Fleming et al. 2005). A Flood Studies Update was issued in 2005 to tackle urban flooding with an emphasis of alternative stormwater management systems (O'Sullivan et al. 2012). Since the inclusion of SUDs in the policy, the discharge water quality along with the discharge frequency and intensity gain more importance to mitigate flooding issues (O'Sullivan et al. 2012). Today, Dublin Climate Change Action Plan include flood resilience target that covers the use of nature-based solutions and SUDs, including GRs, to reduce the risk of flooding (Dublin City Council 2019).

In conclusion, under climate change and urbanization implications, considering the benefits of sustainable stormwater management systems including GRs and barriers for their adoption and acceptance in Ireland and elsewhere in the world; case studies related with their performance, local and regional impacts, their behaviours in future climatic conditions should be further researched and presented to the literature.

3 Methodology

3.1 GR Setup

GR units are deployed in the CHQ building in the city centre of Dublin (53°20'55.6"N 6°14'50.8"W) in February 2021. A total of 70 modular trays were used, each with an area of 1 m2, making the total GR area 70 m^2. The substrate is 80 mm of commercially available loamy soil and the vegetation is commercially available sedum mat. 4 modular trays are chosen for data collection.

In order to observe run off reduction, the mass of the trays are measured. The run off reduction is estimated through the changes in the mass of the beds. Weather variables necessary for the modelling are obtained by a weather station situated on site registering solar radiation, wind speed, relative humidity. Due to COVID-19 restrictions, the data collection from the site was disrupted and was possible only between 21st February and 28th February 2021.

3.2 Simulation setup

In this study, SWAT model is used due to its ability to simulate hydrological processes for long periods of time (Abbaspour et al. 2007; Jha et al. 2006; Santhi et al. 2001) and effective in simulating changes in the water quantity as well as quality. All calculations are carried out using MATLAB software.

3.3 Data Collection

Historical meteorological inputs (Temperature, precipitation, wind speed, relative humidity, all at hourly scale) were obtained from MET Eireann (Eireann 2020), for the weather station located at Dublin Airport. These historical data is used for the model calibration and validation.

Climate change projection data is obtained from the EURO CORDEX. RCM simulations made by the Rossby Centre of Swedish Meteorological and Hydrological Institute (SMHI) are selected to be used in the model. The selected ensemble data provides meteorological variables between 1st January 1981 and 31st December 2100 and was accessed from Swedish ESGF node (ESGF 2021). Two RCP scenarios are chosen for the analysis: RCP4.5 and RCP.8.5.

3.4 Model Setup to Evaluate GR Performance

The GR performance evaluation using observed meteorological conditions with SWAT tool is based on an unpublished study by Bidroha Basu which is elaborated further in the limitations section of this work.

The runoff reduction performance of GRs is assessed through estimating the overall runoff and the volume of water reduced by the presence of the GR. Below equation shows the water balance is used to calculate runoff generated from the GR.

$$RO = P - ET - \Delta SMC$$

RO represents the overall runoff from the GR which are overland flow and infiltration; P denotes the observed precipitation which is the actual runoff in the absence of a GR; ET is the evapotranspiration and ΔSMC represents the change in the soil moisture content. The input data requirement, the intermediate data calculations and their relationship with the intended output of the model is presented in Figure 1 on the next page.

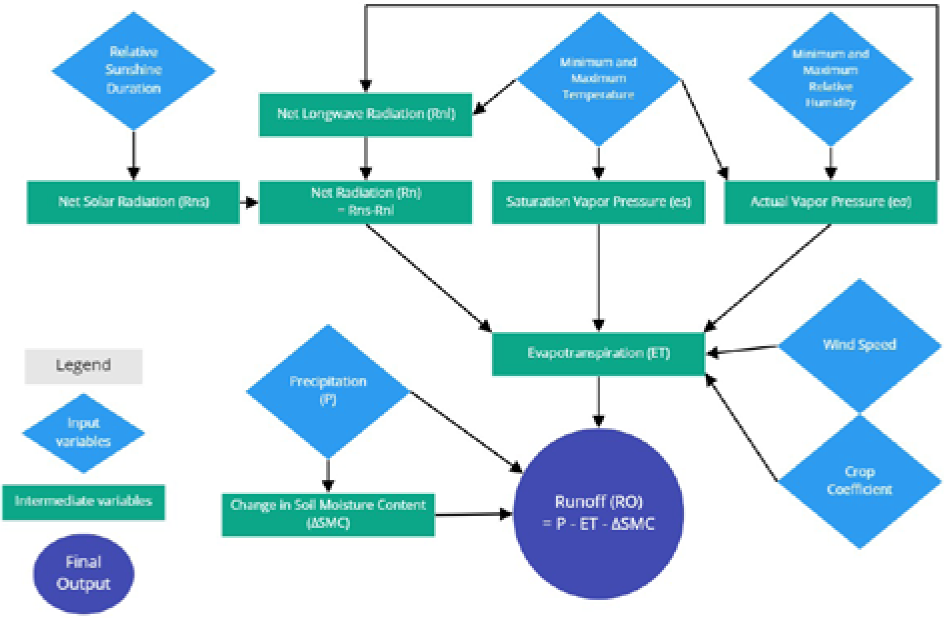

Figure 1. Flowchart of the Simulation Model to estimate the daily runoff from the green roof (Figure: Ozkan 2021)

The existing pilot GR vegetation consists of sedum vegetation layer as mentioned but in order to compare the effect of different type of vegetation, sedum, mint, strawberry, cotton.

3.5 Model Validation

To validate the model, actual runoff from the GR is measured through the changes in mass of the modular beds and compared with the modelled runoff. Only data between 21st February and 28th February, 2021 could be used to validate the model because of COVID-19 restrictions. The differences between the model output runoff and the actual runoff is calculated using three different statistical approaches (Nash-Sutcliffe Efficiency, Pearson correlation coefficient, Kling-Gupta Efficiency) to check whether the differences could be reasonable.

3.6 Bias Correction

GCMs and RCMs usually exhibit large biases compared to the observed datasets due to model parametrization, inadequate data, low quality data or low spatial resolution (Mearns et al. 2012). In this study Quantile Mapping method developed by Li et al. is selected called equidistant CDF matching method (Li et al. 2010).

Bias correction can also be misleading as some studies show bias corrected long term climate data perform worse than the original GCM or RCM data (Maurer et al. 2014; Maraun 2013). Since the model in this study is a highly nonlinear, bias correction of the input variables will lead to even higher bias in the output, so bias correction in this study is applied to the output values of the model, being the runoff.

3.7. Urbanization trend analysis for Dublin

In order to tie the impact of runoff reduction using GRs on the overall runoff volume, urbanization trends in Dublin are analysed through assessment of land use maps in 2006 and 2018 which are obtained from the Urban Atlas (Copernicus 2018). A shapefile showing all the buildings in Dublin is obtained from Geofabrik to identify the total area of the rooftops (Geofabrik 2018)

LULC dynamics are analysed in GIS by using Modules for Land Use Change Evaluation (MOLUSCE) in QGIS software (Guidigan et al. 2019). The changes between 2006 and 2018 are generated and a class statistics and transition matrix are developed which describe the changes occurred between 2006 and 2018.

4 Results and Discussion

4.1 GR Performance with Historical Data

The results depicted in this section describing the GR performance under current meteorological conditions and model validation are taken from the unpublished work of Dr. Bidroha Basu.

The data taken from MET Eirann for the time between 1st January 1990 and 29th February 2020 shows %60.23 of the total days were without precipitation while %39.77 were rainy. The average rainfall in days with precipitation is 3.51 mm/day and the maximum precipitation intensity is 26.5 mm/hour.

The observed runoff and the model results are compared to see how accurate the model is able to simulate the runoff from the GR. The model has a slight tendency to overestimate the peak runoff while underestimating the low runoff. The difference in the compared values are low and the values of statistical measures to indicate the validation are significantly close together, indicating the model is able to simulate runoff close to reality. The NSE, CORR and KGE are calculated as 0.961, 0.999 and 0.806 respectively.

The analysis for estimating the runoff reduction capacity of the GR through the model simulation is carried out for eight scenarios, obtained results are shown in Table 1.

Precipitation			**>50mm**	**>30mm**	**>20mm**	**>10mm**
Number of days		**Crop Coefficient**	**6**	**44**	**120**	**539**
Shallow Substrate 80mm	**Sedum**	1.0	12.10	23.94	32.77	55.09
	Strawberries	0.75	11.01	21.87	29.97	51.40
	Cotton	0.5	9.80	19.96	27.12	47.61
	Mint	1.1	12.53	24.80	33.92	56.57
Medium Substrate 150mm	**Sedum**	1.0	24.31	47.38	60.48	77.21
	Strawberries	0.75	22.68	44.69	57.41	74.57
	Cotton	0.5	20.64	42.27	54.51	71.87
	Mint	1.1	24.91	48.60	64.75	78.21

Rainfall intensity / Percentage of Runoff Reduction		**RCP 4.5** Runoff Reduction Performance (%)	**RCP 8.5** Runoff Reduction Performance (%)
> 10mm rain	**Grass**	61.18	53.01
	Strawberries	56.20	47.77
	Cotton	50.98	42.44
	Mint	63.11	55.08
> 20mm rain	**Grass**	43.99	43.20
	Strawberries	39.52	39.01
	Cotton	34.96	34.84
	Mint	45.77	44.88
> 30mm rain	**Grass**	31.49	37.39
	Strawberries	27.85	33.93
	Cotton	24.12	30.49
	Mint	32.93	38.79
> 50mm rain	**Grass**	8.16	31.71
	Strawberries	6.07	28.96
	Cotton	3.84	26.22
	Mint	8.96	32.81

Table 1. Runoff Reduction rate with a green roof with different substrate depth and vegetation under observed historical climate conditions (Left) and with RCP4.5 and RCP 8.5 Scenarios (Right) (Table: Ozkan 2021)

The results show 150 mm substrate depth performs better in reducing runoff. As the soil depth increases, the substrate is able to collect and store more water. Runoff can only be generated when the GRs is saturated or at its field capacity, hence the recharge capacity of the roof's runoff retention performance depend on substrate's drying rate in between rain events (Bengtsson et al. 2005).

Mint is the most effective in reducing runoff having the highest crop coefficient hence the evapotranspiration capacity, followed by sedum, strawberries and finally cotton in terms of performance.

It is observed that as the rainfall intensity increases, the percentage of runoff reduction decreases. During lower intensity rainfall, the majority of the rainfall is stored in the substrate, increasing the SMC and then consumed during evapotranspiration. On the contrary, during high intensity rainfall, the soil moisture increases rapidly and substrate stay saturated, diminishing the water storage capacity to minimum or non-existent, leading to more runoff. The difference between mint and sedum is fairly marginal for higher intensity rainfall but for lower intensity events, mint performs better.

The runoff performance with and without the GR is compared and presented in Figure 2. The runoff from the GR is represented in the vertical axis while runoff without the GR is shown in the horizontal axis. The points in graphs represent the daily runoff simulated in the model. The cyan coloured line shows the neutrality, meaning the points under the line are indicating there is runoff reduction due to the existence of the GR.

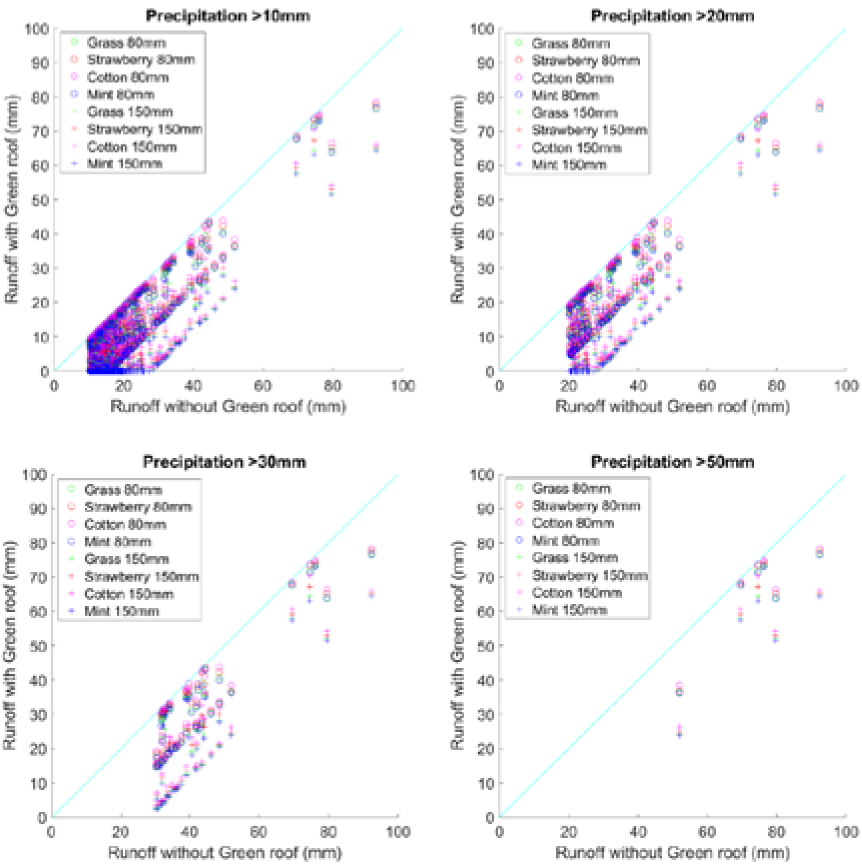

Figure 2. Runoff with and without the green roof with historical data (Figure: Ozkan 2021)

4.2 GR Performance with Climate Change Projection

The results depicted in this section describing the GR performance with climate change projection including bias correction are original to this study.

The data is taken from SMHI for the time between 29th February 2020 and 31st December 2100 for both RCP4.5 and RCP8.5 scenarios. %12.4 and %23.4 of the total days were without precipitation while %87.6 and %76.6 were rainy in RCP4.5 and RCP8.5 respectively. The average rainfall in days with precipitation is 4.37 mm/day and 3.69 mm/day respectively.

RCP8.5 scenario exhibits higher probability of extreme events and more inclination for medium intensity rainfall then RCP4.5 while lower intensity rainfall are lower in number.

The projection data clearly has bias for overestimating precipitation and simulate more rainy days both in RCP4.5 and RCP8.5, as the number of rainy days is extremely high.

80mm substrate depth is chosen for the simulation. The existence of GR still allows a significant reduction in runoff in future projection. Even with very high rainfall GR is able to capture some amount of water as shown in Table 1

The performance decreases significantly for rain intensities greater than 50mm since have higher intensities. High rainfall intensity leads to higher runoff since the SMC is reached very quickly, creating direct runoff from the GR (Shafique et al. 2018).

The runoff performance with and without the GR in Figure 3 for RCP4.5 and RCP8.5.

The difference between runoff performance for rainfall intensities higher than 50mm between RCP4.5 and RCP8.5 can be explained with the nature of the selected bias correction method.

The runoff reduction performance decreased compared to RCP4.5 scenario since the rainfall intensity, amount and frequency are higher in RCP8.5 than RCP4.5. GR is less able to retain runoff due to field capacity being reached quicker and there is less time in between rainfall events to allow the GR to dry out and regenerate. However, even in rainfall intensities greater than 50mm, there is approximately 10-20mm runoff reduction difference between cases with and without the GR. The highest runoff without the GR is approximately 90 mm while with the GR runoff is calculated as 65mm.

The analysis is carried out both with and without bias correction. The values are significantly underestimated without correction hence the runoff reduction with the GR is extremely low. After correcting the results, the runoff reduction is closer to the observed values, making the results more realistic.

This bias correction method tends to underestimate results in the lower quantiles in the model while overestimating them on the high quantiles. The difference between the runoff performance for intensities greater than 50mm in RCP4.5 and RCP8.5 can be explained by this phenomenon.

This study shows GRs can be used to mitigate the flooding risk amplified by climate change and urbanization, supporting many studies in the same field. Similar to this study, building scale runoff experiments and models showed GR performance depend on several factors like climatic conditions, seasonality, antecedent dry periods, substrate depth and type and rainfall intensity (Bengtsson et al. 2005; Carter et al. 2006; Mentens et al. 2006; Berndtsson 2010).

4.3 LULC Changes in Dublin

The results showed the area surrounding the city core mainly consists of agricultural and semi natural areas followed by discontinuous dense urban fabric and industrial, commercial, public, military, private units both in 2006 and 2018. Figure 5 visualizes the transition between the land use classes.

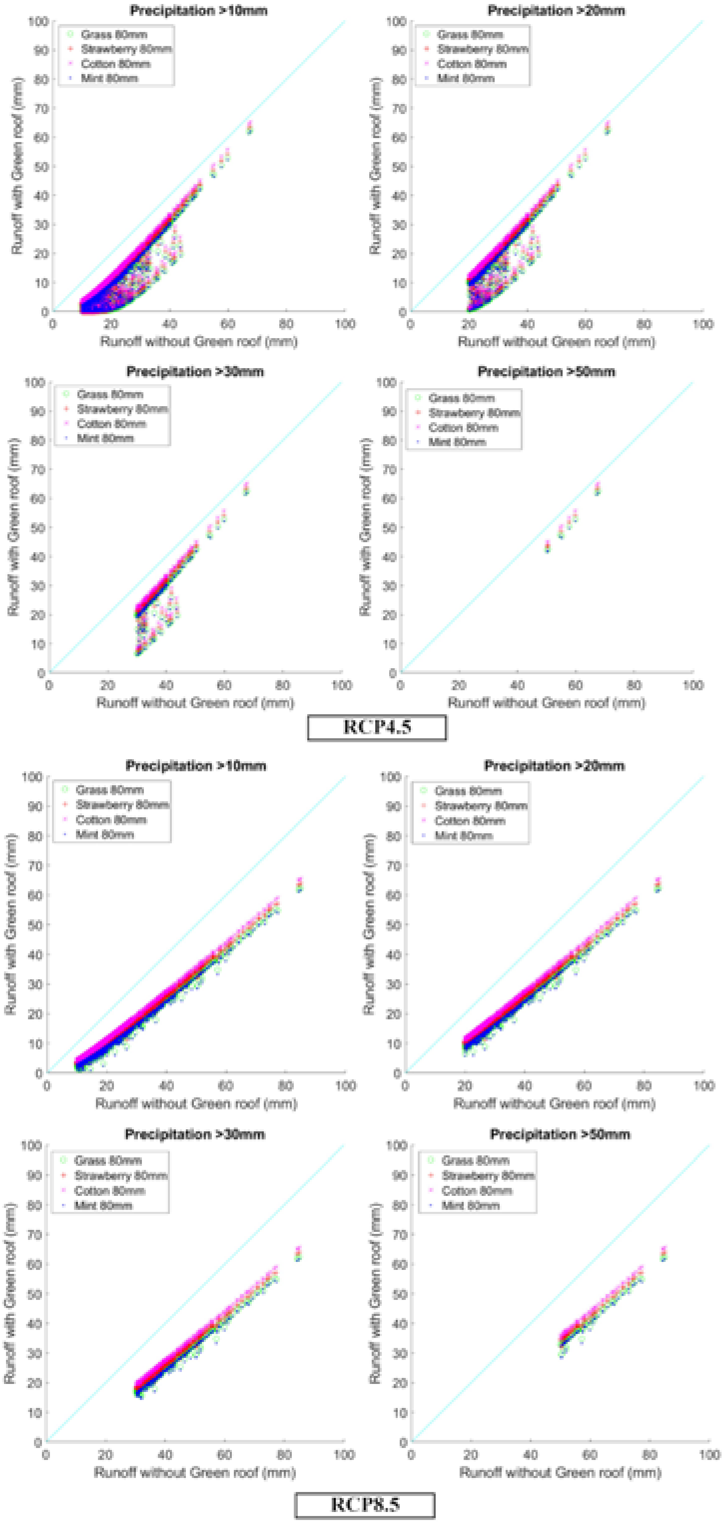

Figure 3. Runoff with and without the green roof in RCP4.5 and RCP8.5 Scenarios (Figure: Ozkan 2021)

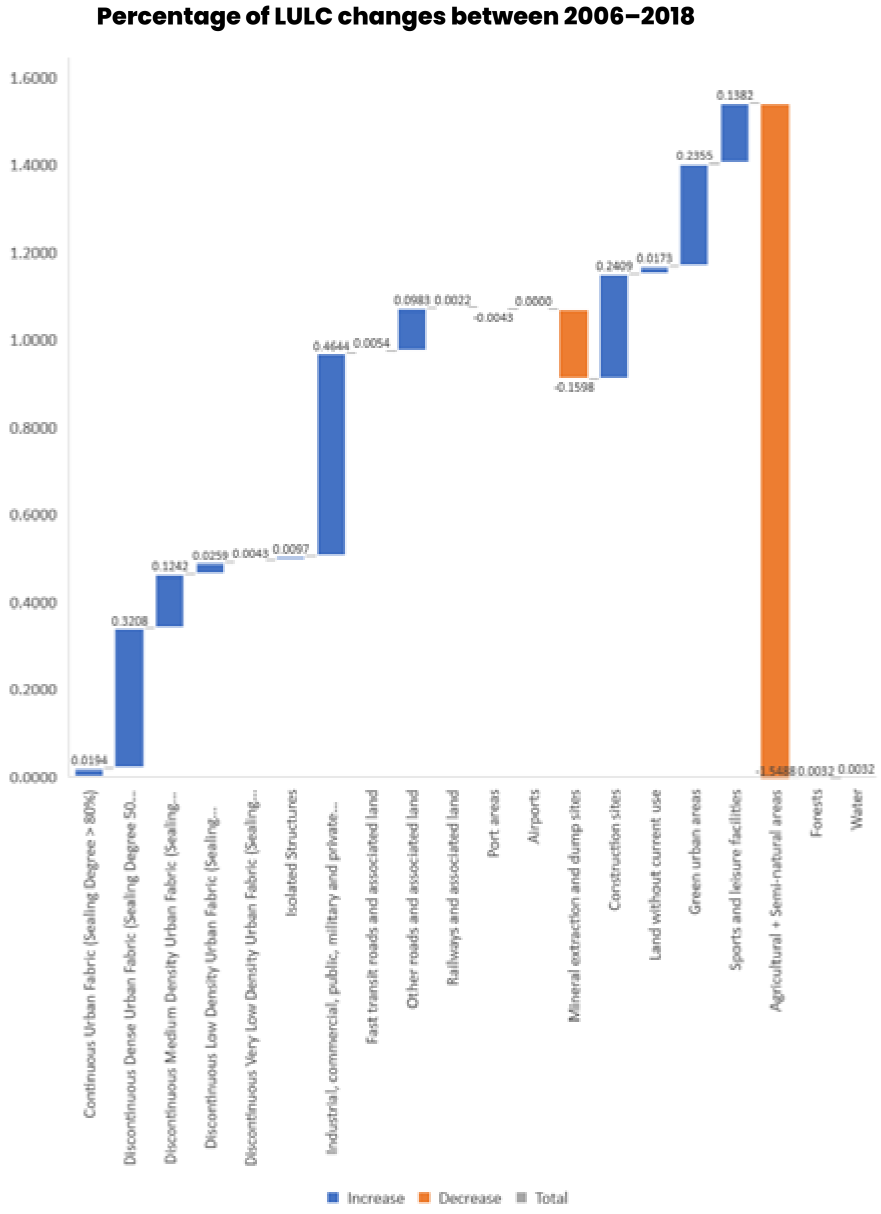

Figure 4. LULC changes between 2006 and 2018 (Figure: Ozkan 2021)

The major change in the land use classes are between agricultural/semi-natural areas, discontinuous urban dense fabric and commercial areas. This trend shows the urban expansion is occurring at the expense of agricultural/semi-natural areas. The increase in discontinuous urban fabric points at urban sprawl. Still, this expansion is significant in terms of stormwater management and urban runoff since these areas have a sealing degree of 50-80%, meaning high imperviousness. Imperviousness has a big impact on evapotranspiration and decreases or inhibits infiltration, changes natural flow routes and runoff quality and creates fast peak discharges (Jennings et al. 2002; Dougherty et al. 2004; Scalenghe et al. 2009, Rim 2009).

The total area of building rooftops is calculated using QGIS and found to be 48.25 km^2. Based on the findings in the model simulation, retrofitting these roofs with GRs can relieve the pressure in drainage systems and reduce the risk of flooding, especially combined with other type of SUDs.

5 Conclusions

Climate change is leading to more frequent extreme events. The observed land surface air temperature rise is affecting hydrological cycles in many regions including Dublin. Increasing impervious land cover due to urbanization especially hinders natural hydrological cycle in cities, limiting natural runoff reduction, creating urban floods.

Researchers established climate change scenarios according to radiative forcing based on anthropological activities. Climate change projections are invaluable tools to understand the future effects of climate change for mitigating and adapting to the shift. Hydrological models depicting green infrastructure deployment can be used by urban planners and researchers to assess future flood risks, catchment management protocols, catchment operations and water quality projections.

This study further developed a hydrological model depicting GR runoff reduction abilities under two climate change scenarios and assessed the urbanization trends in Dublin. The analysis of runoff reduction in both scenarios is significant considering the rainfall events are more frequent and have higher intensities. It is also observed crop coefficient, representing plant evapotranspiration, highly effects runoff reduction as it is one of the most highly sensitive parameters in GR water capture (Schmitter et al. 2016).

On the other hand, the land use change analysis showed there is a slow but increasing trend of urbanization and urban sprawl which corresponds to urban imperviousness. The increase in the urban green areas isn't enough to compensate the sprawl in addition to the loss of semi-natural areas.

The model in this research is based on an unpublished work conducted by Dr. Bidroha Basu who developed, calibrated and validated the model. Dr. Basu's study remains unpublished due to COVID-19 related delays.

Furthermore, this study intended to use collected data from the GR site to provide a real-life runoff reduction performance for a 4 months period but due to COVID-19 restrictions in Dublin, data gathering wasn't possible. This is also why, bias correction could be done using runoff results taken from the original model developed by Dr. Basu, not with the actual runoff data.

It should be also noted that climate change projections are only projections and not reality. Even though the research in this field is rapidly growing, the data are subject to biases. Several bias correction methods are being improved. Hydrological models still provide invaluable resources to understand the effects of future urban development on the climate change mitigation and adaptation approaches.

The study is focused on using hydrological modelling tools to assess impact of GRs on stormwater management in climate change scenarios. This approach can be used by researchers as well as planners and practitioners to mitigate flooding risk with green infrastructures. The model in this study in addition to other models developed by researchers provide relatively straight-forward methods to assess the future urban conditions in terms of stormwater infrastructure (Carter et al. 2007; Versini et al. 2015; Zahmatkesh et al. 2014; Qin et al. 2013). In addition, the impact of urban flooding and urban flooding mapping can be studied with the help of these type of hydrological models (Pathak et al. 2020; Zhao et al. 2019).

The study presented in this thesis focuses on a single GR located at the CHQ building in Dublin. Though it is proven the GR can reduce the runoff from 26%-55% depending on the amount of rainfall received, it should be emphasized that a single GR cannot control flooding at a city scale. For this purpose, multiple GRs as well as other SUDS need to be deployed across the city in a real-world scenario and their cascading impact has the potential to control flooding at larger scale. In order to estimate the impacts that green infrastructures can have at an urban scale, several types of green infrastructures in addition to GRs can be modelled in a street/neighbourhood/city scale. These larger scale models require extensive modifications in the model used in this study in order to operate and accurately assess hydrological performance (Schmitter et al. 2016). The time frame for this study didn’t allow such scope but this type of research is highly recommended.

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4 Urbanisation and climate change effects on urban drainage performance

A case study of SUDS in a risk area in the city of La Paz, Bolivia

The city of La Paz in Bolivia has witnessed many disaster events attributed to a surplus of rainfall, causing flooding and landslides in urban settlements. This study presents a quantitative evaluation of the effects of urbanisation and climate change-induced changes in rainfall over a drainage system in the Achumani District of the city. The study area was selected based on the land-cover transformation, disaster occurrence and risk zones. These factors served as input data for the Storm and Water Management Model (SWMM).

Two scenarios were considered in the digital model and simulation. The first one included urbanisation sprawl, based on land-use changes of 2003, 2013 and 2020. The second comprised potential rainfall reduction/increment due to climate change and land use features as of those in 2020. Results indicated that increments of impervious surfaces positively correlate with peak flows and flooding and that the incidence was higher at the initial state of urban development (between 2003 and 2013). Moreover, even with lower rainfall intensities in the future due to climate change, the drainage system can still overload. The inclusion of sustainable urban drainage systems (SUDS) in existing networks can enhance the performance by reducing flow and flooding effectively. These technologies can be integrated into regulations for complementing urban planning and promoting adaptation to cope climate change.

1 Introduction

Latin America and the Caribbean (LAC) cities rank amongst the most vulnerable to natural disasters (Gu 2019). This condition can be exacerbated by potential climate change (CC) effects whether adaptation lags in the region (University of Notre Dame 2021). Moreover, the Global South requires enhancing collaborative research work for implementing solutions, since comparatively to the Global North, this absence deprives the region of achieving more advancements (Soler & González 2020).

Furthermore, the LAC region needs to provide public services to satisfy the increasing demand for welfare as one of the world's highest urbanised regions. Around 80% of its population lives in cities, with tremendous growth since the 1950s (Muggah 2018). This situation imposed more considerable challenges that are now added to the ones brought by CC. However, lack of budget (Cenci 2020) and poor foresight planning also characterise the region (Muggah 2018).

Under these adverse circumstances, the city of La Paz in Bolivia has been working towards building resilience. The city has faced natural disasters over the last decades, some of them being connected to CC. These extreme events are either related to deficiency or surplus of rainfall. In late 2016, a drought provoked the irregular provision of water to over 340 thousand people (Ayala 2016), despite foreseeing its probability of occurrence years before (Hoffmann 2016). Regarding floods, the most harmful events occurred in February of 2002, with more than 70 people deceased and millions of USD dollars for infrastructure recovery (Hardy 2009); and in February of 2011, heavy rain and soil scouring derived into a landslide dragging hundreds of plots and displacing over a thousand families to other locations (Pagina Siete 2020).

These unfortunate events triggered community attention and public administrators to address flooding control and risk prevention. The Autonomous Municipal Government of La Paz (GAMLP, for its acronym in Spanish) works through the Secretariat of Integral Risk Management (SMGIR) to address these problems, and increased public budget to prevent risks (Hardy 2009). Despite the financial changes, the Municipality still required external sources to develop urban resilience. In 2020, the World Bank granted credit for approximately 59,02 million euros (World Bank 2020; Money 2020). Nonetheless, this investment will focus mainly on large-scale infrastructure and conventional solutions.

In this regard, drainage systems are usually overlooked and observed from a broad perspective. Municipal long-term planning includes canalisation and vaulting of different streams, peak flow control works, landslide prevision and control, and soil stabilisation (GAMLP 2016). Even so, media reports flooding or soil movement events during the wet season every year (Radio Fides 2015; Página Siete 2020; Brújula Digital 2020), being possible that land cover changes provoke these incidents (Arjenaki et al. 2021). In this understanding, this study aimed to evaluate the incidence of urbanisation and potential changes in rainfall, due to CC, over the drainage network's functioning. Moreover, it determined whether the inclusion of sustainable urban drainage systems (SUDS) can enhance its performance.

2 Background

2.1 Rapid urbanisation

Around 55% of the people on the planet lived in urban areas by 2018, and it is estimated to reach two-thirds of the world's population by 2050 (Gu 2019). Urbanisation has been attributed to diverse socioeconomic factors where 70% to 80% of many countries gross domestic product (GDP) is estimated to be produced by cities (Gu 2019; World Bank 2020). However, while urban population and economic growth are expected to increase in the coming years, the investment needed to address natural disasters will likely rise due to their frequent occurrence (Gu 2019).

The LAC region is the second most urbanised region worldwide, with 79% of its population living in cities as of mid-2020 (Szmigiera 2021). However, one of the problems with its current urbanisation degree is its large infrastructure gap with lower rates of basic services coverage, e.g., housing, sanitation, or wastewater collection (Muggah 2018). Moreover, the land-use changes due to cities' expansion increase vulnerabilities.

The city of La Paz in Bolivia has combined characteristics of urban sprawl, poverty, and vulnerability worth analysing. Moreover, because of its location and connectivity (Barrientos 2012), migration into the city soared. Nonetheless, current conditions are still inadequate, with a poverty gap of 16,4% and a high demand for land restricted by market supply, topography, and soil instability (GAMLP 2019).

2.2 Latin America under the water

LAC is one of the most vulnerable regions to the El Niño/La Niña phenomenon, bringing droughts and extreme rainfall events due to the water temperature shift in the Pacific Ocean (OCHA 2019). According to Gu (2019), four megacities (Mexico City, Buenos Aires, Rio de Janeiro, and Lima) have low exposure to droughts but are highly vulnerable to related economic losses. On the other hand, flooding has been the most common type of natural-caused disaster in LAC in the last two decades (OCHA 2019). Although droughts were the events that affected more people (around fifty-three million), floods are the most common type of disaster, affecting approximately 41 million people as of 2019 (OCHA 2019). Furthermore, until 2020, this type of event has caused the death of 48.866 people in South America since 1926, affecting more than sixty-nine million people and causing damage over thirty-seven billion USD dollars since 1926 (EM-DAT 2021).

2.3 The future of rainfall and resilience adaptation

Climate projections indicate a more profound influence from global warming on surface temperature, sea-level rise, and precipitation due to greenhouse gas (GHG) emissions (IPCC 2014). However, despite hydrological changes being a likelihood of CC emerging patterns (Dore 2005), a specific extreme event impact cannot be assigned as the only causation of CC unequivocally (Shepard 2018).

Dore (2005) noticed an overall increase in regional and continental precipitation, where usual wet areas are becoming wetter, and drier ones are experiencing harsher conditions. The aftermath of water availability, in deficiency or excess, reach diverse components of society's development. Therefore, adaptation and resilience become substantial to confront the global challenges of CC, with vulnerability playing an essential role in this regard.

Developed economies like the ones from partner countries of the MUrCS Program place high in the Global Adaptation Index (ND-GAIN) as of 2019: Finland (3rd), UK (11th) and Spain (26th) (University of Notre Dame 2021). Contrarily, LAC countries rank poorly, with Bolivia as the second most vulnerable in South America (133rd on the ND-GAIN out of 182 in total) and the fifth least prepared to mitigate the impacts of CC (Francois 2016; University of Notre Dame 2021). Although Bolivia is one of the lowest contributors of GHG emissions, with a global share of 0,06% as of 2019 (Ritchie & Roser 2017), it is vulnerable to CC due to extreme poverty, deforestation, changes in the ecosystems, unstable weather (Francois 2016), and glaciers retreat (Rangecroft et al. 2013).

2.4 The situation in the city of La Paz, Bolivia

La Paz is an interesting case concerning urban development and vulnerability because of its location and population, with over a million inhabitants. It is settled on the basins' slopes that conform La Paz River watershed, at altitudes varying between 3.000 and 4.000 metres. It is divided into nine macro districts, seven urban and two rural. However, the urban area occupies approximately 5% of the whole territory and lodges almost 93% of the population (GAMLP 2015). This characteristic imposes pressure on the provision of housing and public services in a context of increasing migration from close municipalities and constant transit from its neighbour city of El Alto (Arbona & Kohl 2004).

Moreover, the steep topography and geological features create different vulnerability ranges (GAMLP 2011), which the Municipality aims to control through risk management and urban planning (GAMLP 2019). The Law of Urban Land Use (LUSU, for its acronym in Spanish) is the latest norm updated with this objective (GAMLP 2014). However, irregular occupation and illegal plots trading are not uncommon, hampering the regular provision of services and infrastructure or delaying them due to legal conflicts (Vargas 2014).

Furthermore, due to the different types of vulnerabilities and risks (GAMLP 2011; CAF 2019) associated with urban drainage (Hardy 2009), a master plan is being developed (IDB 2016). These actions aim to reduce the risk of similar events as the 2002 flooding or the 2011 landslide. However, most of this planning and actions are focused on conventional and large-scale solutions, like channelling, vaulting, energy sinks and retaining walls.

2.5 SUDS and modelling: an approach to a solution?

A local scale alternative for stormwater management is sustainable urban drainage systems (SUDS) which aim to integrate natural water processes into current systems. Some examples of SUDS involve permeable pavements, green roofs, retention ponds, and swales. However, these solutions can present challenges, whether lack of information or institutionalism (Reed 2004) and uncontrolled and unplanned land use transformation takes place.

Nonetheless, SUDS have proved to be efficiently modelled to ameliorate potential flooding and overloading of drainage systems. This assessment can be done through the Storm Water Management Model (SWMM) software. Various studies under different environments and conditions proved the impact of urbanisation on runoff (Borris et al. 2013; Zhou et al. 2016) and its potential reduction using SUDS (Arjenaki et al. 2021).

3 Methodology

This study approach was framed by the inductive research type, applying developed knowledge from remote sensing, hydrology, hydraulics, and computerised simulation packages to understand urban climate and infrastructure performance. Moreover, it combined qualitative and quantitative methods for determining the inputs for the further process under the scheme of a simulation research type. Figure 1

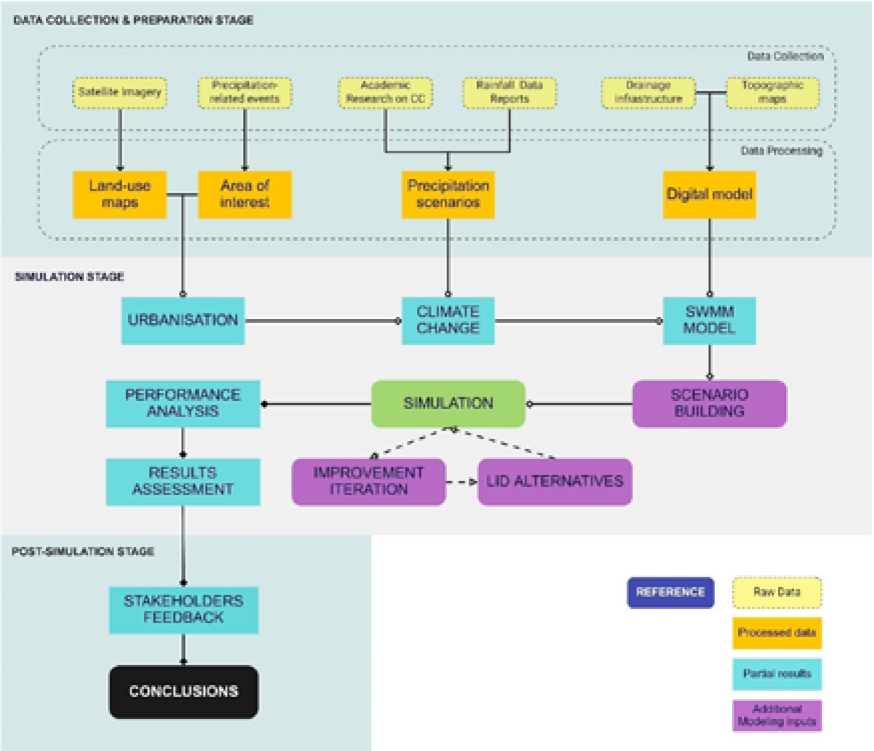


Figure 1. Framework flowchart designed and adopted for the study (Figure: Stohmann 2021)

3.1 Urbanisation growth

Two different sets of land-use cover maps were created based on the satellite data. The first one utilised Landsat 7 images of May 2000 and July 2020 covering the entire urban area of La Paz. Whilst, the second set was created for the area of interest (AOI) from higher-resolution images. The latter data were collected from the GAMLP, including RGB images from QuickBird (2003) and GeoEye (2013) with a 1,2 by 1,2 metres per pixel resolution. Additionally, an image from Bing Maps of 2020 was created from mosaic aerial photos, previously coupled, georeferenced and resampled to match the resolution of the two previous sources. Finally, maps from both sets were elaborated utilising a supervised classification technique (Price 2010) in ArcMap v10.7.1, identifying different land-cover types each year.

3.2 Disasters and Climate change scenarios

A database was constructed by collecting and reviewing online news media portals, institutional reports, and other public sources. Additionally, academic papers and reports were collected and reviewed regarding potential rain pattern changes in the future.

Moreover, rainfall data were collected from ten different stations within the urban limits of La Paz. This data was obtained from SENAMHI, which provided records of monthly accumulated precipitation and monthly maximum precipitation in a day. Data were analysed by season to identify probable trends, corroborated by non-parametric Mann-Kendall tests (at 90% confidence level), widely used to evaluate trends in environmental time series (Thibeault et al. 2010).

3.3 Area of Interest

The AOI was selected based on three considerations: land-use cover evolution maps (1,2 by 1,2-metres per pixel), disasters occurrence (disaster database), and vulnerability (risk map of La Paz). Once the AOI was defined, urban sub-catchments were delimited based on topographic cartography, with contours every one meter. This information was complemented with a digital elevaton model (DEM) from Google Earth. In total, sixty-one sub-catchments were delimited for their inclusion in the digital model.

3.4 Modelling of drainage performance

SWMM v5.1 was used to build the digital drainage system of the AOI. First, subcatchments were included in SWMM with their corresponding areas, impervious and pervious percentages, and weighted Manning overflow (runoff = n) coefficients determined by applying equation [1].

For pervious and impervious areas (n):

$$n = \frac{\sum_{i=1}^{n} n_i \times A_i}{\sum_{i=1}^{n} A_i}$$

Where:

n_i = coefficient according to each land-use polygon in a single sub-catchment

A_i = area of each land-use polygon in a single sub-catchment, in square meters

The coefficients were assigned according to their physical representation on-site, which was determined based on their types of surfaces through supervised classification of the AOI.

Second, the drainage network information was obtained from the water company (EPSAS). Their elements comprised three sub-systems with three discharging points (outfalls in SWMM), sixty-three utility holes (nodes) and sixty pipes (links), and subdivided in Zone 1, Zone 2 and Zone 3. Elevation was complemented with the DEM.

Finally, a rain gauge with a time-series synthetic design storm was calculated from intensity-frequency-duration (IDF) curves and a hyetograph. IDF curves were computed with Achumani station precipitation data. The analysis was done using the Gumbel distribution, widely applied to study extreme values regarding rainfall and other extreme events (Meehl et al. 2000; Sánchez 2013).

The simulation was run adopting the Horton formula, where infiltration decreases exponentially on time (EPA 2015). Also, routing was determined under the kinematic wave method based on the continuity equation where 'acceleration and pressure terms in the momentum equation are negligible' (Chow 1988). Finally, friction losses were determined using the Hazen-Williams formulas as the main force equation.

Two scenarios were modelled in the AOI. The first included land-use changes evolution (LUCE) from 2003, 2013 and 2020, and reflected in their sub catchments runoff coefficients due to urbanisation. The second scenario included the year 2020 urban structure characteristics (LUCE20), adding synthetic storms for a rainfall increase (RI20) and rainfall decrease (RD20) cases.

Based on the results, two types of SUDS were applied to Zone 3 due to its underperformance: green roofs (GRs) and permeable pavement (PP). These proposals were discussed with two officials from the Municipality.

4 Results

4.1 Urbanisation sprawl

The development in the urban area of La Paz between 2000 and 2020 has been consolidated over two main types of land-use cover. Built-up areas grew 36,72%, whilst bare soil decreased 18,73% in that period. These two categories had the most significant changes. On the other hand, the rest four categories identified (agriculture, forest, green areas, and waterways) had minor changes. As of 2020, bare soil occupied a 48,93% of the total urban territory and built-up areas a 41,55%, whilst green areas covered 4,84%, forests 2,48%, waterways 1,37%, and agriculture 0,84%. Therefore, urban sprawl was the most noticeable transformation in the last two decades, replacing most of the bare soil for built-up areas.

Moreover, population increased more rapidly than urbanisation growth (3,66% and 1,84% annually, respectively). It can be possible that complementing the horizontal expansion, the city also experienced vertical growth to accommodate all these people. This significant development imposes enormous tasks for urban planning and its relationship with risk management, primarily in high-risk areas prone to flooding and landslides.

4.2 Disasters and climate change incidence on precipitation

Sixteen significant incidents were catalogued and compiled during the 20 years frame, with most of them having occurred in macro district Sur. However, some of their impacts reached more than one macro district. Moreover, the most repeating type of event was rain and flooding. The peaks in rainfall of 2002 and 2011 (Figure 2a) coincided with the disasters of those years (Hardy 2009; GAMLP 2012). Nonetheless, two main factors were identified in these types of disasters in La Paz: natural causes like heavy precipitation, topographic conditions, and geological conformation (Hardy 2009; GAMLP 2012; Otero 2016), and drainage infrastructure deficiency (Hardy 2009).

Still, precipitation projections and estimates in Bolivia's future are difficult to define precisely in magnitude due to the limitations of climate models (Seiler et al. 2013). In the Altiplano area (subsequently La Paz), variations may decrease (Vuille 1999; Rangecroft et al. 2013) between 10 to 30% (Minvielle & Gerraud 2011) during El Nino (EN) phases. While during the La Niña phase (Vuille 1999) or by growing GHG emissions in the future years, they might increment by 20% (Seiler et al. 2013). Therefore, precise rainfall changes are still uncertain.

4.3 Precipitation analysis

The analysis of precipitation records permitted to identify a wetter season from December to February in La Paz, although October, November and March are also rainy months. The average precipitation in these six months (wet season) was 82,02 mm, while the rest (dry season) was 16,31 mm. The records ranged from 18 to 101 years of extension.

Moreover, uptrends in the average yearly precipitation and maximum 24-hours precipitation per year were confirmed with Mann-Kendall tests of the data as statistically significant (p-value of 0,0502 and 2,54x10-8, respectively). The trends in both cases considered all available data across all ten stations from 1917 to 2020 (Figures 2b and 2c). However, these results cannot confirm whether this pattern is directly correlated with climate change effects.

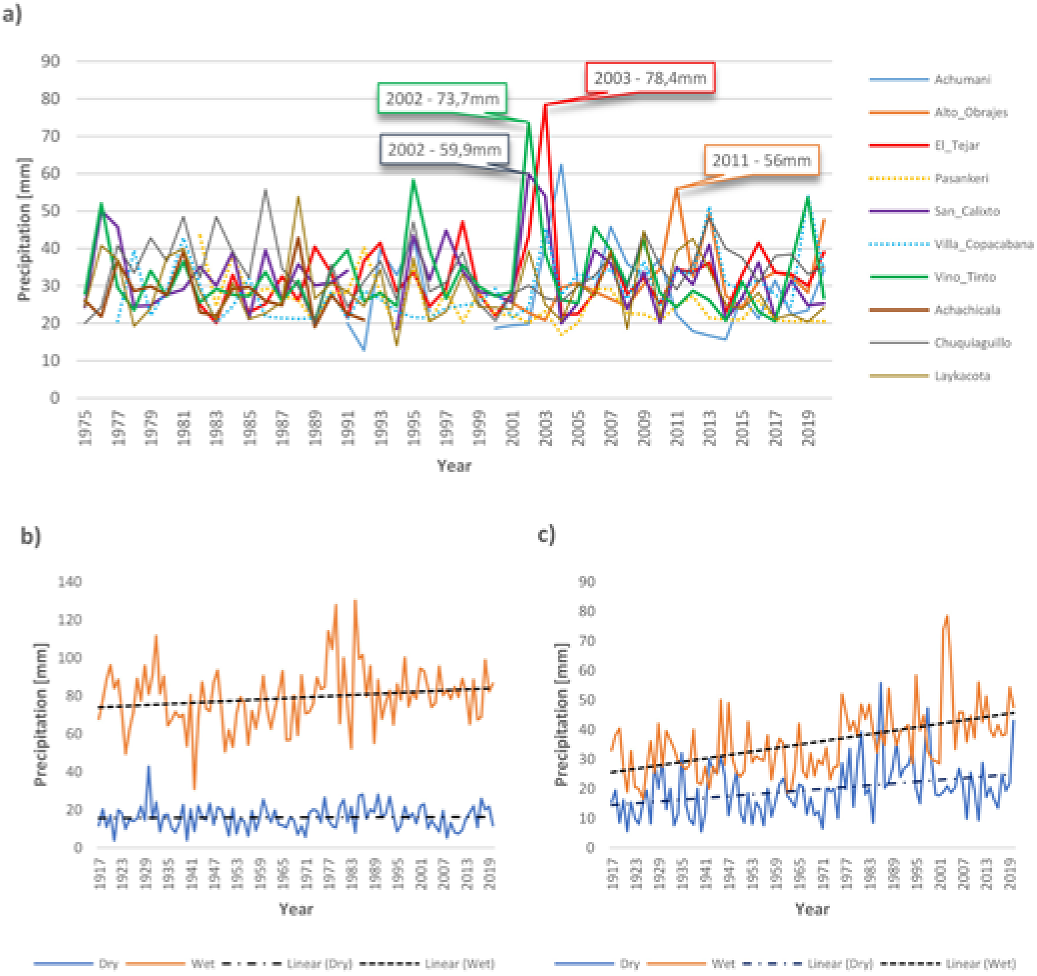


Figure 2. (a) Maximum daily precipitation records from 1975 to 2020 by station, in millimetres. *Note: Records earlier than 1975 from San Calixto and Laykacota stations are not shown in the graphic. (b) Average yearly precipitation (1917 to 2020) in millimetres considering all ten stations, by season; and (c) Maximum yearly precipitation (1917 to 2020) in millimetres considering all ten stations, by season. (Figure: Stohmann 2021 based on SENAMHI data)

Finally, to include CC effects on the drainage performance assessment, a safety factor of ± 20% was assumed for the selected station. This assumption was made pondering the results of Minvielle & Garreaud (2012), Seiler et al. (2013), and other authors. With this factor, additional IDF curves were calculated for a rainfall increase of 20% (RI20 case) and a rainfall decrease of 20% (RD20 case).

4.4 Site selection and drainage network simulation

Twelve hectares in an urban catchment were selected as the AOI. It located in one of the 36 higher risk areas of the city (GAMLP 2012), in the Lomas del Sur sector in the Achumani district. The AOI depicted the rapid urbanisation process (Figure 3a) reflected on its subcatchments' imperviousness grade (Figures 3b & 3c). Nonetheless, most of the buildings and settlements followed the requirements stablished in the LUSU (GAMLP 2014).

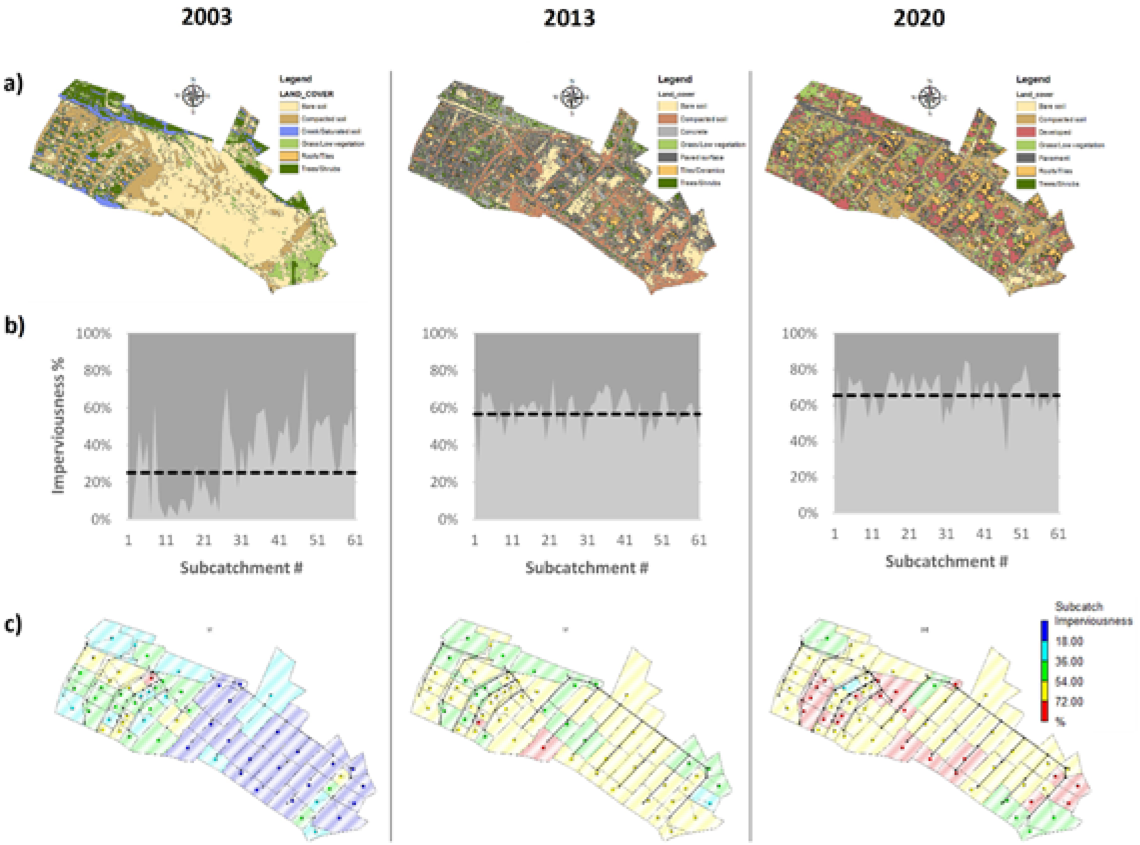


Figure 3. (a) Land-use cover maps from 1,2 by 1,2-metre per pixel resolution satellite images; (b) Weighted impervious area for each sub-catchment in percentage. The dotted line represents the year's weighted impervious percentage; and (c) SWMM model of each subcatchments imperviousness percentage. (Figure: Stohmann 2021)

For the simulation, a design storm was derived from the IDF curves obtained from Achumani station (1,85 kilometres away from the AOI) using equation [1] and alternating block method for return periods (TR) of 2, 5-, 10-, 25-, and 50-years.

Results for scenario 1 proved that land-use changes (LUCE) in the study area played a crucial role in the drainage system performance. As the site developed and became more urbanised, the impervious areas increased from 25,02% in 2003 to 56,62% and 65,47% in 2013 and 2020, respectively. These changes increased peak flow (FW) in 110,52% for 2003-2013, with a lower increment of 8,56% in 2013-2020. Flooding (FD) between 2003 and 2013 increased substantially (~1374%), whilst 2013-2020 was around 14%, both on average (Figure 4). Moreover, in most return periods, the system performed overloaded, causing flooding in utility holes for up to eighteen minutes and up to sixteen surcharged pipes.

In scenario 2, even with a reduction of precipitation in the future (RD20), the system would overload. Peak flow dropped 23,04% and flooding 12%, on average, compared to the scenario 1. Nonetheless, the drainage system still presented overloading (5~13 flooded utility holes, 4~11 surcharged pipes, 12~17 minutes under flooding depending on TRs). Reasonably, the system performance worsened under the RI20 case. FW incremented by 23,86%, while FD by 40,22%, on average (Figure 4). Also, the system had more overloaded elements (11~26 flooded utility holes, 8~21 surcharged pipes, 15~20 minutes under flooding varying with TRs).

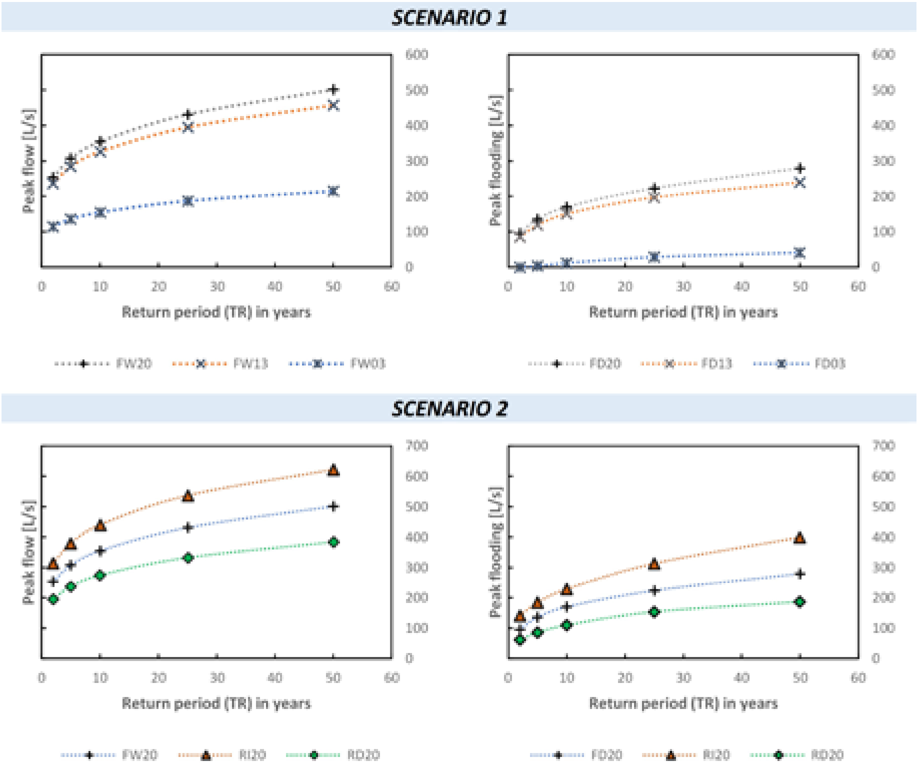


Figure 4. Comparison charts for peak flowing (FW) on the left and peak flooding (FD) on the right by return period (TR). Scenario 1 includes years 2003, 2013 and 2020, while scenario 2 includes year 2020 and RI20 and RD20 cases (Figure: Stohmann 2021)

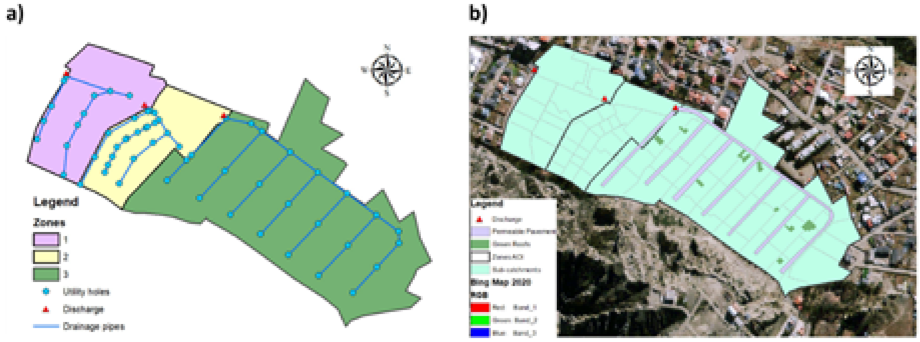
4.5 Sustainable urban drainage systems (SUDS) and stakeholders' feedback

Due to the underperformance of Zone 3 in the AOI, and space limitations, two types of SUDS were selected. The first included nine apartment buildings with green roofs (GR), and the second permeable pavements on the streets (PP) (Figures 5a and 5b).

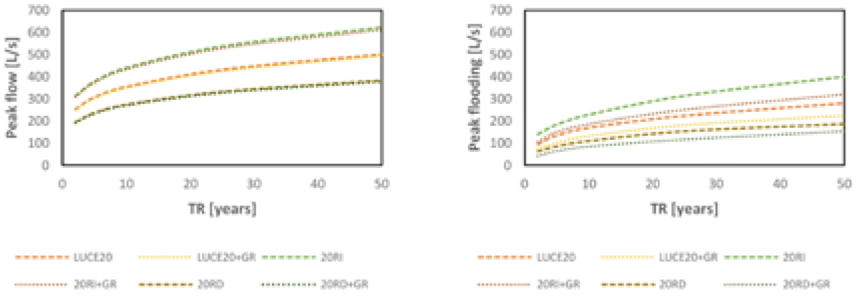
In the GR alternative, peak flow (FW) reduction was negligible (-1,65% on average), while effectiveness increased for peak flooding (FD) with a -21,86% on average (Figure 5c).

In the case of PP, the reduction of FW and FD were larger than in the first alternative. However, the area occupied by the PP is almost four times the one of GRs. nevertheless, the average percentual decrease in FW was -9,70%, and in FD was -36,44% (Figure 5d).

Municipality representatives considered the proposals were feasible to apply, needing first to analyse some planning, monetary and institutional barriers. Also, they indicated SUDS need regulations or norms to reinforce its applicability in La Paz and at national level.



c) Green roofs



d) Permeable pavement

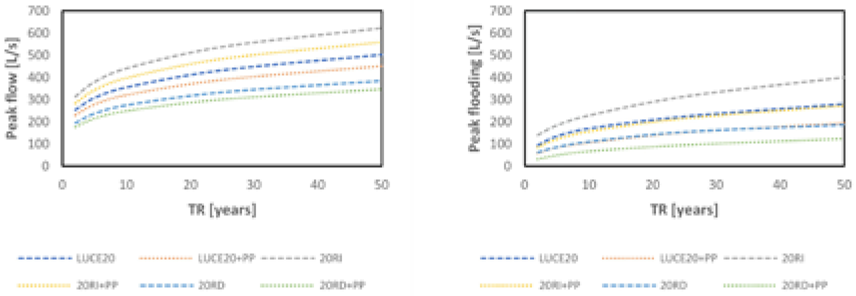


Figure 5. (a) Drainage system zones and elements; (b) Green roofs and permeable pavements proposal location; (c) Peak flow (left) and peak flooding (right) green roofs results for year 2020 with RI20 and RD20 cases; and (d) Peak flow (left) and peak flooding (right) permeable pavement results for year 2020 with RI20 and RD20 cases. (Figure: Stohmann 2021)

5 Discussion and Conclusions

The drainage performance was assessed considering the urbanisation and climate change impacts through simulation modelling using SWMM in a study area in La Paz, Bolivia. The results indicated that changes in land-use cover have a direct correlation with the increase in stormwater runoff, which was more significant at the initial state of development. Whether the urban growth pattern continues to evolve like it did in the last two decades, flooding is expected to occur even with less rainfall intensity due to climate change.

Moreover, scientific research points to experiencing rainfall variability, in scarcity and excess, depending on the El Niño/La Niña phases and GHG emissions effects. Therefore, prone to risk areas in La Paz can increase its vulnerability due to flooding and overloading of the drainage system. When the infrastructure works at its total capacity, it originates overflow and increase the pressure in the conduct, which can exacerbate filtration due to a lack of maintenance or replacement. The flooding of 2002 and the landslide of 2011 are examples of what can happen when a drainage system is overloaded. Nevertheless, these disasters also had other triggering factors like heavy rainfall, steep topography, settlements on risk areas, and inadequate infrastructure (Hardy 2009; GAMLP 2012; Otero 2016).

The findings demonstrated that the inclusion of SUDS in existing networks can benefit the drainage systems' performance by reducing flow effectively. Moreover, while peak flows are lowered, they have a positive correlation with the decline of flooding, confirming other authors results. This link can be decisive in areas prone to flooding or erosion, reducing their vulnerability and disaster probability occurrence. Therefore, SUDS can alleviate the pressure set on study area's infrastructure configuration (diameters, lengths, depths) and land-use cover (higher imperviousness), whether an extreme rainfall event arises there.

However, there were several limitations in this research that should be considered in the interpretation of results. First, due to the pandemic of Covid-19 it was not possible to make an on-site recognition, which can enhance the resulting land-use maps and their adopted runoff coefficient values. Second, disaster occurrence was obtained from secondary sources online instead of the Municipality because it did not reply to an information request. Third, instruments utilised by SENAMHI do not provide shorter time intervals when recording precipitation, limiting detailed analysis for the model. Fourth, updated topography and soils information can enhance the results and adopted SUDS solutions. Some elevation values were adopted from contour lines while soil conditions were assumed as sufficient for implementing permeable pavements. Finally and foremost, there were assumptions regarding the storm design, adopting a duration of 60 minutes as a critical scenario.

Nevertheless, based on the quantitative and qualitative analysis of land-use cover modification and projected precipitations events, it can be concluded that urban sprawl and climate change-induced rainfall changes are crucial factors in the drainage system's functioning. Furthermore, the results indicated that increments of impervious surfaces have a positive correlation effect on peak flows and flooding. Moreover, through the findings of the system's performance, it was possible to simulate the inclusion of sustainable urban drainage solutions (SUDS) in the network. The results proved that green roofs and permeable pavements can effectively reduce peak flows between 2% to 10%, while diminishing flooding between 22% to 36%, respectively. These technologies can be integrated into regulations for complementing urban planning in La Paz.

Finally, the simulation approach can provide valuable guidance for practitioners and public administrators, as it includes criteria for addressing potential risks associated with drainage systems performance. Such results can help assess areas located on risk zones to activate prevention measures and predict probable disaster events related to overloaded systems. They also provide an alternative for implementing solutions through SUDS, which can ameliorate the peak flows while increasing permeability and reducing runoff. Integrating SUDS criteria into new settlements can significantly improve the drainage functioning, but also on existing ones where retrofitting is possible.

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RATTANAKIJANANT, NICHAMON

5

Linking ecosystem health and services of novel green network for climate change adaptation

This dissertation aims to critically appraise the capabilities of a novel ecosystem in Glasgow city, i.e., Green Network (GN), in delivering "ecosystem services" (ES) along with abilities to host a healthy ecosystem. By addressing the role of ecosystem integrity in climate change adaptation, this study discusses correlations of benefits and unexpected harms if policy disregard "ecosystem health" (EH) in ES implementation. As such, Glasgow city assessment detected the extent of (1) policy-focused ESs (i.e., biosecurity, carbon sequestration, and flood regulation), (2) a healthy ecosystem. Indicative ecosystem attributes are used to appraise the capabilities computed by weighted multi-criterion decision method based on practitioners' opinions. As a result, Glasgow's GN supports the "Climate Ready Clyde" action plan as EH ranges from average to adequate health. While ES provisioning is inadequate, great extents have good health. Furthermore, a novel environment could adapt to climate change and provide services to some degree despite hosting a novel ecosystem. Still, an "unhealthy" environment poses links to several ecosystem disservices (EDS). Therefore, targeting the multifunctionality of ES could be the first step to manage adverse EDS and endeavor towards ecosystem integrity.

1 Introduction

Climate change significantly amplifies urbanization impact across ecosystems (Maes et al. 2018). Consequently, increase ecosystem health vulnerability (Munang 2013) and exposes the city's dwellers to climate disaster risk.

We depend on healthy ecosystems to continue delivering a range of ES (Maes et al. 2018). In a functional natural environment, EH synthesize with ES by underpinning the facilitation of ES provisioning (Lackey 2003; Maes et al. 2016), which is a vital process, especially under climatic pressure. Accordingly, GN is well known for providing ES in urban ecosystems (Majekodunmi et al. 2020). Contemporary conservation and restoration schemes have played a significant role in GN implementation, but reversing urbanization to the initial natural condition has proven to be challenging (Lyytimäki & Faehnle 2009). Therefore, GN is heavily delineated upon humanly-selection traits where human tends to spatially alter the landscape to gain ES or favor particular ES that they deem vital to the city's welfare (Evers et al. 2018).

Consequently, selected traits that shaped novelty in the urban ecosystem could minimize ES compared to their original condition (Collier & Devitt 2016). It generates a compensation situation between ES benefits (Perring et al. 2014) or emerged unexpected effects on EH and wellbeing (Evers et al. 2018). Understanding society's demand for ES could help inform anthropogenic pressures' influence on the urban ecosystem (Maes et al. 2016).

The pressing pressure from climate change, especially the high emission scenario, calls for the need to deepen the understanding to safeguard and maximize the underpinning ecosystem health and integrity or, condition to providing benefits beyond human needs) (Hatziiordanou et al. 2019).

Unfortunately, knowledge of the EH and ES provided by novel ecosystems is ununiform and led to uncertainty in GN management (Evers et al. 2018). Due to quantitative data linking between EH and ES are not well established in the literature (Erhard et al. 2016; Maes et al. 2016; Maes et al. 2018) whereas the existing method to quantify ES is based on GN typology in the city, not GN quality or health condition (Majekodunmi et al. 2020).

Therefore, this study investigates the following questions: How to measure the health condition of GN in promoting climate change adaptation in an urban area? How to examine a relationship between EH and climate change adaptation ES? Moreover, do novel ecosystems provide similar or better climatic adaptation services for the city?

The answers are obtained through the following objectives:

- Review the literature to gain fundamental knowledge regarding the "ecosystem" frameworks
- To investigate the current degree of novelty of Glasgow's GN
- Assess the relevant attributes that determine EH and ES of GN in the local content of Glasgow
- To develop an approach to measure GN condition and climatic ES
- Highlight the capability and threats from novel ecosystem to inform local policy

2 Background

The ecosystem services approach (ES) can be defined as benefits ecosystems provide (Burkhard & Maes 2017).

Ecosystem "health" mentioned in the ecological integrity framework refers to a condition that displays the intactness and complex interactions between natural components. Healthy condition sustains the continuity of ecosystem functionality and provision of ES (Lackey 2003; Maes et al. 2016). Simultaneously, an ecosystem that constitutes high ES capability might also indicate good health conditions (Maes et al. 2016.).

Urbanization has deleted the nature footprint from cities. As such, a "Green Network" (GN) framework is adopted to solve urban problems and create an element of a "regional self-reliance" system (Wu 2014). The presence of GN within city parameters increases the resiliency of social capital by "provides physical defense from climate-related disasters" (Munang 2013). Glasgow City Council (GCC 2017) describes GN as a "multifunctional network" of open spaces. GN links green spaces to optimize "combined" or "multifunctionality" or "synergized" benefits of ES from "connected" green spaces. At the same time, also equally distribute ES to ensure society's gains from the improved urban environment.

Although, literature mentioned that GN has a state of "novelty" (Heger et al. 2019) because they function differently from the original ecosystem in terms of colonized species, physical environments, and different ranges of ES where benefits and/harm could be created (Evers et al. 2018).

Novel ecosystems framework does not explicitly specify "urban ecosystem," but broader ecology field relates "novelty" in an urban context to ES (Evers et al. 2018). The two approaches aim to incorporate ES as a tool to "improve" and emphasize "the ways that human and ecological systems evolve together" towards the sustainability of the cities. Which sustainability could be more secured "if properly designed, planned, and managed" (Wu 2014). Therefore, shortcomings of urbanization must be tackled. Maes et al. (2016) reason EH and ES quantification are essential in GN management, such as restoration and conservation strategies, because of the ability to target and prioritize ecosystem degradation areas. The prioritized area could insinuate vulnerable climatic areas or hotspots of environmental, societal, or economic issues in an urban setting.

Existing researches raise a controversial case of environmental issue termed "Ecosystem Disservices" (EDS). EDS addresses the properties of ES "that are perceived as harmful or unwanted by humans" (Lyytimäki 2014). Thus, EDS is highly subjective to various social groups. The disservice ranges from natural phenomena such as natural disasters to anthropogenic causes, for instance, poisonous species and seasonal floods in urban areas. Lyytimäki (2014) found that the area of the world with high biodiversities, like tropical areas, has the highest occurrence of EDS. At the same time, Saunders & Luck (2016) explain that EDS can be eliminated by enhanced biodiversity. What is perceived as EDS could provide ES in other aspects, and some ES and EDS can exist together. Thus, enhancing one ES could also create EDS, which is known as a trade-offs environment.

2.1 A case study of Glasgow city

This study uses Glasgow city as a case to quantify EH and ES. For the background setting of Glasgow's urban ecological context, the condition of Glasgow's GN was compared to its naturalness reference or ecosystem with minimal human interference to understand novelty degree. Comparing ecosystem conditions reflects pressures from anthropogenic and environmental changes that occurred to the native ecosystem. Data were gathered around the pre-industrial era, where naturalness conditions existed in Europe (Heger et al. 2019).

Climate projections (CRC 2017) inform 4.5ºC rises in temperature by 2050 under continuity of high carbon emissions activities (RCP 8.5). The increasing precipitation trend could be expected, causing the change in seasonal variation, drier summers, milder but wetter winters, and increasing extreme storm events associated with sea-level rise. The climatic impact combined with anthropogenic change has impacted Glasgow's adaptability, the natural process, climate, and biodiversity security.

In brief, industrialization has had considerably modified Glasgow and Clyde Valley. Due to Glasgow's geographical floodplains characteristic, inundation is sustaining the ecosystem. Currently, river and coastal banks were extensively managed for flood protection mechanisms. 90% of Glasgow's rainfall depends on the urban drainage system. Which, however, could suffer a system failure under certain extreme climate events (Zala 2020).

The build-up densification is associated with pollution and elevated surface temperatures. Although air and water quality in Glasgow have been improved by good action plans such as "Climate Ready Clyde (CRC)" and "Glasgow and Clyde Green Network (GCV)." The action plans integrated the GN framework with the "urban regeneration" process and derelict land regeneration to ensure nature restoration, along with inward investment, and attract population growth by 2035 (GCC 2019). Accordingly, GCC reports that 35.7% of the Glasgow area is open space. Moreover, 12% are natural areas, which is adequate compared to other Scottish cities (GCC 2020). The "Forestry and Woodland Strategy" aims to expand 21% trees which until now, the trees population has been gain due to commercial reforestation and the state-owned forestry commission (GCV 2006).

All in all, Glasgow has a hybrid ecosystem condition comprised of both historical and novel elements. Through the past 250 years of land change, little remains of the native ecosystem. Exist are a mixture of 5% native nature that survives industrialization, novel self-assembled on wasteland, and novel landscape design resulted from active management to elevate degraded ecosystem (Evers et al. 2018; Miller & Bestelmeyer 2016). Glasgow's GN conservation and restoration strategies aim to reverse the ecosystem back to its historical trajectory. In contrast, most open spaces will only be restored some of their original attributes, which confronts the reality that many ecosystems cannot be restored to a natural baseline, such as altered River Clyde banks. Therefore, human-induced design requires strong intervention suitability.

3 Methodology

In order to deal with the complexity of ecosystem data, this study utilized an "indicator-based approach" to "map" EH and ES because of the potential to quantify and visualize the ecosystem's capacity into one single measurement (European Comission 2021). A mixed-method approach sorted into four steps contains quantitative and qualitative strategies for data collection, data processing, and analysis. The workflow started from qualitative methods of step 1, reviewing "Ecosystem frameworks" from literature to identify their role in an urban area and their quantifying methods. The founding concepts and empirical data from literature help build Glasgow's background setting in step 2; this step explains the degree of novelty of Glasgow's GN, Glasgow's reference condition, e alterations, and environmental change trends. Later on, step 2 guiding the development of the indicator for health assessment in step 3. Here, also focus on deriving key climatic adaptation ESs from policy content. Finally, step 4 applied the quantitative appraisal method linking EH and ES by Multi-Criteria Decision Analysis (MCDA).

3.1 Indicators development method

The method is adapted from Hatziiordanou et al. (2019) whose research mapped particular ES with only selective composition. Therefore, EH in this study is composed of "pressure indicator" and "ecosystem adaptivity indicator," synthesized at equal priority as they influence EH supply equally.

> **Ecosystem adaptability indicators** are adapted from formalized indicators offer by Scotland's ClimateXChange, i.e., "CXC's natural environment adaptation." The 105 indicators were filtered out the irrelevances using the knowledge obtained from qualitative literature reviews.
>
> **Pressure indicators** are derived from key alterations that occur on Glasgow's landscape.

For each indicator, collected are raw geospatial data obtained from various source providers. Figure 1 shows the overall indicators and methods to customize the raw data to fit this study purpose.

Indicators processiong method						
Adaptability indicators	**Date**	**Format**	**Raw data**	**Source Provider**	**Values examined**	**Calculation approach**
Natural regeneration	2012	Vector	CSGN Integrated Habitat Networks	SNH	Seed dispersal ability (SNH, 2012) from key habitats at (1) Core habitats, (2) 0 to 500m. from core habitats (3) 500 to 2,000m. from core habitats	ArcMap offset tool
Protected area	2000	Vector	Native woodland survey of Scotland	SNH	Protected nature sites (Natural England's, 2010) including (1) Ancient woodland preservation, (2) Sites of Importance for Nature Conservation or SINCs, & designated green corridors (3) Site of Special Landscape Importance or SSLIs	ArcMap reclassify data
			PAN65	GCC		
Habitat connectivity	2020	Vector	PAN65	GCC	Modularity of suitable green space for species dispersal in a changing climate at fixed distances of at least 300 m. to express the foraging range of solitary bees (Natural England, 2010)	Graphab 2.6 modularity analysis
Extent of key habitats	2019	Vector	PAN65	GCC	Tracking suitable green space for species dispersal in a changing climate (Natural England's, 2010) at (1) More than 50 ha of open spaces (2) 0 to 0.5 ha of natural woodlands (3) 0.5 to 2ha of open spaces	ArcMap selected attribute & reclassify data
Vegetation health	2021	Raster	Landsat-8, dated 28/06/2021 at 11.00am, 20% cloud coverage	USGS	Vegetation health was analyzed via Normalized Difference Vegetation Index (NDVI) to distinguish landcover surfaces by measuring vegetation's light reflection at specific frequencies (EOS, 2021).	Calculation via ArcMap using below formula; NDVI= ((NIR – R))/((NIR+ R))
Pollinators & key species	2018 to 2021	Raster	Species records	NBN Atlas	Sighting records of; Arvicola amphibius, Rana temporaria, Bufo bufo, Bat Species, Erinaceus europaeus, Apus apus, wintering bird. Pollinators included; bumblebee, dragonflies species, falcons, hawks, eagles and ospreys species, Alauda arvensis.	ArcMap density analysis and zonal statistic
Water quality	2018	Raster	Water environment hub	SEPA GCV	Surface water quality data collected from water stations across Clyde River and its tributaries classified into three values; poor, average, and good. Urban wetlands water assigned moderate quality	ArcMap reclassify data
Floodplain area	2015	Vector	Delineation of riparian zones	CGLS	Floodplain and riparian zone including; (1) Delineation of Potential Riparian Zones or DRZP (2) Observable Riparian Zones or DRZO & potential flood detention areas (3) Area under good policy, City Development Plan on Water Environment (CDP 8) due to areas are being monitored.	ArcMap reclassify data
	2019	Vector	Potential of Policy CDP8	GCC		
	2018	Raster	Landsat-8	USGS		
Soil sealing	2018	Vector	Urban atlas landcover map	CGLS	Sealing degree of land surface at (1) Less than 30% (2) 30% to 50% (3) More than 80%	ArcMap reclassify land cover data & NDVI map help locate and "erase" the builtup area
	2021	Raster	Landsat-8	USGS		
Pressure Indicator	**Date**	**Format**	**Raw data**	**Source Provider**	**Values examined**	**Calculation approach**
Landscape degradation	2018	Vector	Urban atlas l andcover map	CGLS	Area of human dominance examine from urban fabric density and population density	ArcMap reclassify data & zonal statistic tool
Deprived area	2020	Vector	Scottish Index of Multiple Deprivation (SIMD2020)	GCC	Deprived area to climate change risk examine from SIMD2020 and greenspaces accessibility	ArcMap weigthed overlay of SIMD2020 with result of open space density
	2020	Vector	PAN65	GCC		
Flood risk	2021	Vector	Flood risk interactive map	SEPA	Area under the worst-case scenario of 200-year flood return includes three types of inundation; coastal, riverine, and surface.	ArcMap reclassify data
Urban temperature	2021	Raster	Landsat-8, dated 28/06/2021 at 11.00am, 20% cloud coverage	USGS	Land surface temperature (LST) to capture urban materials and vegetation's skin temperature.	ArcMap computation following Jeevalakshmi et al. (2017)
Invasive species dominance	2011 to 2021	Raster	Species records	NBN Atlas	Sigthing records of invasive species controlled under the Wildlife and Natural Environment (Scotland) Act 2011, i.e., Fallopia j aponica, Mantegazzianum, Lysichiton americanus, Persicaria wallichii, Rhododendron L., Sciurus carolinensis, Neovison vison, Muntiacus reevesi	ArcMap, weighted overlay, density analysis and zonal statistic analysis
	2020	Vector	PAN65	GCCC	Intensity of ground maintenance	

Figure1. Summary of the overall data applied for mapping assessment (Figure: Rattanakijanant 2021)

3.2 ES valued in local policy

Mae et al. suggest that policy objectives can be built around ES. On the contrary, this study reverses the rationale by using the local policy to extract needed ES. In this way, a policy could help specify ES for this study. The policy content analysis is undertaken for "Glasgow City Region's first Adaptation Strategy and Action Plan 2020–2030; Intervention 9: Deliver nature-based solutions for resilient, Bluegreen ecosystems, landscapes, and neighborhoods." (CRC 2021). Extracted three key ES that Glasgow city valued and planned to supplement; "Biosecurity," "Carbon sequestration," and "Flooding regulation." The selection of policy ES presents an example of multifunctionality ES quantification. They are vital for Glasgow city adaptation in magnifying environmental, social and economic according to policy and do not signify more importance than ES, which have not been mentioned here.

3.3 Method to synthesize EH & ES

Finding synthesis between EH and ES provides new insight into the role of ecosystem integrity. The framework adapted from Maes et al.'s conveying that composite indicator that supports EH constitution are strongly interconnected to ES supplementation. Therefore, the same set of indicators are also used to map ES. By MCDA computed via ArcMap 10.7.1 application, this process engaged practitioners' participation for two purposes; (1) to selected relevant indicators to assess ES, (2) to assign numerical weightings to reflect the importance of each indicator. Opinions were collected from across GN-related public organizations through questionnaires via the "Google forms" platform.

The scoring system normalized the mapping appraisal results range from 1 to 5, indicating poor, inadequate, average, adequate, and excellent value, respectively (Hatziiordanou et al., 2019).

3.4 Consensus analysis and site analysis

This method sets out to understand the capability and threats of novel GN. The MCDA mapping assessments present (1) Indicator maps, (2) EH map, (3) ES maps, i.e., biosecurity map, carbon sequestration map, and flood regulation map. These three items are overlaid in ArcMap 10.7.1 to arrive at final consensus evaluations described in 5 scenarios, as further explained in the result section.

Lastly is to identify threats or probable EDS. EDS is not directly quantified in this method but identified by analyzing pressures factor on GN. Accordingly, sites were selected from the particular consensus evaluation following the criteria that the areas are under the GCV's development plan and reflect CRC's action plan. Analysis of sites is based on observing ground truth data from Google Map. Implications are made in light of existing literature.

4 Results

4.1 Results of Indicators mapping

Figure 2 shows fourteen indicators mappings computed as described in Figure 1. The results illustrate spatial locations and configurations in which these attributes are present.

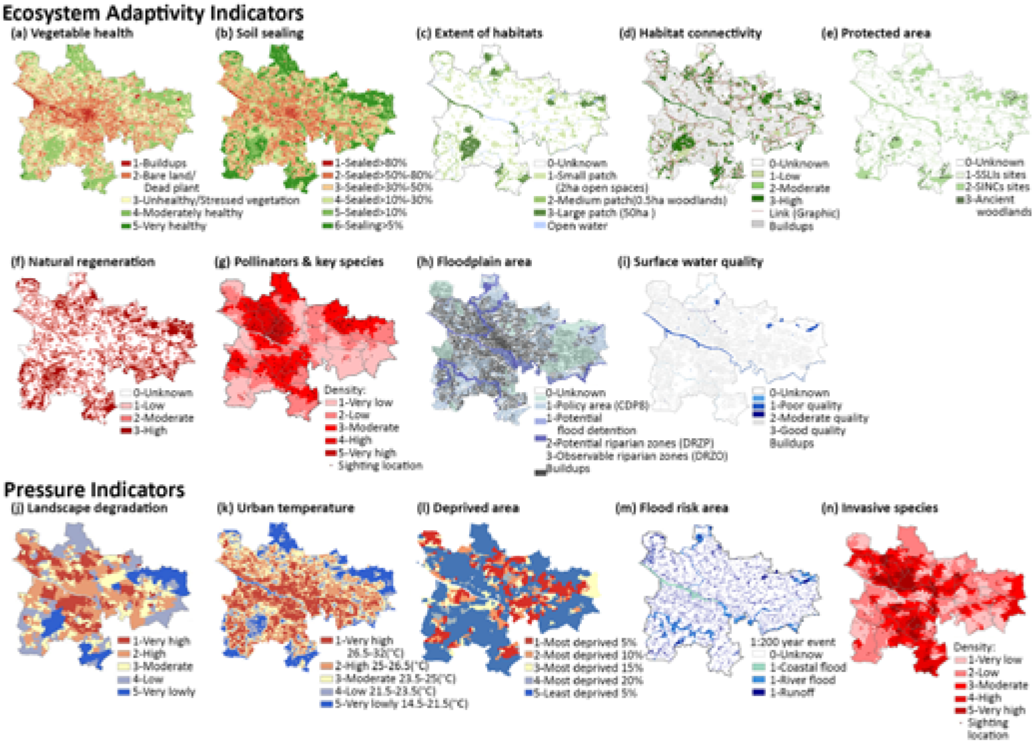


Figure2. Results of Indicators mapping (Figure: Rattanakijanant 2021)

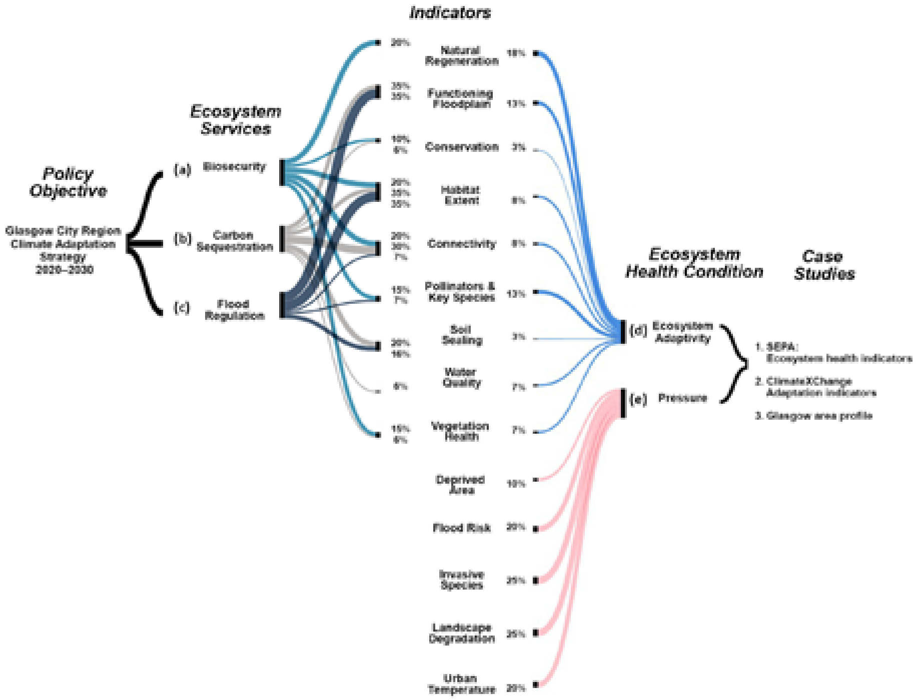
4.2 Result of ES and EH mapping based on practitioner's opinion

To map EH and ES, practitioners were asked to assign importance scores for the above fourteen indicators. Three practitioners participated; they represent Glasgow's local governments and environmental agencies, Glasgow city council, South Lanarkshire city council, and NatureScot. Figure 3 summarizes the result of indicators' importance.

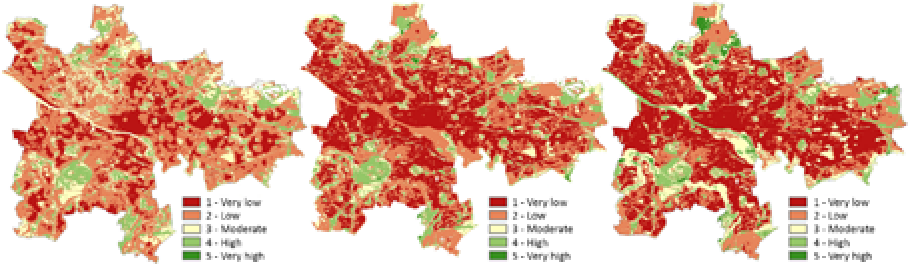
For "**Ecosystem Services mapping**," all practitioners agreed that landscapes configurations, i.e., "extent of habitat" and "connectivity," are a founding attribute to ES delivery. On the contrary, management aspects like "water quality" and "protected area" are the least focused. Importance scores are not essentially different for "natural regeneration," "vegetation health," "pollinator & key species," and "soil sealing" because they are secondary attributes that could be introduced after landscape configurations are established. However, they should be monitored to sustain habitat quality or to imply appropriate interventions. Nevertheless, one opinion suggested that all indicators should take equal priority for large-scale assessment like Glasgow. For **Biosecurity mapping**, none of Glasgow area has an “excellent” supply even though the city has a high proportion of open space. The cluster of biosecurity can be observed in the proximity of Pollock county park, Seven lochs wetland, and Kelvin walkway. For **Carbon sequestration mapping**, regardless of the presence of water bodies, vegetation, and unsealed soil, “Carbon sequestration” potential in inner-city areas score “inadequate” to “poor” value. **Flooding regulation mapping** prioritizes substantial floodplains. Thus, the potential of rivers and riparian for flood regulation is pronounced on the result. Although, the potential is “average” given the influence of sealed soil.

For “**Ecosystem health mapping**,” composes of “Ecosystem adaptivity” and “Pressure.” Here, the “sustainability” factor like “natural regeneration” is deemed significant, implying that the ecosystem is functioning and would continue doing so. The same rationale applies to “pollinators and key species.” “Landscape degradation” is considered the foremost cause of all other pressures, while “invasive species” are the primary concern in novel environments. The mapping results show that 33.1% of “healthy” areas fall into the policy area of “Planning and open space” (PAN65), whereas 0.5% locate in derelict land. A significant proportion of GN denoted “average” health and is most likely to occur in the transitional space where paved structures and landscapes are difficult to delineate.

Synthesis of ES & EH based on practisioners's opinions
This framework guide the final mapping analysis



(a) Map of Biosecurity (b) Map of Carbon sequestration (c) Map of Flood regulation



(d) Map of Ecosystem adaptivity (e) Map of Pressure

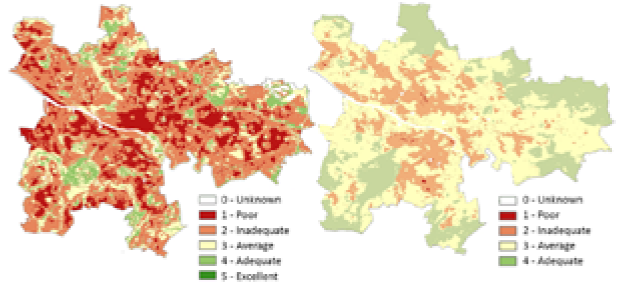
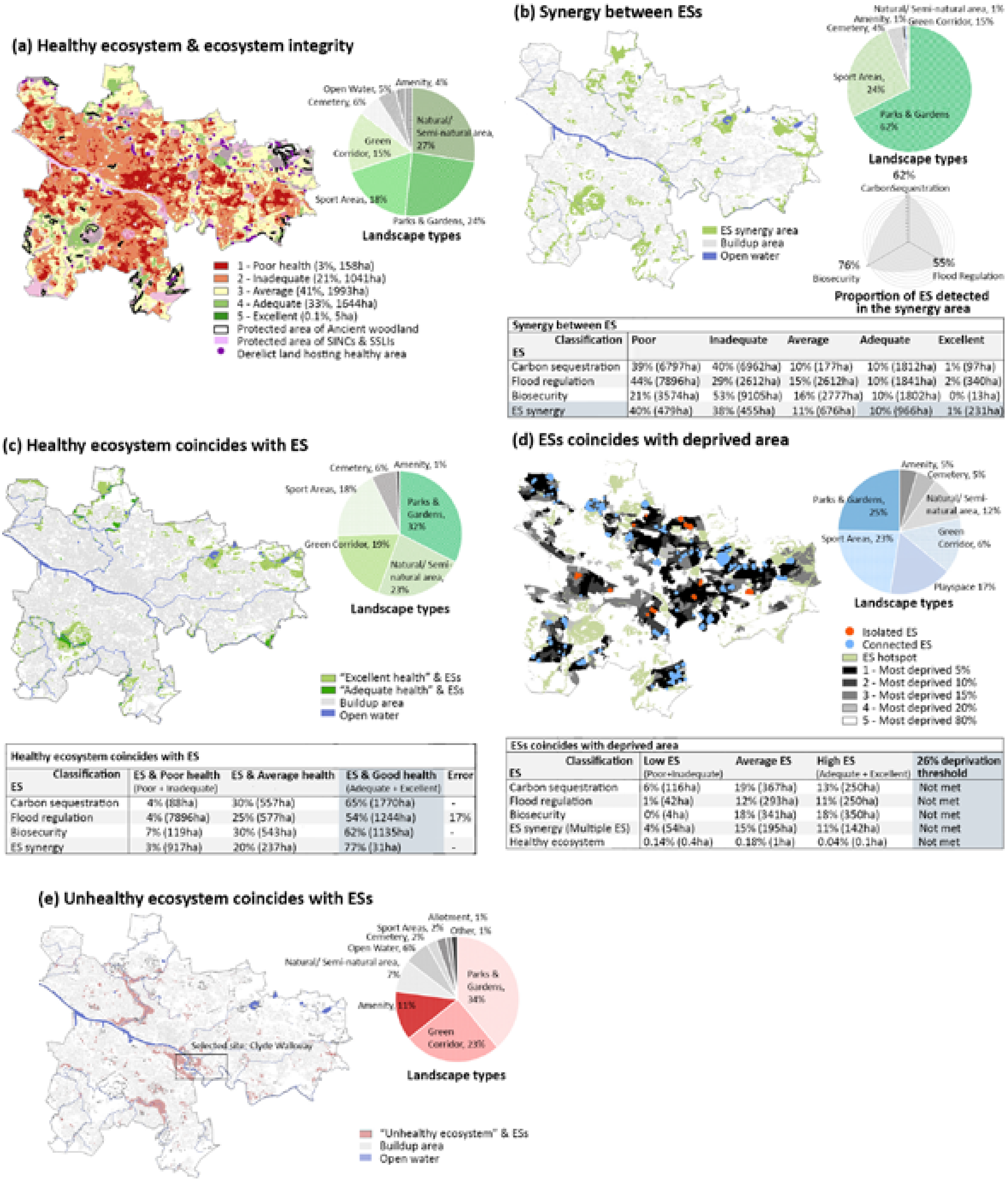


Figure3. Result of ES and EH mapping based on practitioner's opinion (Figure: Rattanakijanant 2021)



Synergy between ES

Classification ES	Poor	Inadequate	Average	Adequate	Excellent
Carbon sequestration	39% (6797ha)	40% (6962ha)	10% (177ha)	10% (1812ha)	1% (97ha)
Flood regulation	44% (7896ha)	29% (2612ha)	15% (2612ha)	10% (1841ha)	2% (340ha)
Biosecurity	21% (3574ha)	53% (9105ha)	16% (2777ha)	10% (1802ha)	0% (13ha)
ES synergy	40% (479ha)	38% (455ha)	11% (676ha)	10% (966ha)	1% (231ha)

Healthy ecosystem coincides with ES

Classification ES	ES & Poor health (Poor + Inadequate)	ES & Average health	ES & Good health (Adequate + Excellent)	Error
Carbon sequestration	4% (88ha)	30% (557ha)	65% (1770ha)	-
Flood regulation	4% (7896ha)	25% (577ha)	54% (1244ha)	17%
Biosecurity	7% (119ha)	30% (543ha)	62% (1135ha)	-
ES synergy	3% (917ha)	20% (237ha)	77% (31ha)	-

ESs coincides with deprived area

Classification ES	Low ES (Poor+Inadequate)	Average ES	High ES (Adequate + Excellent)	26% deprivation threshold
Carbon sequestration	6% (116ha)	19% (367ha)	13% (250ha)	Not met
Flood regulation	1% (42ha)	12% (293ha)	11% (250ha)	Not met
Biosecurity	0% (4ha)	18% (341ha)	18% (350ha)	Not met
ES synergy (Multiple ES)	4% (54ha)	15% (195ha)	11% (142ha)	Not met
Healthy ecosystem	0.14% (0.4ha)	0.18% (1ha)	0.04% (0.1ha)	Not met

Figure 4a–e. Consensuses between mapping results (Figure: Rattanakijanant 2021)

4.3 Consensus between mapping results

Healthy ecosystem & ecosystem integrity

Figure 4a. shows the overlaid result between ecosystem health & protected area. This scenario provides insight into ecosystem integrity because protected areas host hypothetical naturalness. An interesting finding is that 30% of a healthy area does not belong in "Protected nature." As expected, the hotspot is most pronounced in the protected area of the designated green corridor, natural and semi-natural landscape, and parks and gardens. Also, the health score varies within this protected area despite being conserved, even range from poor to adequate health. Protected sites such as "Jordan Hill Ancient Woodland," "Capeland Hill Ancient Woodland," and "Mall's Mire Community Woodland" are isolated from other nature cores.

Synergy between ESs

Synergy occurs spatially between intent ESs as shown in Figure 4b. "Biosecurity" shown the most significant supply (76%) in the synergy, while "flood regulation" has seen the least (55%). Public parks, gardens, and sports areas are the leading provider of multiple services due to their extent in the city. Regardless of the lowest synergy, flood regulation has the most significant extent.

Healthy ecosystem coincides with ES

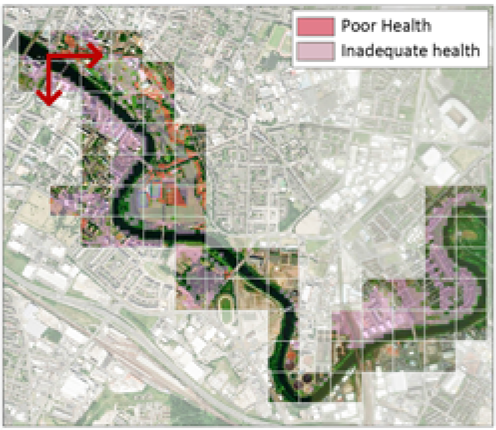
Figure 4c illustrates compiled maps of "ES synergy" and "ecosystem health." The majority of the "ES synergy area" (77%) falls within the "excellent" and "adequate" health areas. Similar scenarios are observed for each ES where high supply coincides with "Good health." Therefore, 65% of the PAN65 area has a natural potential to provide intent ESs.

ESs coincides with the deprived area

On to the social vulnerability aspect, Figure 4d shows a mapping overlaid between deprived area and ES synergy maps. 15% of ES hotspot deliver multiple ES to the deprived area, and 1 ha has a "healthy ecosystem," but "flood regulation" is the least available. Coinciding areas are pronounced around important GN sites in the peri-urban area and sites of the industrial declined area along River Clyde. The "equitable distribution" method adapted from Makanjuola et al. (2020) hypothesized that Glasgow city has 26% delineated as "deprived" by this study. Thus, 26% of ES hotspots that fall into the most deprived area would account for 'equitable distribution (Majekodunmi et al. 2020). None of the ES met the equitable distribution threshold.

Unhealthy ecosystem coincides with ESs

EDS traits could be observed in environments where ES is deficient or in areas which undergone an ecological change, such as the reduction of ecosystem health (Potgieter et al. 2019; Dohren 2015). Thus, this study identifying EDS by locating ES areas that exist within an "unhealthy" area. One of the hotspots locates in the Clyde walkway (Figure 5). Open spaces on the site connect through a green corridor, including parklands, riparian landscapes, River Clyde, industrial areas, and residential areas, which have undergone urban regeneration from former derelict land. Flood risk, invasive species, and landscape degradation are equal influencers of EDS. Figure 5 summarized identified EDS. For instance, channelized landscape riparians link to the disappearance of coastal and riverine habitats and lower their ability to withstand rising sea levels. Sustainable drainage systems (SuDS) are sufficiently integrated into the residential area but could link to simplified landscapes. The issue of simplified landscape and non-native species causes health issues and creates vulnerable landscapes prone to flood and drought. High maintenance activity on parks and gardens could cause green waste generation and carbon emission (Bisgrove & Hadley 2002). Nevertheless, 17% of the site areas sequester carbon. Literature mentioned that even reforestation and peatland restoration, mainly commercial plantation, is associated with carbon release and acidification even though it does not concern the current site situation but is relevant to future climate forest policy deployment.



Location of Clyde Walkway

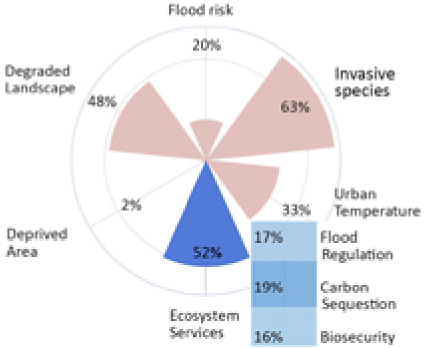


Chart comparing proportion of ESs & EDS

3D perspective of Site B and surroundings

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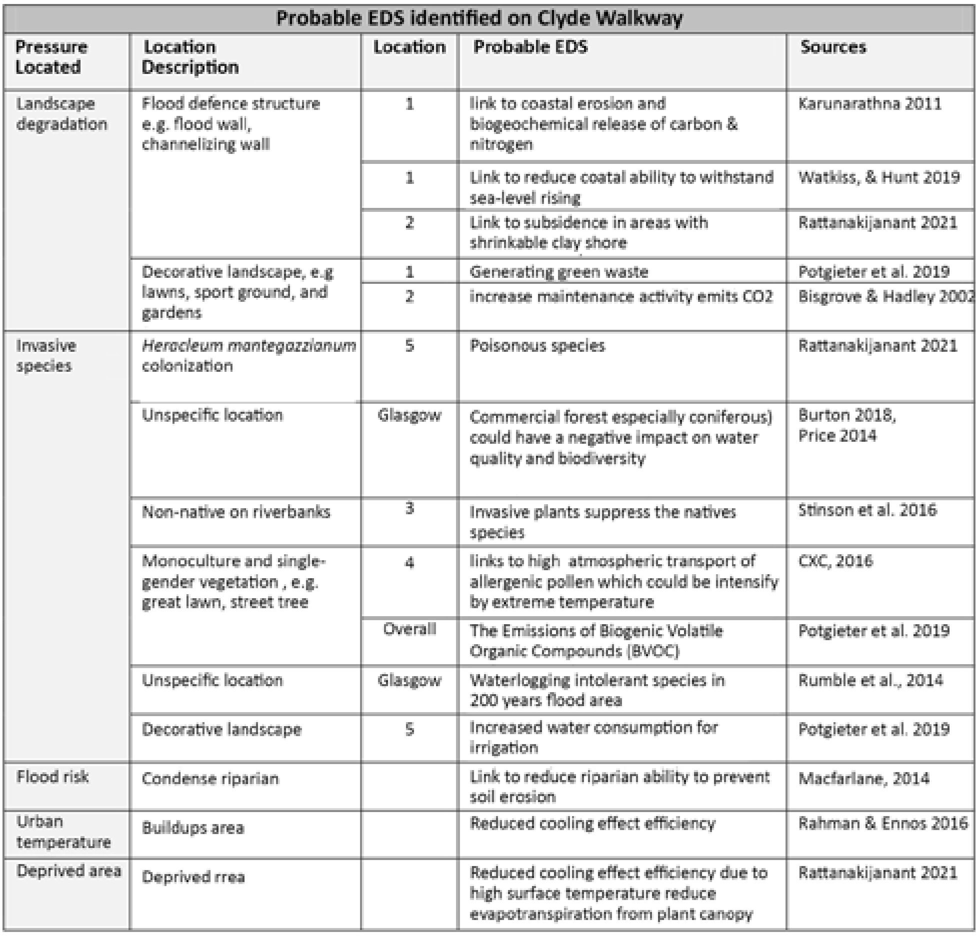

Probable EDS identified on Clyde Walkway

Pressure Located	Location Description	Location	Probable EDS	Sources
Landscape degradation	Flood defence structure e.g. flood wall, channelizing wall	1	link to coastal erosion and biogeochemical release of carbon & nitrogen	Karunarathna 2011
		1	Link to reduce coatal ability to withstand sea-level rising	Watkiss, & Hunt 2019
		2	Link to subsidence in areas with shrinkable clay shore	Rattanakijanant 2021
	Decorative landscape, e.g lawns, sport ground, and gardens	1	Generating green waste	Potgieter et al. 2019
		2	increase maintenance activity emits CO2	Bisgrove & Hadley 2002
Invasive species	*Heracleum mantegazzianum* colonization	5	Poisonous species	Rattanakijanant 2021
	Unspecific location	Glasgow	Commercial forest especially coniferous) could have a negative impact on water quality and biodiversity	Burton 2018, Price 2014
	Non-native on riverbanks	3	Invasive plants suppress the natives species	Stinson et al. 2016
	Monoculture and single-gender vegetation , e.g. great lawn, street tree	4	links to high atmospheric transport of allergenic pollen which could be intensify by extreme temperature	CXC, 2016
		Overall	The Emissions of Biogenic Volatile Organic Compounds (BVOC)	Potgieter et al. 2019
	Unspecific location	Glasgow	Waterlogging intolerant species in 200 years flood area	Rumble et al., 2014
	Decorative landscape	5	Increased water consumption for irrigation	Potgieter et al. 2019
Flood risk	Condense riparian		Link to reduce riparian ability to prevent soil erosion	Macfarlane, 2014
Urban temperature	Buildups area		Reduced cooling effect efficiency	Rahman & Ennos 2016
Deprived area	Deprived rrea		Reduced cooling effect efficiency due to high surface temperature reduce evapotranspiration from plant canopy	Rattanakijanant 2021

Figure 5. Visualization of Clyde Walkway to explain probable EDS (Figure: Rattanakijanant 2021)

5 Conclusions and discussion

Determining EH contributing to the understanding of ES supply in several ways. Firstly, ES is proportionally increased where "healthy" conditions exist. Glasgow city's GN has average health conditions and, to some measure, can: (1) host a naturalness remaining since the industrial revolution and (2) withstand urban climatic challenges as described in CXC adaptation policy. Furthermore, synergies of multifunctional ESs are also found in Glasgow's "healthy" areas and safeguard by "biosecurity."

Although, unhealthy ecosystems presence implicates the circumstance where unhealthiness can host ES supplies. Thus, Glasgow GN could deliver climatic ESs in an environment with lesser naturalness. Of which by fostering novel GN would eventually have benefits on degraded Glasgow's landscapes. Nevertheless, biodiversity is complex and challenging to achieve, therefore emerge EDS as explained.

Urban EDS management is a delicate process. Lyytimäki (2014) suggests the probability of removing EDSs without compromising the newly established ecosystems. Mainstreaming movement has informed interventions to minimize ES-EDS trade-offs, such as relaxing landscaping management, removing large channelized structures like seawalls and dams, and incorporating overtopping wetlands dikes.

This study does not solely intend to underscore EDS's negative impacts or suggest approaches to eliminate them. Instead, appreciate ecosystem integrity and emphasize the benefits of targetting ES multifunctionality to achieve more resilient ecosystems. A new condition does not always translate as adversity. The lesson learned is that any GN planning has to consider impacts on the adjacent ecosystems fully. Planners have to clearly define where and how to integrate nature-based solutions (NBS), to what degree restoration or conservation would reach. And most importantly, would NBS withstand the worst-case scenario?

RCP 8.5 scenario implies a need for careful selection of NBS and re-evaluation of the current GN. Extra attention could be given to restoring nature as the results reaffirm that natural areas host healthy ecosystems. However, some ancient natural woodlands are isolated in Glasgow urban area and could be preserved by good management such as "Clyde Climate Forest" and "Rewilding framework" (SCOTLAND: The Big Picture 2021). Attention could be assigned according to health score. Eventually, the restoration needs to be addressed immediately and substantially because natural areas are slow-growing. The implementation could be challenging as after all, restoration involves multidimensional stakeholders. A policy to encounter loss of urban property to habitats restoration is crucial for the succession of the project.

Rumble et al. (2014) explain that natural areas that are unlikely to reconnect with habitat core could obtain novel aspects, such as integrating low intensive cultural, educational, or recreational aspects to attract subsidies.

Natural regeneration has gained momentum in restoration science (Potgieter et al. 2019; GCC 2017) for a cost-effective and sustainable way to achieve natural ecosystem structure. Although for highly altered landscapes, naturally restoring processes are not feasible. In Glasgow's case, despite facilitating EDS, the "urban regeneration" strategy is an effective simulator moving forward environment along with the economy and social needs.

On to social aspect, the inner-city exposure to climate change "risk" is pronounced as the most in need could access the least ES. Nevertheless, the results suggest distributions of ES in a deprived peri-urban setting where 85% of ES are reasonably connected, to the fact that Glasgow has well-distributed GN (Makanjuola et al., 2020). Indeed, sites like walkable green corridors, parks, and sports grounds are the primary "healthiness" provider. This notion provides room to integrate social and environmental aspects into one comprehensive picture per the CRC'S policy that GN should be developed along with the adaptive community. Ultimately to implement GN, communities' needs have to be heard to prevent shortcomings, e.g., maintenance burden, crimes, or vandalization.

To conclude, this approach to assessing and linking EH and ES reflects that Glasgow's GN supports CRC's policy. The method is informative in identifying characteristics of highly adaptive environments around Glasgow city. It set a baseline for the current GN condition to be further tracked in monitoring climatic impact trends. Indicators method to capture the full range of EH and ES may lead to uncertain results, although it is a helpful tool for compiling accessible data. Thus, there is a need to acknowledge that urban ecosystem integrity is interconnecting to a broader range of social cohesion, health and wellbeing, economic, and comprehensive climatic and biodiversity knowledge.

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Urban Heat Island

Urban overheating mitigation

ANANYEVA, OKSANA

6

Green Infrastructure Cooling Strategies for Urban Heat Island Mitigation in Cities:

A Case Study of Glasgow, United Kingdom

Urban green infrastructure (UGI) is an acknowledged strategy for mitigating Urban Heat Island (UHI) effect in cities. However, lack of comparable information on effectiveness of UGI types and realistic case studies poses challenges for transferring existing knowledge into city planning practice. This study describes the spatiotemporal patterns of UHI in the context of Glasgow (Scotland, UK), explores scale-dependent interactions between UHI and UGI, and, finally, examines the cooling potential of UGI types and quantities. ENVI-met modelling is applied to investigate the microclimate and thermal comfort implications of the Avenues Programme, Glasgow city centre retrofitting strategy, and alternative greening scenarios.

In Glasgow, UHI intensity is the highest in summer with significant spatial clustering observed in the inner urban areas. UGI determines variations of surface temperatures in 75% of city data zones. Greening scheme proposed by the Avenues Programme can mitigate air temperatures and Physiologically Equivalent Temperatures (PET) by 0.91 K and 13.0 ˚C, respectively. Planting Tilia sp. on the Avenues streets can further decrease air temperatures by 1.27 K. In contrast, adding more trees, introducing grass and shrubs, or green roofs will have negligible effects on PET. Therefore, planting trees strategically in heat-exposed areas with selection of high albedo species is more effective than just general increase in green cover. Study results provide empirical evidence to support targeted, scale-specific UGI cooling interventions and assist urban planners in decision-making process.

1 Introduction

City residents are being increasingly exposed to the heat stress due to the localized warming associated with the Urban Heat Island (UHI) effect (Oke 1973). Development of UHIs is the result of excess heat accumulation in manmade features that replace natural surfaces in urban areas (Memon et al. 2008; Voogt & Oke 2003). The synergy between the warming produced by the UHI and projected climate change impacts poses a threat to sustainability and climate adaptation capacity of the cities (Emmanuel & Krüger 2012).

Urban overheating is a growing concern for Scotland (UK), as research indicates that preferred thermal comfort conditions reported by local population are even lower than the ones defined in literature for the temperate climate zone (Krüger et al. 2013). Considering record-breaking heatwaves of 2018/2021 and projected temperature increase (IPCC 2018), UHI mitigation should be in focus of the current climate change adaptation and city planning strategies.

Urban green infrastructure (UGI), i.e., network of green spaces (parks, street trees, green roofs etc.) is a promising strategy to address overheating in urban areas as vegetation provides cooling through evapotranspiration and shading (European Commission 2013; Winbourne et al. 2020). Additionally, UGI offers multiple environmental and social benefits and can be retrofitted in the existing built environment (European Commission 2013). In Scotland, role of UGI in regulating urban climate is well recognized within research circles, by authorities and outlined across several policies (Scottish Government 2004, 2008, 2014a, 2014b). However, integration of the UGI into urban planning practices with UHI mitigation and climate adaptation purposes remains insufficient (Emmanuel et al. 2015, 2021; Matthews et al. 2015). The reasons behind this research-policy-practice disconnection are related to the overload of theoretical research without providing clear recommendations, as well as lack of comparable information and realistic case studies to demonstrate the cooling potential of UGI types in the local context (Monteiro et al. 2019). Additionally, the risks of the UHI are often overlooked in the context of climate change.

This study aims to quantify the cooling effectiveness of the UGI across different spatial scales, which may inform best planning practices for urban heat mitigation and adaptation in the context of Glasgow city (UK). To achieve this aim and fill the outlined gaps, given research (a) investigates seasonal and spatial patterns of the surface UHI (SUHI) at the city-scale level and identifies the areas of potential overheating; (b) assesses the relationship between the summertime SUHI and present citywide vegetation cover with respect to UGI types; (c) through traverse study, examines the intra-urban UHI at local scale and in relation to the existent tree canopy cover; (d) investigates the UHI mitigation potential and microclimate implications of the Glasgow city centre retrofitting project the Avenues Programme based on the case study of Sauchiehall St., Holland St., Elmbank St. and St Vincent St.; (e) analyses the performance of UGI types and quantities based on proposed alternative greening scenarios.

2 Background

2.1 Urban Heat Island Phenomenon and Why to Mitigate

Cityscapes are dominated by hard impervious features such as roads and buildings, which replace natural surfaces and trap heat, provoking warming of the surrounding environment (Memon et al. 2008). This microclimatic phenomenon is known as the Urban Heat Island (UHI) effect (Oke 1973) and has been reported from cities of different sizes and climates. On average, urban areas can be 1.0 – 8.0 ˚C degrees warmer than the nearby rural regions (Tzavali et al. 2015). For instance, Birmingham and Manchester were 5.0 ˚C to 8.0 ˚C warmer (Tomlinson et al. 2011; Cheung 2011), while even higher temperatures of 8.9 ˚C were reported in London (Kolokotroni & Giridharan 2008). Though urbanization is recognized to be the major reason behind UHI emergence (Oke 1973; Chen et al. 2020), Emmanuel and Krüger (2012) demonstrated that such heat patterns also persist in the shrinking cities, like Glasgow. While some benefits of city warming can be anticipated, the UHI effect has negative implications for energy demand (Li et al. 2019), air quality (US EPA 2008), human thermal comfort (Emmanuel 2005), public health (Paravantis et al. 2017), and climate change adaptation (Watkiss et al. 2018), which all lead to increased economic and societal costs (Miner et al. 2017).

To address the outlined heat-related risks through policy-making and urban planning, quantification of the UHI intensities, understanding of its spatial patterns across different scales and mitigation options is essential. As all climate variable, the UHI can be delineated across three spatial scales: citywide, local/neighbourhood scale and micro-scale, corresponding to separate buildings or streets (Grimmond et al. 2016). Traditionally, the UHI intensity is estimated based on the difference in air temperatures measured at fixed monitoring stations situated in urban and rural areas (e.g., Steeneveld et al. 2011; Emmanuel 2013). However, as such approach has spatial limitations (Effat et al. 2014) and ignores the heterogeneity of the urban areas (Makido et al. 2019), remote sensing data became a widely used proxy for analysing UHI patterns (Xian et al. 2021). Research demonstrated that intensity of the surface UHI (SUHI, estimated from LSTs) is associated with high intensity urban land cover and significantly varies across the city forming clustered “hot” and “cold” spots (Emmanuel 2015; Guha et al. 2019; Wang et al. 2020). Microclimate modelling and in-situ/mobile monitoring studies investigated intra-urban temperature discrepancies and strategies available to mitigate UHI (Ziter et al. 2019; Maharoof et al. 2020). Though most available UHI studies focus on one scale, and rarely consider the UHI effect across multiple scales in the context of one city.

2.2 Role of Green Infrastructure in Urban Heat Mitigation

Urban Green Infrastructure is a promising option to mitigate urban heat stress. Taleghani (2018) demonstrated that although high albedo materials decrease the surface temperatures, they increase heat re-radiation to the pedestrians; therefore, the UGI would be a preferable design option for improving urban thermal environment. While parks and urban forests are acknowledged for temperature regulation due to the “Park Cool Island” effect (Spronken-Smith & Oke 1998), cities face spatial and economic barriers to densifying network of greenspaces. Consequently, integrating vegetation into the city fabric at finer scales is more feasible and will ensure thermal comfort at the scale of the pedestrians' everyday activities.

Several GIS-based studies assessed the cooling impacts of green areas by exploring relationships between the UHI and NDVI index (Farina 2012; Guha et al. 2019), thus such approach ignores the diversity of the UGI. Balany et al. (2020) identified that trees are the most investigated and suggested UHI mitigation strategy, followed by grass and green roofs. Cooling benefits of the UGI have been mostly shown by empirical and microclimate simulation studies, many of which focused on a single measure or generalized green cover. Multiple works highlighted the role of trees in moderating air temperatures (Tsoka 2017; Makido et al. 2019) and thermal comfort (Zölch et al. 2016; Teshnehdel et al. 2020). Some studies demonstrated the effects of grass and shrubs on surface temperatures (Zhang 2020) and of green roofs on mean daily air temperatures (Tsoka et al. 2018). These greening strategies have less control over thermal comfort compared to trees (Lobaccaro & Acero 2015; Zölch et al. 2016), but, as they require less space and are easier in maintenance, could be a good greening design choice if the space or finance is limited.

Although the importance of greenspaces is acknowledged in Scottish policy in terms of amenity value, flood management, air purification (Scottish Government 2008, 2014a, 2014b), UHI mitigation benefits are not seen as the priority in design and management of UGI (Monteiro et al. 2019). In this respect, there is a need for Scotland-based empirical data and realistic case studies to demonstrate the cooling potential of UGI types in the local conditions and support planners in decision-making process.

3 Methodology

3.1 Study Area

Glasgow (55° 51′ 39″ N, 4° 15′ 5″ W) was selected as a geographical focus of this study due to the emerging risks of overheating and city's engagement in the Avenues Programme, a quality place-making scheme that will transform 21 key streets ("Avenues") in Glasgow city centre by introducing green and SMART infrastructure (Glasgow city council n.d.). Previous research indicated that, even though urban growth has subsided in Glasgow, the observed UHI is already of the same magnitude as temperature increase expected due to the climate warming by 2050 (Emmanuel & Krüger 2012; Krüger et al. 2013). As climate impacts intensify, green infrastructure can be a viable strategy to moderate the local overheating (Emmanuel 2015). While UHI mitigation and climate adaptation are not the primary aims of the Glasgow Avenues project, proposed UGI might affect the thermal environment of the retrofitted streets and provide a valuable case study. This research analyses the impacts of the Avenues Programme greening interventions proposed for four city centre streets: Sauchiehall St., Holland St., Elmbank St., St Vincent St. on the local microclimate and thermal comfort.

3.2 Research Framework

Given study is quantitative by design and utilizes multi-method approach, which is a combination of the GIS-based spatial analysis methods, fieldwork, microclimate modelling and statistical analysis techniques, as demonstrated by Figure 1.

ArcGIS Pro software package was applied to retrieve UHI estimates, analyse spatial patterns and relationship between SUHI and UGI distribution. Microclimate simulations were performed with ENVI-met v.4.4.5 model and outputs finalized using LEONARDO and BIO-met v.4.4.5 post-processed tools. All data management and analysis were performed with IBM SPSS Statistics 26 and Microsoft Excel.

The major limitations of this study relate to temporal constrains of the remote sensing data, lack of high-quality data on UGI with differentiation by type, and time-consuming nature of the ENVI-met simulations.

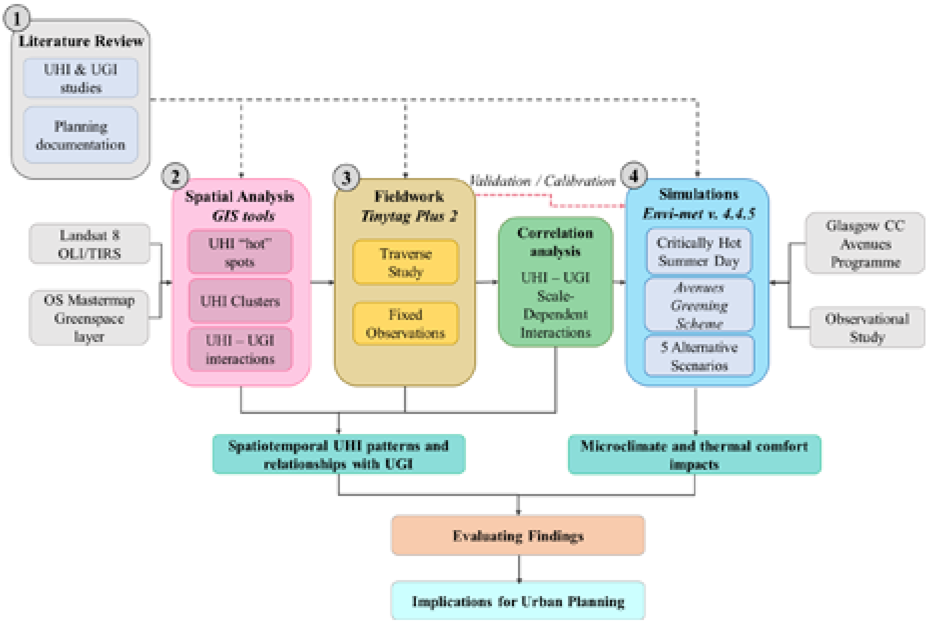

Figure 1. SStudy design and major research steps (Figure: Ananyeva 2021)

3.3 Citywide Analysis of the Spatiotemporal Patterns of UHI

3.3.1 Land Surface Temperatures Retrieval

Land surface temperatures (LSTs) were used to explore the seasonal and spatial variation of UHI within Glasgow city area. Eight cloud-free (< 10%) Landsat 8 OLI/TIRS remote sensing datasets corresponding to each season in three consecutive years (2018-2020) were downloaded from USGS EarthExplorer data portal and further processed to retrieve LSTs following the methodology by Avdan & Jovanovska (2016). Winter season was represented by two images only, as there was no accurate data available for 2020.

3.3.2 Quantification of the Surface UHI Intensities

SUHI intensities were obtained with ArcGIS Pro raster statistics and calculator tools using equation (Xian et al. 2021):

$$SUHI = \Delta LST = LST\left(i, urban\right) - \overline{LST}rural$$

where SUHI – surface UHI, ΔLST – temperature difference, LST (i, urban) – LST of an urban pixel i, LST-rural – mean LST of pixels corresponding to pastures and arable lands within 3-km non-urban buffer.

High resolution land cover data used in the analysis was downloaded as the Urban Atlas 2018 geopackage from the website of the Copernicus Land Monitoring Service.

Distribution of the mean summertime SUHIs, retrieved as an average of pixel-based values, was described in relation to 13 land use categories and across 23 Glasgow city wards (National Records of Scotland 2020).

3.3.3 Analysis of Urban "Hot" Spots and SUHI Clusters

Urban "hot" spots, areas with higher-than-average temperatures within UHI zone, were defined for the hottest day of observations (25 June 2018) by following the equation (Ma et al. 2010; Guha et al. 2019):

$$LST > \mu + 0.5 \times \delta$$

Where μ and δ are the mean and standard deviation of the LST in the study area, respectively.

Local Moran's I spatial autocorrelation index was used to estimate the degree of spatial clustering of SUHI based on data zones, geographical units for analysis of small area statistics (Scottish Government 2021).

3.3.4 UHI – UGI Relationship Analysis

Pearson correlation analysis was performed between SUHI and UGI datasets for 746 data zones. UGI information was obtained from OS Mastermap Layer (Ordinance Survey 2020) and further classified into grass, shrubs and trees using LIDAR data (UBDC 2021). UHI dataset corresponded to 25 June 2018.

To explore the spatial variation of relationship between SUHI and UGI (all types combined), GIS-based Geographically Weighted Regression (GWR) analysis was used.

3.4 Traverse Study

Air temperatures were collected from 24 locations along 3.5 km transect crossing Glasgow city centre in W – E direction (Figure 2). Sampling was conducted twice a day (14:00 – 15:00 and 19:00 – 21:00) on 6 precipitation free days in May 2021 using Tinytag Plus 2 (TGP-4500) air temperature data logger. Device, covered with naturally ventilated sun-protection foil shield, was fixed to the backpack at 1.5 m height. To enable comparison, measurements were time corrected and converted into temperature differences relative to data obtained from the reference sensor, which was mounted in Stevenson type screen to the street pole at 2.5 m height at Glasgow Caledonian University residential court.

Further, correlation analysis between intra-urban temperature differences observed on 31 May 2021, the hottest day of fieldwork, and tree canopy cover within buffers of 20- 50- and 100-m radii was performed.

Total area	521,110 m²	Greenspace	7.8%	P 1 – 7	Townhead – residential area
Built area	68.6 %	LCZ	Compact midrise	P 9 – 17	Sauchiehall St
Traverse route	3.5 km	Monitoring points	24	P 18 – 24	Holland St, Pitt St, St Vincent St

Figure 2. Glasgow city centre study area, traverse route, location of reference site, and equipment used (Figure: Ananyeva 2021)

3.5 Microclimate Simulations

Envi-met v.4.4.5 micro-scale model was used to investigate the cooling effectiveness of the Glasgow Avenues Programme and alternative UGI treatments for the study area located in the city centre and delineated by the future Avenues streets: Sauchiehall St. (completed pilot), Holland St., Elmbank St., St Vincent St. (Figure 3). Buildings' parameters were obtained from OS Mastermap Topography Layer (Ordinance Survey 2019) and LIDAR data (UBDC 2021); surface properties were defined through observational study. Trees arrangement, quantity and species were taken from the Avenues Programme proposals (Glasgow city council n.d.).

Modelling domain was set to 181×138×30 grids (cell size: 5m×5m×3m). Initially, model was calibrated and validated based on the fieldwork data obtained for 31 May 2021. Two interactions were performed to adjust input parameters and material properties, which allowed to acquire outputs statistically comparable to observations.

Further, 7 scenarios, as given below and demonstrated by Figure 3, were digitized, and modelled with ENVI-met for a critically hot summer day (28 June during 2018 heatwave):

- Base Case (BC) – no vegetation scenario, reference for comparison of UGI effects;
- Avenues (AV) – tree arrangement as proposed by the Avenues Programme, tree species: Acer platanoides Deborah, Acer campestre William Caldwell, Ulmus Columella, Carpinus betula Fastigiata and Ginkgo biloba;
- Alternative trees (AV_AT) – all trees in the Avenues scenario were replaced with Tilia sp.;
- +20% trees (AV+20) – 20% more trees than in the Avenues scenario, tree species as in Avenues;
- +50% trees (AV+50) – 50% more trees than in the Avenues scenario, tree species as in Avenues;
- Simple Vegetation (AV_SV) – greening the Avenues' streets with grass and shrubs only;
- Green Roofs (AV_GR) – the Avenues scenario complemented by green roofs proposed for buildings with flat roof.

Meteorological data used for initiating the model was obtained from UK Met Office 2018 observations (Met Office 2021).

Given the focus on pedestrian outdoor thermal comfort, results were reported as air temperature (Ta), mean radiant temperature (MRT) and physiologically equivalent temperature (PET). PET, a thermal comfort index, was calculated in BioMet v.4.4.5 and further assessed in terms of thermal stress using a standardized scale (Matzarakis et al. 1999). PET range of 18 – 23 ˚C was considered as "no thermal stress" condition.

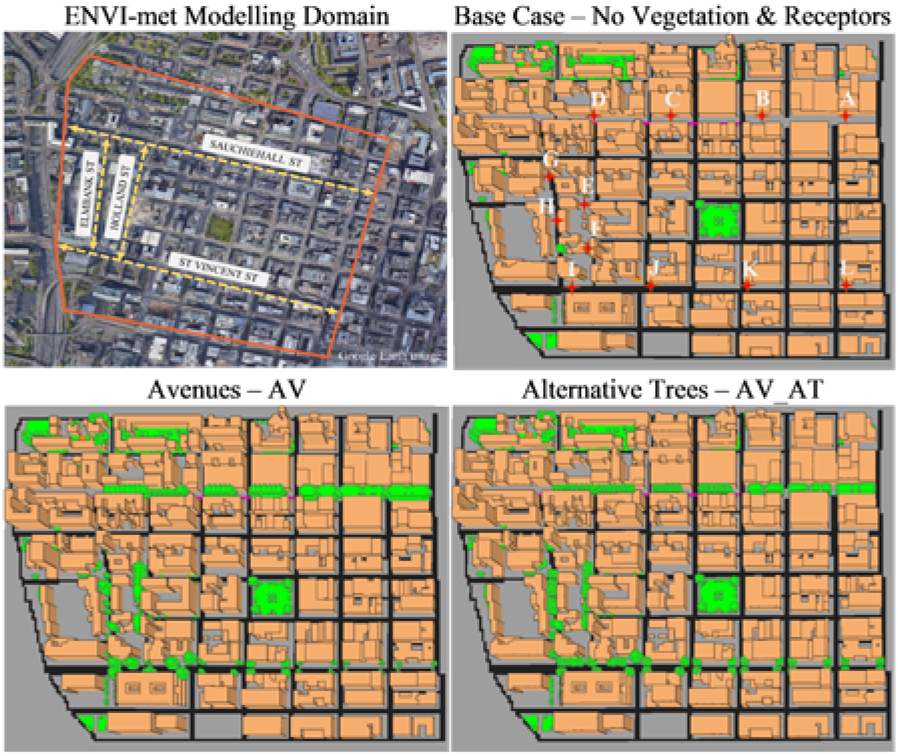
ENVI-met Modelling Domain
Base Case – No Vegetation & Receptors
Avenues – AV
Alternative Trees – AV_AT

Figure continues on the next page

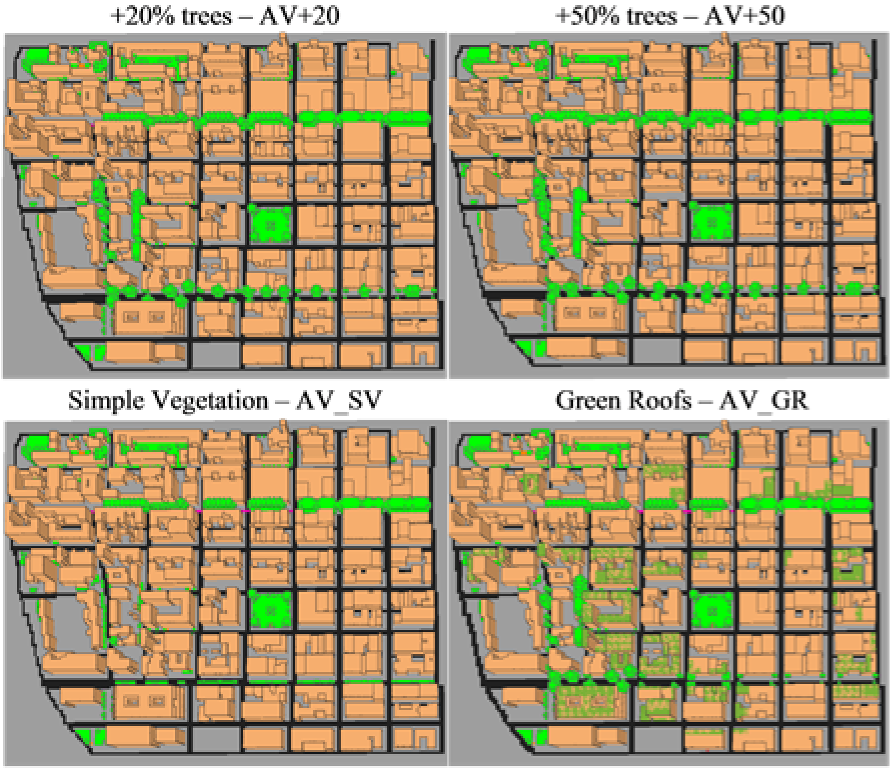

Figure 3. Visualization of the modelling domain and 7 simulation scenarios (Figure: Ananyeva 2021)

4 Results

4.1. LST Profile, SUHI Intensity and Patterns

Citywide, mean LST varied between -3.5 ˚C – 10.2 ˚C and 12.8 ˚C – 23.5 ˚C for the cold (October – March) and warm (April – September) periods, respectively. Temperatures were the highest in June 2018, during the heatwave (Kendon et al. 2019). City centre warmed up to 29.0 – 30.0 ˚C, while in other built-up regions LSTs ranged from 25.0 ˚C to 27.0 ˚C. Urban fringe areas were cooler with LSTs up to 25.0 ˚C.

The SUHI was most pronounced in summer (Figure 4A). In Glasgow central areas, average summertime SUHI intensity ranged from 4.0 to 6.0 ˚C, with occasional 10.0 ˚C peaks. Northern, eastern, and southern city corners, corresponding to parks, sports/leisure facilities, and semi-natural areas were cooler. Four out of 23 Glasgow city electoral wards experienced SUHI intensities over 5.0 ˚C: Dennistoun, Anderston/City/Yorkhill, Southside Central, Calton (Figure 4B).

Analysis of the intra-urban surface temperature variations showed that SUHI "hot" spots were localized in the central areas, and scattered to the north and south-west, corresponding to the residential and commercial areas, industry sites (to the west and along the river Clyde), parking lots (Figure 4B). Figure 4C highlights the clustering of SUHI at data zone level. Red zones, "High-High Cluster", indicated regions with high SUHI and located next to other heated areas, forming overheated clusters. "Low-Low Cluster", given in blue, corresponded to "cold" spots, mainly observed in green areas. Dashed red polygons demonstrated areas affected by heat stress during the heat-wave. The red areas represented regions most effected by SUHI, which should be targeted with heat mitigation incentives.

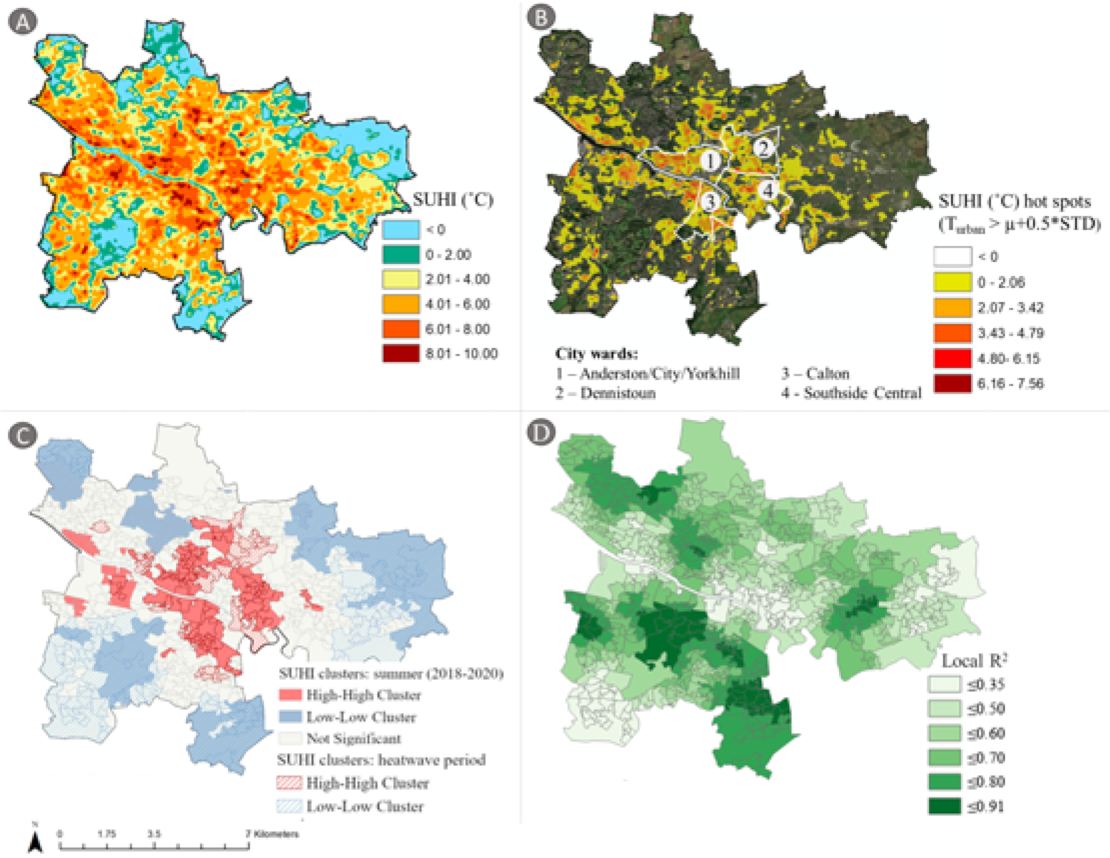

Figure 4. (A) Mean summertime SUHI intensity in Glasgow; (B) SUIH "hot" spots; (C) SUHI clusters; (D) Local R2 of GWR between UGI and SUHI; darker colour corresponds to the areas of high goodness-of-fit (Figure: Ananyeva 2021)

4.2 Correlation between SUHI and Urban Vegetation

Pearson correlation analysis showed various degree of relationship between SUHI and UGI types:

- total vegetation cover was strongly related, with SUHI (r = – 0.60);
- trees demonstrated medium negative impact (r = – 0.43) and slightly higher, when combined with grass (r = – 0.49);
- grass and shrubs had negative weak impact on SUHI, with r = – 0.16 and r = – 0.21, respectively;
- shrubs combined with grass showed weak negative effect (r = – 0.36).

GWR-based analysis revealed that depending on UGI types and location, the effects of vegetation on SUHI varied from (Figure 4D):

- strong ($R2 \geq 0.6$) to moderate ($0.5 \leq R2 < 0.6$) in 75% of data zones;
- insignificant to moderate in 25% of data zones ($0.2 \leq R2 < 0.5$).

These findings recognize that small, isolated patches of vegetation are not effective for cooling the clusters of overheated areas (except very local effects), and, therefore, complex greening strategies should be prioritized.

4.3 Mobile Measurements and Local-Scale UGI Effects

Air temperatures (T_a) varied along the traverse route. Mean within-route temperature range (i.e., difference between the coldest and hottest location) was 2.8 ˚C in the afternoon and 1.9 ˚C in the evening. Four days of fieldwork were warm (18.0 ˚C), while on 2 others, temperatures were over 20 ˚C. On the hottest day (31 May 2021 – Day 6), the maximum and minimum temperatures were 28.2 ˚C and 21.4 ˚C, respectively, which is 10˚C higher than the corresponding Glasgow daily mean maximum and minimum values (recorded in 1981-2010) for May (Met Office 2016). A cool island was observed in Townhead (sampling points: 1-7), due to the on-site vegetation, as local T_a were 0.2 ˚C and 1.8 ˚C lower than on reference site on warm and hot days, respectively. Sauchiehall St. was 0.79 ˚C and 2.2 ˚C warmer than the reference site on the warm and hot days, respectively. Though, the highest temperature differences were recorded on streets without vegetation: Holland St., W Regent St. – Pitt St. and St Vincent St. (points: 18-23).

Along the traverse route, air temperature varied non-linearly with increasing tree canopy cover. Correlation was weak at the scale of 20 m buffer with r = – 0.42, though the tree cover at the scales of 50-100 m had stronger effect at local temperature variations (r ≈ – 0.5).

4.4 Heat Mitigating Potential of the Glasgow Avenues Programme and Alternative Greening Schemes

With its final settings, ENVI-met model slightly underestimated (RMSE = 2.40, R^2 = 0.88) temperatures in the afternoon (at 15:00) and overestimated (RMSE = 0.42, R^2 = 0.55) for the evening hours (at 21:00), which correlated with findings from previous studies (Emmanuel 2015; Tsoka et al. 2018).

Analysed scenarios showed air temperature mitigation effect of vegetation between 9:00 and 19:00, though trees slightly increased night-time temperatures, by trapping heat (Rahman et al. 2017). Figure 5A highlights the T_a reductions observed for each greening scenario in comparison to Base Case (No Vegetation). The Avenues model demonstrated cooling capability with maximum T_a reduction of 0.91 K. Though, increasing tree cover by 20% (AV+20) and 50% (AV+50) had little further effect on T_a: decrease of 0.92 K and 0.93 K, respectively. Alternative trees (AV_AT) scenario was the most effective (1.27 K reduction), demonstrating better cooling properties of the Tilia sp. trees. *Simple vegetation* (AV_SV) setting was less efficient and mitigated T_a by 0.88 K only, while *Green Roofs*, in combination with trees as in the *Avenues scenario*, could cool the area by 0.96 K.

Effect of the greening on mean radiant temperature (MRT) was more pronounced. All tree-planting scenarios performed equally good and reduced MRTs by 27.0 – 28.0 ˚C on average, though Alternative Trees (AV_AT) model performed slightly better, with 29.0 ˚C decrease. Green roofs (AV_GR) had little effect on pedestrian level MRTs with around 0.01 ˚C MRT reduction, which was similar to findings from Portland, Oregon (Makido et al. 2019).

PET, a thermal comfort index, was calculated at pedestrian level (1.5 m height) for 12 receptors located on Sauchiehall St., Holland St., Elmbank St., St Vincent St (Figure 3). Base Case (No Vegetation) scenario showed that, on a hot summer day, study area was thermally uncomfortable (PET > 23.0 ˚C) for 7-9 hours, with PET peaks of 40.0 – 42.2 ˚C in the afternoon (12:00 – 16:00). Trees demonstrated good potential to mitigate heat and pedestrian's thermal sensation from hot thermophysiological class observed in Base Case scenario to slightly warm and warm, as shown in Figure 5B. In graph, the coloured bars represent the range of observed PET values for each scenario, the line inside the "boxes" corresponds to the median. The lowest PET levels were achieved in the Alternative Trees model, PET value of 29.7 ˚C, followed by the Avenues scenario, with PET equal to 29.0 ˚C. In contrast, planting 20% (AV+20) and 50% (AV+50) more trees did not reduce PET further. However, increasing tree canopy could make more areas thermally comfortable by providing additional shading. Greening streets with grass and shrubs had a negligible effect on PET (mean reduction of 0.2 ˚C). The impact of Green Roofs was also minimal, which implies that this strategy is not effective for the studied area.

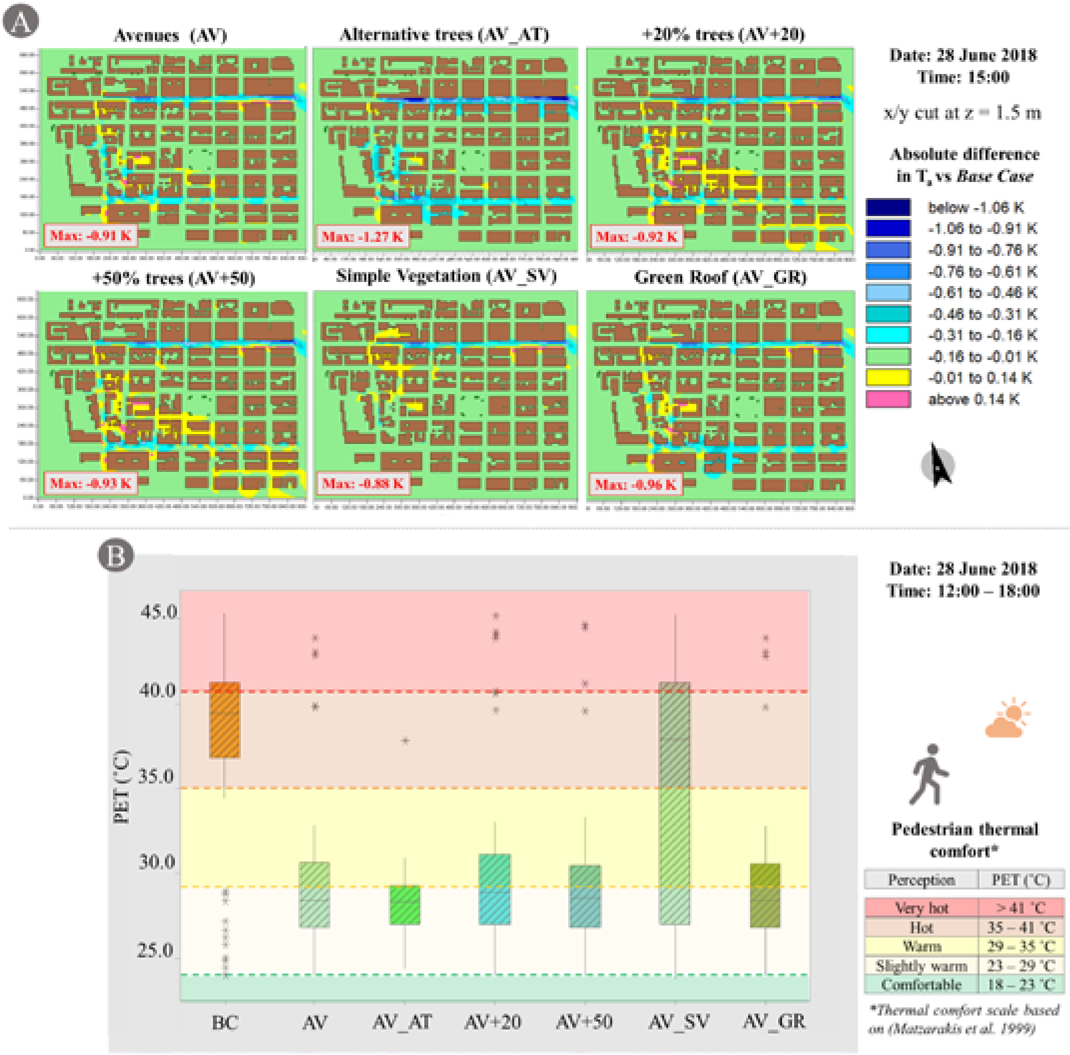

Figure 5. Results of microclimate simulations: (A) Air temperature mitigation effect of each scenario in comparison to the Base Case; (B) Estimated PET values for all scenarios (Figure: Ananyeva 2021)

5 Conclusions and Discussion

As Glasgow City Centre Living Strategy intends to double population and encourages new developments in the central districts (Glasgow City Council 2019), the UHI consideration should be in focus of the area development process. This study has demonstrated that, in summer, urban areas of Glasgow are 4.0 – 6.0 ˚C warmer than the surrounding rural regions, though temperature discrepancies can reach up to 10.0 ˚C in the regions with dense urban fabric. Intra-urban temperature differences observed within the city are of the same magnitude as urban-rural anomaly (up to 7.5 ˚C) and play a key role in delineating urban "hot" spots, which due to imbalance in grey vs green infrastructure distribution, exhibit clustering pattern in data zones along the river Clyde in the central part of the city. These overheating clusters should be considered as strategic areas for UHI mitigation.

Findings demonstrated that vegetation is a key factor of lowering surface temperatures in 75% of Glasgow city data zones, with trees having most impact on LSTs, while shrubs minor and grass – very little. Trees have more impact on urban heat at the larger scale, within 50-100 m radii (the size of a city block), while at finer scale (10-20 m) – the cooling is weak. Therefore, to counterbalance the clustering effect of UHI, when planning an area, UGI (with priority to trees and grass) should also be incorporated in a clustered manner to disperse paved areas. Small and isolated patches of grass or trees are not effective at cooling the clusters of overheated areas, and only complex greening projects, e.g., street trees cooling network or green management of parking, will yield effective temperature reductions.

Microclimate simulations revealed that, at present state, Glasgow city centre is thermally uncomfortable as, on a hot summer day, pedestrians experience strong to extreme heat stress (PET ≥ 40.0 ˚C). Greening scheme proposed by the Glasgow Avenues Programme for the Sauchiehall St., Holland St., Elmbank St., St. Vincent St. can mitigate local air temperatures by 0.91 K and improve pedestrian thermal perception. Therefore, it can be assumed that the Avenues Programme, when implemented at full scale, i.e., across 21 city centre streets, will positively contribute to the sustainability and climate resilience of the city and, additionally, will provide a successful case study of cooling potential of the city centre retrofitting project. The UHI mitigation effect of the Avenues Programme, can be further enhanced by strategical placement of trees and revision of the selected tree species to prioritize the ones with better cooling properties. Thus, further economic estimates of anticipated costs and benefits of each intervention might be useful.

Findings of this study contribute to existing knowledge on UHI in temperate climate and provide empirical evidence on the cooling potential of UGI types that can be further used to develop targeted, scale-specific cooling interventions as well as to inform and refine current guidance to achieve urban climate adaptation goals.

As this work has focused on daytime UHI only, further investigation of the diurnal UHI trends and thermal comfort effects on consecutive hot days might have useful implications for the heat-risk management. Additionally, more evidence is need on the cooling effectiveness of different street trees in dense urban environment and performance of green roofs in terms of surface temperature mitigation.

Acknowledgements

The author expresses her gratitude to Prof. Rohinton Emmanuel for the mentorship and guidance of this research. The author also thanks Urban Big Data Centre (UBDC) team for providing LIDAR data and meteorological records for Glasgow city.

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7

Urban Morphology and Streetscaping as an Approach to Mitigate Urban Heat Island in Glasgow City Centre

The urban heat island (UHI) is an urban area that is considerably warmer than its surrounding (Oke 1981), mainly due to population increase and anthropogenic heat. Although densification affects the city's environmental condition, many studies have recognised it as a key to sustainability. Thus, there is a need for UHI mitigation strategies to stop its anticipated effects.

Glasgow, Scotland is not far from facing intense UHI in the near future, especially since the local authority plans to double its population by 2050. This paper analysed the impacts of UHI in Glasgow city centre through an urban form modification approach and streetscaping through fieldwork, experimental research, and simulation software.

The results show that an open geometry does not always favour urban areas, and although street orientation has a significant influence on air temperature, the aspect ratio has a stronger correlation to it. Of all the streetscaping elements, urban trees demonstrate the optimum benefit in cooling the microclimate, then shading, and the least is surface materials. This paper presents the importance of an integrated approach in UHI mitigation schemes on a local scale.

1 Introduction

“Around 70% of the world’s population is projected to live in cities by year 2050” (UN 2018). Because of the population increase, many cities are continuously growing despite already being highly urbanised. This growth corresponds to the construction of new infrastructures, which could generate local warming effects in addition to climate change (Zhao 2018).

Glasgow, for instance, is the largest and most densely populated city in Scotland. And like any other metropolis, it has been experiencing climate change over the last century. Probably the most affected area is its city core because of its anthropogenic environmental conditions. The presence of various commercial and industrial buildings and emissions from motor vehicles corresponds to air pollution, which adds to the emergence of UHI. Consequently, Glasgow is implementing action plans to alleviate urban climate change and make the city future-proof. The local government is currently renovating its streets through the Avenues programme – an initiative to transform the city centre’s public realm and make the streets more pedestrian and cycle-friendly, attractive, sustainable, and economically competitive (GCC n.d.-a).

Indeed, a well-designed street is essential in improving airflow and shading. Similarly, a holistic approach to urban morphology could be applied to achieve a more satisfactory thermal comfort. Urban morphology is the arrangement of buildings, the space between structures, street patterns, and the presence of other street infrastructures and vegetation (Lilley 2009). Hence, modifying the urban form can also add to enhancing thermal comfort and mitigating the UHI. The urban form modification referred to here is the alteration of the built-up areas’ physical characteristics, including the structures’ shape, size, and density (Williams 2014).

Moreover, it is important to consider the city’s character. At present, Glasgow comprises mid-rise structures with multiple listed buildings. According to the City Centre Strategic Development Framework (GCC 2019), protecting heritage buildings is vital in order to display Glasgow’s uniqueness. Besides preserving the city’s identity and social cohesion, the conservation of old buildings will also bring in adaptive building reuse that will offer environmental advantages, establishing a more sustainable city (Orbasli 2009).

In the next decade, the city will experience an upturn of new construction and retrofitting buildings due to the continuing economic development and demand for more commercial property. The purpose of this study is to examine the consequences of urban form modification and streetscaping and their possibilities of becoming elements of UHI mitigation measures in Glasgow city centre. In doing so, it will then be possible to demonstrate innovation while at the same time preserving the city’s cultural heritage and making it fit for the future.

2 Background

The impacts of climate change in cities will depend on the type of environment they have as it affects different places in different ways (DELWP 2020), which explains why place-specific strategies are essential. As cities grow denser, urban form manipulation strategies for UHI mitigation is becoming more vital. It is therefore essential to assess the unique characteristics of a city to understand its urban morphology and its effects on the surrounding.

In tackling the rising temperature on a street scale, Giguere (2009) categorised four UHI mitigation measures: greening, high albedo surfaces, stormwater management and soil absorptivity, and anthropogenic heat reduction measures. Although heat is not an immediate concern in Glasgow city centre at present, this would likely be the main problem in the following decades if climate change exacerbates.

Recent studies show that UHI is closely associated with the urban form. Hu et al. (2016) studied the effects of varying built densities on the urban microclimate of a Chinese city and how adjusting the sky view factor (SVF) value can implement urban form manipulation strategies to mitigate UHI. SVF is “the ratio of the visible sky area and the total sky dome of an observation point on the ground” (Oke 1981). The result indicated that the best distribution form is establishing a low SVF area in the centre and gradually increasing the SVF value as it goes outward. Their experiment demonstrates that the layout of the density distribution of an area is as significant as the layout of specific building forms. Yuan et al. (2015), on the other hand, did model configurations using Mong Kok, Hong Kong’s urban conditions to investigate how air quality varies in different urban forms by creating simulation scenarios with different building forms. Compared to the city’s current design strategies, their proposed mitigation strategy can substantially enhance the wind permeability and reduce the traffic air pollutant concentration. Thus, their experiment could change architecture design and urban planning from “experience-based to more scientific and evidence-based decision making” (Yuan et al. 2015, 246). A similar study was conducted using Singapore city’s physical features. Yuan et al. (2020) concluded that diluting anthropogenic heat is a challenge in high-density city centres because of stagnant airflow due to closely packed tall buildings.

These papers demonstrate that urban form modification experiments mainly use the Asian city context due to their high-density characteristics. There is a lack of study where similar experiments used European cities due to their mid-rise and low-density features. In Europe, preserving the built environment is vital as it displays its significant culture through its historic buildings. Thus, they limit the construction of high-rise buildings to conserve the landscape. But due to the changing climate and continuing urban growth, it is essential to investigate how heat can affect the future of city cores and develop strategies that would alleviate UHI while safeguarding the cultural heritage of an area.

The city centre of Glasgow characterises a grid-iron street layout in North-South (N-S) and East-West (E-W) orientation, consisting of medium to high-density developments that are a mix of Victorian and modern mid-rise buildings (People Make Glasgow n.d.). Its historic environment has established a rich foundation of listed buildings and conservation areas (GCC n.d.-b). However, the demands of modernising the city may affect its preservation. Furthermore, the Glasgow City Council (GCC) plans to double its population by 2050 (GCC 2019). Although this would sustain the centre's economic success, it would affect its environmental condition because population increase stimulates climate change.

According to various reports, Glasgow is among the cities that will drastically experience climate change in the next 30 years (ASC 2016). Nevertheless, the GCC is making the city sustainable while adapting to climate change (GCC 2019). Some of these long-term action programmes are the Placemaking Principle and Sustainable Spatial Strategy, which establishes a broader place-based approach to develop a more effective strategic framework that responds to the local environment and enhances the historic environment to maintain the city's cultural identity. In addition, the Strategic Development Framework (SDF) – which is featured by the Sustainable Spatial Strategy – implements strategies to the city's particular area's context and issues, helping the city meet the challenges of a changing climate and build a resilient environment (The Scottish Government 2020; GCC 2018a).

Following the above action plans, the GCC is currently transforming 17 crucial streets to make it "more pedestrian and cycle-friendly", which they call the Avenues programme. It aims to improve connectivity and make car-dominated streets people-friendly and public transport-oriented while making them more attractive (GCC n.d.-a).

Just like urban form modification, streetscaping plays an essential role in mitigating UHI at the pedestrian level. In an article written by Maharoof et al. (2020), they examined the microclimate of three street types within Glasgow for climate-sensitive urban planning. Their method incorporated the use of SVF, aspect ratio (height/width ratio or H/W ratio), and surface albedo (a) of the three streets. It was conducted through a traverse study and simulation-based approach called ENVI-met – a software that simulates microclimate in an urban area (ENVI-met 2021; Langer et al. 2012). The result shows that a fixed design strategy for all street types is not applicable due to various considerations like orientation, building fabric, shading, wind speed, and so on. Maharoof et al. (2020) prove that a generic street design strategy is not feasible for all urban areas. And this paper validates their finding by establishing alternative proposals for Glasgow's streetscape improvement project. In identifying the streetscape elements and principles, it is important to apply sustainable solutions to provide a sustainable urban environment.

Combining the Avenues programme and urban form modification strategies will significantly enhance Glasgow's streets, protecting its historic environment through careful consideration of building heights, scale, and façade design, and enhancing the cityscape by associating old with new buildings to consider its contribution to the city centre's urban morphology (GCC 2019). The implications of this paper can provide the local government, developers, planners, and architects in the decision-making for the development of new infrastructures.

3 Methodology

The study examines the impacts of urban morphology and streetscaping in managing UHI in Glasgow city centre through an urban form modification approach, with the view to evaluating the effectiveness of the Avenues streetscape project. The method begins with reviewing relevant documents to serve as a foundation for the research topic, followed by spatial analysis to select suitable streets for the urban form modification approach. These streets were comprehensively assessed through qualitative and quantitative fieldwork. Next, experimental research was carried out to examine how different factors of urban morphology affect the microclimate on the local scale. Finally, implementing the urban form manipulation strategies and proposal of new street designs through 3D modelling and simulation software.

Government Publication Review – It is vital to tackle the Placemaking Principle and SDF to have a general view of the city's action plans and adaptation strategies.

Archival Research – As mentioned in the Placemaking principle (GCC 2018a), the community should be involved in the planning process to promote a sense of ownership. But due to the limitation caused by the global pandemic, a secondary source, i.e., community engagement report, substituted the community involvement. This method helped assess the effectiveness of the Avenues programme and determine critical information underlying Glasgow's crucial streets.

Street Selection – To provide extensive research about the topic, the focus of the study was narrowed down to two streets. A spatial analysis helped identify ideal streets from the Avenues programme that require quality Placemaking schemes. The selected areas are Argyle Street West (E-W) and Hope and Oswald Streets (N-S), and both have the following criteria:

- N-S and E-W orientation – focusing on two perpendicular streets were sufficient in analysing the entire Avenues programme
- Vehicular access – to assess anthropogenic heat
- Occurrence of air quality deterioration – air quality can serve as a heat indicator in urban areas (Wu et al. 2017)
- Presence of old and new buildings – to verify that urban form modification approach can be applied while protecting Glasgow's conservation area

Traverse Study and Meteorological Survey – This measures air temperature and examine its correlation with the estimated SVF and aspect ratio since both are commonly used indicators of urban morphology (Theeuwes et al. 2014). This study was conducted using two air temperature data loggers; one installed on a fixed station, and another used for the 15 locations within the focus areas (Drach et al. 2018; Maharoof et al. 2020).

Estimation of Aspect Ratio, UHI, and SVF – As this paper explores the effectiveness of UHI mitigation through adjusting the building forms, the use of Oke's model (Oke 1988; Montavez et al. 2007; Nakata-Osaki et al. 2017) primarily helped establish appropriate building masses and heights within the two study areas. Oke's model (Eq. 1) was used to calculate the UHI intensity of both existing and proposed urban forms. This method justified the building modifications and prevented speculating random alteration without any basis. The SVFs were developed using SkyHelios, which calculates the SVF, to analyse its relation to the measured air temperature (Matzarakis & Matuschek 2011).

$$\Delta T_{u-r(max)} = 7.54 + 3.97 \ln\ (H/W)$$

Where : $\Delta T_{u-r(max)}$ = maximum UHI
H/W = relationship between height and width

Modelling and Simulation – ENVI-met and other 3D modelling software were used to integrate urban form modification, propose new street designs, measure UHI, and implement urban form manipulation strategies. Four simulation scenarios were generated to compare the air temperature differences and evaluate their thermal comfort:

- Scenario 1 – Existing streets and building forms
- Scenario 2 – Avenues programme proposals
- Scenario 3 and 4 – Two proposed urban form modifications integrated with new street design

Simultaneously, this paper evaluated the materials from the Placemaking Principle (GCC 2018b) and the Avenues draft plans (Civic Engineers 2021) for the streetscaping proposal. Because the surface materials employed in the Avenues programme mostly depict low albedo values, additional materials with higher albedo were assessed to explore other potentials. In addition, typical and green covered pathways at street level were also evaluated. These streetscaping elements were modelled in ENVI-met using Glasgow's meteorological conditions to assess how they perform in the site.

This study used the potential air temperature (PAT) to analyse the air temperature in the environment (Li, 2015) and mean radiant temperature (MRT) to evaluate the impacts of the microclimate on human thermal comfort (Huttner et al. 2008).

4 Results

4.1 City Centre's Spatial Development Strategy

Part of the SDF is to densify and re-populate the centre. However, improving its place quality will be a challenge as it will require greater infrastructure, leading to environmental degradation. Although the council encourages planners to demonstrate innovation in new developments, it is vital that heritage buildings are protected to display Glasgow's distinctiveness. Therefore, successful integration of old and new buildings should be considered to enrich the city centre's character (GCC 2018a). Figure 1a presents the allocation of development areas as proposed by the SDF. The distribution of each zone is described below (GCC 2019):

- **Urban Intensification Area** – suitable for buildings of scale due to its larger blocks and wider streets
- **Conservation Area** – existing context should be respected
- **Densification Area** – should seek to rebuild the fragmented area through tenemental human-scale buildings

The urban intensification and densification areas will be the primary sites for the GCC's proposal to double its population by 2050. Based on Fig. 1b, there are many opportunity areas within these sites because they have lesser and lower structures at present.

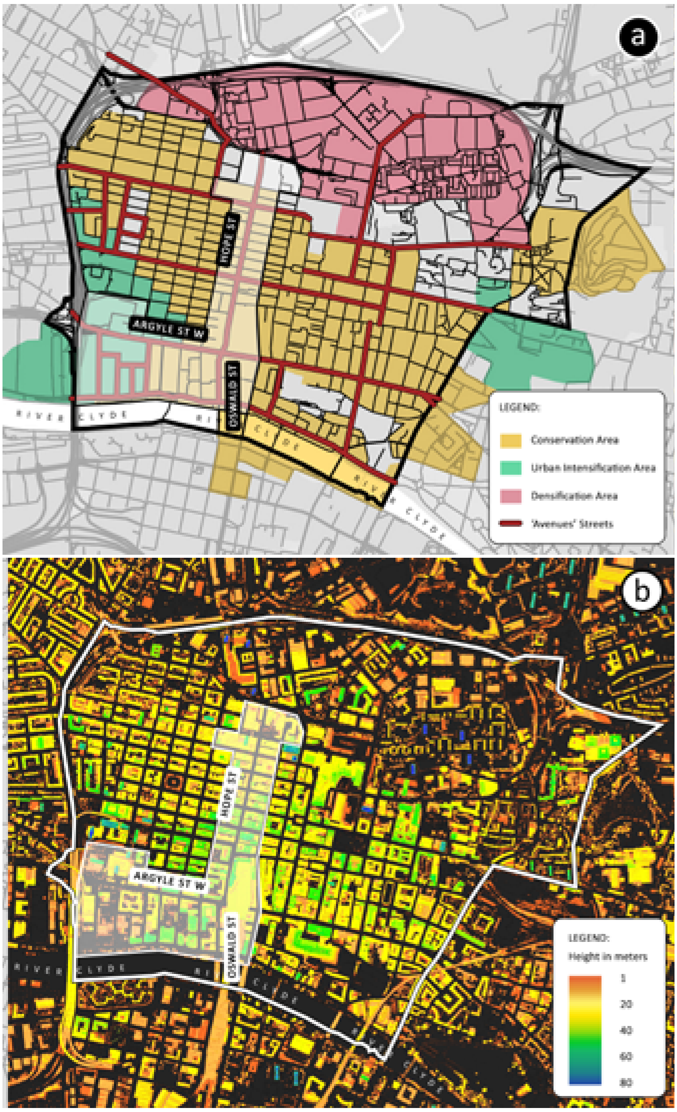


Figure 1. (a) Allocation of development areas and (b) existing building heights in Glasgow city centre. (Figure: Valdez 2021)

4.2 Focus Areas

Argyle Street West – A significant part of the street lies in the urban intensification zone, implying that this can be developed with greater density and scale. Some city blocks have broad pedestrian walkways wide enough to make way for street design elements. However, the area is car-dominated and presents a fragmented cycling network, impeding the promotion of sustainable travel modes.

Hope and Oswald Streets – Aside from being identified as the most polluted street in Scotland in terms of air quality (Friends of the Earth Scotland 2020), the urban fabric of Hope Street is mainly composed of historic buildings, narrow thoroughfare, and on-street parking. The latter gave less importance to pedestrians and more value to vehicles. On the other hand, the existing character of Oswald Street is adaptable and has ample space for improvement.

The community engagement report mainly emphasised the stakeholders' transportation demands, like modes of transport and numbers of vehicles (Ironside Farrar 2019). While these do not relate to the research topic, they can be derived into more concrete features such as the need for cycling spaces, roadway space reduction, wider footpaths, and provision of greeneries.

4.3 Traverse Study

In Fig. 2, only three mobile measurements demonstrating the highest temperature were comprehensively assessed and categorised according to the modified Pasquill–Gifford–Turner (PGT) classification system (Pasquill 1961; Gifford 1961; Turner 1970). Because this system involves only standard national weather service observations, it has proven to be a practical and widely used approach (Hunter 2012).

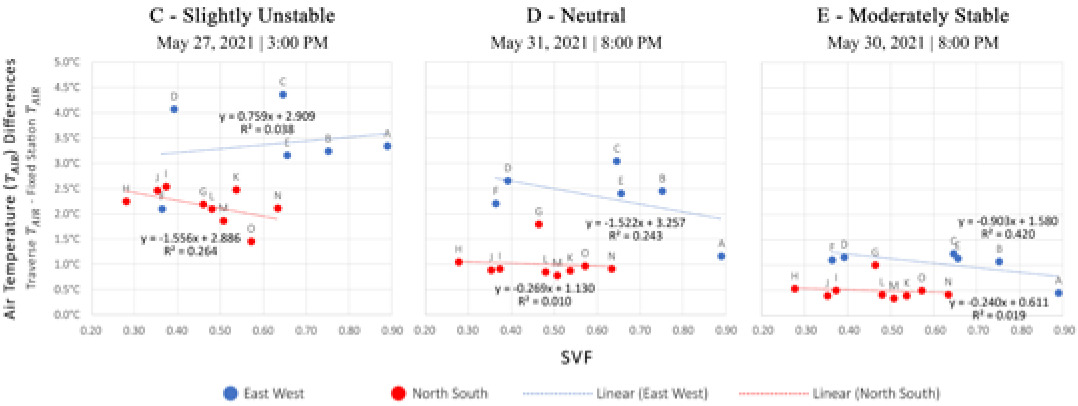


Figure 2. Relationship between air temperature difference and SVF. (Figure: Valdez 2021)

4.4 Experimentation

The aspect ratio, UHI max, and SVF of each 15 monitoring points of the focus area were estimated and shown in Fig. 3 to critically assess its urban morphology.

	Axis	Ave H	Ave W	Aspect Ratio	UHI max by Oke's model	SVF
Argyle Street West	A	21.25	72.80	0.29	2.56	0.89
	B	31.10	42.12	0.74	6.25	0.75
	C	19.67	23.57	0.83	6.73	0.65
	D	29.00	31.69	0.92	7.10	0.39
	E	25.50	62.33	0.41	3.90	0.66
	F	28.00	22.12	1.27	8.39	0.36
Hope and Oswald Street	G	20.08	19.84	1.01	7.50	0.46
	H	30.31	22.80	1.33	8.58	0.28
	I	24.50	18.10	1.35	8.65	0.37
	J	26.75	18.48	1.45	8.92	0.35
	K	16.50	18.36	0.90	7.03	0.54
	L	18.80	18.37	1.02	7.54	0.48
	M	15.75	18.48	0.85	6.82	0.51
	N	17.00	17.96	0.95	7.23	0.63
	O	18.88	19.84	0.95	7.25	0.57

LEGEND:
- 🟥 Modifiable
- 🟧 Fixed (Listed Buildings)
- ▨ Under Construction Buildings

Figure 3. Estimation of aspect ratio, UHI max by Oke's Model, and SVF of the 15 point locations. (Figure: Valdez 2021)

4.5 Proposed Scenarios

Two proposals were made with the help of an urban form modification assessment criteria; one comprises buildings with basic rectangular forms oriented towards dominant wind and sun position (P1), and the other contains buildings with internal courtyards (P2). Other implementations present in both proposals are:

- Shaded pathways to reduce the solar radiation intensity
- Further greening
- Surface materials with high albedo values
- Grouping of buildings to manage airflow pattern
- Staggered building facades to establish openness

Both proposals have increased floor area ratio (FAR) on the urban intensification and densification zones. In contrast, the FAR in the conservation area is retained. This allocation of FAR justifies the SDF's definition of the three zones. The two proposals exhibit a decrease in aspect ratio and an increase of SVF, except for points A to E because these blocks require urban infill, and points I to K, since these were not altered.

4.6 NVI-met Simulation Results

Streetscaping Elements – The results show that the materials with lower albedo generate warmer temperatures and vice versa, as in studies of Levinson & Akbari (2002) and Hall et al. (2005). Thus, light-coloured granite was used as a walkway material for the proposed scenarios since it has the lowest surface temperature of all the materials evaluated. Additionally, it balances Glasgow's character and comfort. Buff-coloured asphalt was employed for the intersections. Lastly, red brick was utilised for bike lanes. Because this paper critically assesses these materials' ability to mitigate UHI rather than maintenance and durability, brick was still utilised for this purpose.

On the other hand, both typical and green covered pathways demonstrate low temperature, with the green case showing slightly less temperature reduction than the typical canopy. To understand how the two cases enhance the street canyon of the focus areas, both were applied in points I to K of P1 and P2, respectively.

Focus Areas – The simulation results were evaluated for 28 June 2018 at 18:00 to assess the model performance displaying the highest PAT as estimated by ENVI-met.

As seen in Fig. 4, there is a slight net radiant heat loss in the Avenues scenario, except for point A, where it shows an MRT reduction of 8.31°C due to the proposed vegetation, significantly enhancing the microclimate of the area. Likewise, the most apparent changes are visible in areas with proposed vegetation (points A, G, M, and O). In some instances, the Avenues scenario demonstrates higher temperatures (points B, E, F, and J) due to the use of surface material with a low albedo value.

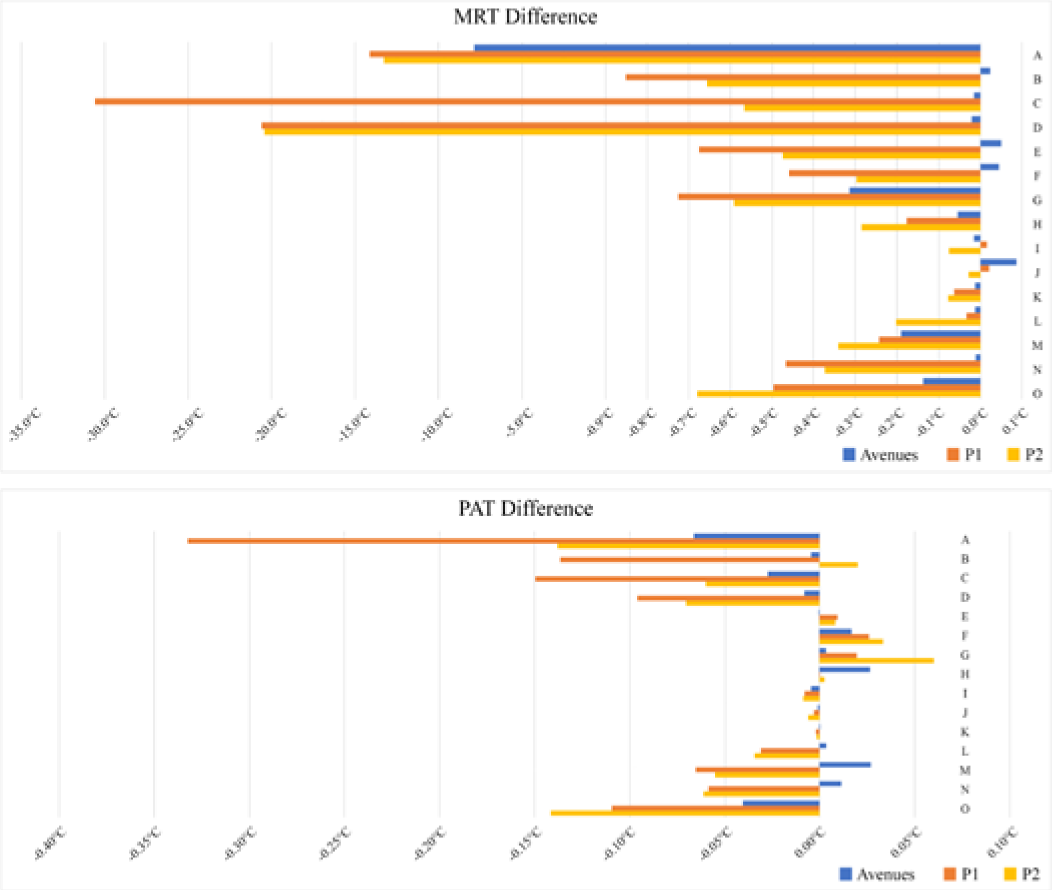
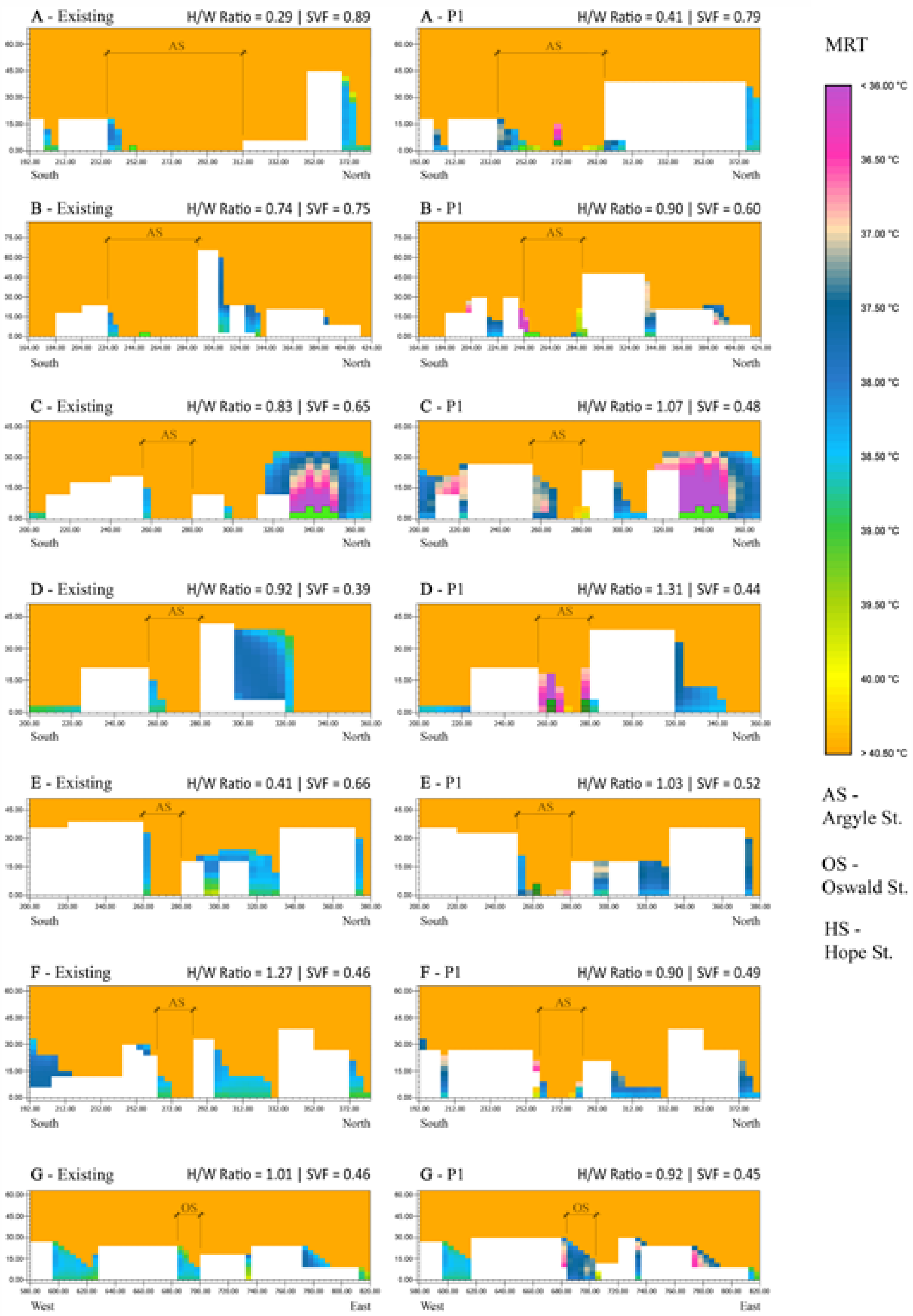


Figure 4. MRT and PAT differences of Avenues, P1, and P2 scenarios in relation to the existing scenario. (Figure: Valdez 2021)

Both P1 and P2 show a considerable net radiant heat loss compared to current and Avenues scenarios. However, points I and J displayed higher temperatures. Because these areas already characterise high aspect ratios, the structures already cast shadows in the street level, making the use of a canopy insignificant.

Fig. 5 illustrates elevation views of the existing and better performing proposed scenarios. As observed, the E-W street favours the P1 more than P2. Perhaps the additional building height presented in the former affected the result since it blocked the solar radiation from reaching the ground, thus providing a shading effect. On the other hand, most of the N-S points benefitted from P2 mainly because of improved SVF. P1 and P2 proved that higher FAR could demonstrate lower temperatures.



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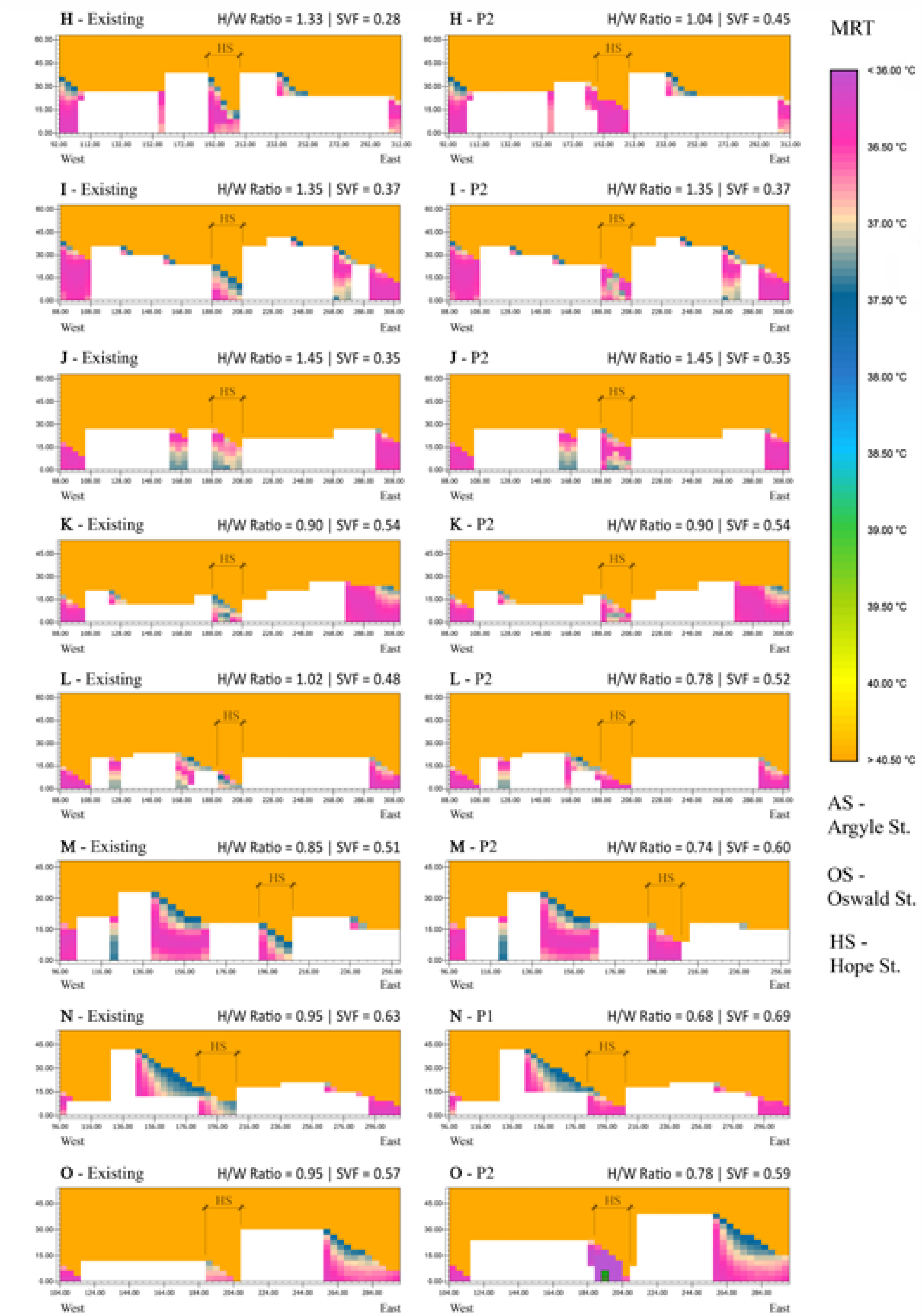

Figure 5. MRT of existing and better performing proposed scenarios in elevation view. (Figure: Valdez 2021)

5 Discussion

5.1 Fieldwork

In Fig. 2, PGT class C signifies a more noticeable UHI effect than the other two, implying that the relationship between air temperature and SVF strongly depends on atmospheric conditions. This finding agrees with the studies of Drach et al. (2018), in which they concluded that variations were much more noticeable in unstable conditions.

As observed in Fig. 3, the higher the UHI max, the lower the SVF value. However, this is not entirely the case in the measured air temperature. The E-W of PGT class C (Fig. 2) exhibits an upward trend contrary to what the theory exemplifies. Hence, although higher air temperature associates with lower SVF and higher aspect ratio (Oke et al. 2017), other circumstances affect this behaviour, such as land surface temperature (Janak & Bhatt 2012; Kaplan et al. 2018), blocking of onshore breeze and south-westerly winds by high-rise structures, and the amount of solar radiation received.

Comparing the SVF of the measured (Fig. 2) and estimated (Fig. 3) UHI max, the more stable conditions exhibited a similar pattern to the latter. In contrast, the temperature variations in N-S street (Fig. 2) does not show significant differences. This observation contradicts Maharoof et al.'s (2020) findings, in which they concluded that the N-S streets have a stronger correlation between temperature and SVF. Perhaps the characteristic of Hope Street, having homogeneous building height and street width, influenced the insignificant temperature difference.

5.2 Simulations

Although P1 and 2 have similar FAR, P1 exhibited a more pronounced temperature drop. The reduction in MRT could be mainly due to the shading effect and only little effect from the surface material it used, which is light-coloured granite (α=0.50). According to Dessi (2011), there are cases when light-coloured surfaces increase the amount of reflection or indirect solar radiation, thus affecting other urban areas.

Argyle Street displays a higher temperature variation and more pronounced temperature drop than Hope and Oswald Streets because the former has more space for improvement, thus providing further street greening. Moreover, Argyle Street is situated in the intensification zone, where there are taller buildings that can block the sun.

Although an improved MRT is observed in all points in both P1 and P2 (except points I and J), it can be seen that PAT increased in some points, wherein the most prominent are in points E to H. The confined airflow near the intersection of N-S and E-W street could have affected this. Also, the reductions in PAT in points I to K are not as significant due to the blocking of wind movement by the canopy, indicating that an improvement in MRT is not always synonymous with a better PAT.

In Fig. 5, there is an apparent cooler temperature as streets become more compact. However, this only occurred to some extent because in points H to M, where the road is narrow, the net radiant heat loss is negligible compared to those points in the broader streets of Argyle. According to Theeuwes et al. (2014), the shading effects can lessen the UHI an aspect ratio between 0.5 and 1. Fig. 5 presents aspect ratios greater than 1 yet managed to mitigate UHI, which is still relative to Theeuwes et al.'s (2014) observation.

In the centre of the street, where neither shading nor street greening is present, there is no incidence of cooling, thus indicating the negligible effect of surface materials in improving the pedestrian level microclimate despite the enhanced surface temperature.

5.3 Conclusions

In recognising the impacts of urban morphology in Glasgow city centre, open geometry does not always favour urban areas. Therefore, a high SVF value does not constantly pertain to good thermal comfort.

E-W oriented street constantly exhibits higher air temperature, supplementing the arguments of Maharoof et al. (2020). Hence, although street orientation significantly influences air temperature, the aspect ratio has a stronger correlation to it.

Of all the streetscaping elements, the urban trees demonstrated the optimum benefit in cooling the microclimate, which is evident on Argyle Street. Next is shading, and the least is surface materials.

This paper concludes that incorporating urban morphology and streetscaping is essential in managing the negative consequences of UHI, signifying the importance of an integrated approach in urban climate mitigation.

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8

A Critical Evaluation of Different Methods of Urban Climate Mapping:

A Case Study of Glasgow City

Urban Heat Island (UHI) is an emerging concern that increases the heat risk likelihood in urban settings together with the climate change effect. In this regard, urban climate mapping (UCM) can be exercised to visualize the combined effect of urban climatic, socio-economic, and terrestrial features on urban heat risk (UHR) systematically and applied in the planning scheme. This study performs a UHR analysis for Glasgow city, largely evaluating the effect of synthesizing processes on the outputs. With an abductive approach, mixed-method research is designed to integrate both qualitative and quantitative secondary data. Nine relevant indicators are selected for hazard, exposure, and vulnerability components to synthesize UHR maps in different combinations with two geographic information system techniques. The resultant maps demonstrate that both GIS techniques provide a similar overarching result, but map algebra gives heterogeneous UHR reading at a smaller scale compared to the weighted overlay method. This study also signifies that the selection of the number and type of indicators and risk components affect the spatial distribution of UHR. It is concluded that UCM is an effective tool to determine priority interventions and is useful in climate-sensitive urban planning, but its methods should be scrutinized.

1 Introduction

Rapid urbanization and growing urban inhabitants (projected to be nearly 68% of the world's population by 2050) influence the near-surface urban atmosphere with densely built forms and associated urban activities (United Nations 2019; Ren 2015; Mills 2015). Urban Heat Island (UHI) and air pollution are two of many urban climatic anomalies, which challenge the comfort and quality of life of urban inhabitants (Ren 2015; Parsee et al. 2019; Xu et al. 2020; Maragno et al. 2021) together with climate change effect (Picone & Campo 2019; Larsen 2015). Sustainable urban planning should be adopted by urban planners and decision-makers to address such urban problems and ensure a comfortable, affordable, and healthy urban environment for the world's majority population (Parsee et al. 2019; Knudsen et al. 2020; CUHK 2012).

Even though climatic contexts are equally valuable as any other planning components (Ren 2015), urban planning seemed lacking in climatic information for several reasons. Firstly, planners had insufficient knowledge about climatic aspects and their connection with urban structure. Secondly, inadequate climatic information is available in planning language (Mills 2015; Ren 2015; Ren et al. 2013; Isa et al. 2018). Thus, the urban climate mapping (UCM) concept was introduced to convert climatic knowledge into planners' user-friendly language such as maps (Ren et al. 2013; Ren 2015). Each UCM study addressed a specific urban issue such as UHI, poor air ventilation, etc. and adopted a unique research method, but all the UCM research followed the same fundamental concept (CUHK 2012). However, comparison and evaluation of the UCM research methods are rarely studied. Thus, it is needed to underline the factors that may result in different UCM outcomes, simultaneously evaluating the synthesizing processes to test the practical application of available data and identify the climate-sensitive hotspots.

This paper intends to generate urban climatic maps, specifically urban heat risk maps, in different methods by using socio-economic, terrestrial, and climatic parameters as well as evaluate the chosen indicators and processes so that critical factors are considered while making climate-sensitive plans in Glasgow city. The major objectives of this study are: (i) to investigate the state-of-the-art for urban climatic maps (UCMaps) and their implication in city planning, (ii) to explain the data and methods required for urban heat risk mapping, (ii) to construct urban heat risk maps by using multiple methods and alternative approaches, and (iv) to critically evaluate the resultant atlases and the adopted methods in determining climate-conscious plans.

2 Background

2.1 The link between Urban Features and Urban Climate

Two- and three-dimensional urban features and their material compositions and urban geometry control energy exchange in between the surface and its overlying atmosphere through influencing the air ventilation route, shadow cover, and soil capping (Mills 2015; CUHK 2012; Picone & Campo 2019; Ren, 2015). Waste materials and waste energy produced via urban functions and metabolism also affect the cities' thermal balance and air quality (Mills 2015). In addition, the geographical location that determines the access to the amount of annual and diurnal solar radiation, prevalent wind type, and topography shapes the urban environment along with historical background and local government's decision for economic development, social equity, etc. (Mills 2015; Ren 2015). Overall, the urban climate is a modified climate overlying the urban territory (Picone & Campo 2019; Mills, 2015) resulted from a complex interaction of all these aforementioned urban features.

2.2 Context and History of Urban Climate Mapping

UHI, an inflection of air temperature in between the city and its rural counterpart, is caused by heat budget inconsistency in between atmosphere and urban area (Oke et al. 2017; Sarricolea & Meseguer-Ruiz 2019). The combined effect of UHI, air pollution, and climate change put challenges on urban inhabitants' quality of life (Picone & Campo 2019; Larsen 2015; Mills 2015; Oke et al. 2017; Ren 2015; CUHK 2012; Ashie et al. 2015) which are evident through weather events like heatwaves, floods, droughts, etc. (Georgiadis 2017; Armond & Neto 2019). Whilst poor urban ventilation gives rise to air-borne diseases like SARS (Ng 2009), extreme temperature costs additional heat-related deaths (Georgiadis 2017). A single event like 2003's heatwave caused 72,210 extra deaths in Italy, France, Spain, Germany, Portugal, and Switzerland (Kosatsky 2005) that highlighted the role of UHI hit by extreme climatic events (Conti et al. 2005).

Urban Climate Mapping (UCM) is a breakthrough to address the climatic risks by identifying the climate-sensitive zones in an urban setting and conveying climatic information in urban planning languages to contribute to sustainable urban planning (Mills 2015; Ren et al. 2013; Ren 2015; Picone & Campo 2019; Knudsen et al. 2020). Urban climate mapping is a fifty-year-old concept that was first developed by Germany in the 1970s (Ren 2015) and first applied by the city of Stuttgart to mitigate air pollution (Ren 2015, Urban Climate Stuttgart 2021; Matzarakis 2005). UCMap contains two key components: Urban Climatic Analysis map (UC-AnMap) and Urban Climatic Planning Recommendation map (UC-ReMap) (Ren 2015). UC-AnMap visualizes and evaluates urban climate science data and land data in a spatial framework and discovers "climatopes", the spatial units with similar near-surface atmospheric characteristics (Ren 2015). Moreover, UC-ReMap demonstrates planning instructions for climate-sensitive areas. UCMap presents an overall picture of urban climate in a spatial framework and guides to carry out a suitable development plan.

Cities like Hong Kong had accomplished UCM with extensive datasets from both observation and simulation while Kaohsiung used readily available data only. Few parameters like temperature, wind, topography, land cover, greenery, building information, etc. are commonly found in published studies (Ren et al. 2013; CUHK 2012; Ashie et al. 2015; & Xu et al. 2020), but socio-economic parameters are seldom used as indicated by Parsee et al. (2019) too. Thus, this study adopted an urban climate risk analysis approach to fill the gap of socio-economic aspects by following the UCM study of Smith, Cavan, and Lindley (2015) for Greater Manchester.

2.3 Risk Definitions and Urban Heat Risk Processes

The risk-based approach emphasizes the importance of integrated assessment entailing social, economic, physical, climatic, and governmental parameters before planning sustainable urbanization (Andersson-Sköld et al. 2015; Smith, Cavan, & Lindley 2015). According to IPCC (2014), the risk is a function of hazard, vulnerability, and exposure where a hazard is a potential climatic incident. However, the climatic incidents alone cannot jeopardize the urban environment unless encountering any physically exposed elements with vulnerable characteristics (Georgiadis 2017; Cardona et al. 2012). Vulnerability is further defined by a function of sensitivity and lack of adaptability (IPCC 2014; Dickson et al. 2012; Leis & Kienberger 2020). Therefore, as risk can be defined in several ways adapted from IPCC's definition (Yu et al. 2021; World Bank 2021; Smith, Cavan, and Lindley 2015; Tapia et al. 2016; IPCC 2014; Buscail, Upegui, & Viel 2012), UHR mapping needs to start with specifying its required risk definition.

Existing studies used either Map Algebra or Overlay application in GIS (Tomlinson et al. 2011; Smith, Cavan, and Lindley 2015; Greater London Authority 2021) to assess UHR, but their comparative analysis is hardly studied. Räsänen et al. (2019) stressed the change in risk and vulnerability mapping due to uncertainty and discrepancy of different weighting and zoning factors. Moreover, UHR studies used either LST or Ta or both as hazard components, (Arup 2014; Sun, Sun, & Chen 2020; Tomlinson et al. 2011; Azevedo, Chapman, & Muller 2016; Estoque et al. 2020; Buscail, Upegui, & Viel 2012; Liu, Song, & Yu 2017; Ho et al. 2014; Schwarz et al. 2012), but these two indicators are rarely compared in UHR studies.

Therefore, several novel approaches are adopted in this study based on the literature review. This research endeavored for an urban heat risk mapping exercise with available data. It has sought a different combination of relevant risk indicators among which some are alternatives of each other. It tested both weighted overlay and map algebra (raster calculation) techniques to analyze their role in UHR mapping outputs. Furthermore, this research will pinpoint the priority intervention zones for heat risk management in Glasgow city by developing a UC-ReMap. Overall, this paper not only generates UHR maps but also critically evaluates the synthesizing process to identify the influencing factors of UHR outputs so that the local government can be aware of the critical factors to get profound results.

3 Methodology

3.1 Study Area Profile

Glasgow is the biggest city in Scotland (55.8642° N, 4.2518° W) with a population density of 3,590 persons per square kilometer (Glasgow City Council 2017a; Google Earth 2019). River Clyde is flowing through the heart of the city, a great source of ecosystem services and economic growth historically and concurrently (GCC 2017a). It is located in a low-lying area and highly urbanized and contains nominal agricultural lands in the periphery along with limited water bodies. There are only 16 hectares of green space per 1000 inhabitants, the lowest in the region, principally serves for recreational purposes (Sniffer 2020; HLAmap 2017). A temperate maritime climate gives cool summer, mild winter, and rainfall around the year in Glasgow city (SEPA 2014). Its mean annual temperature of approximately 9.5°C is slightly higher than its surrounding areas due to the UHI effect (Met office 2021a). According to UK Climate Projections 2018 report, an increase in heatwave frequency is expected during the summer season in Glasgow city because of UHI intensity, global warming, and climate change effect due to magnification of the drier and warmer nature of the season (Scottish Government 2019; The guardian 2021; Kruger, Drach, & Rohinton 2018; O'Neill & Tett 2019). Moreover, by reviewing the existing plans and strategies, it is found that there is a lack of attention and priority on heat risk assessment and management plans by the local government (GCC 2017a; GCC 2017b; GCC 2017c; CRC 2021; England et al. 2018)

3.2. Data sources and preparation

Abduction research is designed for this study that has used both qualitative and quantitative data (Saunders, Lewis, & Thornhill 2019) to visualize the heat-sensitive hotspots in ArcGIS. Based on the literature review, readily available and relevant datasets are obtained from various sources and websites in different formats. Figure 1 presents an overall framework of this research from base indicators to UC-ReMap construction.

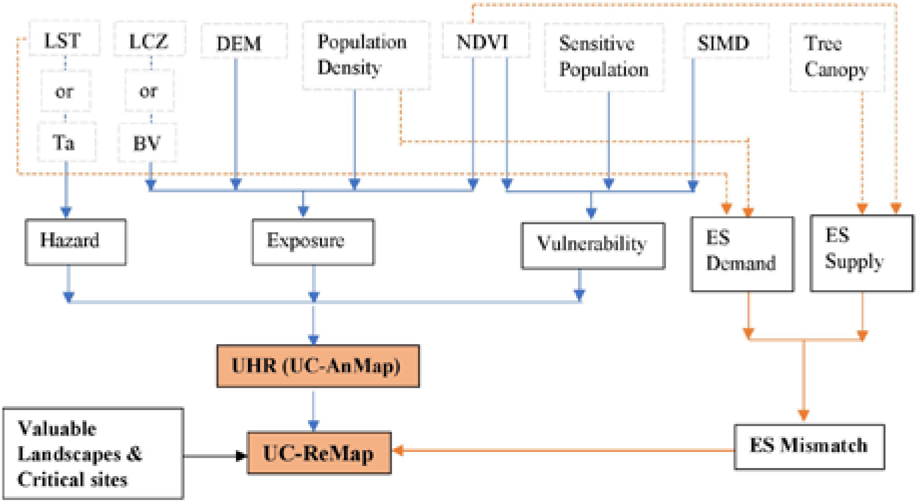

Figure 1. An overview of this study's process flow chart (Figure: Begum 2021)

3.3 Selected Risk Components and Indicators

Total nine components, which are either positively or negatively linked to UHR, are selected for hazard, exposure, and vulnerability components by reviewing existing literature (CUHK 2012; Arup 2014; Sun, Sun, & Chen 2020; Tomlinson et al. 2011; Azevedo, Chapman, & Muller 2016; Estoque et al. 2020; Buscail, Upegui, & Viel 2012; Liu, Song, & Yu 2017;

Mehrotra, Bardhan, & Ramamritham 2019; Smith, Cavan, and Lindley 2015; Heilmann and Kahn 2019; Chen et al. 2018; Scottish government 2020). They are Land Surface Temperature (USGS 2021), air temperature (Ta) (Met Office et al. 2020), Normalized Difference Vegetation Index (USGS 2021), Building Volume (OS Mastermap 2020), Local Climate Zones (Zala 2020), Scottish Index of Multiple Deprivation (Scottish government 2020), Digital Elevation Model (UBDC 2021), population density (Scottish government 2020), and sensitive population ratio (Scotland's Census 2011) among which some are proxy of each other. All these parameters are reclassified into three categories (low, medium, and high) to create a homogenous dataset on a scale of 1 to 3. 'High'category means high correlation to heat risk.

3.4 Risk Analysis Method

This study defined heat risk from two perspectives considering it is a function of three or four risk components as mentioned below :

Perspective 1: Risk = f {hazard, exposure, vulnerability}
Perspective 2: Risk = f {hazard, exposure, sensitivity, adaptive capacity}

Besides, this research used both weighted overlay and map algebra to synthesize both risk components and heat risk (Smith, Cavan, and Lindley 2015; Buscail, Upegui, & Viel 2012). Moreover, NDVI is an exceptional parameter that is used in both exposure and vulnerability layers, but when it is used in the exposure layer, it is not considered in the vulnerability layer.

Furthermore, ecosystem service mismatch is calculated by following Sebastiani, Marando, & Manes (2021) study to assist in identifying the priority intervention areas of Glasgow city for which Tree Canopy data is adapted from PAN 65 of Glasgow city council (Glasgow city council 2021).

4 Result and analysis

4. 1 Study Area's Climatic Features

There is no significant increasing trend observed in the mean air temperature and daily mean wind speed but in total rainfall over twenty years (2000-2020) at two nearby Met office's weather stations (Bishopton and Salsburgh) of Glasgow city (Met office 2021c). Climatic data of these two stations are different which implies the effect of geographical variation at the mesoscale. As Salsburgh station is located in hilly areas, it records lesser temperature and more wind speed data compared to Bishopton station. Moreover, wind information from HadUK-Grid (Met office et al. 2020) reveals that the north side of the city receives more wind speed than other parts.

4.2 Base Layers of UHR

Figure 2 presents an overview of nine base layers used in this study to assess UHR. Even though the range of LST value is different from the range of air temperature value, both maps signify green spaces as cool places and the central part of the city as a warm place relatively. Besides, the LST map reflects a discrete nature of high surface temperature (highlighted in red color) in densely built areas whereas the highest Ta is evident in and around the city center that gradually gets reduced in the outskirts.

The maximum and minimum value of NDVI of a data zone (DZ) is 75.45% and 2.12% respectively in Glasgow city, containing limited vegetation in the city center. It is also visible that a low LST value is reflected in the high NDVI zones. BV data uncovers that nearly 63% area of a DZ is capped by buildings. LCZ 8 (mostly enclosing large low-rise buildings) is prevalent in the city that covers almost 25% of the surface area followed by LCZ 9, the sparsely built zone. According to map analysis, it is observed that both BV and LCZ are seemingly presenting similar information on Glasgow city's urban form.

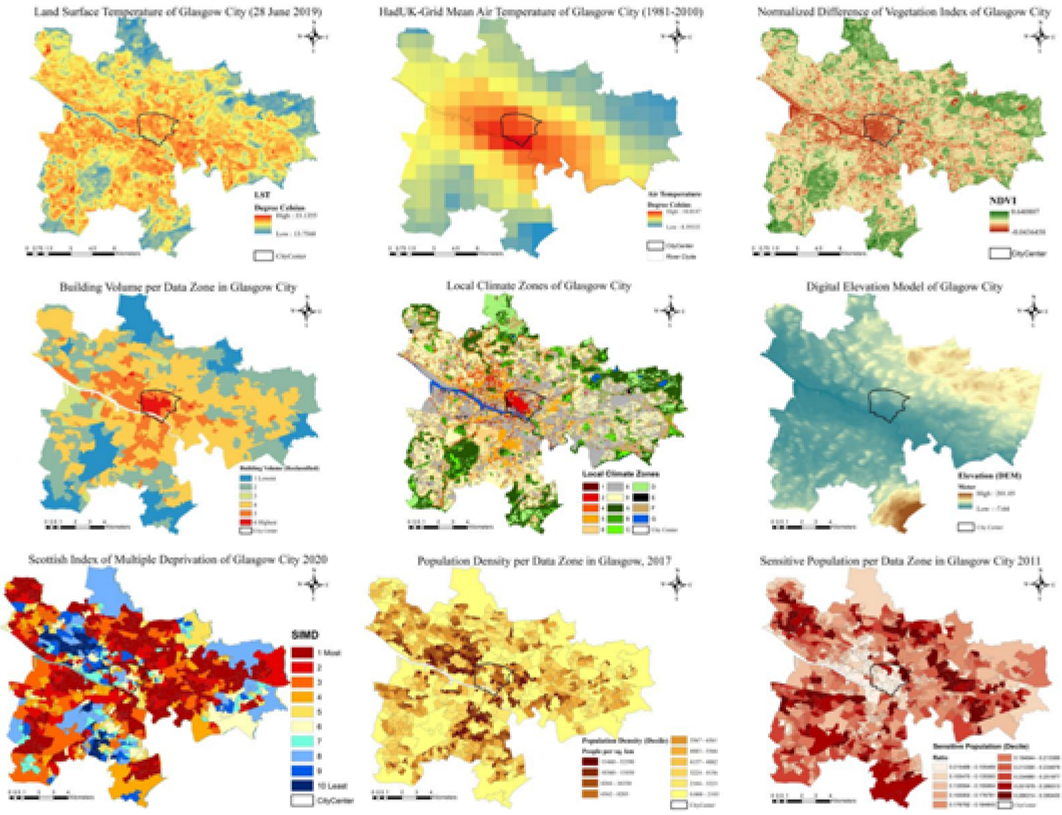

Figure 2. Maps of nine base indicators (Figure: Begum 2021)

Only 3% of Glasow city is located above 100m found in the northeast side. SIMD map displays that nearly 68% area of the city is facing high deprivation. However, the least-deprived communities are prevalent in only 3% area (i.e., Partick town, the city center, and south of Shawlands town) although these are medium to high densely populated areas. The sensitive population ratio is evident in the suburbs up to 0.39 at maximum in a DZ. Therefore, the maps of base indicators immediately provide hints on the high and low heat risk magnitude of Glasgow city.

4.3 Urban Heat Risk Analysis

A total of 40 UHR maps are created from different combinations of 2 hazard, 4 vulnerability, and 8 exposure layers where 20 maps are generated for each GIS technique (weighted overlay and map algebra). However, only eight UHR maps from number 33 to 40, where risk consists of three components and NDVI is accounted in the vulnerability layer, are described in this paper as the representatives of all the constructed maps.

The weighted overlay method divides the study area into three risk categories: moderate (76%), high (17%), and low (7%). However, raster calculation (sum) divides the study area into more than six classes and discovers about 5% and 4% of areas as the lowest and highest heat risk susceptible zones respectively. The number and proportion of UHR classes fluctuate tremendously based on the number of risk elements and the number of indicators used to prepare those elements. According to figure 3, the ordinal risk classes show a bell curve pattern in statistical distribution where the percentage of high and low heat risk zones is nominal compared to moderate heat risk zones.

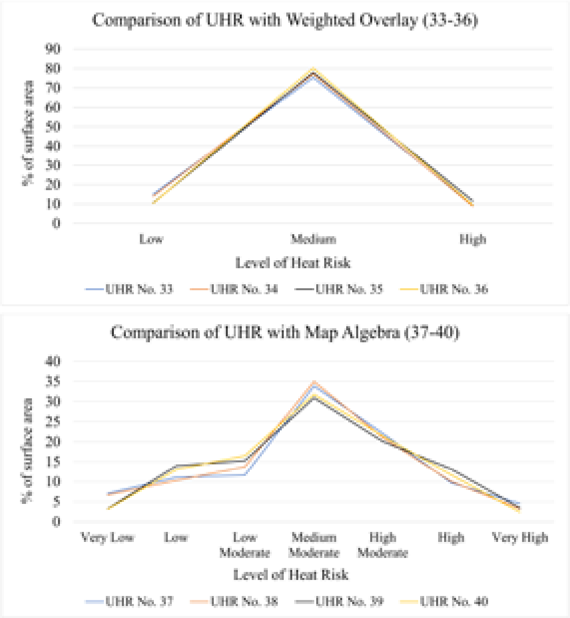

Figure 3: Statistical analysis of UHR maps from No. 33 to 36 with equal-weighted overlay (top) and from No. 37 to 40 with map algebra (bottom) (Figure: Begum 2021)

4.4 Description of Climate-sensitive Hotspots

The spatial distribution in figure 4 highlights the riverside areas including the city center as the most 'high heat risk' potential whereas 'low heat risk' areas are mostly visible in the northern edges of the city. According to this study, six UHR hotspots are discovered containing 'high' to 'very high' heat risk potentiality and denoted as A, B, C, D, E, and F. Hotspot 'A' is found in the city center having high exposure and low vulnerability index. Hotspot 'B' is an urban area located in between Parkhead town center and Glasgow Green Park largely used for commercial or industrial activities (HLAmap 2017). Hotspot 'C' is located in the northeast of Parkhead town center containing similar physical characteristics to B and relatively with a high vulnerability index. Hotspot 'D' in the south of the city center encompasses a large area with high deprivation and high hazard index. Hotspot 'E' is a small pocket containing a high vulnerability index. Lastly, 'F' is a UHR hotspot in the west of the city alongside the river Clyde bank and entirely used for industrial or commercial purposes and highly exposed to heat risk. Overall, five out of six hotspots are located within the River Clyde Development Corridor, a prospective development area under the City Development Plan (GCC 2017a). Besides, large parks and green belts are possessing low heat risk potentiality, which accounts for almost 18% of surface area in the north, northeast, and southern peripheral part of the city.

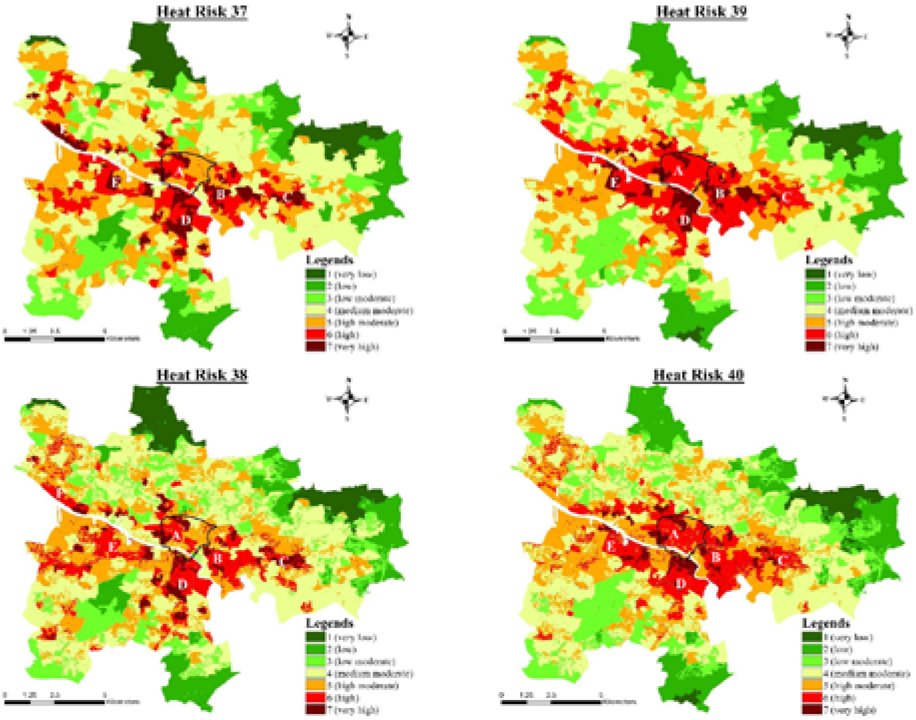

Figure 4. Spatial distribution of UHR maps from number 37 to 40 (No. 37 with LST & BV, No. 38 with LST & LCZ, No. 39 with Ta & BV, and No. 40 with Ta & LCZ) (Figure: Begum 2021)

4.5 Description of Comparative Analyses

Regardless of GIS spatial analysis techniques, the majority surface area of Glasgow city is prone to moderate heat risk. Detailed information on spatial heat-risk distribution can be gathered with the map algebra method as it produced more risk classes compared to only three classes of the overlay method. However, both techniques spotted the 'low' and 'high' heat risk zones in similar locations.

As for the two hazard components, all LST-based maps regardless of GIS techniques generate about 3% - 4% more 'low' UHR zones than Ta-based maps, but similar percentages of 'high' UHR areas. Besides, the extent and magnitude of six climatic hotspots vary spatially between LST and Ta-based maps. This study appraises LST-based UHR mapping over Ta-based UHR mapping because of the detailed UHR reading given by LST at a small scale coupled with the poor resolution of Ta data. Besides, the use of LCZ in place of BV revealed a similar result spatially and statistically.

5 Discussion and Conclusion

Existing UCM studies constructed and described UC-AnMaps and UC-ReMaps straight-forwardly without linking the methodological processes to UCM outputs. This study is the first of its kind that not only generated UHR maps but also pointed out the factors that cause deviation in final risk maps. Thus, this paper implies that each step in GIS-based risk mapping from indicator selection to risk synthesizing process is crucial to determine the spatial risk distribution within the study area.

When the risk is a function of three components, about 33.3% weight factor is assigned to each risk element. However, it gets down to 25% per risk element when risk is a function of four risk elements. Thus, this study highlights that risk definition plays a key role by essentially changing the contributing factor of each base layer in risk mapping, which is also argued by Andersson-Sköld et al. (2015) and Räsänen et al. (2019). The discrepancy between LST-based and Ta-based UHR maps lies in the base layer's data quality. The Ta data used in this study is originally an interpolated data created through the Had-UKGrid project by the Met Office (Met Office, 2021b). While Ta is coarse and does not represent proper Ta distribution of the city, satellite-based LST data reflects the nature of urban land cover at 30m grid size. Hence, the LST map represents a better heat risk scenario than Ta in this study.

This study found a spatial clustering of 'high' heat risk zones in the City Center, similar to the study findings of Wolf and McGregor (2013) for London, and Smith, Cavan, and Lindley (2015) for Greater Manchester. Many other studies also highlighted that city centers are likely to be hit by high heat risk in the whole city (Tomlinson et al. 2011; Buscail, Upegui, & Viel 2012). Like the findings of Arup (2014) for London city, this research also observed a decreasing pattern of heat risk intensity from the city center toward the peripheral zones and found that 'low' UHR zones coincide with large parks (Buscail, Upegui, & Viel 2012) such as Pollok Country Park. Besides, despite having high exposure index, Partick town is strong socio-economically which resulted in low UHR intensity as these areas are wealthy (Scottish government 2020), and thus, have more ability to cope up with heat risk. Overall, this study identified the city center, Parkhead, and northside of Shawlands as highly susceptible to heat risk whereas green belts and large parks are seemingly less potential.

Heat risk intensity among different groups and zones can be mitigated through spatial and strategic climate-cautious urban planning and design at different scales as indicated by Arup (2014) and pressed by Emmanuel (2021). As for strategic intervention, this paper suggests incorporating compact neighborhoods scheme with sufficient public open spaces (Johansson & Yahia 2010), and to increase surface permeability and shading effect with tree plantation (Arup 2014; Dursun & Yavas 2015; Doick & Hutchings 2013). Besides, public participation in climate-sensitive community development, arrangement of sustainable city design competition, (Djukic, Vukmirovic, & Stankovic 2016), heatwave forecasting scheme (CRC 2021), Heatwave Management Guideline development like England (UK Government, 2014), and designated local cooling centers (Arup 2014) can be implemented to fight against projected heat risk potential in Glasgow city. As for spatial intervention, this study constructed a UC-ReMap as shown in figure 5 by overlaying the map of ES mismatch for temperature regulation (34% weightage) with the UHR map No. 38 (66% weightage). The UC-ReMap divides the study area into five planning zones where UPZ 1 needs to be conserved and UPZ 5 needs immediate intervention to lessen UHR. Improvement of green infrastructure can play a key role in UHI and UHR reduction (Naylor et al. 2017; Marando et al. 2019; CRC 2021), essentially in the Glasgow city center.

Urban Climate Planning Recommendation Map for Glascow City

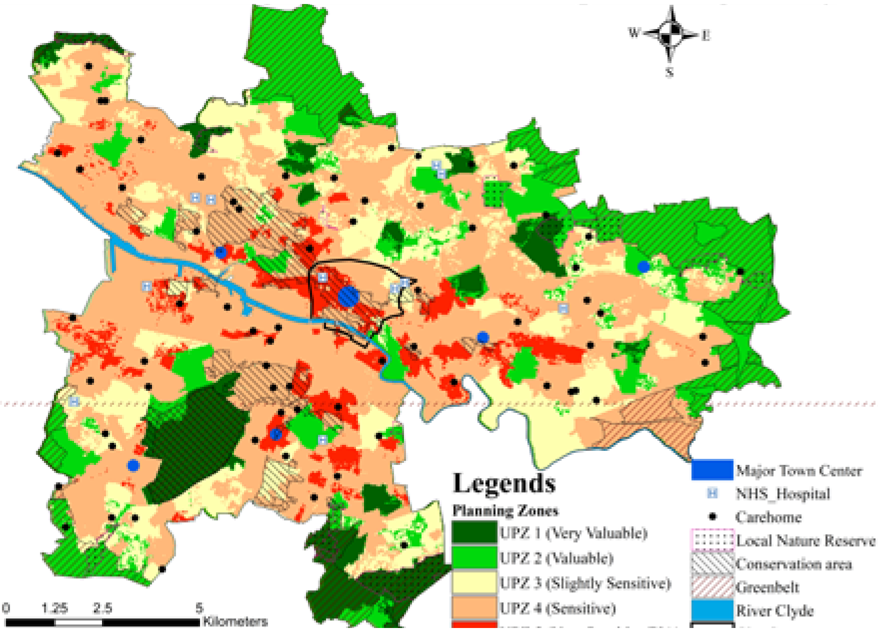

Figure 5. UC-ReMap for Glasgow City (Figure: Begum 2021)

5.1 Conclusion

Urban climate mapping is crucial to highlight the priority zones for specific causes like UHI mitigation, flood control, air pollution reduction, etc. A risk-based approach is applied in this study to create UCMaps in form of urban heat risk maps for the whole Glasgow city. Unlike existing studies, this research used multiple ways to generate a total of 40 UHR maps by exploiting readily available data to explore the effect of methodological choices. The resultant maps and critical evaluation infer that any of the two GIS techniques are useful to produce urban climatic maps but map algebra has provided detailed risk information compared to the weighted overlay method in this study. Besides, the LST data gives better mapping outputs than the air temperature data as it is coarse and lacks spatial detail at the local scale. The number of indicators for the risk components and the number of risk components for the risk analysis affect the final mapping statistically and spatially by changing the weightage of the base layers. From the appraised maps, this paper concludes that the city center is detected as a heat risk hotspot regardless of any changes in the mapping processes, which calls for immediate actions by GCC to control the sources of the UHI in the city center. The planning recommendation map highlights the zones that need priority interventions and urges for urban green infrastructures to mitigate heat risks.

The implications of climate-cautious measures in the priority zones need proper spatial UCM mapping which is even further dependent on the UCM synthesizing processes. Thus, special attention needs to be paid off on the methods of UCM mapping before using the UCM results for climate change adaptation plans and strategies. Overall, this study’s findings provide insights on the key factors that the local government and planners should be aware of while making climate-proof planning and resilient design for the anticipated overheating effect.

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SALOMA PACHECO, MILAGROS GUADALUPE

9 The impact of Public Space's Temporary Interventions in Outdoor Thermal Comfort and Microclimate

Analysis of Lahti's Market Square during Spring

Temporary interventions (TI) in the public spaces are common in the urban landscape (e.g., street markets, parklets or sun sails); however, few studies have analysed their effects on microclimate and Outdoor Thermal Comfort, especially in the Nordic countries. This study analyses the Potential air temperature (T_{Air}), Mean Radiant Temperature (MRT) and Physiological Equivalent Temperature (PET) of scenarios with and without TIs during two critical spring days (warm and cold) and considers Lahti's Market Square (Finland) as the case study. In parallel, an online survey revealed users' behaviour and desires for the plaza.

Results exposed that existing TI created more comfortable environments at specific hours, especially for creating various microclimates. However, effects were more substantial on the warm day and with higher occupancy of the plaza. Proximate vegetation presented better results than TIs on the warm day. Due to cultural preferences and the lack of evening activities, the most "comfortable" hours were not the public's preferred visiting hours. Therefore, a list of recommendations for both critical dates was complemented with explorative proposals that considered climate-sensitive strategies and the placemaking theory. The study can inform decision-makers to find effective and low-cost solutions that create more liveable places and cope with climate change adaptation and mitigation.

1 Introduction

Climate change has shown a rapid temperature rise in the last years (IPCC 2014). Moreover, cities are already dealing with the effects of climate change, like constant heatwaves, which expose people to the risk of illness and death (Campbell et al. 2018). The temperature rise in high-latitude cities was not considered a problem (Suomi & Kayhko 2012; Yan et al. 2020), but RCPs scenarios have raised local awareness. In Finland, the temperature is expected to be 1.5 times higher than the global average temperature rise (Ministry of the Environment and Statistics Finland 2017). Thus, there is a need to find adaptation measures that cope with the speed of changes and allow resilience.

Different authors agree that outdoor spaces are potential contributors to alleviate the built environment's climatic impacts and incorporate climate change adaptive responses (Emmanuel 2016; Nouri & Costa 2017). Its relevance relies on being part of the public realm and impacting microclimate and Outdoor Thermal Comfort (OTC). Moreover, attractive public spaces also generate social, cultural, and economic benefits (Cheung & Jim 2018; Madden 2000) and have been a focus of attention during the COVID19 pandemic (Gehl 2020; Gehl 2021). Additionally, most OTC studies cover winter or summer (Gatto et al. 2020; Yilmaz et al. 2021; Maharoof et al. 2020), but not transitional seasons.

Microclimate and OTC impacts in the users' behaviour and attendance (Martinelli et al. 2015; Thorsson et al. 2004; Eliasson et al. 2007) and require site-specific studies because it involves physiological and psychological aspects (e.g., experience, expectations or culture) (Johansson 2016). Nevertheless, it has scarce studies in arctic or subarctic areas (Yang et al. 2020).

In this same line, Climate-Sensitive Urban Design (CSUD) uses design tools to create pleasant spaces from the climatic perspective and mitigate the outcomes of urbanisation (Oke et al. 2017) (e.g., vegetation and shelter canopies). A good design should include adaptive/responsive measures and diversity in the urban forms to respond to expected changes in weather and seasons.

Temporary interventions (TI) in the public realm can be found in every city in different contexts (Duarte 2016; Lin 2016; Nouri 2015) but are not necessarily conceived as CSUD. Moreover, they can be seen as experimental, low-cost and community engagement elements. Market Square in Lahti, Finland, is an excellent example of TIs because it has multiple events around the year, being some seasons more active than others. Additionally, the area has a historical significance that limits constructions in the site and reinforces the use of ephemeral elements. The present study aims to evaluate the influence of existing TI in the microclimate and OTC in Lahti's Market Square during spring and discuss other proposals with a climate-sensitive approach. The objectives are:

- Understand local meteorological characteristics with an annual and seasonal insight, especially in spring.
- Investigate the users’ behaviour and opinions about OTC and activities in the study area.
- Identify existing TIs and analyze their impact of on OTC and microclimate in spring.
- Identify, if any, strategies to improve the plaza and make it more climate-sensitive using TI.

2 Background

2.1 Microclimate, outdoor thermal comfort and Users’ Behaviour

The main focus of microclimate is human wellbeing. Moreover, outdoor microclimate is directly affected by urban geometry (Emmanuel et al. 2007). Therefore, studies in this field can help optimise public spaces’ design, improve city liveability, and save heating and air conditioning energy inside buildings by spending more time outdoor (Yang et al. 2016). Meanwhile, thermal comfort is a mental state where the person is satisfied with the thermal environment (ASHRAE 2009); consequently, it is a human being’s response to the microclimate conditions. Climate change has dangerously altered thermal comfort; heatwaves cause thermal stress, discomfort, hyperthermia, and death (Oke et al. 2017; Duarte 2015).

OTC studies have not been widely developed in Nordic countries; existing studies used PET, MRT and Universal Thermal Comfort Index (UTCI) to assess OTC. However, a survey in Umea, Sweden, proposed contextual rearrangements of Thermal Sensation Values (TSV) scales of thermal indexes during summer because local people are more sensitive to warmer environments (Yang et al. 2016).

Several studies demonstrate the relationship between environmental factors, OTC, and user’s behaviour in public spaces. “Behavioural adaptation” refers to a person’s adjustment to the environment to search for their comfort (Lin 2009; Johansson 2016). A study in a plaza in Rome (Martinelli et al. 2015) evidenced significant attendance in the plaza in shaded areas during summer, where PET was the lowest.

Aside from the physiological factors, the psychological aspect has a vital role in OTC, e.g., available choice, culture, memory (Johansson 2016; Martinelli et al. 2015). Extreme and long winters in severe cold areas generate that people cherish summer and have more outdoor activities (Yang et al. 2017). Studies in Sweden have shown high expectations to solar radiation, preferences of “warm” conditions (Thorsson et al. 2004) and a significant influence of air temperature, wind speed and clearness index (cloud cover) in people’s place perceptions and attendance (Eliasson et al. 2007).

2.2 Climate-Sensitive Urban Design

Different authors expose the need to collect and analyse the environmental data before the design process for CSUD. Then the data is processed in programmes (e.g., ENVI-met) for a detailed understanding of the microclimate.

Vegetation presents essential qualities for OTC: evapotranspiration processes, sun reflection, solar protection, alteration of wind flow retention of particles (Duarte 2016; Gatto et al. 2020). Greenery has shown better thermal comfort effects in summer than in winter (Gatto et al. 2020; Yilmaz et al. 2021); hence, their implementation needs evaluation, especially in cooler climates (Nouri 2015). Additionally, planted areas in a city show effects also in the surroundings and mitigate UHI (Chen & Wong 2006). On the other hand, artificial shelter canopies restrain the solar access, reducing short wave radiation fluxes, the temperature of shaded surfaces and long-wave radiation. They affect the MRT directly and has a general cooling effect (Emmanuel et al. 2007). However, depending on the geometry, materials, and wind patterns, the outcome can change (Nouri 2015; Lin 2016). In Turkey, semi-open canopy street canyons are suggested during winter to provide high thermal comfort but not during summer (Yilmaz et al. 2021). Nevertheless, in Glasgow, the use of sun sails showed a significant reduction in PMV during summer (Maharoof et al. 2020). In this same season, a comparative study in Hong Kong between a tree and a concrete shelter showed that both had cooling effects (Cheung & Jim 2018). However, the tree indicated better performance in air temperature and UTCI, while PET presented similar values in both cases.

CSUD proposals need to be site-specific for considering the cultural aspects. Moreover, the design must evaluate different seasons and adapt if required (Yilmaz et al., 2020). As general strategies, design should focus on deviating wind during winter; while sun protection and more wind circulation during summer (Brown 2010). Nevertheless, subarctic contexts suggest enhancing sunshine and weakening wind (Yang et al. 2017). The function of the street will also lead to the definition of the proposals (Oke et al. 2017). Finally, there is a consensus that public spaces' design must offer a diversity of microclimates so users can select the area where they find more thermal comfort (Thorsson et al. 2004; Martinelli 2015; Oke et al. 2017).

2.3 Temporary interventions: solutions for specific needs

There are multiple TIs in the outdoor environment. Aligned with CSUD, Nouri (2014) identifies that temporary shelter canopies can attack critical climatic periods, like heatwaves, in public spaces. Additionally, temporary canopies are an alternative when the implementation of greeneries has obstacles (Martinelli et al. 2015). Meanwhile, spontaneous greeneries (e.g., green walls, community gardens) are found in the formal and informal contexts, benefiting urban life from a social and environmental perspective (Duarte 2016). Other TIs like street markets, community celebrations, or sports also transform the public spaces.

The Placemaking process includes implementing short-term experiments as one of its principles because it is low-cost and has a high impact for improving public spaces, generates new uses and revenue for sites in transition (Madden 2000). However, Nouri and Costa (2017) considered that the theory needs to include pedestrian comfort considerations in the designs.

Tactical urbanism has similarities with the previous concept. However, it aims to be short-term to respond to specific needs and impact urban socio-economic environments (Andres & Zhang 2020). Projects can start from the governments, the communities or a combination of both. During the current pandemic, temporary urban solutions became crucial strategies for cities adaptation (Gehl 2020). Also, TIs are identified as art installations with high social engagement and appropriation of space (Zecevic 2017).

Combining all the references exposed, TIs responds to a particular purpose in a specific time and context. Additionally, they generally have low-cost, a reduced scale and involves the community. TIs significantly affects human activity in public spaces.

3 Methodology

3.1 Study Area

Lahti is in southern Finland; it presents warm to hot summers and cold winters (Köppen's climate classification: Dfb). The study location is Market Square in the city centre. It is the most important venue for outdoor events, with a capacity of 12 000 people. (Lahti n.d.). The place is very flexible and hosts various activities and events, especially a traditional market on the first Wednesday of every month since 1879. Its surface is of cobblestones, with a red-coloured path for accessibility. The perimeter presents rows of trees (Tilia cordata Mill) with an average height of 15 m (Gatto et al. 2020). It is managed by Lahentori company, which rents the place to the city council. Additionally, it is a National Cultural Heritage site.

3.2 Interviews

In-depth interviews were considered to cover Market Square's management, perception, responsibilities, future projects and other issues that were not found in other media. The interviewees were the CEO of Lahentori and the City architect of the city council.

3.3 Meteorological records and seasonal analysis

The meteorological records from Lahti were obtained from the Finnish Meteorological Institute (n.d.) website and considered two observation stations: Lahti Laune (2000-2018) and Lahti Sopenkorpi (2018-2021). They represent a basepoint for understanding the contrast between seasons and the yearly variations due to climate change. The analysis will focus on spring's mean temperature variance from 2000-2020 to determine two critical days (warm and cold).

3.4 Users' behaviour and opinions

Assuming that the results are linked with OTC, the seasonal and hour preferences for visiting Market Square were assessed with an online questionnaire (sample size of 108 participants, confidence level of 95% and a margin of error of 10%). It also covers the site's perception of environmental elements linked with thermal comfort (wind, sun, and rain). Other aspects include the activities, desires, and opinions of the place. The hour preferences will be used in the simulations. It was developed with Google Forms and was shared with the general public from May 21st to June 25th, 2021. The study also considers a previous survey in the city centre (Saari & Niskanen 2017).

3.5 TI identification and Traverse survey

Two dates were selected to identify TIs and develop a traverse survey: May 5th, 2021 (monthly market), and May 6th, 2021 (daily market). The traverse survey's route measured 20 points in the Market Square and its surroundings and used a pocket weather meter (Kestrel 3000). The route was covered in 1 hour and was taken at 11:00, 15:00 and 21:30.

The traverse survey presented non-synchronous observation times of the different points; hence it was required to conduct temporal corrections. Data collected from a fixed station in Mukkula (Tiny Tag TGP-4020) and the city's meteorological station Sopenkorpi were used for this purpose.

3.6 Initial Simulations

Calibration

The selected software used for analysing the microclimate and thermal comfort was ENVI-met, version V4.4.5 Summer20. The calibration of the model used the daily market (May 6th, 2021) as the reference case for practical reasons. Different models were compared in terms of T_{Air}, and the one presenting the lowest Square Root Mean Error (SRME) value was selected for the study. Finally, SRME was also calculated for the monthly market (May 5th, 2021) and a day with stable conditions (June 18th, 2021).

Simulations

The model was used in two critical spring days; in each one, three scenarios were calculated: the Market Square without interventions will be used as the base case (S1), daily market (S2) and monthly market (S3). In terms of microclimate, the study evaluates T_{Air} and MRT. The calculation of OTC used BioMet, a post-processor tool from ENVI-met (Bruse 2014) and the index selected was PET because it is the most used one and has been applied previously in the Nordic region.

3.7 Proposal and validation

Two proposals are developed as an output of the discussion to improve OTC. It also includes the reflections obtained from the users' behaviour and preferences and the logistics and management of the market. Finally, the proposal was validated with a second group of simulations.

4 Results

4.1 Seasonal meteorological analysis, Users' Behaviour and Opinions

Lahti's weather drastically changes around the year. For statistical studies, spring covers March, April and May. It is a transitional season in which the temperature rises, the sun hours increase (winter: 6 hours, summer:18 hours), the snow events fade, and the precipitation events reduce. The mean temperature between 2000-2020 in this season was 4.16°C and presents a rising trendline due to climate change.

The online questionnaire showed a variation of the users' behaviour throughout the seasons (Figure 1). Overall, winter and summer are the most contrasting results, while spring and autumn show similarities. In spring, the most popular answer for visits to the study area was "rarely" (62.0%), followed by "often" (26%). Additionally, 3pm-6pm is the preferred time for visits, followed by 12pm-3pm, with a similar tendency in all seasons. Users stay in the Market Square mostly for 15 minutes in all the seasons (spring: 54.2%). Nevertheless, people increase their visiting time throughout the year.

The main reasons for visiting the study area are commercial activities (30.2%) and its centric location (25.4%). Regarding weather conditions, 11.9% mentioned that they considered the Market Square comfortable during hot days, while just 2.4% indicated it is comfortable for cold days. Users answered that they do not find enough shade and wind and rain protection during critical days.

There is a consensus of implementing evening activities (74%), especially cultural events, coffee shops and food vendors. Another group of people suggested the implementation of plants. Additionally, Lahti's City Centre Survey (Saari & Niskanen 2017) mentions citizen's desire to implement benches, public art, plants, trash bins and bike racks on the site.

4.2 Identification of existing TI

The monthly market (May 5th) and daily market (May 6th) demonstrate the dynamic characteristic of the study site (Figure 2). Despite just one day apart, the occupied area of the available space was 25% in the monthly market (97 TI) and 12% in the daily market (20 TI). The east area has higher occupancy in both cases, while the west side is occupied during the monthly event. In the daily case, the west and the centre were empty. There is a particular alignment of TIs next to Aleksanterinkatu Street during the monthly market for taking advantage of the pedestrians' flow.

Existing TIs were classified into six groups. During the Monthly Market, the main typology were the Tents representing more than half of the elements (52), Vehicles and Modules had a similar count (13), followed by Tables (8). In the daily market, the main typologies are the Modules (11), followed by the Tents (8). All the detected activities were commercial. Regarding the materials Polyester & PVC represented 70% of the interventions during the monthly market, whereas in the daily case was 39%; sources were the tents and umbrellas. On the other hand, metal allocated in vehicles and modules represented 27% of the monthly market and 50% of the daily market. The other identified materials were wood and wood with metal.

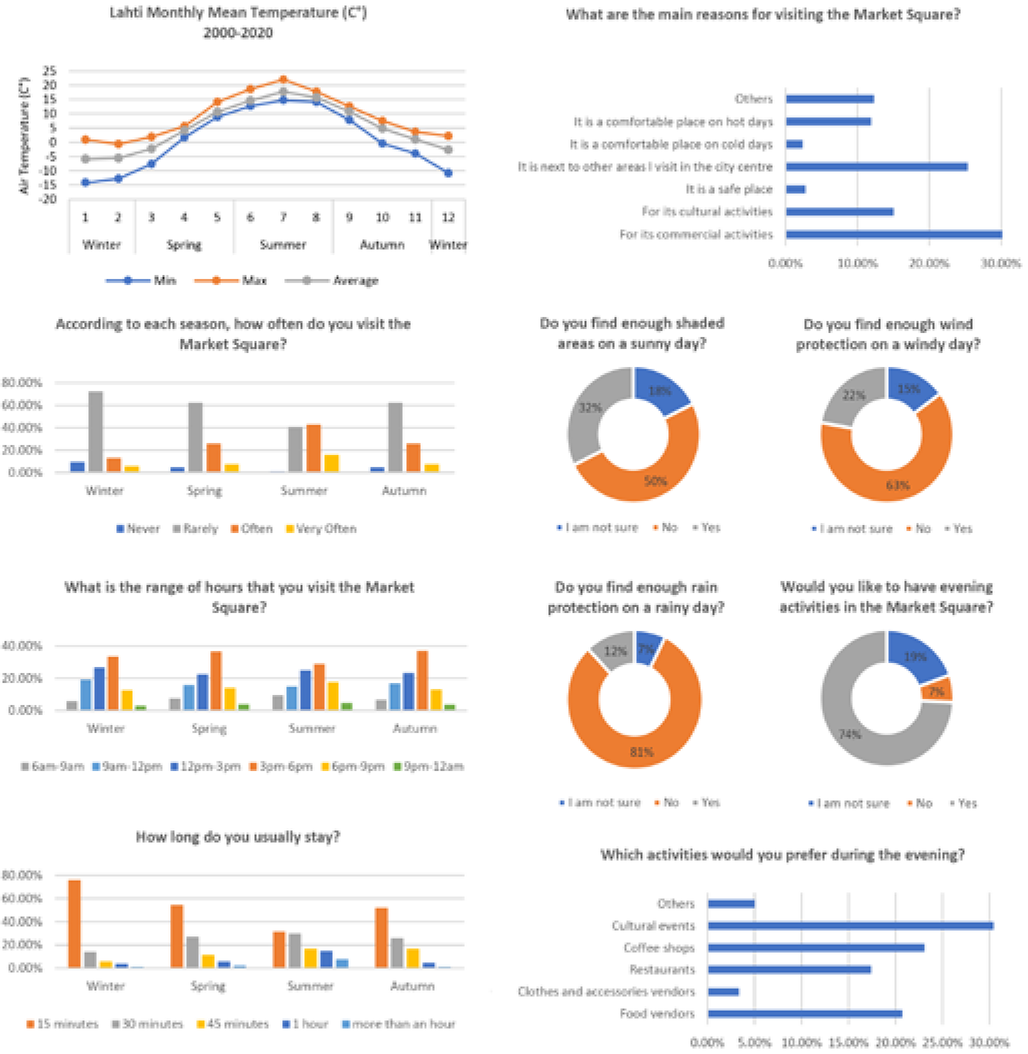
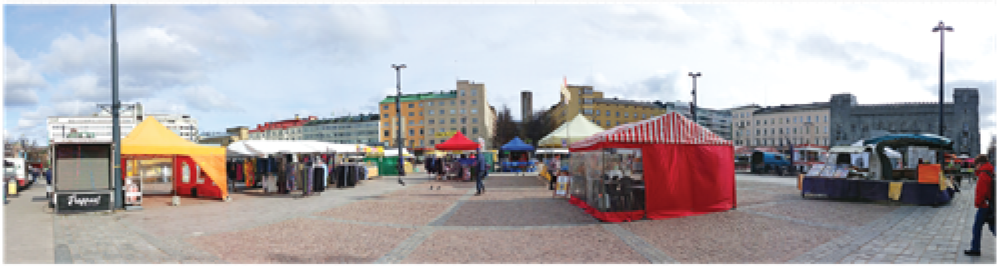


Figure 1. Seasonal meteorological and behavioural analysis and other questionnaire results (Figure: Saloma 2021)

Monthly Market



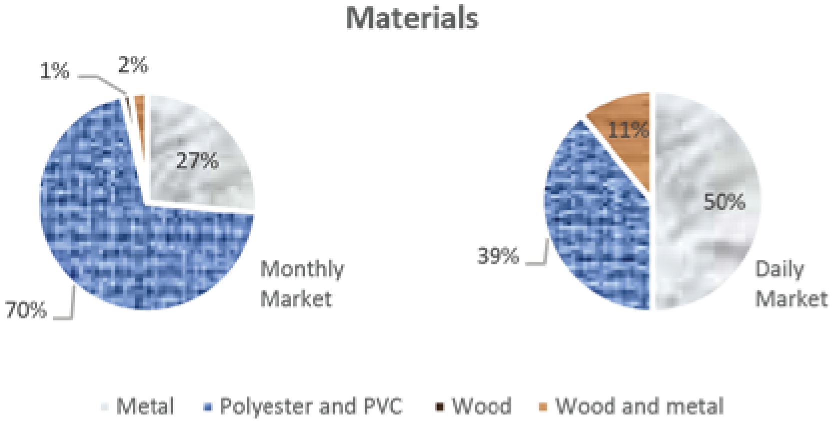


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Figure 2. Identification of Temporary interventions (Figure: Saloma 2021)

4.3 Spring's Microclimate and OTC analysis

Two days were considered for the present study:

- Critical cold day - March 14th, 2013: the average Air temperature was -13.95°C, with a maximum of -4.2°C at 13:30 and a minimum of -26.9 °C at 04:20. It presented snow, cloudiness and the average relative humidity was 75.65%.
- Critical warm day - May 10th, 2016: the average Air temperature was 16.30°C, a maximum of 24.7C° at 10:50 and a minimum of 5.2°C at 01:40, average relative humidity was 55% (RH max. 98%, RH min 20%) The sky was mostly clear but with fluctuating clouds after 10:30.

Results for T_{Air}, MRT and PET of the three scenarios mentioned previously are presented as heat maps (Figure 3). Additionally, it includes a PET comparison between six reference points (Figure 4).

Potential Air Temperature (T_{Air})

Both days present a concentric distribution of T_{Air} being the plaza the centre with lowest values. The cold day did not present significant effects, as expected. Meanwhile, the warm day showed a cooling effect in S2 and S3. Additionally, the shelter canopies (tents and umbrellas) had a warmer temperature at 15:00 and 18:00 than the open-air area. At 18:00, the situation between the three scenarios is more contrasting. Additionally, the cooling effect in the surrounding buildings is higher in S3 than in S2.

MRT

In both cases, TIs show an evident impact in MRT and generate a variety of microclimates. On the cold day, MRT between the TIs reduces, but their perimeters have higher values than other open-air areas. It shows lower values beneath the TIs than open-air ones at 13:00 and 15:00, but at 18:00, the situation is the opposite. The trees have a warming effect at 18:00, but the presence of the TIs reduce the effect in S3 (east side of the plaza).

At 13:00 S3 shows a cooling effect on the warm day, but at 18:00 the MRT rises. S2 has similar behaviour to S3, but the effect is more punctual around TI. Also, the surrounding areas show a reduction of MRT in S2 and S3. At 13:00, MRT between TIs has the same temperature category as the grass of the neighbour park (Alatori).

PET

The scenarios show different effects on both days. S2 and S3 show mostly cooling and warming effects during the cold day, which varied within hours and locations. However, warming effects at 18:00 were marginal. Meanwhile, TIs effects were constantly cooling on the warm day, with a higher impact in S3 than S2.

Moreover, on both days, the perimeter of TIs show cooling and warming effects according to the hour. Nevertheless, on the cold day, TI's inner temperature was colder than the open-air areas (13:00 &15:00), but warmer in the evening; on the warm day, PET was always colder inside TI. Additionally, in both days, the trees show a cooling effect at 13:00, while at 15:00 and 18:00 it presents both effects (cooling/warming). On the warm day, the trees' warming effect reduces in S3.

Using the original PET and TSV (Matzarakis et al. 1999), in the cold day 13:00 shows values closer to "Comfortable" levels (despite T_{Air} in the plaza is below -8.90°C), while on the warm day, it was at 18:00.

*ENVImet Cell size: 3x3x3. View plane: z=1.5m

Figure 3. T_{Air}, MRT and PET heat maps for three scenarios at different hours (Figure: Saloma 2021)

Figure 4. PET analysis for specific points in the plaza (Figure: Saloma 2020)

5 Conclusions and discussion

5.1 Comments, recommendations and exploratory proposals

People visit and spend more time in the square during summer, followed by spring and autumn, while winter had the worst results as expected. Nevertheless, autumn presents more overcast days than spring, but they show similar users' behaviour. However, the pandemic has shown an increase in outdoor spaces' use, regardless of weather conditions.

Users' perception aligns with the PET study, in which existing TIs had better effects regards thermal comfort in the critical warm day. Moreover, interviewees expressed that weather determines the number of vendors for the monthly market because, on unfavourable days (e.g., rainy), lesser public and vendors are expected; hence the area's occupancy is also affected.

People prefer visiting the square during spring between 15:00-18:00, followed by 12:00-15:00. The first presents a decrease of T_{Air} and PET, while the second shows an increase of both parameters. So, the preference for visiting hours is due to psychological and time-availability aspects more than physiological factors. Also, participants were mainly in the working-age group, and regular office hours finish at 16:00.

The primary motivation for visiting the plaza is its commercial activities. Additionally, all the assessed TIs in May were commercial. Therefore, TIs supports and allows different activities, which attract the public. The idea aligns with the placemaking theory (Madden 2000). There is an abrupt decrease in visiting hours from 6pm-9pm. However, on the warm day, 6pm was the most comfortable hour, so the reduction of visits is mainly related to the lack of evening activities. In parallel, the survey also showed that people are eager for more evening events.

The survey results show a common perception of the lack of shaded areas, wind protection and rain protection on critical days. Hence, more variety of microclimates in the plaza are desirable, which are enhanced by implementing more and different TI.

The daily market is present most of the month; hence its effects have more impact on the liveability of the city centre than the monthly market. The microclimate and thermal comfort analysis showed that the monthly market had better performance than the daily one in most cases due to more occupancy. More daily activities and interventions could bring positive effects to the study area.

Figure 5 summarises climate-sensitive strategies for improving the Market Square with TIs during spring's critical cold and warm days. The increase and decrease of PET are desirable for the corresponding days; however, the primary strategy is to provide various microclimates to the user. Specific strategies for the cold day include rain/snow protection and wind protection, while shaded areas and vegetation modules are proposed in the case of a warm day.

Climate-Sensitive Strategies		Critical Cold Day	Critical Warm Day
Microclimate & Thermal Comfort	Increase PET	X	
	Decrease PET		X
	Variety of microclimates	X	X
	Shaded areas		X
	Rain/snow protection	X	
	Wind protection	X	
	Vegetation mobile modules		X
	Create Clusters in Layout	X	X
	Increase % of occupancy	X	X
Activities & more interventions	Consider users' desires	X	X
	Enhance evening Open air Activities		X
	Enhance noon Open air Activities	X	

Figure 5. Strategies, proposals, and validation (Figure: Saloma 2021)

The strategies were implemented in two exploratory proposals for the daily market on both days, also applying Placemaking concepts. Existing TIs are relocated in the centre, and new TIs are implemented to host other activities (performance stage, leisure area and open-air exhibitions). On the critical cold day new TIs enhance wind, rain, and snow protection (PVC domes and exhibition area). In contrast, on the warm day TIs aim for shadow (artificial canopies and vegetation modules). Both proposals improved the environment in terms of thermal comfort; nevertheless, interventions in the warmer days had a more significant impact. The plaza use during cold days' evenings is not recommended due to the highly uncomfortable level.

5.2 Limitations

ENVI-met does not assess rain or snow in the simulations.

The model used for the study presented optimal SRME on May 5th and 6th, 2021 (cloudy and rainy) but not on June 18th, 2021 (clear sky).

Online questionnaires limited the spread of the survey to the senior population.

5.3 Conclusions

TIs positively affect OTC in the study area and have better performance in MRT than in T_{Air} because of the shadow enhancement. Implementing more climate-sensitive strategies and new activities in the plaza would lead to more comfortable and microclimate-diverse public spaces and should be complemented with new activities. Hence, the plaza will become more attractive, will receive more public and have more active hours. The two presented examples show positive outcomes, but interventions in the warmer days should be prioritised due to significant results. Stakeholders must consider the social, cultural, and economic benefits of using climate-sensitive strategies on the Market Square's TI.

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SETHUPATU BALA, RAJU

10 Microclimatic analysis to mitigate urban heat islands using urban climatic map approach

Toulouse, France

Cities are urbanising at a fast phase to accommodate more people, which leads to global and local warming. Since the urban infrastructures are responsible for climatic issues, it is essential to inform the urban planning and design community about it. Urban climatic maps are used to inform about the urban climatic issues. But, the information provided through the maps is not sufficient to make climate-responsive decisions since they do not provide information about the urban planning and design parameters that cause the climatic issue in the city. Therefore, this research aims to provide complementary spatialized indicators useful for climate-responsive decisions. UHI is the climatic issue studied in this research, and the research is conducted in three phases. In the first phase, 17 urban planning and design indicators that cause UHI are identified. In the second phase, various GIS tools were explored to calculate the identified indicators, using the data generated under the MApUCE project for Toulouse. In the last phase, the calculated indicators are grouped, and Geographically Weighted Regression (GWR), a local regression method, was applied to each group to find the relationship between the urban planning & design and meteorological indicators. The identified indicators can be used for future urban climatic research purposes.

1 Introduction

1.1 Rationale

In the year 2050, the expectation is that 68% of the world's population will live in urban areas. In France, the urban population is already 80% (Martins et al. 2016). The rapid urbanisation, to accommodate more people and necessary infrastructures, stressing the natural and built environment causing global and local warming. From the French national perspective, between the years 1900 and 2020, the year 2020 was the hottest year of France. The mean average temperature of the country increased by 2.3 degrees Celsius than the normal (Mardi 2021).

The significant changes in the natural surfaces and the built morphology alters the climatic variables, which leads to a human-induced microclimate phenomena called Urban heat island (UHI) (Oke et al. 2017). The cities are often warmer compared to the surrounding rural areas, in particular during nighttime. Luke Howard first identified this in the year 1833, opening a new field of study in climate sciences and geography (Cleugh 1995). This is an important issue because, the higher the temperature, the higher the health, economic and environmental risk (Parapari et al. 2015).

Urban climate effects are studied to address the climatic issues in an existing urban settlement or to plan a new development that is climate-sensitive to avoid climate-related problems in the future (Oke et al. 2017). However, climatic studies are not often perceived from an urban planning or design perspective, and they are mostly studied from a scientific perspective. Often, climatologists do not understand spatial planning procedures and processes. On the other hand, planners and designers often do not understand the climatic effects (Ren et al. 2012). To make the climate knowledge available to the urban planning and design community, and also to connect the two fields of study, the Urban climatic map (UC-Map) approach was introduced (Ren et al. 2010).

But, Urban planners and designers are finding it difficult to use the maps since they do not have any prior knowledge or experience in climatic issues (Johansson 2006). Ren et al (2012) also mention that the UC-Map is a fragile bridge connecting the two disciplines and the introduction of UC-Map technique in operational practices is not still habitual.

This research attempts to strengthen the connection between the scientific and practical world by complementing the urban climatic maps with spatialized useful information for urban planning and urban design purposes.

1.2 Aims & Objectives

Based on previous research done on the framework of MApUCE[1] and PAENDORA[2] research programs in France, this research aims to complement the urban climatic mapping approach to support urban planners and urban designers for climate-responsive decisions adopted to the French operational and scientific practices and legal framework.

To achieve the aim, the formulated objectives are:

1. To make urban climatic maps useful for urban planning & urban design community.
2. To identify meteorological and urban planning & urban design parameters to feed the ensemble of maps composing the UC-Maps framework.
3. To explore the GIS tools to calculate the identified urban planning & urban design parameters.
4. To find the relationship between the identified meteorological and urban planning & urban design parameters.
5. To provide recommendations for future research related to urban climatic mapping.

2 Background

Urban climatic maps are the two-dimensional spatial map that provides climatic information and also acts as an evaluation tool for climatic phenomena and problems. Urban Climatic maps (UC-Map) were first initiated by German researchers in the year 1970, and it was known as the "Synthetic Climate Function Map" during that period. UC-Map consists of two major components, the Urban Climate analysis map (UC-AnMap) and the Urban Climatic recommendation map (UC-ReMap).

UC-AnMap is an analytical map generated through quantitative or qualitative techniques. It provides a climatic understanding and evaluation, which is used to identify climate-sensitive areas. UC-ReMaps provides some measures to solve the identified problems (Ren et al. 2012).

In total, 77 cities in 29 countries conducted Urban climatic map studies (Ng & Ren 2015; Hidalgo et al. 2018). Out of which two cities, Arnhem, Netherlands and Tokyo, Japan, were randomly selected for critical examination, to understand the UC-Map's limitations and defects, in this study.

For Arnhem, the physical and climatic data were gathered and classified to calculate thermal load contribution and Dynamic potential. The collected information was synthesized for urban morphological understanding. On top of the urban morphological information, the analysed wind information, and the topographical condition, were overlapped to create UC-AnMap. Three built-up area climatops, two greenery area climatopes, one water climatope, and one transport area climatope were identified from UC-AnMap. Based on this, high to low sensitive zones concerning urban climatic issues were identified, and appropriate recommendations for each zone were provided through UC-ReMap (Ren et al. 2012).

Similarly, meteorological and planning parameters, heat release data such as anthropogenic heat release, vaporization latent heat, and surface cover sensible heat, were considered in the UC-Maps of Tokyo. The generated UC-AnMap was overlapped with the heat release data to derive reasons behind the climatic effect of a particular urban zone.

The recommendations provided in Arnhem's UC-ReMap was too generic and would be difficult for an urban planner or designer to address the climatic issue since the recommendations were not linked with the urban planning or design elements. For example, urban areas where the valley winds should be strengthened to overcome the climatic issue was identified using the UC-Map. But urban planners and designers, without any climatic knowledge, do not know how to achieve this recommendation. A similar defect was noticed in the thermal environment map of Tokyo, Japan. The map explains the level of thermal load at different areas and the reason behind them. But these reasons are not linked with the urban planning or design elements, making it difficult for the urban planner and designer to understand. This agrees with the argument of Johansson (2006) that the climatic maps do not provide detailed advice to planners and designers.

The critical understanding and examination of Arnhem's and Tokyo's UC-Map, lead to two important questions that need to be addressed through UC-Maps to make them useful for climate-sensitive planning and design decisions.

1. Who / What is responsible for the urban climatic issue in a particular place?
2. How to reduce or mitigate the climatic issue in a particular place?

2.1 MApUCE Project

Fight against climate change and adaptation to this change, saving fossil fuel resources, control of energy and the production of energy from renewable resources, and reduction of greenhouse gas emissions is one among the eight objectives of the Town planning code of France (Article L101-2), introduced in the year 2015 (Republique 2021). To achieve this objective MApUCE (Modelling applied to town planning Law: Urban climate and Energy) project was initiated and funded by France research funding agency ANR (National research agency). This project was carried out in partnership with seven research laboratories and coordinated by CNRM (National centre for Meteorological Research) and LISST (Interdisciplinary Solidarity, Societies, Territories Laboratory) (MApUCE 2019).

The main aim of this MApUCE project was to produce data and identify methods to improvise the integration of climatic issues into French urban policies. The first piece of work was to generate urban microclimate, climate, and residential energy consumption quantitative data through numerical simulation and to generate an urban database for the panel of forty French cities. The second piece of work was to explore methodologies to integrate the generated information into French legal documents (Hidalgo et al. n.d.). The urban climatic map was the method explored since Urban planners and designers use cartographic representation in their day to day work.

This research is part of the internship program offered at LISST, concentrating on the second section of the MApUCE Project. The objective of this internship is to make the climatic data produced under the MApUCE project useful for urban planning and design purposes. Since Toulouse was the city already chosen to explore different cartographic representations, the available Toulouse data were considered for this research.

In total, 64 urban indicators values are available in three spatial scales, building, block and islet scale, and two categories of climatic information are available. The first set of climatic information is related to the sequence of meteorological situations, called local weather type classification (LWT). The second climatic information comes from SURFEX numerical simulation providing spatialized microclimate data. The numerical simulation provides three pieces of information, Thermal stress (UTCI), urban heat island intensity (UHI), and wind information (Hidalgo et al. n.d.).

The number of LWT varies from city to city. Based on the meteorological situation that frequently occurs with similar effects at the atmospheric boundary layer, the LWT classification was performed, using diurnal air temperature amplitude, daily mean wind speed values, wind direction, precipitation, and specific humidity numbers. In total, Toulouse has 11 LWTs. LWT 7, 8, and 9 are the summertime LWTs (Hidalgo & Jougla 2018). LWT 9 is used for the urban climatic studies since it is the hottest summer LWT and Toulouse summertime temperature sometimes rise to 40 degrees Celsius and is responsible for the heatwave in the city (Shi et al. n.d.).

3 Research approach and design

To answer the identified research question, a "Sequential exploratory design – Mixed method" methodology was followed. Qualitative research informs about the quantitative research.

To construct the urban climatic map for urban planning and design purposes, this research was conducted in three phases. In the first phase, literature study, interview, and case study were the three qualitative techniques followed to identify the parameters. In the second phase, different QGIS and ArcGIS tools were explored to calculate the identified parameters. In the last phase, a Geographically Weighted Regression (GWR), an ArcGIS tool, was used to analyse the relationship between the meteorological and urban planning & design parameters. Objectives 2, 3, and 4 were achieved through phases 1, 2, and 3, respectively. Figure 1 illustrates the methodological overview of this research.

Phase 1: List of urban climatic map indicators

To create urban climatic maps, analytical maps of climatic elements, geographical terrain information, and greenery and planning parameters are required (Ren et al. 2010). Since this research is focused on producing urban climatic maps for climate-responsive urban planning and urban design decision making, the identified parameters are classified as meteorological parameters and urban planning & urban design parameters. These can also be called meteorological and urban planning & urban design indicators.

To make the urban climatic maps useful for urban planning and design communities, it is essential to explain the causes of the climatic issues through urban planning and urban design elements. To better understand the causes of UHI and their relationship with urban planning and urban design elements, the book "Heat Island – Understand-

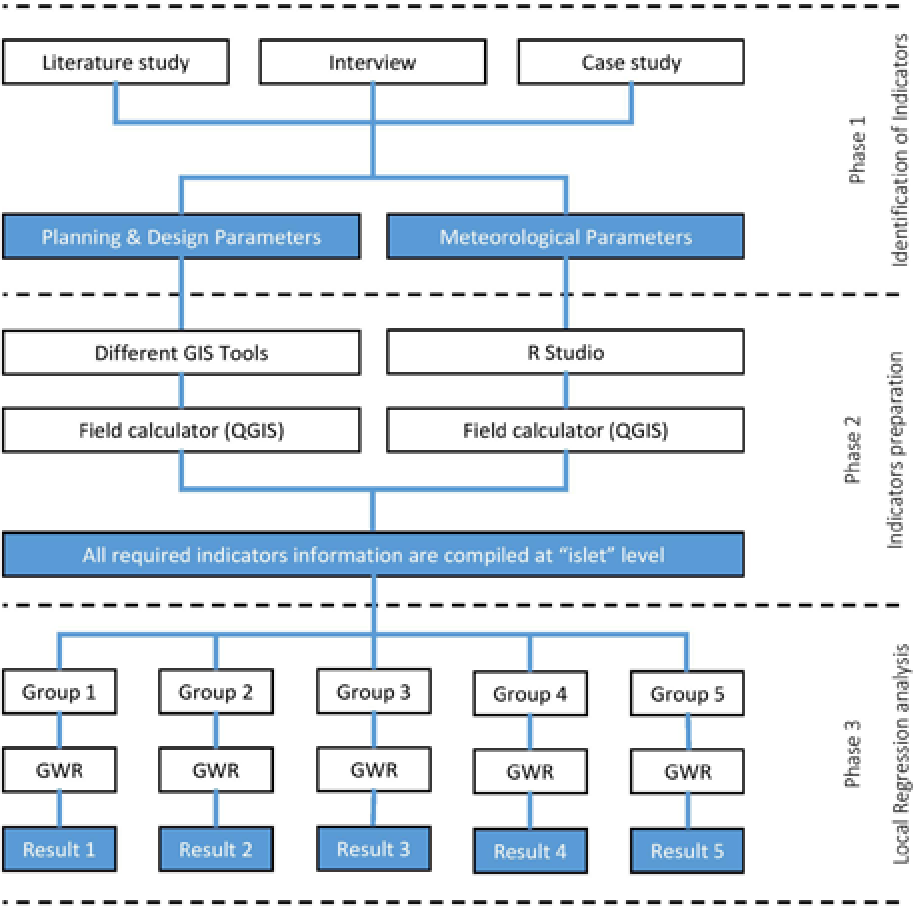


Figure 1. Research Methodology (Figure: Bala 2021)

ing and mitigating heat in urban areas" authored by Lisa Gartland was referred. This book was chosen for the literature study since it provides a concise summary of the UHI causes and their relationship with urban planning & urban design elements. Reduced evaporation, Increased heat storage, Increased net radiation, Reduced convection, and Increased anthropogenic heat are the five causes of UHI. These causes are due to lack of urban vegetation, urban impermeable surfaces, high thermal diffusivity and low solar reflectance of the urban materials, high air pollution, urban geometry, and high building energy use (Gartland 2008).

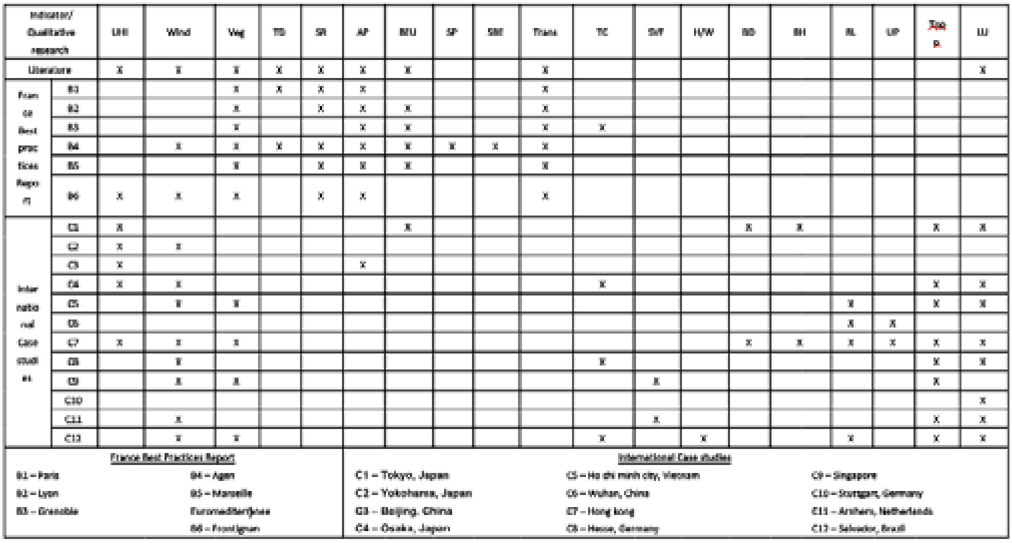
Interviewing the urban professionals involved in climate responsive practices will help to identify the linkage between various urban planning & urban design elements and the climatic issues. This will also help to understand the requirement of the target group, urban planners and designers. However, due to practical difficulties during this pandemic period, the best French urban practices report prepared under the MApUCE project was referred instead of conducting interviews. This report was prepared based on grey literature, city network exploration, and interviews of urban professionals involved in four best urban planning and two best urban design climate responsive projects in France. Since the thoughts and reflections of the urban planning and urban design professionals are already summarised in this report, this report was referred.

To understand the urban climatic map creation process better, the book "The urban climatic Map – A method for sustainable urban planning" edited by Edward Nd and Chao Ren in the year 2015 was referred. Out of 23 cities UC-Map summaries available in this book, 12 cities were randomly selected and studied. The list of indicators related to urban planning and urban design elements from these case studies were included along with the indicators identified through literature and the best practices report. Table 1 presents the list of identified indicators, a description of each indicator, the relationship between different identified indicators, and a list of qualitative references that studied the identified indicators.

List of indicators	Discerption
Near surface temperature / UHI (UHI) (Meteorological indicator)	Near surface temperature or UHI data is necessary to assess the thermal load of the studied place. The difference in near surface air temperature (2m height) in the urban and the surrounding rural areas is known as canopy UHI. Apart from Roughness length, and urban permeability all the other indicators can be analysed with near surface temperature and UHI
Wind speed, Wind direction and Wind velocity ratio (Wind) (Meteorological indicator)	Lower the wind speed, the higher the UHI intensity. The ratio between the wind speed at the pedestrian level (2m) and a reference point at roof level is described as wind velocity ratio. Apart from Thermal diffusivity, solar reflectance, Building shadow pattern, and solar building exposure, all the other indicators can be analysed with the wind information.
Vegetation (Veg) (Urban planning and urban design indicator)	Compare to natural vegetated surfaces man-made surfaces absorb more heat. The least vegetated surfaces are the hottest due to a reduction in shading, evaporation and evapotranspiration. Grass, bush and trees in an urban setup decreases air pollution, removes carbon dioxide, decreases stormwater run-off, reduce building energy use, improve the outdoor thermal comfort and more.
Thermal diffusivity (TD) (Urban planning and urban design indicator)	Urban materials store heat. Thermal conductivity divided by heat capacity is Known as thermal diffusivity. Higher the thermal diffusivity of the material, the higher the heat storage. Thermal diffusivity value of a particular area can be related to the sky view factor (SVF) and shadow pattern.
Solar reflectance (SR) (Urban planning and urban design indicator)	The urban materials mostly have low albedo value, that absorbs and stores more energy compared to rural materials. The stored energy will get emitted at night, which increases the nocturnal urban temperature. Similar to thermal diffusivity, solar reflectance value of a particular area can be related to the sky view factor (SVF) and shadow pattern.

List of indicators	Discerption
Air pollution (AP) (Urban planning and urban design indicator)	Air pollution decreases the amount of incoming solar radiation reaching the earth surface during the day, and it also increases the amount of longwave infrared radiation emitted by the atmosphere to the earth surface. Air pollution data can be analysed with land use, sky view factor, vegetation data, and building density
Building energy use (BEU) (Urban planning and urban design indicator)	The heat generated by buildings, machinery etc., known as anthropogenic heat, is another factor responsible for UHI formation. Increased energy use, Increases anthropogenic heat. In a dense urban setup, the anthropogenic heat stays longer. Trees around the building provide shade to the building walls and windows that reduces cooling energy needs during summer.
Building Shadow pattern (SP) (Urban planning and urban design indicator)	The shade provided by the surrounding building might affect the building energy needs. Due to shade, building and ground surfaces absorb less heat. It lowers the air and surface temperature (Wong N.H., Tan C.L., 2021). Hence, it has positive benefits towards thermal comfort.
Solar – Building exposure (SBE) (Urban planning and urban design indicator)	The energy demand of the building and the thermal diffusivity of the building material depends on the amount of solar energy it receives. Hence, building facade sun exposure was studied in Agen- France, to solve energy and climatic issues.
Transportation (Trans) (Urban planning and urban design indicator)	Road transportation is one of the reasons for the increase in air pollution and higher anthropogenic heat. Transportation information can be analysed with vegetation, building density, sky view factor and land use.
Thermal comfort (TC) (Urban planning and urban design indicator)	Thermal comfort is a subjective evaluation that expresses human mind satisfaction with the thermal environment (ASHRAE, 2021). Thermal comfort can be related to meteorological variables to understand the influence of the thermal environment on thermal comfort. Thermal comfort can also be analysed with other indicators, such as tree cover and building shadow pattern, to understand the contribution of shade on the thermal comfort levels
Sky view factor (SVF) (Urban planning and urban design indicator)	The sky view factor (SVF) is a three dimensional measurement for the given point in the surface, which explains the visibility of the sky from a particular point (Oke et al., 2017). SVF can be related to thermal diffusivity, solar reflectance and air pollution values.
Canyon aspect ratio (H/W) (Urban planning and urban design indicator)	Canyon aspect ratio is a unit less ratio that describes a two-dimensional cross-section of the street. It is also known as the H/W ratio. Where H is the average height of the building adjacent to the road and W is the width of the road. This is a universal way of describing the building density (Oke et al., 2017). Similar to SVF, the canyon aspect ratio can be related to solar radiation access, thermal diffusivity, solar reflectance, and air pollution dispersion. Apart from this, the H/W ratio can also be related to shade, wind effects, and thermal comfort (Oke et al., 2017).
Building density (BD) (Urban planning and urban design indicator)	Building density, building footprint area divided by site area. Apart from the two meteorological indicators, this indicator can be analysed with building energy use, air pollution, and transportation data.

List of indicators	Discerption
Building Height (BH) (Urban planning and urban design indicator)	The urban precinct experience good ventilation, if there is a good variability in the building height (Badach et al., 2020). Building height is an essential data, since it is required to calculate H/W ratio and SVF.
Roughness length (RL) (Urban planning and urban design indicator)	Roughness length (z0) is a critical indicator that controls the wind turbulence in the city. The intensity of turbulence increases when the z0 is greater (Oke, 1988).
Urban permeability (UP) (Urban planning and urban design indicator)	To improve outdoor natural air ventilation performance, potential air paths should be detected. Urban permeability is calculated to identify the potential air paths in the city (Yuan, Ren and Ng, 2014). It is calculated using three variables, frontal area density, roughness length, and zero plane displacement (Ng and Ren, 2015).
Topography (Topo) (Urban planning and urban design indicator)	In the referred urban climatic map studies, Topography was combined with different other indicators for urban climatic analysis. In Hong Kong, it was combined with Building volume and green spaces to assess the thermal load of the city. The building height information was added with elevation levels, and the same was used to calculate SVF using GIS tools (Chen et al., 2012).
Land use/Building use (LU) (Urban planning and urban design indicator)	The climatic modifications in the urban areas are due to their form and function (Oke et al., 2017). Including the land use or building use information in the urban climatic map will inform the relationship between the urban function and the climatic issue. This indicator can be combined with all the identified indicators for better understanding.



Indicator/ Qualitative research		UHI	Wind	Veg	TD	SR	AP	BMU	SP	SM	Trans	TC	SVF	H/W	BD	BH	RL	UP	Topo	LU
Literature		X	X	X	X	X	X	X			X									X
France Best practices Report	B1			X	X	X	X				X									
	B2			X		X	X	X			X									
	B3			X			X	X			X	X								
	B4		X	X	X	X	X	X	X	X	X									
	B5			X		X	X	X			X									
	B6	X	X	X		X	X				X									
International Case studies	C1	X						X							X	X			X	X
	C2	X	X																	
	C3	X					X													
	C4	X	X									X							X	X
	C5		X	X													X		X	X
	C6																X	X		
	C7	X	X	X											X	X	X	X	X	X
	C8		X									X							X	X
	C9		X	X									X						X	
	C10																			X
	C11		X										X						X	X
	C12		X	X								X		X			X		X	X

France Best Practices Report		International Case studies		
B1 – Paris	B4 – Agen	C1 – Tokyo, Japan	C5 – Ho chi minh city, Vietnam	C9 – Singapore
B2 – Lyon	B5 – Marseille Euromediterranee	C2 – Yokohama, Japan	C6 – Wuhan, China	C10 – Stuttgart, Germany
B3 – Grenoble	B6 – Frontignan	C3 – Beijing, China	C7 – Hong kong	C11 – Arnhem, Netherlands
		C4 – Osaka, Japan	C8 – Hesse, Germany	C12 – Salvador, Brazil

Table 1. List of identified indicators along with their description, relationship between the identified indicators, and list of different referred studies that studied the identified indicators. (Table: Bala 2021)

Phase 2: Generating and prepairing the identified indicators based on available data

The assemblage of different urban elements such as buildings, streets, parks, and gardens creates a distinctive microclimate in an urban block (group of buildings surrounded by roads), and different urban blocks put together became a neighbourhood. This creates a diversified microclimate within the neighbourhood. Above the roof level of the neighbourhood, a distinct boundary layer is created and mixes with the other neighbourhood boundary layers to form an urban boundary layer (Oke et al. 2017). Therefore, an urban block scale analysis would provide sufficient information to the urban planning and design community for mitigating or reducing climatic issues at the local scale. Hence, the urban islet scale was chosen for this research since each islet represents an urban block of the city.

MApUCE project provides urban data at three different scales and climatic data at 250m spatial resolution. Therefore, all the required information has to be transferred to islet polygons. In this phase, different studies were referred to find appropriate GIS tools and methods, to combine and calculate the identified indicators using available data. Some alternatives were also explored to replace certain indicators that do not have any data or are difficult to calculate. It was made sure that all the required information for the analysis are available in the islet polygons.

The 250 m spatial resolution UHI, Wind velocity ratio, and Thermal comfort (UTCI) data of Toulouse, generated under the MApUCE project, was assigned to each islet polygon using the majority function in the “Zonal statistics” QGIS tool. Comparing the three summertime LWTs, nocturnal UHI values of LWT9 and daytime UTCI numbers of LWT 7 are the highest. Hence, these maps were considered for this research.

For Toulouse, the percentage of Base and High vegetation data cover at islet scale are available. Base vegetation data represent grass, and High vegetation data represents bush and trees. This was prepared using a 1.5 m spatial resolution SPOT 6 satellite image. Similar to vegetation, islet scale building density, building height standard deviation, and floor area ratio numbers were also available. Building height standard deviation numbers are considered to analyse the building height variation. The floor area ratio was used as a substitute for the roughness length indicator since it is not suitable for municipal scale analysis. To identify air circulation problematic areas, floor area ratio was used as a substitute for roughness length and sky view factor in Antwerp and Gdansk (Badach et al. 2020).

Building polygons of Toulouse, with building height data, was converted into a 2m resolution raster image and it was used as an input for calculating shadow pattern and SVF. The “Daily shadow pattern” tool available under UMEP, a QGIS Plugin and “Ambient occlusion (sky-view factor)” tool, available under “Terrain shading” QGIS Plugin was used to calculate building shadow pattern and SVF, respectively. The 2m resolution raster outputs were assigned to respective islet polygons using the “Zonal statistics” tool in QGIS. The ADMS Street canyon, an ArcGIS tool developed by CERC (Cambridge Environmental Research consultants ltd), was used to calculate the canyon aspect ratio. The islet polygons were converted into polylines, and they were treated as street centreline input. Therefore, only the buildings adjacent to these lines were considered for calculating the H/W ratio, but not the buildings surrounded by other public spaces within the islets. SVF can be used as a substitute for the H/W ratio, and SVF was calculated for every 2m spatial distance covering all the buildings of Toulouse. Hence, only the SVF was considered for further analysis.

The air pollution spatial data is not available. Hence, High and Low air pollution zones were assumed based on the land use information acquired from the urban atlas. Out of 21 available land use categories, 12100, 1220, and 13100 were classified as high air pollution potential zones. 12100 represents Industrial, commercial, public, military and private lands. 12210 represents fast transit roads and associated lands. 13100 represents mineral extraction and dumpsite. Similarly, building energy use data is also not available. High vegetation cover around each building, within a 15m buffer, was calculated and used as a substitute for building energy use. Trees around the building will reduce the energy demand, the higher the vegetation cover, the lower the energy use and vice versa.

Toulouse is located on a relatively flat plane. Therefore, the topography information of Toulouse was not considered for this research. Apart from topography, thermal diffusivity, solar reflectance, solar building exposure, transport, and urban permeability were also not considered for further analysis due to lack of data availability.

The maps of calculated indicators are presented in Figure 2. Except air pollution and H/W ratio maps, all the other maps are in islet scale.

Phase 3: Understanding the reason behind the uhi formation in Tolouse

To understand the reason behind the climatic issue, it is important to provide information about the relationships between different variables. This helps the urban planners and designers to identify appropriate mitigation strategies. Correlation techniques and statistical regression were generally used to understand the relationship between two variables. One of the well-known statistical regression methods is Ordinary Least Squares (OLS) global regression. But the spatial relationship in this global model is ignored. It is assumed that the relationship between the two variables is constant in the entire study area. Hence, a Geographically Weighted Regression (GWR) analysis was performed using ArcGIS, to identify the indicators responsible for the UHI effects at the islet level, in this research. GWR is a local regression model that has higher explanatory powers. Using GWR, the spatial heterogeneity of the statistical regression can be explored. Different urban climatic studies have acknowledged that GWR provides better results compared to the OLS (Zhao et al. 2010; Zhao et al. 2018; Sun et al. 2019).

Urban geometry, urban surface thermal properties, anthropogenic heat release, low albedo materials, loss of evapotranspiration, air pollution, and wind shelter are the major cause of UHI (Emmanuel and Fernando 2007). The five causes of UHI are reduced evaporation, increased heat storage, increased net radiation, reduced convec-

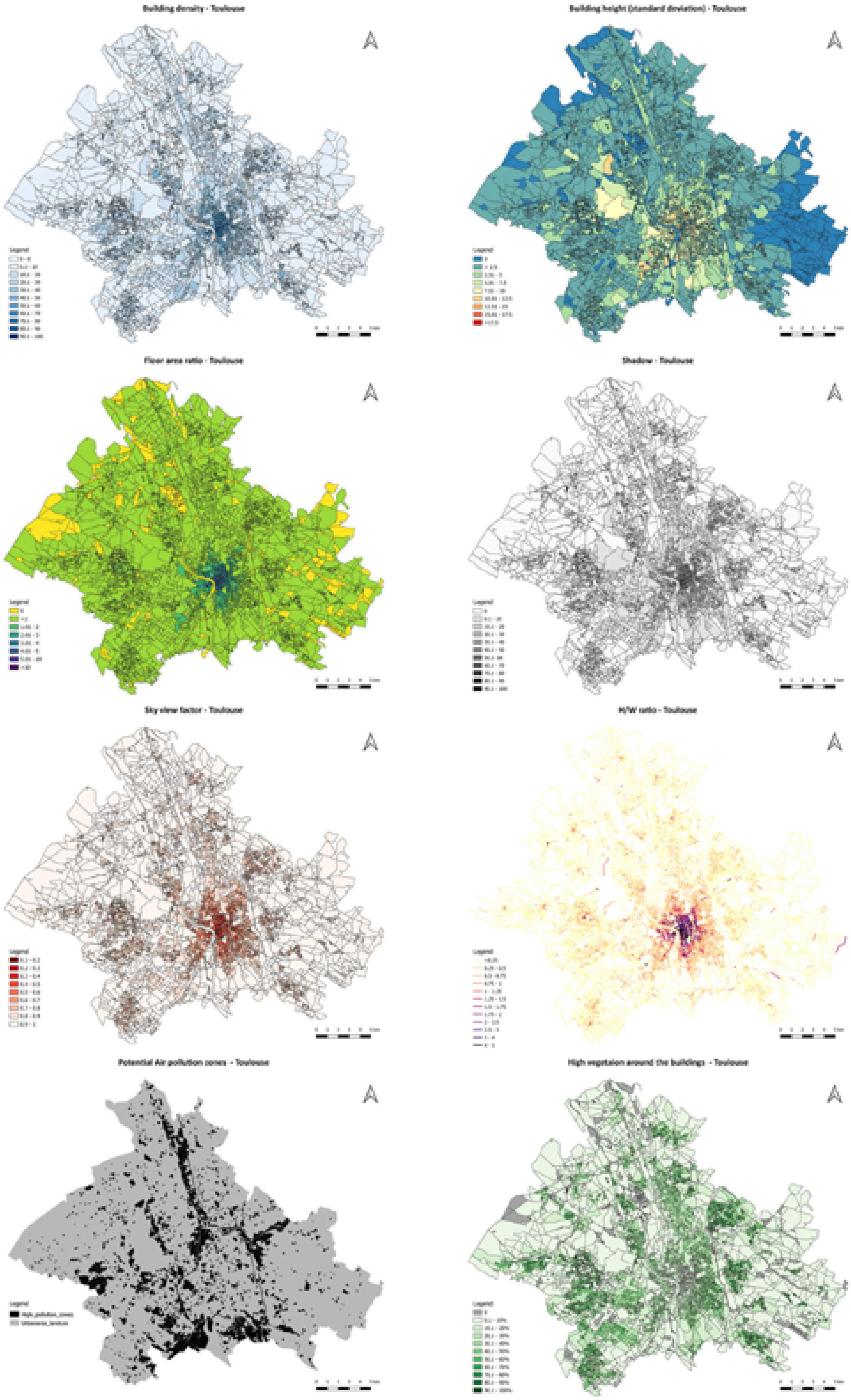


Figure 2. Calculated indicators maps (Figure: Bala 2021)

tion, and increased anthropogenic heat (Gartland 2008). Based on the causes of UHI, the results of the two research phases, and the availability of data, the indicators were arranged into five groups.

Group 1 (Nocturnal UHI):
- UHI (3 to 6h, Local time (LT))
- Wind velocity ratio (3 to 6h, LT)
- Vegetation cover
- SVF
- Building density

Group 2 (Nocturnal wind velocity ratio):
- Wind velocity ratio (3 to 6h, LT)
- High vegetation cover
- Building density
- Building height standard deviation
- Floor area ratio

Group 3 (Thermal comfort):
- UTCI (13 to 16h, LT)
- UHI (13 to 16h, LT)
- Wind speed (13 to 16h, LT)
- Building shadow pattern (13 to 16h, LT)
- High vegetation cover

Group 4 (Building energy):
- UHI (3 to 6h, LT)
- Vegetation cover
- Building density

Group 5 (Air pollution):
- UHI (3 to 6h, LT)
- Land use

Out of five groups, the GWR method was performed in first four groups. Since the air pollution map was generated based on certain assumptions, the GWR was not performed using the group five indicators. Instead, the air pollution map was overlapped on the UHI map, a map generated using UHI data, to understand its contribution to the UHI formation. All the five groups are interlinked and overall trying to understand the reason behind the UHI formation in Toulouse, except group 3. Group 3 is trying to understand the impact of UHI, wind, vegetation, and building geometry on Thermal comfort.

In ArcMap's, the GWR tool can be found inside "Modelling spatial relationship" within "Spatial statistics tools". Toulouse islet shapefile, with all the indicators values in the attributes, was selected as the input feature. The attribute column containing values of nocturnal UHI (3 to 6h_LT), the wind velocity ratio (3 to 6h_LT), and UTCI (13 to 16h_LT), were chosen as dependent variables for analysing group 1 and 4, group 2, and group 3, respectively. Based on the group analysed, the attributes of the listed variables in each group were selected as explanatory variables.

Figure 3 and 4 illustrates the results of this research phase. The R2 value represents the percentage of the relationship between the dependent and the independent variable. The higher the R2 number, the higher the correlation between the dependent and independent variables. In the map, higher R2 islets are marked in a darker colour, and the lesser R2 islets are marked in a lighter colour. Higher the goodness of fit, if the colour is darker. The colour shade and their corresponding R2 values are present in the legends of each map.

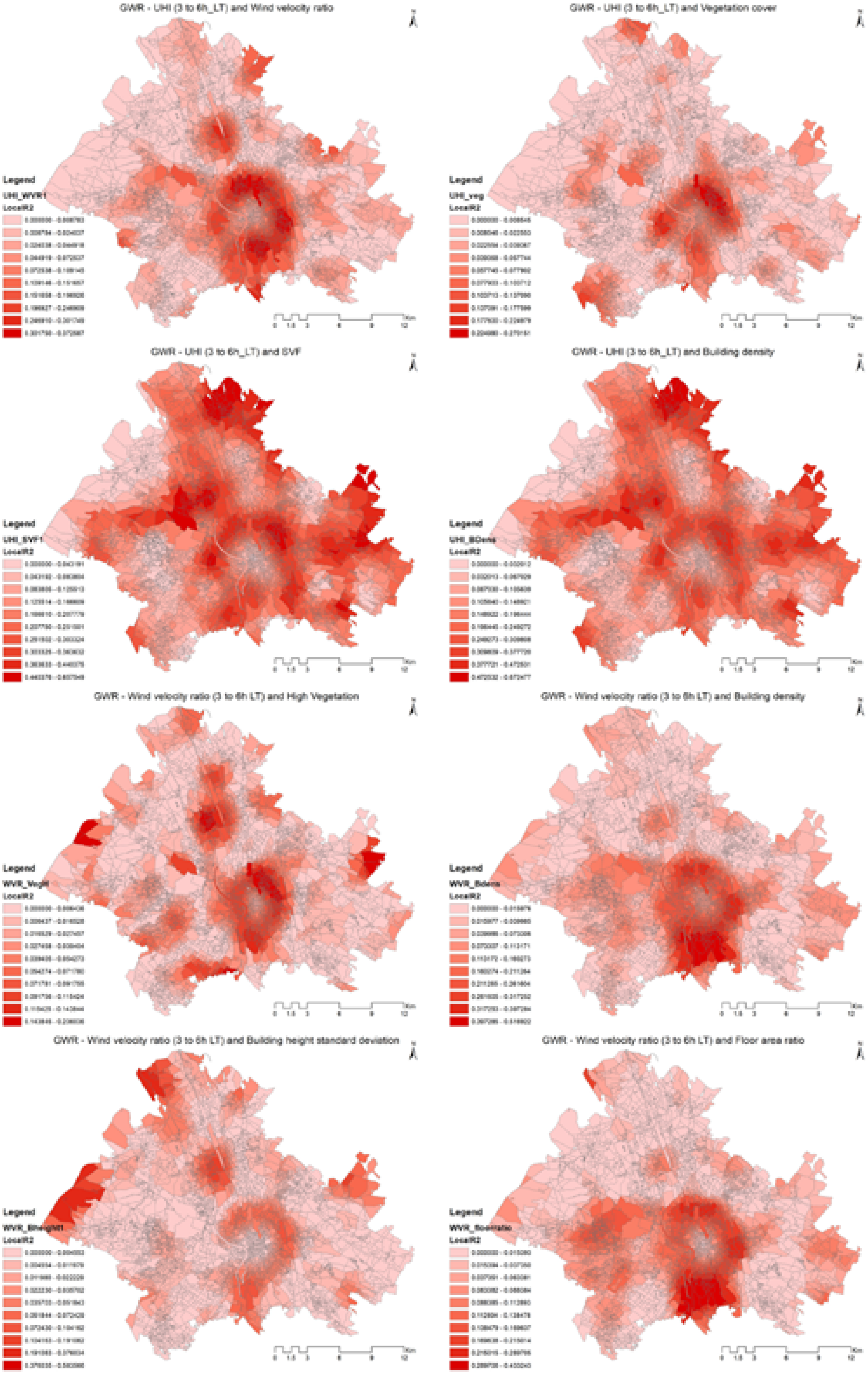


Figure 3. Group 1 and Group 2- GWR analysis results (Figure: Bala 2021)

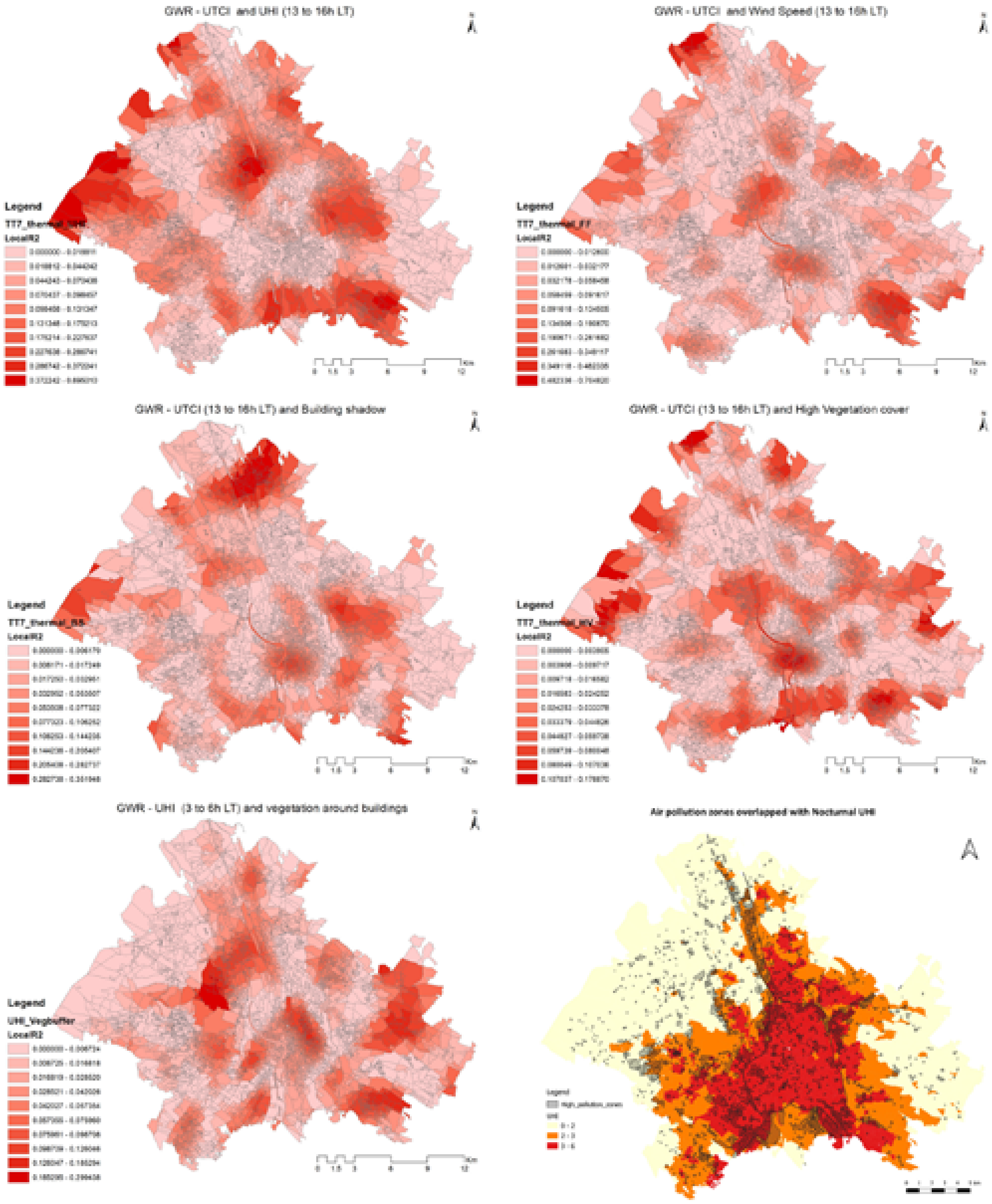


Figure 4. Group 3, Group 4, and Group 5- analysis results (Figure: Bala 2021)

4 Discussion, Limitations and Future Work

Based on the climatic data produce under the MApUCE project, researchers at LISST have already identified that the area around the city centre experiences the most thermal discomfort during summertime. The nocturnal UHI reaches up to 6 degrees Celsius under LWT 9 weather conditions (Hidalgo et al. no date). The wind velocity ratio at this particular zone is very low. Hence, this particular zone was chosen to explain, how the phase three results could be used for urban planning and design decisions.

From the group 1 GWR results, it can be concluded that the urban building geometry has a greater impact on the nocturnal UHI effects since building density and SVF R2 values are greater compared to the other two indicators in the zone around the city centre. However, compared to the other islets in the city, the R2 value of wind velocity ratio is high in the islets within the thermal discomfort zone.

According to the group 2 wind velocity ratio GWR results, the R2 value of building density and floor area ratio is high in the thermal discomfort zone, compared to the other group 2 indicators.

UHI and wind speed have a high R2 value, overall, when analysed against thermal comfort. But Building shadow has the highest R2 value in the thermal discomfort zone, compared to all the group 3 indicators. Only fewer air pollution zones fall within the thermal discomfort zone.

Therefore, it can be concluded that urban building geometry has the highest responsibility for the issue identified around the city centre area. However, some of the identified indicators are not considered in the analysis due to a lack of data. For accurate results, the missing data has to be generated and included in the analysis.

Compare to the other climatic maps produced worldwide, the results obtained through the demonstrated approach answers the two identified research questions by pointing out the urban planning and design elements that are most responsible for the climatic issue at the urban block level. However, the reliability of these results is unknown. Hence, it is essential to devise a method or framework to assess the reliability of these results. Also, a validation of the entire approach is required. Although the thoughts and viewpoints of the target group were considered during the first phase, feedback and comments from them on the usefulness of this approach and results is very important.

5 Conclusion

Overall, this research explored how to generate spatialized urban and climatic information, that can be useful for urban planning and urban design decisions.

This research act as a reference for the urban planning and urban design professionals, who do not have any climatic knowledge but are responsible for the climatic issues in the city. This research is also useful for urban climate professionals, who are trying to convey the urban climatic issues to urban planning and urban design community through cartographic representation.

The first phase of this research provides appropriate climatic knowledge to the urban planning and urban design community by providing information about the urban elements responsible for the modification of atmospheric variables. Using this part of the research as a reference, urban planners and designers can able to make appropriate climate responsive decisions. This phase also informs the urban climatic community about the relevant indicators that should be included in the urban climatic maps to make them useful for urban planning and design communities.

Different GIS tools were identified and explained to calculate the identified indicators in the second phase. This teaches the urban professionals to calculate different indicators without relying on expensive software and tedious traditional calculation techniques.

The third phase of the research demonstrated a method to explain the relationship between the indicators through cartographic representation. This phase results also provide some useful pieces of information to the French urban professionals who are trying to mitigate or reduce the climatic effects in Toulouse.

Acknowledgment

I thank Dr Julia Hidalgo for the internship opportunity at the LISST laboratories, Toulouse. I also thank Najla TOUATI for her timely guidance and advice on the data and GIS application. I am thankful to my two supervisors Prof. Francisco Pérez-Bernal and Dr Craig Thomson, and Dr Rohinton Emmanuel, for their support and guidance.

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SUHER CARTHY, BANU MELIS

11

Translation of Urban Climate Analysis Output Using Chorematic Representation:

Case of French Cities

This research aims to devise a methodology to conduct microclimatic analysis and deliver recommendations for 47 French cities. The approach builds on the chorematic technique that has been recently applied on Toulouse. In this context, the urban climate data of 47 French cities is analysed with a focus on Urban Heat Island (UHI) effect.

To categorise the cities according to their UHI intensities, spatial metrics were employed. These metrics allowed to quantify the spatial form of UHI trends in cities. Based on this input the cities were partitioned via cluster analysis. Four clusters were obtained with different characteristics. Application of the Toulouse chorematic model structure was validated for the other cities regarding their coherence within the cluster. This was followed by the reproduction of the chorematic representation for other clusters, which was demonstrated on the city of Metz as one of the representative cities, through chorematic representation of UHI analysis and recommendations.

The research showed that the clustering method coupled with spatial metrics yielded the desired outcomes for grouping similar cases. It is concluded that this workflow contributes to communicating the urban climatic information of multiple cities to planners through a holistic and time-efficient approach.

1 Introduction

Since the Earth Summit in 1992, as the first large scale organized step towards addressing climate change with UN's initiation (UN 2019), there has been increasing efforts to express and guide action towards climate change at global scale. In an environment of growing concern for climatic issues, researchers have urged for special attention to be directed on cities (Masson et al. 2020). Beginning from Luke Howard's discovery of urban impact on microclimate in the 19th century, Oke's contribution in the 1970s provided a major leap towards understanding urban climate dynamics. In association with Urban Heat Island (UHI) phenomenon the field has received wider attention in research throughout the last decade (Hidalgo et al. 2019). Nevertheless, the climatic aspect of urbanization has many impediments to be conveyed in urban development and planning practices (Ren et al. 2011). The narrow context of climatology in urban planning is explained by the lack of a systematic approach towards the city-planning-climate relationship and extensive climate sensitive design methods (Alcoforado & Matzarakis 2014).

In this regard, among the practices of bridging climatology and planning, maps have been instrumental for communication with decision makers (Hebbert 2014). In relation, urban climate mapping has been applied for this purpose under different forms (Hebbert 2014). As one of the most commonly used type of urban climate mapping practices, Urban Climate Maps (UCMaps) have been adapted to the national contexts of more than 15 countries (Ng & Ren 2015; Ren et al. 2012). UCMaps support the integration of climatic considerations into planning through their Recommendation Map (UC-ReMap) component where propositions for climate-oriented planning are provided (Ren et al. 2011). Following this step, the output needs to be passed on to the planning domain in the form of master plans, zoning and land use plans and related policy documents. Considering the stratified and complex structure of planning processes, simpler representation techniques are sought that are easily communicable and capable of expressing the outcomes of analyses and recommendations in the clearest way possible (Mills et al. 2010; Ren et al. 2011).

Founding on these concerns, different approaches in semiology of graphics and geographic visualisation with a focus on urban microclimatic analyses has been proposed by the research team of the LISST2 in the context of ANR-MApUCE Project3 (Hidalgo et al. 2021; Jegou et al. 2021; Yin et al. 2021). Jégou and colleagues (2021) have explored the potential of the "chorematic scheme" as a form of graphic modelling to translate urban climate output integrated with Urban Climate Analysis Maps (UC-AnMaps) and Recommendation Maps (UC-ReMaps).

Building on this previous research for Toulouse, this paper further explores the potential of genericity of chorematic techniques to support the communication of climatic requirements and simplification of technical input representation for planning and policy making processes. In this context, a methodology is devised to implement the chorematic representation method applied on Toulouse to 47 French cities towards delivering urban climate analysis and recommendations.

2 Background

Chorems (chorèmes in French) were conceptualised by Brunet in 1980 and defined as elementary structures of spatial organisation (Brunet 1980; Brunet 1986). In this regard, they refer to elements that represent complex geospatial situations (Reimer 2010) alongside spatial, temporal and logical relationships (Casanova Enault & Chatel 2017; Reimer 2010). For the scheme of chorems that define a geography with its most significant components through graphic figures, Brunet used the expression, "the alphabet of space" (Dhieb 2020). Thus, this representation is illustrated as a way of communication, in a sense, a language for complex spatial processes. In relation, chorematics (chorématique in French) is an approach that combines geographic modelling with this symbolic language to depict spatial models (Reimer 2010).

Although the chorematic representation method, as a form of graphic modelling, is not widely employed as a visual representation tool, it has been emphasised and utilised by many researchers for its strong potential in geovisualisation. The use of chorems saw a wider application in academy beginning from the mid-90s. It is possible to come across chorematic representations in many different countries and contexts beginning from France where it was originated and used the most. More cases from Brazil, Bolivia, Argentina, Spain, Poland, Saudi Arabia, India, Thailand, Indonesia joined French predecessors in facilitating chorems to represent spatial organisation and spatio-temporal dynamics (Arreghini 1995; Brunet 1986; Dhieb 2020; Laurini et al. 2009; Reimer 2010; Velut 2001).

Several different research from various fields have proven the wide range of application and flexibility of chorematic schemes. Besides the agricultural research where chorematic representation is most commonly employed and coupled with different methods and tools (Houdart et al. 2005; Lardon & Capitaine 2008), applications are observed in the context of professional education (Piveteau & Lardon 2002), natural resource issues (Laurini et al. 2009), restructuring of spatial organisation and dynamics (Ducruet 2006), urban/territorial planning and projection of alternative futures (Casanova Enault & Chatel 2017).

Certain researchers took the method one step further through automation of chorem generation and visual summary production for geodatabases (Reimer 2010). In order to overcome the limitations of manual creation process, these researchers introduced a computational component in the method (Cherni 2019; De Chiara et al. 2011; Del Fatto et al. 2008; Laurini et al. 2009).

The potentials of chorematic representation were recognised by the LISST research team to support the communication of urban climate data for urban professionals. It was presented for use in a pedagogical manner to allow for the representation of highly technical processes to non-specialist users in climatology. Within this framework, the case of Toulouse has been taken through an intensive groundwork up to the process of chorematic representation. The steps followed for the chorematic representation of Toulouse's climatic considerations were based on the structure of UC-Maps. The components of Analysis Map were represented individually to form a combined synthetic model which laid the foundation for recommendations, represented as a separate graphic model. Each chorematic representation termed as a "chorotype" or "chorematic map-model" indicated a component (Jégou et al. 2021). In this context, two separate processes were applied. Combined with wind and topography data, UHI represented the night-time situation and thermal comfort (UTCI) represented the day-time situation in the form of two chorotypes.

The process of graphic modelling was based on H. Théry's modelling structure (Théry 1988). At this stage, the process of representation is highly significant. The pedagogical and communication qualities of the chorematic method is based on the fact that it is constructed and communicated step by step, progressively. To be employed throughout this process, a combination of Brunet and Cheylan's chorems were used for Toulouse case. Following the selection of chorems, a "basic model" was prepared. With the integration of modifiers into the basic model, a "theoretical model" was produced. After the territorial form was applied on the theoretical model, the "final graphic model" was obtained (Jégou et al. 2021).

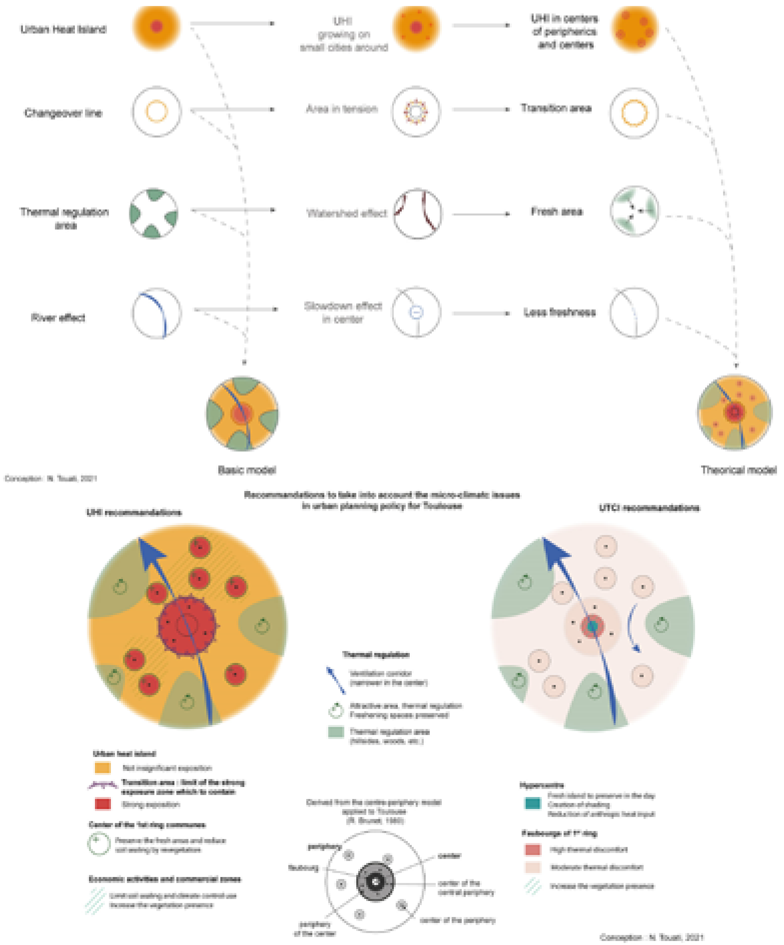


Figure 1. Application of Chorematic Representation on Toulouse (Figure: Suher Carthy 2021)

The initial models were produced with a focus to detect and depict the current nocturnal Urban Heat Island and diurnal heat stress situations. These models emphasised the heat intensity, represented with a hierarchical structure between the core and the surrounding intensities in small cities, propagation and contact fronts created at tension areas, thermal comfort zones, and the river effect (Jégou et al. 2021). On these analyses, recommendations were provided in the form of a graphic model.

The practicality of these models can be observed through the capability of representing not just a static structure but also the dynamics. Building on these dynamics and tendencies, focus areas were detected more easily which led to the proposal of recommendations. The recommendation models for Toulouse helped determine the zones that needed attention for policy making. Through this model, it was shown that the cool island effect during the day required preservation. The boundaries of strong UHI cores were pointed out to be managed by reducing thermal stress through introduction of natural ventilation and intervention in structure orientations. In the surrounding areas of small centres permeabilisation in pavement and vegetation was suggested along with reduction of air conditioning. Finally, attractive zones with cooling effect and ventilation corridors were highlighted for preservation.

As was observed from the work of Jégou and colleagues (2021), through chorematic representation, urban climate considerations were brought to an easily interpretable context. Thus, a supportive step was introduced in delivering the outputs of urban climate mapping to planners and urban policy makers. This approach is taken to a next step through exploration of a methodology to validate this representation technique on 47 French cities as elaborated in the next section.

3 Methodology

The chorematic representation of urban climate analysis is based on the Urban Heat Island (UHI) data for the case of 47 French cities. The scope was determined by the availability of climate data for the cities. Since there was no UTCI indicator available for all of the cities, it could not be included in the context of the research.

The UHI data used in this research was produced by the CNRM4 during the MApUCE Project using the MésoNH-SURFEX atmospheric model. In the MApUCE database, there are two weather situations for each city that were simulated according to the temperature values of a 6-day summer period between the years 2000 and 2009. These weather situations are based on Local Weather Types (LWT) as were formulated by Hidalgo & Jougla (2018) and provided by the LISST. The LWT were defined according to daily values of temperature amplitude, specific humidity, precipitation, wind speed and wind direction (Hidalgo & Jougla 2018; Jougla et al. 2019). For the extent of the cities, Urban Unit boundaries were taken into consideration.

The simulated UHI data include grid points of 250mx250m horizontal resolution for each city that store the 24-hour air temperature (in K) information at 2 meters height. These points provide the urban impact in terms of temperature difference between two scenarios of with and without urban pattern (Kwok et al. 2019).

To represent 47 French cities' microclimatic data through chorematic schemes, the approach was shaped according to how the urban climate trends could be reflected by graphic modelling for multiple cities. Thus, the methodology was founded on collective analysis and interpretation of similar cases based on their microclimatic resemblances from a spatial point of view.

Patch analysis, through employment of spatial metrics, was fundamental to the investigation of UHI intensity trends for cities and to detecting similarities between them. This method allowed to analyse the form and spatial distribution of UHI zones corresponding to the intensity classes. In this context, Urban Units were investigated under 5 UHI Intensity Classes:

- Class 1-Cool Zones: Showing a temperature difference below 0ºC
- Class 2-Negligible Exposure: Showing a temperature difference of 0-2ºC
- Class 3-Significant Exposure: Showing a temperature difference of 2-3ºC
- Class 4-Strong Eposure: Showing a temperature difference of 3-6ºC
- Class 5-Very Strong Eposure: Showing a temperature difference above 6ºC (Only Paris)

The choice of spatial metrics for patch analysis was built on FRAGSTATS metrics (McGarigal & Marks 1994) as provided in ArcMap Patch Analyst (Rempel et al. 2012). Within this framework, dimensions were identified that would lay the foundation for comparison in the next stages:

- **Homogeneity:** the purity of the Urban Unit in terms of its patchy/mosiaced structure;
- **Complexity:** the shape irregularity based on individual patches;
- **Depth:** the breadth of individual patches referring to the dimensions of patch shape;
- **Fragmentation & Isolation:** the extent of dispersity of patches among classes.

In order to detect typologies according to cities' UHI intensity trends, cluster analysis was determined as the optimal method. After testing with several tools and statistical methods the Partitioning Around Medoids – PAM algorithm was selected for the clustering to be based around real observations. The partitioning was applied on R through {factoextra} package (Kassambara 2017).

At the analysis stage, which was executed iteratively, Paris was removed from the clustering as it could not be clustered with any other city and its observation point appeared much more remote from the rest during the visualisation of clusters. Thus, the number of cases was decreased to 46. It was concluded that Paris should be represented through a separate review process considering its peculiarities. Following the partitioning of the 46 cities, clusters were examined in terms of the UHI intensity trends they show. They were compared with their medoid cities in relation to the footprint of UHI intensity classes on reclassified raster datasets and the patch analysis tables. Based on the clusters formed at the Cluster Analysis stage, chorematic elements were suggested according to the characteristics they show. This step went hand in hand with the validation of Toulouse model for other cities. At this step, the group that Toulouse was clustered in was reviewed together with Toulouse's chorematic model. In the light of the outcomes achieved in the validation step, suggestions on chorematic representation were provided for other clusters. For graphic modelling, the clusters that were showing strong UHI intensities were given priority.

4 Results

The Cluster Analysis yielded four clusters around the medoid cities of Orléans, Lorient, Metz and Toulon (Figure 2).

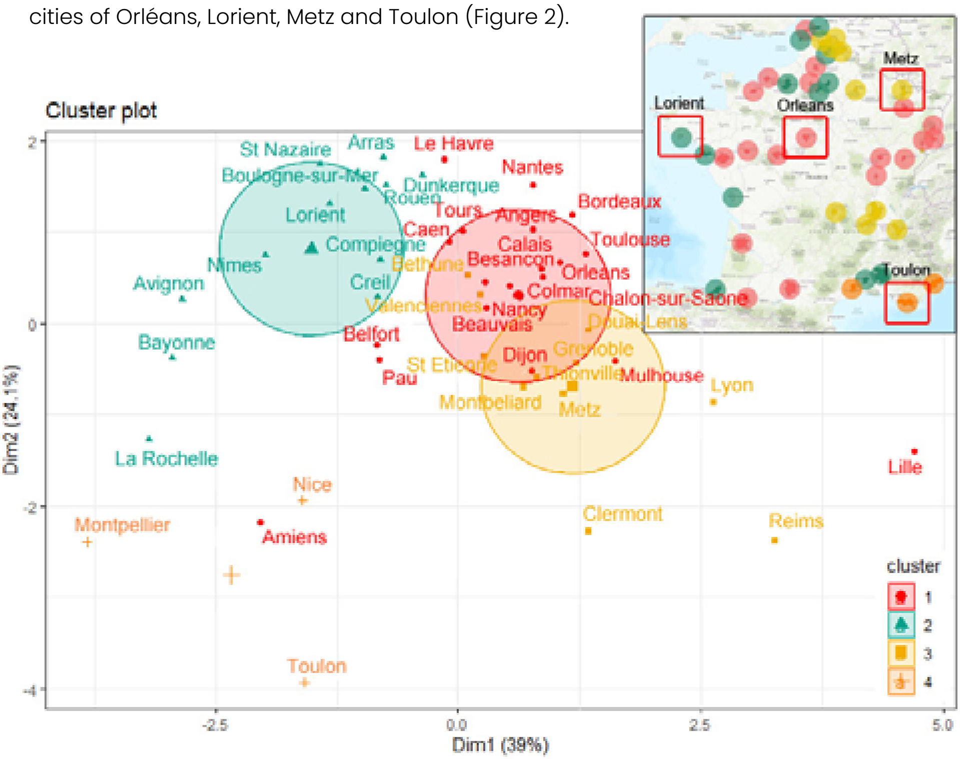


Figure 2. Cluster Analysis Plot and the Distribution of Cities in the Map (Figure: Suher Carthy 2021)

When the general distribution of the clusters and their features were analysed together with the UHI maps of urban units, it was observed that the partitioning satisfied the expectations to classify similar cases in associated clusters. Depending on the UHI intensity features they showed, the clusters were categorised according to their main characteristics:

- Cluster 1-Concentrated High Intensity
- Cluster 2-Limited Intensity
- Cluster 3-Dispersed High Intensity
- Cluster 4-Dispersed Cool Zones

The dimensions of clusters were compared with a focus on high intensity classes (strong and significant exposures) (Figure 3). It was shown that Cluster 1 had the highest depth features with high complexity and homogeneity values. Showing similarities in shape complexity with Cluster 3, the main distinction between Clusters 1 and 3 seemed to be the difference in fragmentation which was significantly lower for Cluster 1. This also showed in the values of homogeneity and depth. Meanwhile, Clusters 2 and 4 had similarities with a clear distinction in homogeneity where Cluster 4 was far more patchy with a wide distribution of cool zones within the Urban Unit.

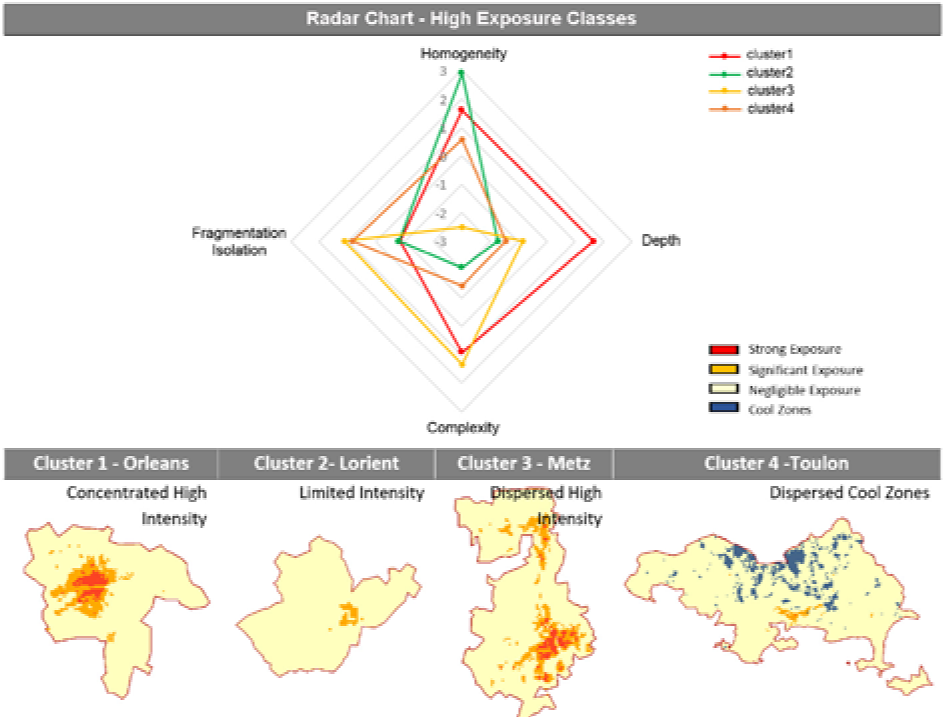
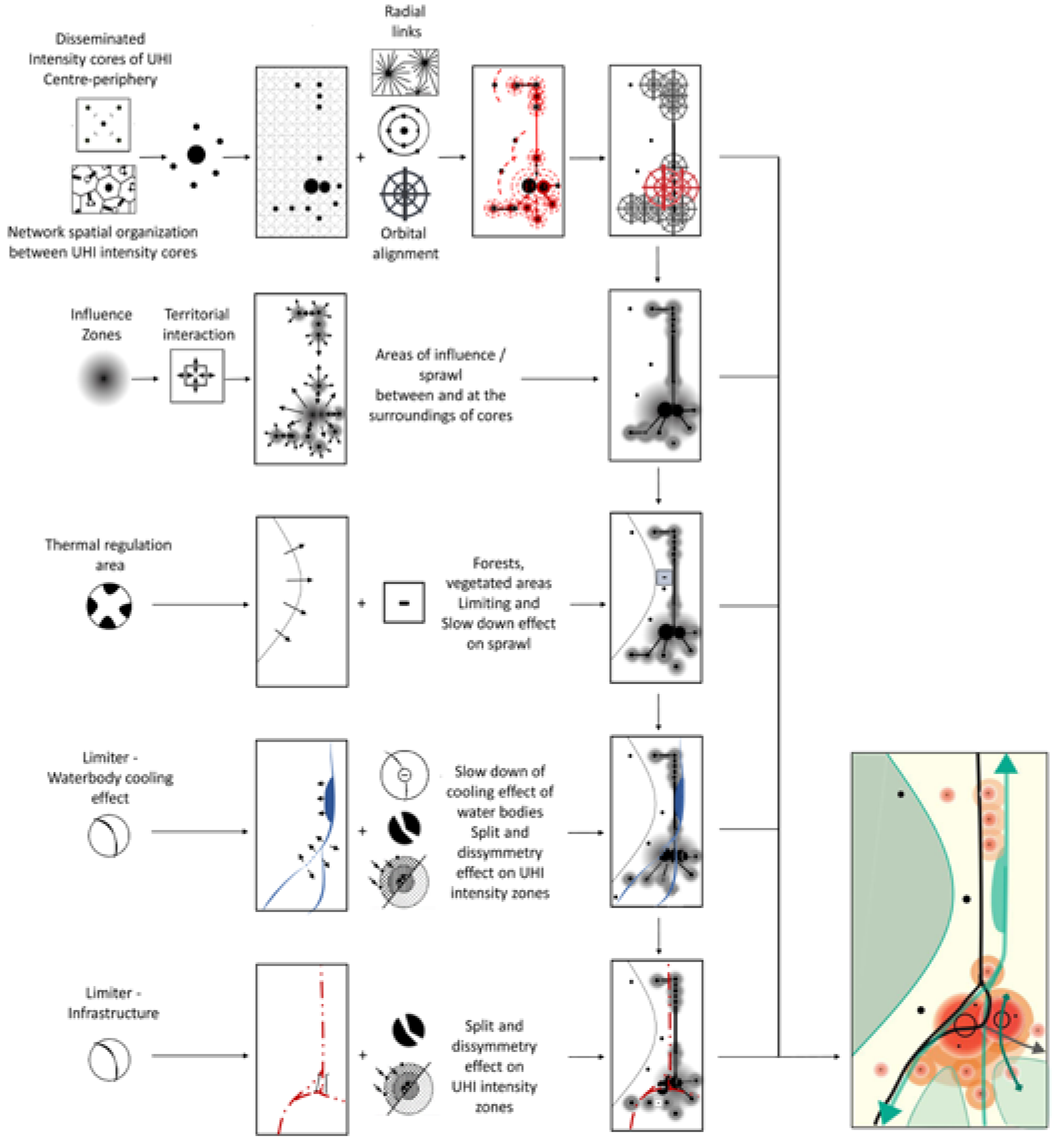


Figure 3. Radar Chart of High Exposure Classes for Clusters and UHI Maps of Medoid Cities
(Figure: Suher Carthy 2021)

For the representation of Toulouse, four elements were used by Jégou and colleagues to form the basic structure. Next, modifier elements were introduced that had a transforming effect as dynamic processes. Hereby, surrounding town centres emerged as UHI attraction nodes in peripheries. Areas in tension, as contact areas of different UHI intensities, formed the transition areas. Watershed effect added on thermal regulation areas constituted the fresh zones. With the influence of topography and the city centre, the river effect underwent a slowdown. In the end, the derived structures combined formed the theoretical model for Toulouse (Jégou et al. 2021).

Regarding the Touluse graphic model, Cluster 1 with Concentrated High Intensity was investigated to decide on the suitability of the suggested chorems and the structure. The most straightforward way for it was to make a qualitative judgement over spatial patterns of UHI in combination with specific geographical characteristics. One of the most definitive aspects was the composition of strong UHI intensity concentrated at the core. In relation, a hierarchical structure of centre-periphery was sought. The second critical aspect was the river effect formed by a water body passing through the city. Thus, Orléans as the representative city of Cluster 1 was checked for these two conditions. Considering the coherence of the cases in Cluster 1 in terms of UHI intensity characteristics, the use of Toulouse model and chorems were validated for application on the rest of the cluster.



Conception: M. Suher-Carthy, 2021

Figure 4. Choreматic Representation of Metz UHI Analysis (Figure: Suher Carthy 2021)

To reproduce the chorematic representation on other clusters, Cluster 3 with Dispersed High Intensity was given priority regarding the criticality of the UHI intensity trends it showed. In this context, a graphic model was produced for the medoid city, Metz, as the representative case of the cluster (Figure 4). Regarding higher complexities in the cases, additional chorems were suggested complementary to the ones used for Cluster 1 combining Brunet (1986), Casanova-Enault & Chatel (2017), Cheylan's (2007) chroems. Spatial configuration of the high intensities was represented by territorial interactions in the form of radial connections and orbital alignments. Following the interaction between nodes the tendency to sprawl and unite around the intensity cores was depicted through influence zones. Thermal regulation areas were illustrated with their limiting impact on the sprawl of the intensity in the western and eastern parts of the Urban Unit. This was also represented with a slowdown in the connection of influence zones between the core and the satellite centers in the north. Finally, while perturbing the UHI intensity at the cores, water bodies' cooling effect slowed down with the density of activities and development in the urban core. As a result of the combination of these transforming effects with the basic model, the theoretical model of Metz was obtained. This theoretical model was defining for the propositions provided for the management of UHI effect in the city and to reduce its severity.

Based on the theoretical model, certain focus areas were emphasised to decrease the impact of UHI intensity within Metz. Recommendations were proposed in the scheme of a graphic model with the use of previously employed chorematic elements (Figure 5).

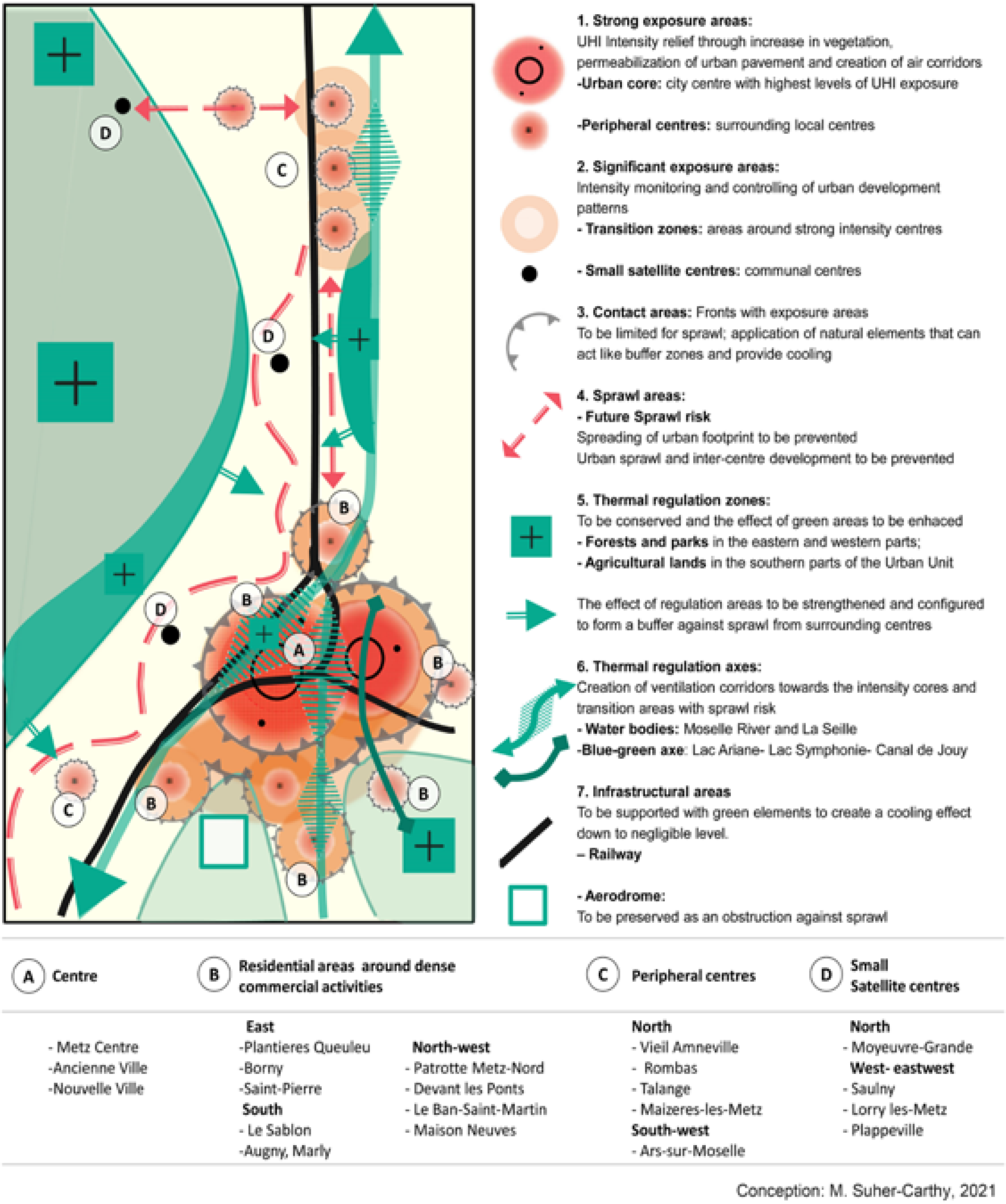
In this context, the focus areas are defined as:

1. **Strong exposure areas**, the most critical areas that show high UHI intensity require measures to support the reduction of UHI impact. These are mostly residential areas concentrated around commercial activities at the core and peripheral centres. Considering the already built structure, complementary policies on increasing vegetation through the introduction of green areas, permeabilisation of urban pavement and providing ventilation corridors where possible are crucial.

2. **Significant exposure areas**, found as transition zones surrounding the strong exposure areas, show considerable but lower UHI intensity. They require intensity monitoring alongside urban development tendencies.

3. **Contact areas**, surrounding the core and circumscribing significant exposure areas, require controlling for sprawl towards the eastern part of the urban core.

4. **Sprawl areas**, the connection zones between high exposure zones and centres, to be considered for UHI intensity prevention through avoiding the sprawl of strong exposures in the area. Vegetated areas are proposed that can act as obstructions or buffer zones for potential sprawl areas.



1. Strong exposure areas:
UHI Intensity relief through increase in vegetation, permeabilization of urban pavement and creation of air corridors
-Urban core: city centre with highest levels of UHI exposure

-Peripheral centres: surrounding local centres

2. Significant exposure areas:
Intensity monitoring and controlling of urban development patterns
- Transition zones: areas around strong intensity centres

- Small satellite centres: communal centres

3. Contact areas: Fronts with exposure areas
To be limited for sprawl; application of natural elements that can act like buffer zones and provide cooling

4. Sprawl areas:
- Future Sprawl risk
Spreading of urban footprint to be prevented
Urban sprawl and inter-centre development to be prevented

5. Thermal regulation zones:
To be conserved and the effect of green areas to be enhaced
- Forests and parks in the eastern and western parts;
- Agricultural lands in the southern parts of the Urban Unit

The effect of regulation areas to be strengthened and configured to form a buffer against sprawl from surrounding centres

6. Thermal regulation axes:
Creation of ventilation corridors towards the intensity cores and transition areas with sprawl risk
- Water bodies: Moselle River and La Seille
-Blue-green axe: Lac Ariane- Lac Symphonie- Canal de Jouy

7. Infrastructural areas
To be supported with green elements to create a cooling effect down to negligible level.
– Railway

- Aerodrome:
To be preserved as an obstruction against sprawl

(A) **Centre**	(B) **Residential areas around dense commercial activities**		(C) **Peripheral centres**	(D) **Small Satellite centres**
	East		**North**	**North**
- Metz Centre	-Plantieres Queuleu	**North-west**	- Vieil Amneville	- Moyeuvre-Grande
-Ancienne Ville	-Borny	- Patrotte Metz-Nord	- Rombas	**West- eastwest**
-Nouvelle Ville	-Saint-Pierre	- Devant les Ponts	- Talange	- Saulny
	South	- Le Ban-Saint-Martin	- Maizeres-les-Metz	- Lorry les-Metz
	- Le Sablon	- Maison Neuves	**South-west**	- Plappeville
	-Augny, Marly		- Ars-sur-Moselle	

Conception: M. Suher-Carthy, 2021

Figure 5. Chorematic Representation of Metz UHI Recommendations (Figure: Suher Carthy 2021)

5. **Thermal regulation zones**, formed by the natural and vegetated areas ought to be conserved. In association with the measures proposed for peripheral centres, the effect of forests and parks is recommended to be enhanced at the west and east. The agricultural lands in the south that create an obstruction against urban development should be preserved to prevent the UHI effect from spreading.

6. **Thermal regulation axes**, formed through the water bodies that interrupt the strong exposure zones. These axes are recommended to be enhanced especially at the urban core and high exposure locations that could penetrate the concentrated intensity areas.

7. **Infrastructural areas**, the railway footprint that disrupts the strong exposure to be turned into an advantage through the addition of green elements and to create a cooling effect. This will also be influential for the side of the railways showing strong exposure.

5 Conclusions and Discussion

With this research it was aimed to devise a methodology to conduct microclimatic analysis and deliver recommendations for 47 French cities. According to the research results, the clustering method paired with spatial metrics served the chorematic representation requirements efficiently. Through the partitioning of the cities, it was first ensured that cases with critical UHI intensity levels were separated from the rest. Following this step, they were grouped according to the spatial characteristics and patterns of UHI intensity classes. This allowed to refine the steps towards obtaining the microclimatic information of multiple cases which is one of the main implications of this research. The other major implication is the introduction of the practicality offered by the chorematic representation method for the communication of urban climate information. This functionality was assessed over two steps; validation of the Toulouse graphical model on Cluster 1 with Concentrated High Intensity and the reproduction of chorematic representation for Cluster 3 with Dispersed High Intensity. Alongside the elements used for the Toulouse model, supportive chorematic elements were added to meet the peculiarities of Cluster 3. The representation of the medoid city - Metz showed that, besides the practicality offered by the pre-determined chorems, clusters with complex cases are more likely to require further focus on individual cases while applying the medoid model to the rest of the cluster.

Apart from the support chorematic map-models provide for the transfer of microclimatic analysis and recommendations to planners, certain points need attention for future applications. Regarding the data availability, the UHI analysis was based on the SURFEX simulation model output. When using simulation data for analyses, there is the risk of not being able to accurately represent the real situation and to amplify inaccuracies and errors in calculations. Although data validation was conducted through expert views in this research, application with real data or comparing the results with real data will improve accuracy for future applications.

In relation to spatial pattern and form analysis, FRAGSTATS metrics were used for partitioning of the cities. Since the indicators were applied to each of the four different UHI intensity classes one by one, this increased the number of variables, thus the dimensionality in statistical terms. A way to improve this aspect can be to formulate specialised calculations for indicators where the relationship between the intensity classes is reflected. This will avoid treating each UHI intensity class as seperate variables and allow the addition of more parameters for the clustering.

Considering the chorematic representation step, although clustering provides practicality for the handling of multiple cases, during the graphic modelling of each city, cases should be considered critically along with complementary information. Especially for clusters with high complexity, incorporation of land use, density, wind, and other influential factors into the modelling will provide an integrated approach for representing the climate data of cities.

The method of chorematic representation as a form of graphic modelling has been applied in several different fields in research that include geovisualisation. Jégou and colleagues' work showed that it could additionally serve as a practical method to provide urban climate information into planning context. Through representation of highly technical climatological situations in simpler forms, graphic models offer a significant step in bridging climatology and planning. The flexibility of these models allows for application in various levels and contexts through coupling with different research methods. In this regard, this research aimed to take the chorematic representation technique one step further to devise a methodology for its application in a collective and time efficient manner. At a time of need for urgent climate action, it shows great potential to speed up the processes of strategy making and putting policies into execution. Nevertheless, this research showed that human input and the artistic interpretation is still needed complementary to the collective analysis. For future developments in the field of geovisualisation, the automated generation of chorems can be explored further to expedite the timely production of easily interpretable urban climate information. The achievements in this field will extensively support enabling communication between climatology and urban planning.

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SIMATH, SHIFANA

12

Towards climate embedded local planning in Sri Lanka to mitigate overheating

The Case of Colombo

Sri Lanka has attracted a range of investments since the aftermath of a civil war. Colombo, the capital city, is undergoing an unprecedented development phase which could permanently alter its land cover and thus contribute to urban overheating. This can have severe consequences on human health and the environment. The planning and building regulations of Colombo did not seem to capture this imminent threat despite the availability of proven urban warming mitigation strategies in the literature. The study takes a pragmatic approach in identifying the barriers and opportunities of implementing urban climate (UC) action through expert knowledge and judgement.

The thermal comfort (UTCI) was calculated and mapped for the metadata obtained from 20 stations throughout Sri Lanka for the past 25 years, and a strong trend towards extreme heat stress was identified in Colombo. This, along with simulations of thermal comfort for a typical street in Colombo on a maximum buildable configuration, were included as aiding materials to probe rich insight from professionals during in-depth interviews. A thematic analysis of the interviews suggests the following as key challenges – lack of continuity of climate initiatives despite socio-political changes, lack of guided local research for UC, fragmented planning institutions, the attitude of authorities and public, political interferences and integration of climate policy initiatives in a third world country which face other socio-economic challenges.

Based on the above, the study suggests a practical course of actions that can be developed as a framework for the successful integration of UC actions in the planning context.

1 Introduction

“Urbanization can influence climate change at local and regional levels” (Cao et al. 2016). The increasing population and the subsequent urban development induce a complex change in the natural environment, and disasters in urban areas such as floods, pollution, UHI etc. are more evident (Srivastava 2021). The ambient temperature of cities is generally known to be higher than that of surrounding suburban and rural areas, which is well known as the Urban heat island effect (UHI) and is a well-documented issue (Oke 1973; Emmanuel & Fernando 2007; Emmanuel 2011; Rosenfeld et al. 1995). This, coupled with the increasing global temperatures and extreme weather events such as heatwaves, results in an urban overheating risk.

This is one of the serious problems that pose risks on human health, for instance, around 70,000 deaths in Europe were related to a major heatwave in 2003 (Stedman 2004; Bhattacharya 2003), and severe acute respiratory syndrome (SARS) was identified due to urban air stagnation in Hong Kong (Ng 2009).

Lack of climate-responsive planning and haphazard development were identified as one of the main contributors to the above mentioned environmental and health ill effects. Thus, manipulating the ‘urban form’ in cities through planning and regulation to mitigate and adapting to the climate is fundamental (Mills et al. 2010), especially in rapidly developing cities. South Asian countries, specifically Sri Lanka, are growing at a rapid phase, due to the global economic competition and its strategic geographic location, which has resulted in enormous development pressure.

Most of the developments in Colombo, are driven by socio-economic, marketing, demand for floor area etc. and is perceived as a real estate bubble. These developments often neglect which impacts the urban climate, mainly urban warming trends, which could lead to severe health and environmental hazards. Further, Colombo experiences more hotter days throughout the year, and this increases the risk of overheating due to unregulated development. Thus, there is an urgent need to capture climate-responsive actions in the local planning system.

2 Background

Heatwaves (HW) are prolonged periods of extreme temperatures (Lee & Painter 2015) which have caused devastating effects and killed many lives all around the world. **The Urban Heat Island** is the existence of “higher temperatures in urban areas than the surrounding rural areas” (Oke 1973). It can be worse in the tropics, where the temperatures are high throughout the year and have serious implications on health and air quality. UHI and HWs can couple to create severe thermal distress due to unplanned urbanization, especially in the rapidly developing South Asian region. These adverse effects have not been adequately researched in the South Asian region (Kotharkar & Ghosh 2021).

Thermal comfort can be described as the physiological interval within which a human can operate or tolerate the environment (Lee et al. 2014) and can vary amongst people even in the same environment (Nikolopoulou 2011). In warmer climates, indoor thermal comfort is achieved mainly through air conditioning but at the expense of releasing waste heat to the environment.

2.1 Climate sensitive design strategies to improve urban climate

2.1.1 Climate sensitive planning

Climate knowledge is usually translated into adaptive strategies (to cope with the change) and mitigative strategies (to limit the ill effects). However, apart from mainstream air quality management guidelines, there is a gap in integrating climate knowledge into planning, one of the reasons being the difficulty of translating complex climate knowledge into policy (Emmanuel 2016).

Every city has its own political, physical, and socio-economic characteristics that should be incorporated when analysing and forming climate policies. No single approach or single sector can deal with climate change. A global survey (2014 MIT – ICLEI), which included 350 cities in the study, identified the key challenges on the urban governance of climate change as - lack of funding; completing priorities – health, housing, economic growth; integrating climate mitigation and adaptation into existing departments and functions; lack of leadership from mayors, officials, and representatives of the governments; diversity and fragmentation of the existing knowledge in climate (Alexander 2014). Ryan (2015) suggests that when assessing climate policy integration, one can easily fall into the "everything matters" trap and thus recommends scrutinizing the problem through local framing of the problem.

2.1.2 Sri Lankan Context

Sri Lanka is an island that lies near the equator, where the solar altitude is high throughout the year and has no seasonal changes except the monsoonal variation. The climate is usually hot and humid. Recent studies indicate the need for awareness on temperature rise and overheating (Lu et al. 2020). Studies on trends analysis of meteorological data indicate that atmospheric temperature increases gradually throughout the country and the warming trends have become faster (Basnayake 2007; Ministry of Mahaweli Development and Environment 2016).

As to manage this warming trend, incorporating climate embedded local planning is essential. The current planning regime of Colombo Sri Lanka is not yet addressed to mitigate the urban climate issues (Perera & Emmanuel 2018).

Urban Development Authority (UDA) is the existing governing body in Colombo which regulates many planning policies. The building regulations which are effective now (2008 Amended version) were reviewed and realized that only a few regulations indirectly contribute to regulating the urban climate (Eg: density control or FAR limit positively or negatively affect the wind flow). However, no conscious effort has been made in incorporating design strategies and climate knowledge into the existing system.

Regardless of the reality of an imminent overheating threat, and despite recommendations of scholars on effective Urban Climate mitigative actions, the planning and building regulations of Colombo haven't captured any of these. 'How' to incorporate these strategies in planning has not been adequately explored in the tropics, especially Colombo. It is very easy for one to fall into the "everything matters" trap when integrating climate policies. Thus, this should be investigated thoroughly, with a focus on the local socio-economic context.

3 Methodology

The ontology of this study is that reality is constantly negotiable and based on the practical outcomes of concepts or ideas. Thus, the research is scrutinized through a lens of pragmatism and aims at the practicality, i.e., "what works", rather than the ideal notion of what is considered "true" or "real" (Frey 2018).

Epistemologically, the study is positioned towards a pragmatic interpretivist approach – the aim is to understand the socially constructed policy through in-depth interaction of the researcher and subject, but through quantified results, which acts as probes and aiding material to gain rich insights.

Thus, the research question was approached with an aim to understand the underlying challenges and barriers and thus contribute to a practical solution in integrating them. The solution relies on Professional experience as "evidence" (data) using thematic analysis (qualitative analysis) to identify the flaw or gap in integration.

To understand the reality of the threat of overheating in Sri Lanka, the overheating issue was quantified, and it also aids in exhorting the timely requirement of incorporating UC actions in planning. For this, historic metadata from 20 stations from the Department of Meteorology - Colombo in Sri Lanka for the period of 1996-2020. The monthly maximum and minimum temperature, relative humidity (RH) and wind speed for the past 25 years were collected for analysis. To analyse the data, maximum temperature, and minimum RH was considered for the hottest month trend and minimum temperature and maximum RH was considered for the coldest month trend. The data set was evaluated and found out that 15 stations out of 20 reflected that the hottest month was April. Similarly, the coldest month in 17 stations of 20 was January.

For the analysis, "Rayman Pro" software was used as it is known to deliver decent simulation outcomes for radiation flux densities and thermo-physiologically significant assessment indices (Matzarakis et al. 2010). The thermal indices considered for the study is UTCI (Universal Thermal Comfort Indices), since it is considered one of the comprehensive indices for calculating heat stress in outdoor environments (Blazejczyk 1994; Zare et al. 2018) and even the slightest variations in the intensity of weather stimuli are captured (Blazejczyk et al. 2012).

To understand the performance of design strategies identified in literature, a typical street in Colombo was considered, and the thermal comfort levels were simulated in this along with an ideal situation where the street is maximum built as per the existing planning regulations governed by FAR, plot coverage etc. Four scenarios (modified from the base model) were modelled with 6m road width and aiming at a maximum development potential (max FAR) for a 400 sqm plot. Aspect ratio, incorporation of trees, albedo and street orientations were defined for RayMan simulations as defined by Table 1.

To understand the barriers and opportunities, semi-structured interviews were chosen due to the nature of the in-depth inquiry that explores subjective viewpoints and at the same time allow new ideas. Since the study focused on rich insights, the selection of appropriate interviewees was important. Thus, five experienced professionals who have contributed to shaping the planning landscape of the built environment, for at least more than 15 years were selected for the interviews. Of them, two were academics who have been involved in climate planning research, two were successful practitioners influencing the built landscape through investor relationships and project approvals, and one was a director of a regulatory body who was also an academic. The structure of interviews consisted of open-ended questions investigating the current planning context of Sri Lanka and the opportunities to integrate UC actions into it.

The interviews were recorded, transcribed and a thematic analysis was conducted with the aid of NVIVO-12 Pro software. The thematic analysis followed six-phase methods outlined in Braun and Clarke (2006) as cited in Braun and Clarke (2012), that allows meaningful insights to emerge through a repeated enquiry into the data, codes, and themes.

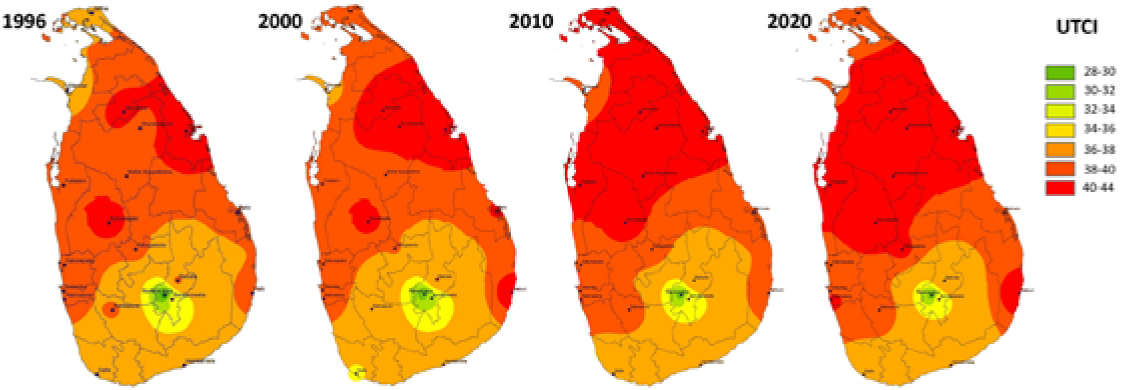
4 Results

4.1 Thermal Comfort Trend in Sri Lanka

UTCI was calculated for all 20 stations in Sri Lanka in 1996-2020 for the hottest month (April) and the coolest month (January). The thermal comfort trend is presented in figure 1.

The hottest month (April) trend indicates a clear trend towards extreme heat stress in almost all the stations, except the central part of the country. Especially the entire Northern and Eastern region shows ***very strong heat stress*** between 40-44ºC. Further, the Western region (Colombo, Ratmalana), which was under ***moderate heat stress***, also range under ***very strong heat stress*** in 2020. Moderate heat stress was observed in the south despite high air temperature (Ta) in the met data. This could be explained by high wind speed compared to other regions.

Thermal Comfort trend for the hottest month (April)



Thermal Comfort trend for the coldest month (January)

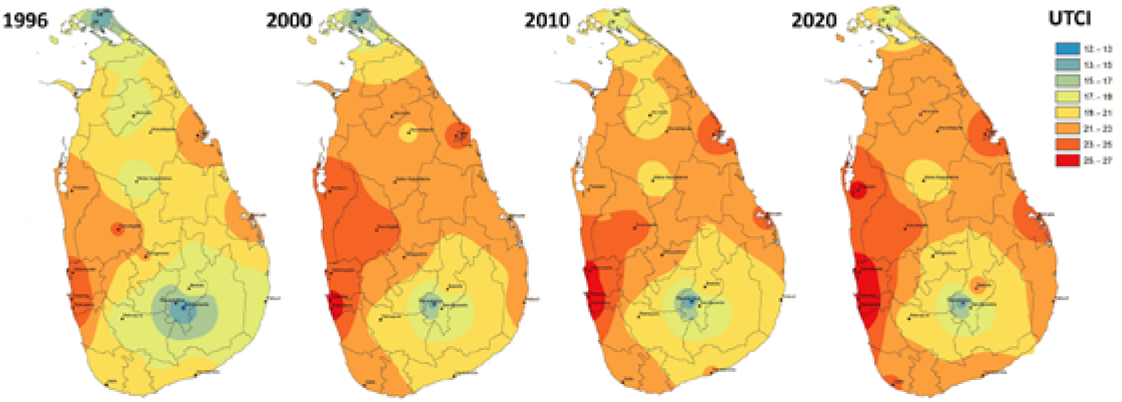


Figure 1. Thermal Comfort Trends- Hottest month (April)& Coolest month (January) (Figure: Simath 2021)

In the year 1996, only three stations ranged between 40-44°C. But in the year 2020, half of the stations range in ***very strong heat stress*** and the entire country has passed the threshold of thermal comfort.

The coolest month (January) trend suggest that the whole island is getting warmer throughout the years, with only the central part of Sri Lanka remaining at the 18°C range. In 1996, almost the entire country ranged between 11-25°C, which depicts ***no thermal stress***. Northern and Central regions vary between 12-15°C. However, in 2020, the western region is moving to ***moderate heat stress***. The rest of the country is also hovering towards the upper ranges of thermal comfort.

A reason for this shift in both instances could be interpreted as the land-use land-cover changes during the last 30 years in the Colombo Metro-Region (Emmanuel 2004) due to urbanization. The urbanization rate in 2020 is 18.71% (Statista 2020), and from 2001-2019 Sri Lanka lost 28.7% of its tree cover (Global Forest Watch 2020). Hence, the need for timely climate sensitive planning and design strategies to mitigate urban overheating issues is vital.

4.2 Design strategies application with RayMan

To identify the effectiveness of design strategies discussed above, a base-case and four other scenarios of a typical street in Colombo were simulated in RayMan and the thermal comfort was calculated using UTCI. The developed scenarios were based on the existing UDA regulations (FAR, Plot coverage etc.). The street sections, RayMan model and SVF for developed scenarios are demonstrated in Table 1.

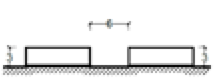
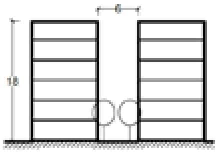
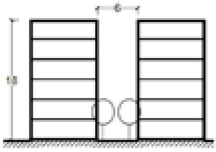
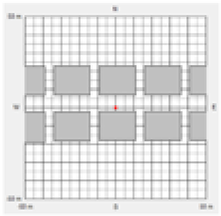
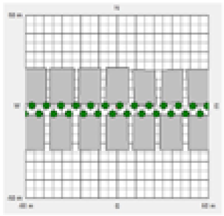
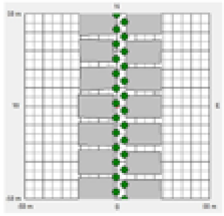
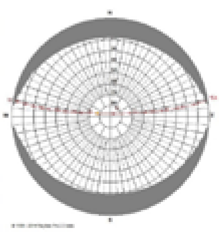
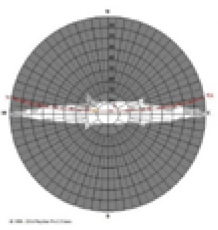
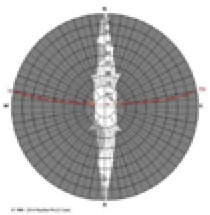
	Base case ●	**Scenario 1& 3** **EW street** ■ ▲	**Scenario 2& 4** **NS street** ☒ ▲
Section	**AR: 0.5** 	**AR: 3** 	**AR: 3** 
RayMan model			
Sky view factor	**SVF=0.87** 	**SVF=0.201** 	**SVF=0.199** 

Table 1. RayMan simulation for different scenarios (Table: Simath 2021)

Figure 2 presents the UTCI comparison between different scenarios. UTCI values on the hottest day can be explained due to high temperature, high RH and relatively low wind speed. The base case scenario obtained the maximum values of UTCI between 38-40 °C, which shows very strong heat stress. And other scenarios followed the same pattern over the years but showed a slight improvement; Sc1 & Sc2 ranges between 37-38 °C and Sc3 & Sc4 ranges between 35-36°C till the year 2013, which belong to strong heat stress conditions. However, after 2013, a significant increasing trend was observed, which again leads to very strong heat stress. It should be noted that a moving average is used to smooth out the irregularities and to recognize the trends easily.

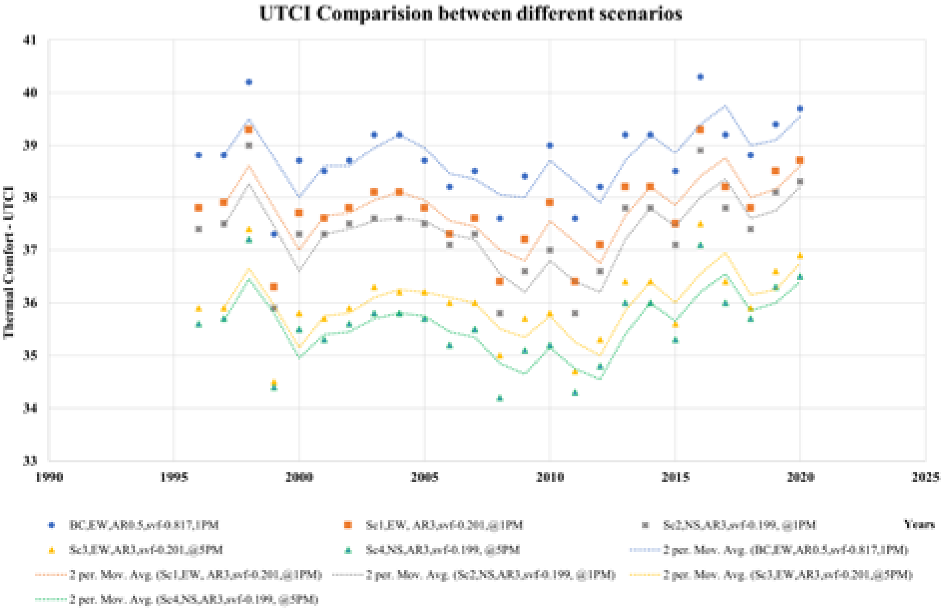


Figure 2. UTCI Comparison between different scenarios (Figure: Simath 2021)

Sc1 & Sc2 show slightly better thermal comfort than the base case, with an average value of 0.8 °C and 1.1 °C, respectively. Further, Sc2 has better performance than Sc1 average value of 0.3°C. Sc3 & Sc4, which were simulated at 5 pm show noticeable thermal comfort than the base case, showing an average value of 2.7°C and 3.1°C, respectively. However, Sc4 showed the best performance out of all scenarios ranging between 34-36 C, showing an average difference of around 3°C than the base case.

5 Discussion

The thermal comfort of an urban street could be regulated by determining the amount of solar radiation and sky visibility through urban form, shade, and street orientation. In this case, EW street is continuously exposed to solar radiation during the day, in contrast, NS street receives solar radiation in different parts at different times and thus, shows a slightly better performance than EW street. However, despite the orientation of the streets, it is complicated to achieve a thermally comfortable range at noontime. In the above scenarios, the high albedo was considered for simulations. This is challenging to apply in the real world as lighter colours in the buildings and roads lead to an uncomfortable level of glare (Emmanuel et al. 2007).

The combination of these strategies should be carefully studied and applied while avoiding adverse effects of each other in the practical context. Although these combinations of approaches are not sufficient to make a significant change in thermal comfort, the developed scenarios show modest improvements. Modifying existing building regulations (FAR, plot coverage etc.) to accommodate these can improve thermal comfort.

5.1 In-depth discussions with Professional

This part of the research focuses on the current degree of implementation of these urban strategies and local planning level and getting insights on underlying problems of strategic implementation. In-depth discussions were held with five professionals who had thorough practical experience in dealing with planning agencies and influencing the planning landscape of Sri Lanka.

The thematic coding results provide 'meanings implied' and insights on the nature of the current planning environment and the strategies to integrate climate sensitive planning. The themes and subthemes generated from the analysis is depicted in Figure 3.

Specify: The CDP is outdated (20 years) and too vague (limited to zoning and land use) to be represented as a ground-level regulatory planning guide for Colombo. Neighbourhood level, regional level planning and specifying regulations in detail are identified as key strategies. A repeated notion is that "if it is not in the documents, we can't expect it to be in action", which also gives an insight to the social values towards policy. As immediate measures, encouragement of retrofitting existing buildings to encourage shade, greenery etc. And climate checkpoint requirements by banks and other donor agencies were suggested.

Integration: There are many institutions that investigate various sectors of planning in Sri Lanka. Fragmentation of these authorities is one of the key issues in effective urban governance. Since social and economic policies draw a lot of attention in a developing country like Sri Lanka, identifying suitable approaches for climate policy and integrating them with social and economic concerns will be effective. A combination of both top-down and bottom-up approaches is required for successful integration of UC actions, thus allowing authoritative political governance and the indigenous knowledge both to be effectively integrated. Integrating professionals and the public were also identified as essential measures for effective integration of climate-sensitive planning.

Exhortation: Climate concerns are not the primary issue of the public in a developing country. Thus, there is a need to create awareness and insist the public and politicians reading the need for climate actions. This can be through mass media, debates and incentives and other means of promoting UC actions. Passive exhortation can be in the form of incentivized planning to promote UC actions, online petitions lobbying political affairs related to UC actions etc.

Name	Files	References
Insights - through research & data	5	23
Through Precedence	1	6
Through data	3	8
Through research	5	9
Continuity - Rome was not built in a day	4	24
Inception to Completion - Audit	3	5
Contnuity of policies despite regime changes	4	9
Periodical review	2	10
Commitment -act upon the word	4	30
Public commitment	2	2
Political Will	3	8
Commitments - Documents to Practice	4	10
Professional Ethics	2	10
Exortation - shout out, convince, urge	5	40
Incentivize	3	11
Awareness	5	29
Integration - policy, authority & expert opnion	5	59
Integration of administrative departments	3	7
Integrate expert opinion	2	7
Public Consultation in planning	3	8
Policy level interventions	5	37
Specify - God is in the details	5	68
Picking the low-hanging fruits	2	3
Vague guidelines - No focus	4	19
Macro to Micro	4	21
Strategic solutions	5	25

Figure 3. Themes and Subthemes developed through NVIVO (Figure: Simath 2021)

Commitment: The policy drafts addressed to international organizations should not only be action plans, but also there should be ground level commitment. Further, professional's ethical role in committing to their oaths, public commitment to the environment etc. were also classified under this theme.

Insights: Gaining insights is what can shape the planning process for unique interventions. Apart from local guided research and precedence, the themes also suggest the importance of data – storing, categorizing, and making them available for inter-department/ future use, is one thing that will guide the UC action landscape of Colombo.

Continuity: This theme strongly suggests the need for policies that are not influenced by changes in the political landscape. The theme also suggests a periodical review of the development plan and periodical audit of execution for a robust implementation.

> The above developed themes can be developed further as a conceptual framework that promotes a spiralling effect of actions, with refined results at each end of cycle.

Throughout the interviews, there were several instances of barriers were identified with regards to implementing an effective solution for urban climate strategies. These were categorized as political, social, and economic and other (policy-related, resource-related & organizational) barriers. Among them lack of political will and political manipulation, lack of awareness and least priority for environmental concerns were highly emphasized. On the other hand, the opportunities identified through the discussions were categorized according to the identified themes as depicted in figure 4.

6 Conclusions and Recommendations

Sri Lanka is on a development spree where the planning and urban development authorities have not considered the threat of Urban overheating, despite the threat it imposes on human health, productivity, and economy.

The study indicates that there is a significant trend shifting from strong heat stress to extreme heat stress throughout the year in the whole island, except the hillside. In the past decade, Colombo has shifted from moderate stress to very strong heat stress and shows a positive trend towards extreme heat stress in the near future.

The overheating issue has begun to ignite debates amongst planners and professionals. The thematic analysis of in-depth discussions gave insights on the barriers and opportunities in incorporating Urban Climate actions in Colombo. Apart from the socio-economical barriers, ‘political interference’ was identified as a key challenge for proper implementation of UC actions, which is similar to ‘lack of political will’ as identified by Emmanuel (2009) and Mahanama et al. (2014). Lack of detailed development plans, fragmented institutions, lack of policy-level initiatives, political interference in the genuine planning efforts, and changes in regime impacting planning were identified as some of the main weaknesses of the existing planning domain in incorporating climate initiatives.

The emergent themes complement the integration of UC actions in the context of Colombo. A pattern was identified among the themes which can be developed as a conceptual framework for the effective implementation of UC actions. This can be further developed as a spiralling course of actions (figure 4) which can improve the integration of UC actions with time.

The study recommends Urban climate mapping and modelling to be developed at a detailed level considering the neighbourhood level/ area-specific level when considering policy implementation. Further, the interviewed policy-making professionals feel that tackling social and economic issues should be the key priority rather than urban climate concerns. As a short-medium term initiative, the study thus suggests further research on the effectiveness of integrating climate policies within social and

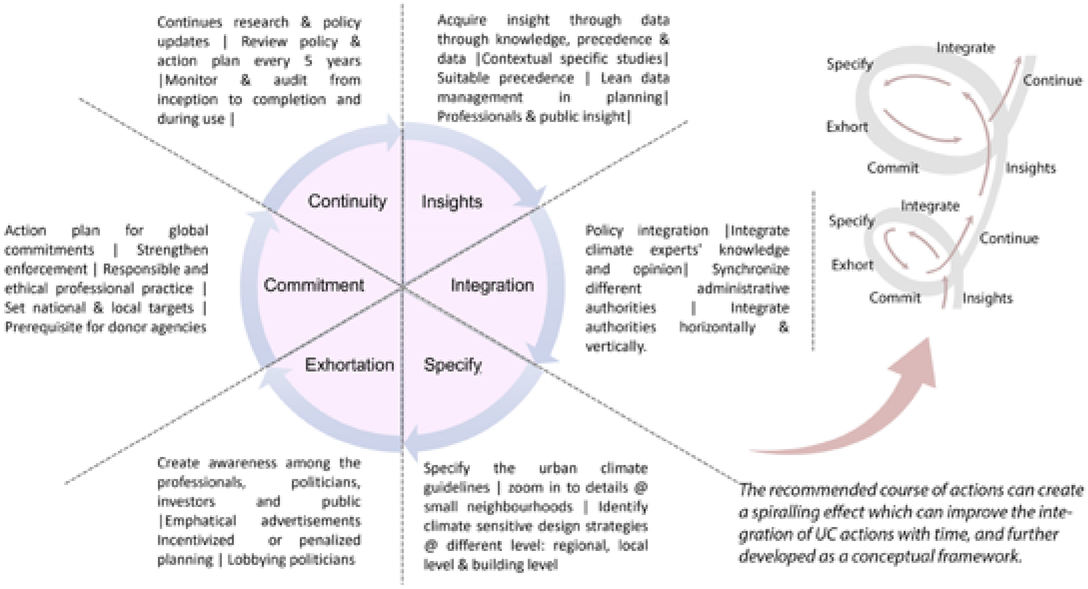


Figure 4. Themes & Effective measures of practical course of actions (Figure: Simath 2021)

economic policies to cater to Colombo's socio-economic, political landscape. However, attempts should also be made to exhort urban climate policy integration as a first-order policy initiative in the long run, since effective climate actions will always be socially and economically beneficial for a developing country in the long by eliminating cooling costs and promoting a healthy society. The key recommendations include locally guided research and awareness, exhorting the need amongst decision-makers and the general public and making a continuous effort and progress.

A significant drawback identified was that the regulations are mainly single entity focused on Colombo, Sri Lanka. Space between buildings and the impact of neighbourhood developments are not assessed through regulations. Guidelines and building regulations should be designed to assess the spaces in between too. (Streetwise or neighbourhood wise).

When assessing climate policy integration, one can easily fall into the "everything matters" trap (Ryan, 2015). The plan of actions of integration suggested above can be developed as a conceptual framework and be applied in the context of Colombo.

Urban overheating is an imminent threat in Sri Lanka that can have severe health consequences and further add an unnecessary burden on the economy. Urban climate design strategies can result in an improved microclimate, yet a broader approach is required for considerable improvement in the urban climate. This can be done through incorporating it with socio-economic concerns (such as under settlement, poverty alleviation, urban regeneration, etc.) and integrating socio-political actors (planners, professionals, politicians, general public etc.). 'How' to do this needs more intense scrutiny, which merges context-specific scientific and sociological debates. One such example is that it can be supported by multidisciplinary research focus on urban climate, facilitating monitoring climate change in an urban context and actively experimenting and developing new planning solutions considering the local climate in different perspectives.

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Cross cutting studies

Cross cutting studies

DAGAY, SONAM

13 Roadmap for decarbonisation of fleet vehicle at NHS Greater Glasgow & Clyde board

Scotland, United Kingdom

Despite the high socio-economic importance, dependence of transport on fossil fuels has significant impact on global climate change and air quality. Transport is now the highest emitter of GHG and a major source of air pollution in UK and Scotland. The UK and Scottish governments have set legally binding targets of achieving net zero emissions and committed to phase out conventional fuel vehicles by 2030. Through a case study research strategy using mixed method approach, the study developed a roadmap for decarbonisation of fleet vehicles at the NHS Greater Glasgow and Clyde board. Extensive literature review was conducted to understand the background of policies, impacts of transport on GHG emission and air pollution and to understand the role of electric vehicles (EVs) in decarbonisation. SWOT analysis was conducted to identify and analyse the key factors affecting the decarbonisation of transport. Backcasting was performed to assess the implications of achieving "net zero emission" fleet. With highly favourable policies and incentives EVs present high potential of reducing emissions in UK and Scottish context. However, it is recommended to undertake mass adoption of EVs with caution to avoid disappointments from technological failure since most of the EV models are yet to be tested and tried. It is recommended to conduct investigation on delivery of specialised medical services using EVs.

1 Introduction

According to the 5th assessment report of the IPCC, there is continued increase in global anthropogenic emission of greenhouse gases due to growth in population and economic activities. Transport sector accounted for 11% of the 10 GtCO2eq increase in global GHG emissions between 2000 and 2010. The average global temperature is projected to increase by 3.7oC to 4.8oC compared to pre-industrial levels by the end of the century if additional measures to reduce emissions are not implemented. Delay in mitigation efforts is expected to significantly increase the difficulty of transitioning to low longer-term emissions levels (IPCC 2014). In UK and Scotland, there has been significant reduction in total GHG emissions between 1990 and 2019. The highest emission reductions have been achieved in the energy supply, waste management and from land use, land use change and forestry (LULUCF). However, there has been nominal reduction in emissions from transport and is currently the highest emitter. In 2019, emissions from transport accounted for 27% of the total emissions in UK with majority of the emissions from combustion of fossil fuel in road transport. In 2018, transport emissions accounted for 36% of the total Scottish emissions of which 68% were from road transport (BEIS 2021; Scottish Government 2020). Road transport is also a major source of air pollution in UK and Scotland. Particulate matter pollution in UK causes about 29000 deaths annually and coupled with nitrogen dioxide pollution, approximately 40,000 persons die each year from exposure to poor air quality (Royal College of Physicians 2016).

Towards achieving emission reduction from transport and improving the air quality numerous policy and legislative interventions have been adopted and implemented in UK and Scotland. Most ambitious legislation for emission reduction was the adoption of the *Climate Change Act 2008 and Climate Change* (Scotland) Act 2009 to set legally binding emission reduction targets. In response to global climate emergency in 2019, the emission reduction targets have been further raised to achieve "net zero emissions" by 2050 and 2045 respectively. Transport is identified as the most important sector for decarbonisation and governments have already made announcements to phase out the conventional fuel vehicles by 2030 and to achieve zero emissions from fleet vehicles owned by the government and public sector organizations by 2030.

Aim:

The aim of the study is to design a roadmap for decarbonisation of fleet vehicle at the NHS Greater Glasgow and Clyde Board towards achieving a "net zero" fleet by 2045.

Objectives:

- To understand the background policies and legislation, fleet composition, baseline emissions and existing infrastructure
- To understand the role of electric vehicles in decarbonisation of transport
- To identify and analyse the key factors influencing decarbonisation of transport
- To assess the implications of achieving net zero fleet by 2025 and 2045
- To design a roadmap to achieve a net zero fleet at NHSGGC by 2045

2 Background

2.1 Road transport and sustainability

Despite the high dependency on fossil fuels, transport is an essential element of social and economic development. A well-developed transport system generates economic and social benefits and is a key component of globalisation (Nistor & Popa 2014). However, in the absence of policies to decouple transport emissions from growth in GDP, global transport emissions are projected to reach approximately 12 Gt CO_2 equivalent per year by 2050 (IPCC 2014). Transport also has significant contribution to air pollution posing risks to environment, human health and mortality (Batterman et al. 2020). Since road transport emissions mostly occur closer to workplace and residential areas in the cities, it is comparatively more harmful than other sources of pollution (EEA 2020). Particulate matter (PM) and nitrogen oxides emitted by road transport are amongst the pollutants with strongest evidence of impacts on human health (WHO 2021).

2.2 Policy context for decarbonisation and air pollution

The Climate Change Act 2008 of UK and the *Climate Change (Scotland) Act 2009* have been successful in creating a consensus amongst all political parties on the need for climate action (Averchenkova et al. 2021) and thus ensure political will and commitment. The "plug-in vehicle grant scheme (PIVG scheme)" in order to promote the uptake of Ultra Low Emission Vehicles (ULEVs) was introduced in 2011. Depending on the type and size of the vehicles, grant amounts ranging from £1500 to £16000 are provided to compensate the higher cost of purchasing. ULEVs are also promoted through other tax benefits and schemes (UK Government 2021). Low Emission Zones (LEZ) restricting access to conventional vehicles are increasingly being introduced in cities across UK. The sale of conventional vehicles will be banned by 2030 and government has committed to decarbonise the government and public sector fleet vehicles by 2027 and 2025 (UK Government 2020; Scottish Government 2020). Highly comprehensive plans with detailed plan of actions and specific commitments for different modes of transport have also been approved to facilitate the transition.

2.3 Health care systems and climate change

The global carbon emission from the health care was 2.2 GtCO2, equivalent to 4.4% of net global emissions in 2019. The National Health Service (NHS) of the UK account for approximately 5.4 % of the national emission (Arup & HCWC 2019) with an estimated 18% of the NHS emissions from transport (BRE 2019). The "Sustainable Development Strategy of NHS Scotland 2009" identifies carbon reduction from fleet vehicles as a key priority area and NHS Scotland committed to achieve net zero emissions from NHS owned vehicles by 2025 (NHS Scotland 2020). There is urgent need and increasing obligations to transition to a cleaner fleet of vehicles. Specifically for health boards in Scotland, there are calls from all levels of governance to replace the fleet. A roadmap or strategy is necessary to ensure a smoother transition. Roadmaps help in strategic decision making through assessment of the existing situation and by helping in identifying the opportunities, challenges and risks associated with achieving the desired objectives (Phaal et al. 2004; Siebelink et al. 2021).

2.4 Foresighting

Foresight is a process of creating alternative future visions and analyzing the consequences in a systematic and participatory manner with the aim of ensuring informed decision-making (Andersen and Andersen, 2017). As such it has been used by numerous governments and corporation for decades to shape futures that are more desirable and advantageous (Wehrmeyer, Clayton and Lum, 2014). There are 03 main approaches to foresighting. Forecasting involves projection of the most likely future based on the historical data and considers future to be an extension of the past (van Bers, Bakkes and Hordijk, 2017). In contrast, backcasting involves looking back from a desired future and developing strategies and action plans towards achieving that future. While forecasting is more predictive and show the likely future, backcasting suggest the implications of policy objectives and determine the feasibility of the goals (Zimmermann & Gracht, 2012; Bibri, 2018).

2.5 Electric vehicles

Electric Vehicles are categorised into three distinct types. (1) Hybrid Electric Vehicles (HEVs) run on one or more electric motors in addition to a traditional internal combustion engine. (2) Plug-in Hybrid Electric Vehicles (PHEVs) can be charged by plugging in to a charger as well as via regenerative braking and by the ICE. (3) Battery Electric vehicles (BEVs) are exclusively driven by electric motors powered by energy stored in batteries (DOE 2017). Although the initial cost of EVs is higher than ICE vehicles, the cost of maintenance and fuelling are lower. Substantial cost reductions have been achieved with advancement in battery chemistry and with increased production capacities. It is expected to drop further with additional technological developments (IEA 2021). EVs have shorter driving range since storage of energy in batteries is bulkier and more expensive (Pearre et al. 2011). Through advancement in EV battery technology, the average driving range of EVs has increased from 211 km in 2015 to 338 km in 2020 (IEA 2021). Compared to ICEV, EVs generate higher emission reduction and air quality benefits during use phase. The emission benefits of the EVs increase with higher share of renewable energy sources in the electricity grid (Burchart-Korol et al. 2018; Nimesh et al. 2021). However, compared over the whole life cycle, EVs have higher impacts on human and environment primarily due to energy intensive process for manufacturing and production of batteries, electric motor and powertrain, and increased mining activities (Hawkins et al. 2013; Bicer & Dincer 2018; Burchart-Korol et al. 2018). Mckinsey & Co. (2009) cited in Hawkins et al. (2013) argue that despite of having millions of point source of emissions (ICEVs), EVs aggregate emissions to fewer sources like the manufacturing units, power plants and mines. This reduces the air pollutants reaching to millions residing mostly in cities. Additionally, benefits from EVs serve as an inspiration for decarbonisation of the electricity grid (Hawkins et al. 2013) thus achieving greater emission reductions.

3 Methodology

The research follows a pragmatist research philosophy and used a mix of qualitative and quantitative methods for analysis. Qualitative method was used to conduct literature review to understand the overarching policies and to evaluate electric vehicles as the technological choice for decarbonisation of the fleet vehicles. Qualitative SWOT analysis and interviews were conducted to identify the key factors influencing decarbonisation of the fleet. Qualitative analysis was also used for analyzing the implications of the scenarios created for decarbonisation of the fleet vehicles. Quantitative analysis was performed for estimating the carbon emissions and related impacts from the existing fleet. An arithmetic quantitative analysis was also conducted for backcasting to assess the implications of achieving a net zero fleet.

3.1 Baseline emissions

The baseline emissions of carbon, particulate matter, NOx and health impact cost of existing fleet vehicles were estimated using basic equations of “Emissions= Emission Factor* Activity data”. The emission factors were obtained from literature and vehicle population data was obtained from the NHSGGC. The baseline emissions were estimated to compare the emission reductions that can be achieved through deployment of electric vehicles.

3.2 SWOT Analysis

This was conducted using secondary data gathered from the web sources using popular search engines “Google” and “Google Scholar” and also interviews with experts. First step involved, identification of the factors influencing the decarbonisation of transport through the literature review and web search. These were then grouped as Strength, Weakness, Threat and Opportunities in the SWOT matrix for analysis.

3.3 Backcasting

Backcasting was performed using desk research to assess the implications of achieving a net zero emission fleet at the NHSGGC by 2025 and 2045. An arithmetic quantitative analysis was conducted to estimate the annual investment required for replacing fleet with EVs as well as to estimate the emission and health cost reductions from decarbonisation of the fleet vehicles. In addition, qualitative analysis using outcomes of the SWOT and additional literature search was performed to assess the implications not covered through the quantitative analysis. The study adapted the backcasting method proposed by Robinson (1990). The steps followed for the exercise as briefly mentioned below in chronological order:

a. Determining the objective
The objective was to assess the implication of achieving a net zero emission fleet vehicles at NHSGGC by 2025 and 2045. Business as usual scenario is not considered since the baseline is considered to be unsustainable.

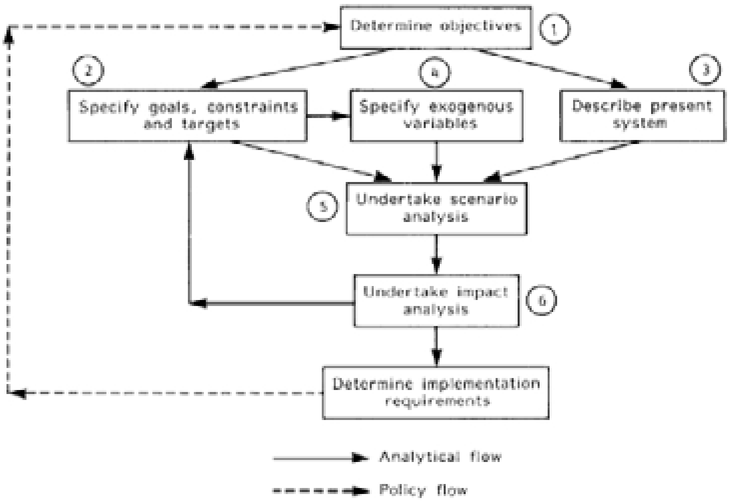


Figure 1. Outline of the backcasting method adapted from Robinson 1990 (Figure: Dagay 2021)

b. Specifying the goals and targets

Two target years were chosen based on the legally binding target of the Scottish government to achieve net zero emission by 2045 and net zero fleet across all public sector organizations by 2025.

c. Describing the present situation

The main purpose of this step was to understand the existing fleet composition, baseline emissions and the factor that affect the decarbonisation of the transport.

d. Specifying variables

The key variables considered are the rate of increase in the total number of fleet vehicles; desired rate of uptake of EVs; average number of EVs added and average number of ICEVs replaced for the quantitative analysis. For the qualitative analysis the key variables considered were technological availability and maturity, adequacy of infrastructure and energy and availability of funds.

e. Scenario and impact analysis

The scenario analysis was conducted through a mix of quantitative and qualitative analysis. While quantitative analysis helped in the estimating the cost and emission reductions, qualitative analysis using outcomes of SWOT and literature enhanced the understanding of the implications of the two scenarios.

f. Determining implementation requirements

The above steps were used as the basis for identifying the interventions that are necessary for achieving a net zero emission fleet at the NHSGGC. The interventions are presented in the form of a roadmap to achieve net zero emission fleet by 2045

3.4 Roadmap

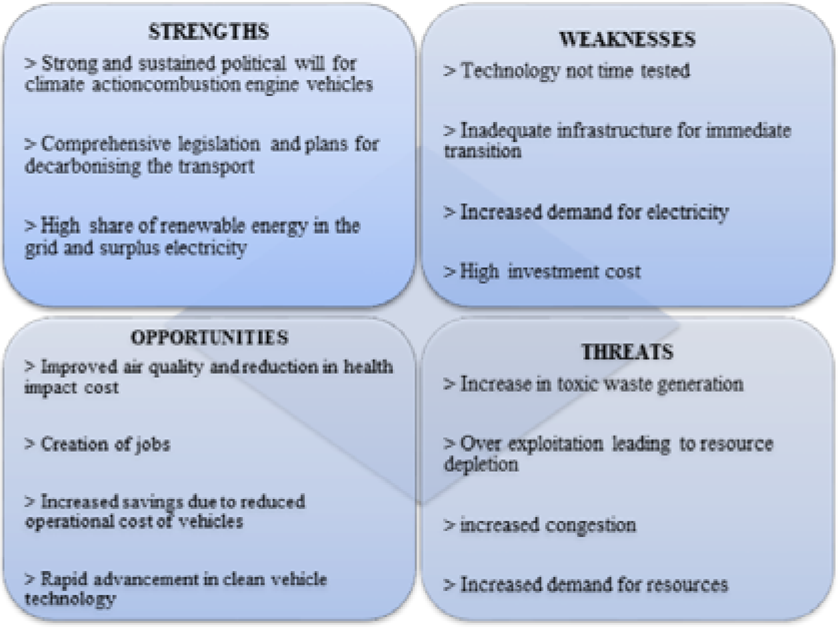
Informed by literature review, SWOT analysis and backcasting exercise, the most important interventions were identified and presented in the form of a roadmap. Design of the roadmap was conducted independently and by referring to existing roadmaps available in the public domain.

4. Results

4.1 Role of Electric vehicles in decarbonisation

Mass deployment of EVs in Norway and China showcase that EVs can achieve significant emission reductions provided there is adequate electricity generated from renewable sources. Guaranteeing higher economic benefits, ease of commute and convenience through incentivisation and provisions of adequate chargers are most important factors in making EVs a preferred choice over ICEVs. This pertains to both the manufacturers and individuals. The existing policy scenario of UK and Scotland has undeniably set the necessary policy environment for mass uptake of EVs. Especially for Scotland as a net exporter of electricity and renewable sources accounting for 97.4% of the energy mix, EVs can achieve significant emission reductions from road transport. Lessons from replacement of fleet vehicles with EVs in UK and Scotland have noted meaningful cost savings and emission reduction.

4.2 SWOT Analysis



STRENGTHS	WEAKNESSES
> Strong and sustained political will for climate actioncombustion engine vehicles > Comprehensive legislation and plans for decarbonising the transport > High share of renewable energy in the grid and surplus electricity	> Technology not time tested > Inadequate infrastructure for immediate transition > Increased demand for electricity > High investment cost
OPPORTUNITIES	**THREATS**
> Improved air quality and reduction in health impact cost > Creation of jobs > Increased savings due to reduced operational cost of vehicles > Rapid advancement in clean vehicle technology	> Increase in toxic waste generation > Over exploitation leading to resource depletion > increased congestion > Increased demand for resources

Table 1. SWOT Matrix (Table: Dagay 2021)

The biggest strength in the decarbonisation of the fleet vehicles with EVs in UK and Scotland are high political commitments, high share of renewable energy and surplus electricity generation to meet the demand. However, uncertainty in the investment for replacing the fleet, availability of adequate chargers and lack of technician to provide after sale service remain a key challenge. Greatest concern is the capability of the EVs to deliver specialised healthcare services. The threats from mass adoption of EVs include resource exploitation, risk to human health from toxic waste generation and increase traffic congestion. Nonetheless, decarbonisation of the fleet has high potential for improving air quality, generation of employment, meeting legal targets and cost savings from the operation of the fleet.

4.3 Scenarios

a. Net zero fleet by 2025

Achieving net zero fleet by 2025 would require addition of an average of 71 EVs annually to replace 67 ICEVs. Compared to the current levels, annual NOx emissions could be reduced by around 20%, PM2.5 by 10%, CO_2 by 20% and health impact cost by around 18%. An annual investment of around £3.11 million will be required to completely replace the fleet by 2025. It is highly unlikely to achieve net zero emission fleet by 2025 due to high yearly investment, uncertainty in adequacy of chargers and fund and capability of the EVs for specialized services. Also, most of the existing fleet vehicles would not have achieved optimal use by 2025 and would result in unnecessary retirement of the vehicles in use today.

b. Net zero fleet by 2045

Achieving net zero fleet by 2045 would require addition of an average of 18 EVs annually to replace 13 ICEV. Compared to the current levels, annual NOx emissions could be reduced by around 4%, PM2.5 by 2%, CO_2 by 4% and health impact cost by around 3%. An annual investment of around £0.79 million will be required to completely replace the fleet by 2045. The scenario is more likely to be achieved since the government has made additional financial commitments for uptake of electric vehicles. The funds are likely to be made available in order to meet the legal commitment to achieve net zero economy by 2045. Most importantly, a majority of the EV models would have already been tested and help avoid disappointments. Also, the existing fleet vehicles would have attained optimal use phase and HGVs run on electric and FCV are also likely to be made available in the next 10-15 years.

4.4 Roadmap

Figure 2 shows the timeline for implementation of interventions to achieve a net zero emission fleet at the NHSGGC by 2045.

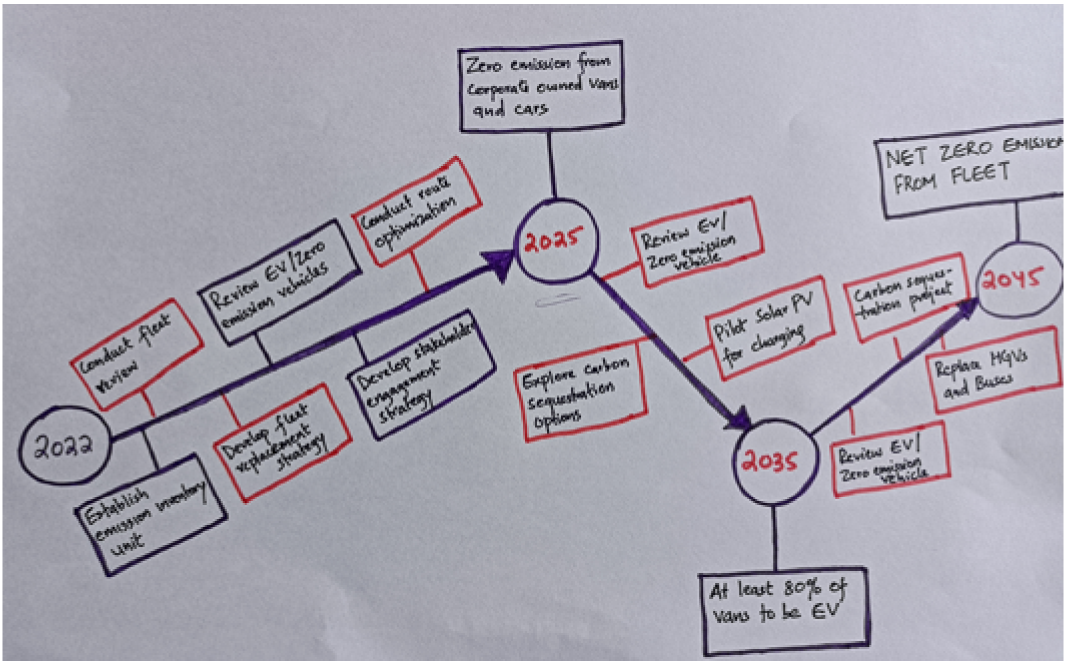


Figure 2. Timeline for implementation of roadmap (Figure: Dagay 2021)

1. Establish emissions inventory unit and maintain inventory of emissions

Emission inventories serve as an important tool in identifying most significant emission sources, generation of historical trends in emissions, establishing basis for decision making including goal setting towards fulfilling the commitments and ensuring compliance (D’Avignon et al. 2010).

2. Devise financing strategy

Uncertainty in funding for phasing out ICEVs with EVs is one of the main concern and challenge facing the board today. A financing strategy will be useful tool in identification of funding sources, exploring fund generation sources to support transitioning to “net zero” fleet.

3. Develop fleet management/replacement strategy

Fleet management strategy would ensure optimal use of the fleet vehicles, cost effectiveness, safety and reliability and prevent excessive fuel consumptions (Spireon 2021; Stazzone 2021). Fleet review for the strategy would assist in estimating emissions from the fleet, determining the vehicles that can be replaced with EV, calculate savings on cost and carbon emissions, increase efficiency through route optimisation and assist in developing strategies to reduce mileage (Energy Saving Trust 2019).

4. Conduct route optimization

Increase in efficiency of vehicles through route optimisation reduces total fleet mileage and consumption of fuel by 20% and also increase the efficiency of the fleet (The Algorithm People 2021). It also helps identify vehicles that can be replaced with available EVs, increase efficiency of fleet and lessen the investment burden by reducing the fleet size.

5. Evaluation of zero emission vehicles

Considering the pace of the technological development of EVs, the sustainability benefits and risks need to be assessed cautiously. Most of the EV models are fairly new and their efficiency and reliability are not time tested. Importantly, life cycle impact of vehicles needs to be taken into consideration to minimise impacts on environment and human. Therefore, it is necessary to conduct detailed and periodic evaluation of the zero emission vehicles including EVs to ascertain the model best suited and with minimal impacts.

6. Strengthen collaboration with stakeholder organizations

It is important to strengthen collaboration with all relevant stakeholders to garner support and keep abreast with the latest developments. For instance, through collaboration with manufacturers, customised EVs can be developed to meet the requirements of the board. Especially since the technology is fast evolving, collaboration with all stakeholders would be vital in achieving a net zero fleet.

7. Explore options for carbon sequestration

Achieving a “net zero emission” fleet would require sequestration of unavoidable emissions. Even with complete replacement of fleet with EVs, carbon sequestration would be relevant because of the embedded carbon in the vehicle. Green spaces in cities reduce the exposure of the residents to air pollution and provide open space for socialising and physical activities and thereby reduce illnesses and early deaths (WHO, 2016).

5. Conclusions and discussion

Learning through experience of two leading countries, Norway and China in terms of mass adoption of electric vehicles, it was found that while policy incentives and adequate infrastructure is the key to ensuring mass adoption of EVs, share of renewable energy in the national electricity grid determined its effectiveness in achieving desired emission reduction benefits. Considering the highest level of political commitment, range of incentives for zero emission vehicles and majority share of electricity generated from renewable sources, EVs are a natural choice for decarbonisation of the road transport in the context of UK and Scotland. However, key challenges to decarbonisation of the fleet vehicles include the high investment cost, uncertainty in adequacy of infrastructure and EVs to deliver specialized medical services. While EVs are well recognised as the technological choice for decarbonisation of the sector, most of the models have emerged in the last 5-6 years and therefore are yet to be tried and tested. Therefore, although deployment of EVs has the potential to deliver, "net zero emission" fleet, deployment of EVs need to be conducted cautiously to avoid technological disappointments and avoid unintended impacts on the environment. The roadmap developed in the study thus, present interventions aimed at avoiding risks from adopting a technology that is yet to prove it full potential in generating sustainability benefits.

Limitations

- Quantitative analysis for the backcasting in the study is not a well-established method. It was done in the absence of adequate data.
- The backcasting exercise in the study was done predominantly through desk research and mostly independently and therefore the impact analysis likely contains inaccuracies and inconsistencies.
- The author developed the roadmap for the study independently and therefore it cannot be claimed to be comprehensive and realistic. There is need for more comprehensive analyses and consultations.

6. Future Work

The study developed a roadmap that is more generic and aimed mostly at ensuring a cautious uptake of EVs. Therefore, my recommendation for future work building on this study is to focus on more in-depth investigation of the EVs for delivering specialised healthcare services. It is highly recommended to conduct investigations through a whole life cycle impact analysis and not just on the technological capabilities

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KEYA, SHAMMI AKTER

14 Rethinking Education:

A Framework for Contextualizing Environmental Education Practice & Urban Green Management in Cities

The worldwide Education system is going through continuous changes since evolution due to changes in strategies for survival. While the traditional idea of Education inclines towards indoor-based learning, the emerging stress on outdoor Education to connect students with local nature increases the potential of climate-responsive Education. Educating people to grow as 'environmentally aware citizens' can also boost their active participation and help cities grow sustainably. Different cities around the world (e.g., Lahti, Kyoto, Glasgow) have adopted 'Outdoor Education' (OE) and 'Environmental Education' (EE) as tools for sustainable development in cities with the collaboration of local communities. However, the scope for outdoor Environmental Education can vary largely in different cities. The majority of cities worldwide are lagging in incorporating local green spaces purposefully, especially in densely built cities (e.g., Dhaka, Bangladesh).

The multiple health benefits related to urban green areas, including enhancing local climate and reducing Attention-deficit hyperactivity disorder (ADHD) at an early age, have put more stress on green management in urban areas. This research focuses on reviewing the potential of Environmental Education Practice (EEP) as an Urban Green (UG) management tool in different cities. This study helps understand whether contextual differences, even within city-scale, can or cannot impact pro-environmental behaviours and willingness for outdoor educational activities. Students' responses and contextual morphology of relative school neighbourhoods, one in densely built-up areas and one in greener areas in Lahti and Dhaka, have been used to identify critical urban built and natural indicators to develop the School Criticality Index (SCI). The SCI model classifies schools based on their contextual differences within a city and indicates required interventions related to greening within school neighbourhoods for optimized EEP. The proposed SCI based Urban Green Management (UGM) framework can help researchers, practitioners, and policymakers to focus on where to increase greeneries for optimum climate resilience Education in cities.

1 Introduction

The history of humanity on earth carries evidence of venturesome adaptation with the change in geography, society, culture, economy. These changes happened gradually throughout the years while responding to climate change directly or indirectly. As stated by Erik (2017), while the temperature on earth increased by 5 degrees Celsius over periods spanning some five thousand years starting from an ice age, recent studies show that temperatures will increase by 2 to 6 degrees by the next century. Now, cities play a critical role in climate change; as reported by UNEP 2018, urban areas are responsible for 70% of carbon dioxide (CO_2) emissions and 60-80% of the total global energy if being consumed by cities through electricity and transport. Moreover, compact urban settings can alter humidity, airflows resulting in excess temperature gradients compared to the global scale as they have characteristics as more built area concentration, more surface roughness, and heat retention, lesser atmospheric dispersion, and ventilation in the street canyons (Janković & Hebbert 2012). Therefore, it is needless to say that cities are facing effects of climate change as Urban Heat Island (UHI), already on so many aspects throughout the world. With this rapid urban climate change, the most relevant question is, are we or our future generation ready to tackle this? The answer might be hidden somewhere within the process that we are adapting to deal with the urban climate change and if the process towards adaptation is leading towards climate resilience.

Since evolution, Education has been the way of every human's tactic towards survival. It started from being educated in some survival skills that later turned into being capable of surviving in different contexts of different countries. The utmost concern here about the evolution of Education is, Formal Education has become "Indoor Based" when the concept of "Outdoor Learning" still only relates to exploring the wilderness. With the era of climate change, outdoor Education should have developed into a formal way of learning how to be resilient towards climate change through hands-on experience in nature as it is more effective than traditional classroom-based Education. Environmental Education (EE) practice with schools strongly aligns with outdoor-based learning since it promotes awareness of the environment through direct and indirect engagement with nature that increases nature connectedness and well-being amongst future citizens (Pirchio et al. 2021; Preston 2011). This dissertation focuses on the potential effects of outdoor Environmental Education Practice (EEP) on health, well-being & urban climate at neighbourhood scale of schools.

2 Background

According to the statistics of UNESCO, the COVID-19 pandemic has disrupted the institutional activities of at least 1.5 billion students worldwide, that is, over 90% of the world's children. Transmission in the outdoors of Corona Virus is much less likely than indoors enclosed space, which stresses the necessity of adequate airflow and a healthy environment for children in the school environment, which also indicates the need of integrating outdoor areas for educational purposes. But this pandemic has shown the scarcity and necessity of accessible urban open space and school fields for Outdoor Education (OE) (Bayulken et al. 2021).

Research by Yang et al. (2015) showed that the surrounding environment of schools directly affects classroom indoor air quality. Specifically, Particle Matter (PM10) and Total Bacteria Count (TBC) highly correlate with existing roads and cross-ventilation at the urban elementary schools in Seoul, Korea, which shows that despite being indoor, the children are eventually exposed to the surrounding urban environmental stressors. Now, Urban Vegetation or Urban Green (UG) (e.g., parks, reserved natural parks, flower beds alongside streets, green playfields) has direct impact on enhancing air quality and health (Hoyle 2020; Fowler et al. 1989; Laia & Kontokostab 2019). Therefore, greening in school neighbourhoods can be stressed here to reduce the impact of environmental pollution on a school neighbourhood scale. Intersecting Environmental Education with preservation of Urban Green spaces and school neighbourhood greening offers excellent potential to add to children's health value and economic and social benefits to the local green areas. However, which parameters of the urban built environment can directly or indirectly affect the establishment of EEP needs further research.

The emergence of outdoor places as learning spaces has become even more crucial considering their impact on climate, social, and economic factors. However, most of the existing urban green spaces within the city do not have a deeper purpose than serving only environmental purposes. Therefore, the argument for more residential areas than green areas is winning this debate most of the time because of the 'Urban Densification' concept. The 'Urban Densification' promotes 'Compact Sustainable Cities' as it promotes mixed land use and the close juxtaposition of buildings, roads, and other infrastructures mainly to limit transport energy use and urban sprawl while limited space is left for urban greenery (Wolsink 2016; Jenks et al. 1996).

On average, students between the age of 7 to 14 in OECD countries spend around 6,898 hours of formal instruction inside classrooms. The age group of 12-15 years old spends more hours inside classrooms than the other age groups (OECD, 2007). The majority of intended hours of instruction are compulsory, and students spend most of their active daytime inside the school environment. Therefore, the school and surrounding environment potentially play the most influential role in students' health and well-being. Quality of school neighbourhood environment needs more attention in equal access to local green so that every child gets access to similar ‘Green Time’ and ‘Green Space.’ Multiple studies, including Kuo et al. (2021) and Kuo et al. (2018), refer to tree cover on school grounds and greeneries within 250m buffer of schools having a significant impact on academic achievement compared to the overall greenness within 1000m buffer or neighbourhood scale. The outdoor activity experience strongly correlates with the frequency of visits researched by Wolsink (2016). However, the correlation between the students’ willingness for outdoor activities, pro-environmental behaviour, and urban environmental quality needs further research. Therefore, the necessity for reinventing and reconnecting the students and locals with neighbourhood green has added another dimension of researching ‘Greening’ within 250m for EEP establishment.

Now, Finland has the least indoor classroom-based learning hours compared to the rest of the OECD countries and has been practicing Environmental Education by ensuring the implementation of the ecologically sustainable development perspective in Education through public sector action programs based on the 1992 Rio de Janeiro UN Conference on Environment and Development (Rohweder 2004; Keya & Aarrevaara 2021). Lahti city, Finland, has received the status of European Green Capital 2021. Lahti City has been actively involved in EEP for over 15 years in association with environmental organizations, Geoparks, kindergartens, and schools. The city got UNICEF’s Child-friendly City status in 2015 and 2018. That makes it a good case study for analyzing the current EEP and identifying if contextual differences of schools considering the urban environment and proximity to nature are impacting students’ outdoor activities and nature connectedness.

The scenario for establishing EEP in densely populated cities like Dhaka, Bangladesh is far more crucial yet complicated considering classroom environment, classroom-oriented Education, lack of green schoolyards and playfields, and existing accessible local green areas for outdoor learning. While a healthy environment for children and livability in cities are potent components to consider for planning, a decrease in child-friendly urban open space, including streets, has reduced the opportunity for developing social capital, as Karsten (2011) mentioned, which also suggests narrowing green space will have similar effects on the value of green space for the development of children and young adults (Baran et al. 2014; Wolsink 2016).

In this dissertation, the value of proximity to green space for outdoor Environmental Education and better nature connectedness is investigated by surveying two schools in Lahti and two schools in Dhaka, for both cases, one in a denser urban context compared to the other, to identify elements of the urban environment that can affect the establishment of EEP in cities and which elements can be directly intersected with the schools for better urban climate management within 250m buffer of schools.

2.1 Research Questions

The research questions are the followings

- What are the similarities and differences between EEPs by different organizations or Environmental bodies and EEPs by schools?
- Which factors in the urban environment alongside green areas might affect optimum EEP by schools in different cities?
- How far can schools contribute towards local climate enhancement and better urban Green (UG) management?

2.2 Aim and Objectives

Aim

The aim is to develop a contextual framework for EEP establishment in cities for Urban Green (UG) management and climate resilience Education.

Objectives

The objectives of this study are the following:

1. To review current EEPs by different organizations/bodies on Socioeconomic and environmental parameters of cities
2. To analyze current exposure of nature corresponding to the surroundings of schools in Dhaka compared to Lahti
3. Identify Urban Environment elements affecting outdoor educational activity amongst students from the EEP in selected Case Study Schools in Finland and Dhaka
4. To develop School criticality Index (SCI) as a tool to analyze the vulnerability of schools considering key urban environment indicators causing more/less nature connectedness in different contexts for optimizing EEP and ensuring ‘Just environment’ for all
5. To develop Urban Environment Improvement Framework using proposed SCI model

3 Methodology

The basic structure for addressing the three research questions included both inductive and deductive approaches, which resulted in a bottom-up strategy for identifying underlying indicators of the problem and proposing the urban green management framework as shown in table 1.

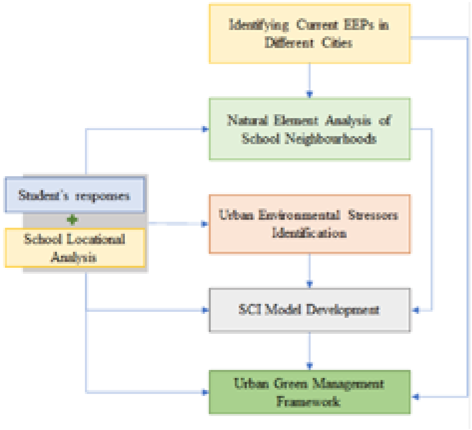
Research Questions and Objectives	Methodology Outline
Research question 01 corresponding to Objective 01	I 
Research question 02 corresponding to Objective 02 and 03	
Research question 03 corresponding to Objective 04 and 05	

Table 1. Outline of methods to address the research questions and objectives (Table: Keya 2021)

3.1 Critical Review of Current EEPs in Different Cities

Literature review and case studies for identifying EE Activities and association with urban climate management in different cities to have a better insight of the current practices and to what extent cities are incorporating outdoor Education for health, well-being, and sustainable development in the local context. (Figure 1)

Primary data has been collected through multiple online interviews with concerned authorities from Salpausselkä Aspiring Global Geopark, Kanerva Kindergarten (Lahti, Finland), Oki Islands UNESCO Global Geopark, and Miyako Ecology Center (Japan) and Environmental agencies such as NatureScot (Glasgow, Scotland). Pre-determined questions with probing have been used for the data collection. Secondary Data has been collected from literature review and online survey data from Lahti City Maptionnaire based questionnaire conducted in 2017, NatureScot official website.

The current activities by the concerned organizations have been grouped into an Environmental, Educational, and Socio-economic parameters to identify commonalities and differences with the activities conducted by the schools in Lahti, Finland.

3.2 Analysis of Existing Exposure to Nature

Current exposure of nature corresponding to the surroundings of schools in Dhaka compared to Lahti has been analyzed to have better understanding of the current scenario of school neighborhoods in both cities. The schools, parks, and open-space location details data have been collected from the Bangladesh Bureau of Educational Information and Statistics (BANBEIS) and Dhaka South City Corporation (DSCC) for Dhaka. For data in Lahti, open-source data from Geofabrik.de, StatisticsFinland, and Maptionnaire services have been used.

3.3 Student's Response & Urban Environmental Stressors Analysis

Urban Environment Stressors that might be affecting the Outdoor Educational activity have been analyzed. More or less willingness for OE activities amongst students from selected Finnish Case studies and identified Schools in Dhaka have been analyzed. Google form and Maptionnaire based questionnaire have been used for collecting students' responses from two schools in Dhaka and two schools in Lahti, respectively.

3.4 Developing School Criticality Index (SCI)

The central concept and indicators for the criticality of schools have been developed based on the understanding of the 'internal and external aspects of vulnerability' explained by Chanbers, R, (1989) and function of three factors as defined by the Intergovernmental Panel on Climate Change (IPCC).

The criticality assessment model called School Criticality Index (SCI) is developed following equation (1) shown below:

$$\text{SCI},\quad I_{SC} = \left(Exposure, I_E - Adaptive\ capacity,\ I_{AC}\right) \times \text{Sensitivity},\ I_S$$

For normalizing the selected indicators, following equation (2) has been used,

$$\text{Indicator Index},\ I_x = \frac{I_d - I_{(\min)}}{I_{(\max)} - I_{(\min)}}$$

The types and magnitude of exposure of the target system can be grouped into three main components:

I. Adaptive capacity

The overall exposure to nature from school locations and 250m buffer neighborhood scale has been calculated following simple average as equation (3):

$$N_{ex} = \sum_{i=1}^{i=n} I_n$$

Here, n = Number of Indicators considered.

II. Zonal sensitivity

Zonal Sensitivity indicates the internal qualities of the urban setup to explain contextual sensitivity for outdoor EEPs. For Dhaka, based on the findings from objectives 2 and 3, lack of ventilation and visibility of existing greens due to congested urban built-up has been considered as zonal sensitivity stressors. Zonal sensitivity was calculated using Zonal Wind Shadow, Atmospheric Stability and Lack of Porosity. SAGA GIS has been used for effective airflow height and wind effect analysis considering average wind speed.

III. Exposure

Exposure indicates the external factors to which a system is susceptible to and unable to cope; here, outdoor activities are vulnerable to thermal comfort, air pollution, noise, road safety, the scale of the population exposed in the system. Land Surface Temperature (LST) has been calculated using LANDSAT 8 thermal infrared sensor Band 10 data following the method explained by Mustafa et al. (2019). Road Density has been calculated by assigning values of 0 to 5 based on the ranking of five categories of roads to identify nodes with higher concentrations of heavy traffic roads, indicating association with poor air quality and noise pollution. The number of students has been considered as an indicator of the scale of exposure considering adolescents.

3.5 Urban Green Management Framework Development

The Urban Green Management Framework (UGMF) for EEP establishment in cities considers the average SCI score for zonal classification, and adjusted SCI scores are considered for school-specific interventions.

4 Results

The results have been divided in five sections according to the five objectives of the study.

4.1 Critical Review of Current EEPs in Different Cities

Overall, the amount of direct or active engagement for ‘nature management’ along with environmental awareness activities amongst the students was found to be ‘very high’ in the current EEPs by Geoparks compared to outdoor learning practices by NatureScot, Glasgow, Scotland. Again, the environmental practices by Miyako Ecology Center, Kyoto, Japan was found to be very much focused on environmental awareness development along with green infrastructure building promotion, while outdoor activities with students were not found to be a frequent activity. The reason is the unavailability of accessible open areas within proximity of the schools in Kyoto city, as it is densely populated. Instead, the rooftop space is acting as an alternative to outdoor areas for hands-on environmental awareness lessons. (Bader 2021; Martin 2021; Munro 2021; Keya & Aarrevaara 2021). See Figure 1 (Keya 2021).

In summary, the adaption of EEP strategy by different bodies specifically for environmental activities can be divided into three major areas: 1) Outdoor Area Based, 2) GI Based, and 3) Combined (Outdoor + GI) Strategy. See Figure 1 (Keya 2021).

4.2 Analysis of Existing Exposure to Nature

The distribution pattern of 'Overall Nature' in Lahti, considering the location and 250m buffer of schools, shows high variability in distribution with an average value of 0.45 and a Standard Deviation (STD) of 0.1342 amongst the schools. 45.1% of the schools fall within the 'High' to 'Very high' in total, 19.3% within 'Moderate', 35.5% within 'Less' and 'Very less' category. Although the data have high STD, the distribution shows uniformity in general.

In Dhaka, the distribution shows a left-skewed pattern with the majority of the schools (56.8%) falling within the 'Less' and 'Very less' category with 32.7% schools in moderate and only 10% schools in 'High' to 'Very high' category of exposure to overall nature. The 324 schools show an STD of 0.066 from a Mean value of 0.34, which means less variability in 'Exposure to Nature' within the urban area.

In summary, schools falling within the 80th percentile of 'very less' exposure to nature are located near the densely built-up areas in both cities. However, in Lahti, all the schools have 'medium' to 'very high' exposure to nature with a minimum normalized value of 0.23 and a minimum green area of 400 sqm within 250m buffer. Inversely, the majority of the schools in Dhaka have 'very less' or no accessible natural areas nearby. The minimum normalized value of overall exposure to nature is 0.19, and the minimum green area within a 250m buffer is 0 sqm. See Figure 1 (Keya 2021).

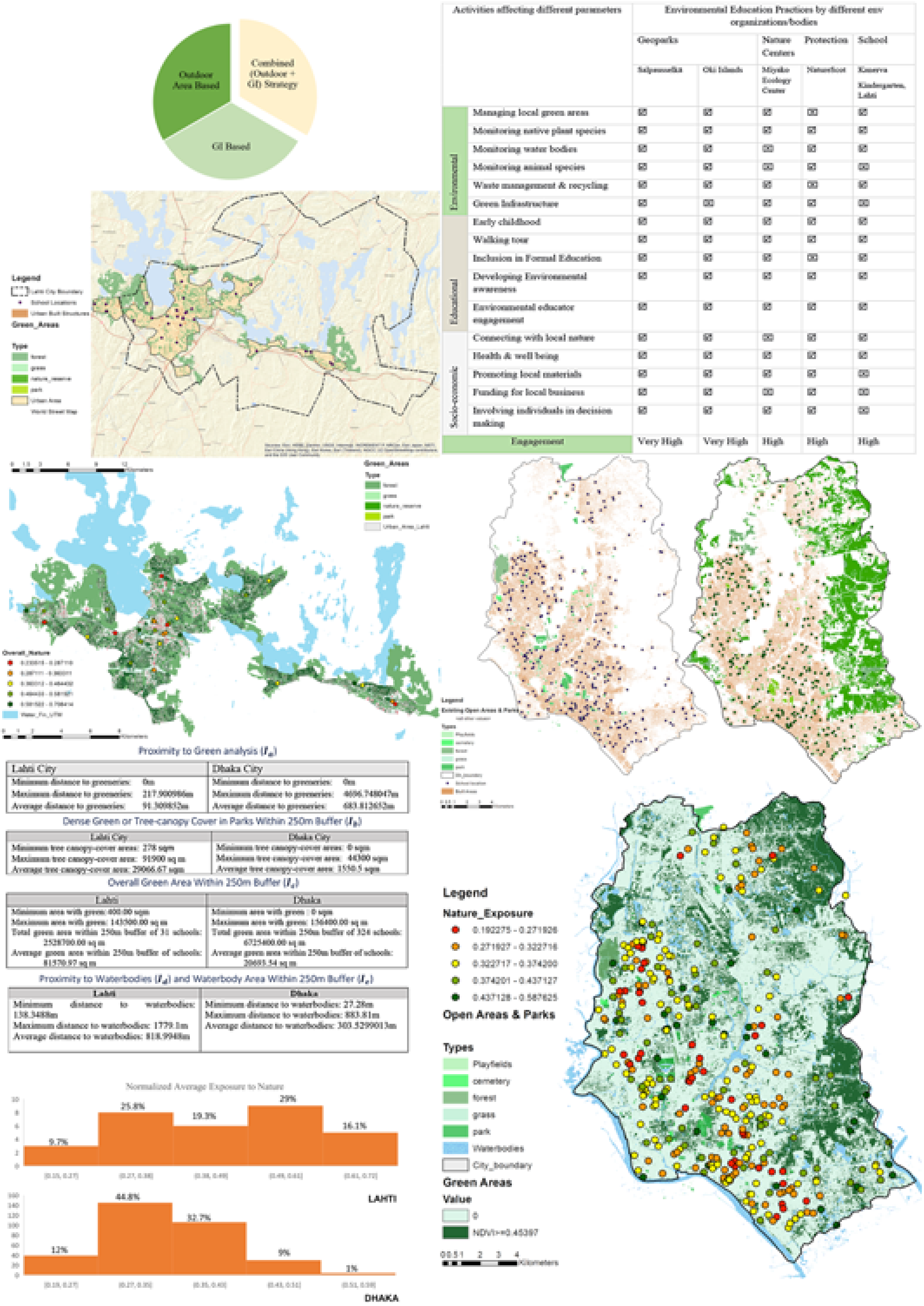
4.3 Student's Response & Urban Environmental Stressors Analysis

4.3.1 Comparison of Student's Responses From Lahti and Dhaka

Student's responses were collected using Maptionnaire application and Google form.

Then the responses were grouped into similar catagories such as:

1) Frequency of Outdoor Activities with School,
2) Types of Outdoor Activities with School,
3) Transportation Usage Behaviour,
4) Identified Problems Related to Outdoor Activity (OA),
4) Usage of Nearby Public Areas for Outdoor Education (OE), and
5) Willingness of Outdoor Activities.



Activities affecting different parameters		Environmental Education Practices by different env organizations/bodies				
		Geoparks		Nature Centers	Protection	School
		Salpausselka	Oki Islands	Miyako Ecology Center	Naturfoot	Kenerva Kindergarten, Lahti
Environmental	Managing local green areas	☒	☒	☒	☐	☒
	Monitoring native plant species	☒	☒	☒	☒	☒
	Monitoring water bodies	☒	☒	☐	☒	☒
	Monitoring animal species	☒	☒	☐	☒	☐
	Waste management & recycling	☒	☒	☒	☐	☒
	Green Infrastructure	☒	☐	☒	☒	☐
Educational	Early childhood	☒	☒	☒	☒	☒
	Walking tour	☒	☒	☒	☒	☒
	Inclusion in Formal Education	☒	☒	☒	☐	☒
	Developing Environmental awareness	☒	☒	☒	☒	☒
	Environmental educator engagement	☒	☒	☒	☒	☒
Socio-economic	Connecting with local nature	☒	☒	☐	☒	☒
	Health & well being	☒	☒	☒	☒	☒
	Promoting local materials	☒	☒	☒	☒	☐
	Funding for local business	☒	☒	☐	☒	☐
	Involving individuals in decision making	☒	☒	☒	☒	☐
Engagement		Very High	Very High	High	High	High

Proximity to Green analysis (I_a)

Lahti City	Dhaka City
Minimum distance to greeneries: 0m Maximum distance to greeneries: 217.900986m Average distance to greeneries: 91.309852m	Minimum distance to greeneries: 0m Maximum distance to greeneries: 4696.748047m Average distance to greeneries: 683.812652m

Dense Green or Tree-canopy Cover in Parks Within 250m Buffer (I_b)

Lahti City	Dhaka City
Minimum tree canopy-cover areas: 278 sqm Maximum tree canopy-cover area: 91900 sq m Average tree canopy-cover area: 29066.67 sqm	Minimum tree canopy-cover areas: 0 sqm Maximum tree canopy-cover area: 44300 sqm Average tree canopy-cover area: 1550.5 sqm

Overall Green Area Within 250m Buffer (I_c)

Lahti	Dhaka
Minimum area with green: 400.00 sqm Maximum area with green: 143500.00 sq m Total green area within 250m buffer of 31 schools: 2528700.00 sq m Average green area within 250m buffer of schools: 81570.97 sq m	Minimum area with green : 0 sqm Maximum area with green: 156400.00 sq m Total green area within 250m buffer of 324 schools: 6725400.00 sq m Average green area within 250m buffer of schools: 20693.54 sq m

Proximity to Waterbodies (I_d) and Waterbody Area Within 250m Buffer (I_e)

Lahti	Dhaka
Minimum distance to waterbodies: 138.3488m Maximum distance to waterbodies: 1779.1m Average distance to waterbodies: 818.9948m	Minimum distance to waterbodies: 27.28m Maximum distance to waterbodies: 883.81m Average distance to waterbodies: 303.5299013m

Figure 1 Existing Exposure to Nature Considering School Neigbourhoods in Both Cities (Figure: Keya 2021)

The responses were calculated following ‘Satisfaction Index’ by Yeh and Tan 1975, (Equation 4)

$$\text{Oudoor Activity Index; } I_{OA} = \left(f_p - f_n\right)/\text{n}$$

Here,
f_p=positive response,
f_n=negative reponse
n= n_i, number of responses

In both cities, students from schools located near nature have a higher percentage of walking. However, in Dhaka, the rickshaw is the second most used vehicle followed by public bus, while in Lahti, public buses and bicycles have the second and third highest percentage. However, the comparison between bike usage between the two cities shows that Dhaka is significantly lagging in bike usage. Despite that, the close green proximity school has more bike users compared to the less green proximity school in Dhaka. But in Lahti, both schools showed the same percentage of users. (Figure 2).

4.3.2 Comparison of Urban Environmental Stressors

LAHTI

The Suburb school in Lahti shows around 1.8°C lesser land surface temperature in both summer and winter months cases. The LST difference strongly aligns with the suburban school students complaining more about the cold temperature as a problem for OA. Moreover, the finding of more indoor green and roof garden usage for outdoor activities in the suburban school of Lahti indicates the school’s measures for adapting Environmental Education activities in extreme weather. (Figure 3)

DHAKA

School D shows 1.34°C lesser land surface temperature than school C, which strongly aligns with the students from School C preferring shading more than students from school D. Lesser willingness for walking can link to heat exposure and lack of shading. The mention of problems related to ‘Safety and Comfort,’ ‘Environmental Pollution (dust, dirt, poor air quality), ‘Transportation Problem’ was higher amongst students from school C, which indicates higher urban stressors exposure. Again, the percentage of students facing ‘no problem’ was highest amongst students from school D. (Figure 3)

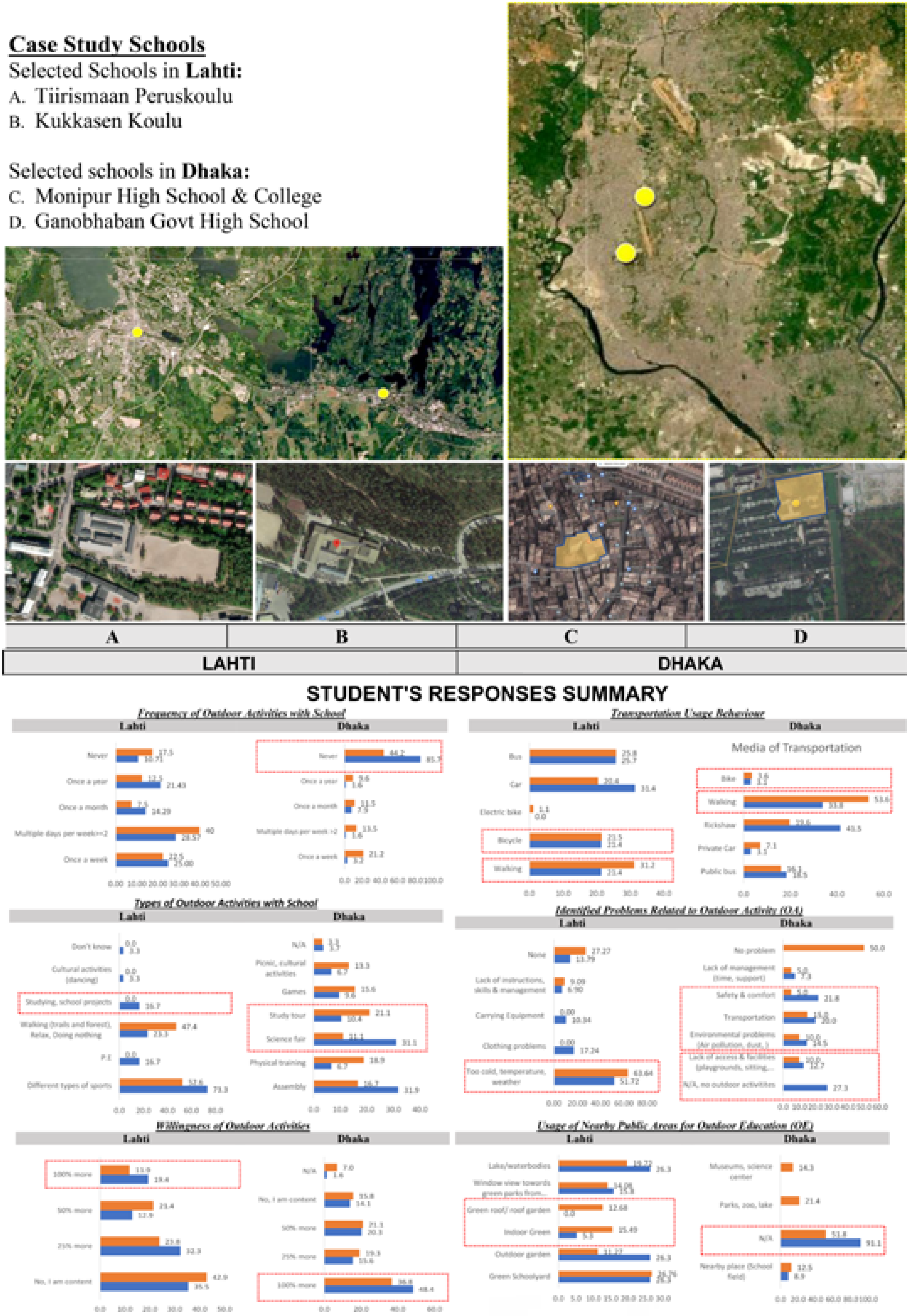


Figure 2. Student's Response Analysis for Selected Schools in Lahti and Dhaka (Figure: Keya 2021)

4.4 Developing School Criticality Index (SCI)

Using the proposed SCI model in Dhaka, 42 schools from the 324 schools around the city showed 'high' to 'very high' in the criticality score index (SCI>=0.09). In comparison, 177 schools showed a medium SCI score (0.00=<SCI>=0.09). In Dhaka's context, the SCI value of more than 0 can be considered moderately critical in terms of existing nature, road density, and thermal comfort. Therefore, 219 schools fall within the 'Critical' category. (Figure 4)

The SCI score graph of the schools in Dhaka shows a normal distribution of critical schools with a minimum value of -0.2, a maximum value of 0.29. The average SCI score of the schools is 0.022, with a standard deviation of 0.069. It indicates the schools show lesser variability in SCI scores and higher resemblance within the contexts. (Figure 3)

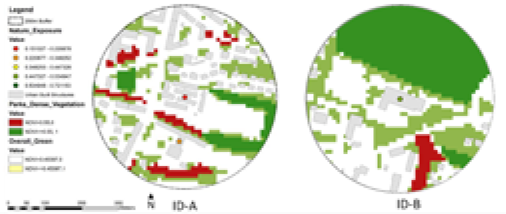
4.5 Urban Green Management Framework Based on SCI Model for EEP Establishment

As shown in Figure 5, the wholistic UGMF based on the SCI model establishes a connection between nature preservation and the active participation of school students and the local community. The framework includes the initial idea of Eco-school district development and contextualized EEP based on the school neighbourhood requirement. Amongst all the considered indicators of School Criticality Index (SCI), overall greenness within 250m buffer and road density showed strong impact on the criticality score of the school neighborhoods which indicates more/less potential for EEP establishment (Table 2). Therefore, the main focus of intervention for improving SCI was School Premise Greening and Green Corridor establishment. (Figure 4)

Intervention scenario	School Id	Exposure	Zonal Sensitivity	Adaptive Capacity	Adjusted SCI
Current Situation SCI Score	C	0.429491	0.59202	0.290023	0.082568
	D	0.261291	0.580409	0.470745	-0.12157
Proposed Situation SCI Score	C	0.328524	0.59202	0.305961	0.013357
	D	0.261291	0.580409	0.504088	-0.14092

Table 2. Current SCI score Vs proposed UGMF based scenario SCI score of two selected schools in Dhaka (Excel) (Table: Keya 2021)

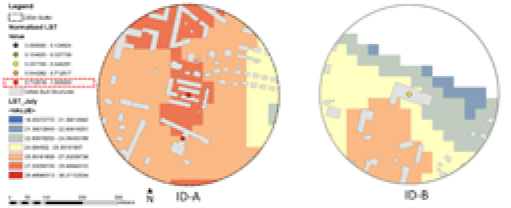
Comparison of Natural & Urban Environmental Stressors in Both Cities



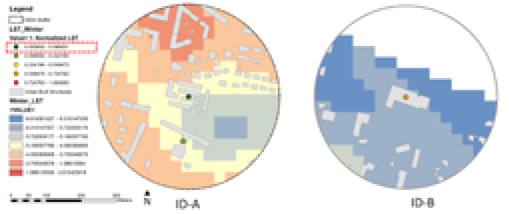
Exposure to Natural Elements in Selected Schools in Lahti

School ID	Distance to Parks (m)	Overall Vegetated Area, NDVI>=0.45397 (sqm)	Parks Active Green (sqm)	Distance to Blue (m)	Blue Area (sqm)
B	58.0149	115700	68600	1046.571	0
A	178.2827	15100	1600	1286.54	0

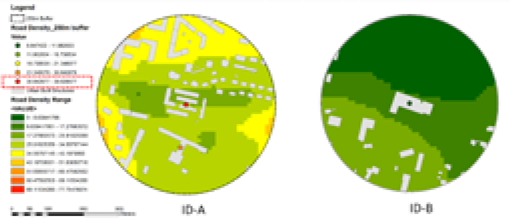
Overall exposure to nature in schools in Lahti



Summer Land Surface Temperature (LST)



Winter Land Surface Temperature (LST)



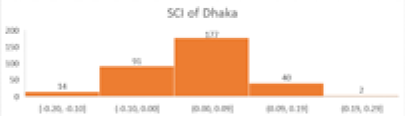
Road density area within 250m buffer (Road Density Area= cell * 100)

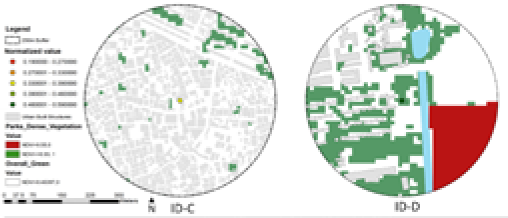
School ID	Road Density (Sqm)	Mean LST_July2020 (°C)	Mean LST_March2020 (°C)	Normalized Urban Environmental Exposure (E)
B	1196.28	24.68	-6.20372	**0.41**
A	3672.01	26.48	-4.09679	**0.56**

Overall exposure to urban stressors in selected schools of Lahti

Identifying Urban Environmental Stressors Affecting EEP Behaviour

Adaptive capacity		**Exposure**		**Sensitivity**	
Indicator	Value/ impact	Indicator	Value/ impact	Indicator	Value/ impact
Proximity to Accessible Parks	More/ +	Land Surface Temperature	More/ +	Coefficient of Variation (CV) (Turbulance)	Less/ +
Overall Greenness within 250m	More/ +	Road Density (AQ, Noise) within 250m	More/ +	Porosity	Less/ +
Active green/trees in parks within 250m	More/ +	Number of students	More/ +	Zonal windshadow	More/ +
School Field Area	More/ +				
Proximity to Water bodies	More/ +				
Waterbody areas within 250m	More/ +				

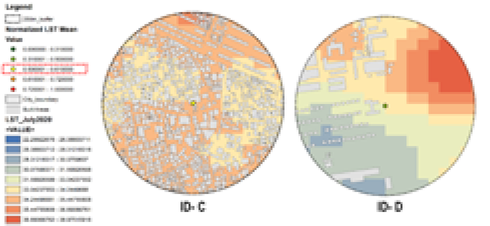




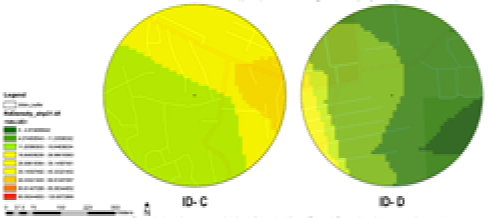
Exposure to Natural Elements in Selected Schools in Dhaka

School ID	Distance to Parks (m)	Overall Vegetated Area, NDVI>=0.45397 (sqm)	Parks Active Green (sqm)	Distance to Blue (m)	Blue Area (sqm)
D	84.67	90100	0.00	124.63	2600
C	267.75	10900	0.00	310.53	0

Overall exposure to nature in schools in Dhaka



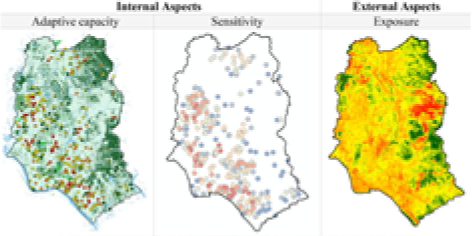
LST within 250m buffer of Schools during Summer (July 2020)



Road density area within 250m buffer (Road Density Area= cell * 100)

School ID	LST (Summer) (°C)	Road Density (sqm)	Normalized UE Exposure (within 324 schools)
C	34.4	2762.50	0.425615
D	33.06	1171.00	0.263029

School Criticality Index Developement for Dhaka



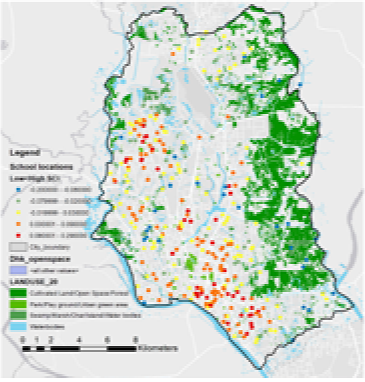


Figure 3. Urban Environmental Stressors Analysis for Selected Schools in Lahti and Dhaka (Figure: Keya 2021)

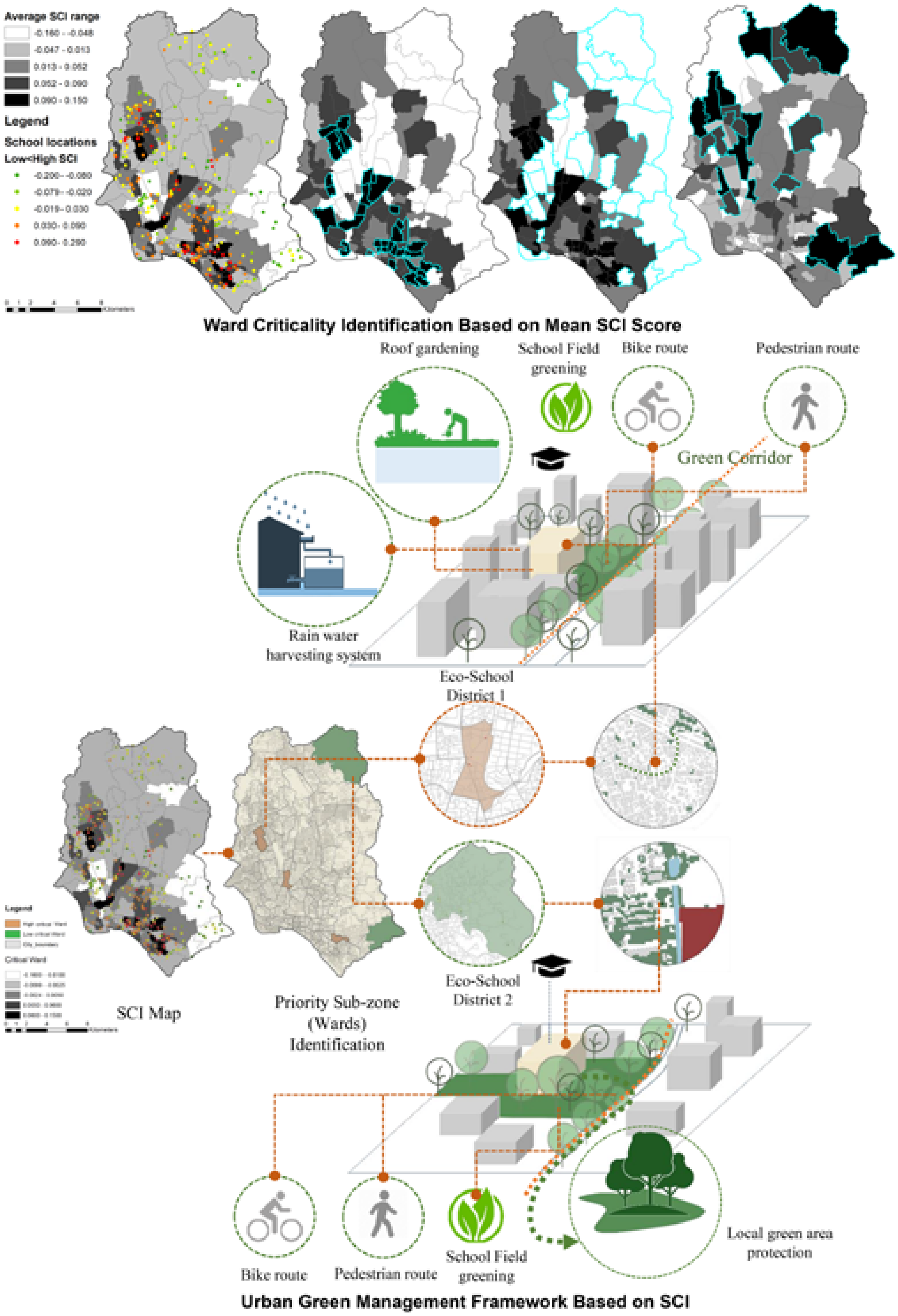


Figure4. SCI Model Based Wholistic Framework of Urban Green Management (UGM) for Environmental Education Practice (EEP) (Figure: Keya 2021)

5 Conclusions and discussion

Environmental Education as a concept has been practiced in many countries for environmental awareness and sustainable lifestyle practices. Even though, the main concept is to make people aware of environmental challenges, knowledge on global scale regardless being aware of local context might not be an effective approach to Environmental Education establishment. This study contributes to the understanding of contextual or local environmental factors that can potentially trigger different environmental behaviour amongst adolescents.

The comparison of student's responses from both cities contributes to understanding contextual differences affecting outdoor activity willingness and pro-environmental behaviour amongst adolescents. The students to have never undertaken any outdoor activities also showed lesser pro-environmental behaviour and disconnectedness from outside nature. Moreover, pro-environmental behaviour (e.g., walking to school) amongst students was higher in the close green proximity schools in both cities. The adaptive capacity of the schools in Lahti during Covid-19 indicates the relation to the availability of accessible nature within 250m distance of the school. On the other hand, schools have been closed since March 2020; despite government and educators' attempts to bring the students back to school premises maintaining social distancing, finding 'enough' space outdoor has been the most crucial problem. The inability to cope with the Covid-19 situation indicates the necessity of open school premises and greeneries within proximity of schools for an effective and resilient Education system. This finding adds more importance to the results on the school ground and greeneries within 250m buffer being more effective than distant green.

In addition to proximity to green being necessary for frequent visits, 'overall greenness within 250m buffer' showed a stronger correlation with thermal comfort in both cities. Moreover, Lahti and Dhaka students' responses showed that thermal comfort plays a significant role in adolescents' willingness for Outdoor Educational activities. The findings from this study indicates that on a neighborhood scale, the quantity of green space is also equally important for promoting outdoor activity therefore enhancing health, well-being, and stress reduction. The findings also contribute to the research gap of identifying which parameters of the urban built environment can directly or indirectly affect EEP establishment in cities.

The SCI model can be a silver lining in the debate of compact city and urban green preservation since it considers neighbourhood-scale greening and reconnects local green areas with schools for EEP in cities. Furthermore, the model promotes local environment enhancement through greening within 250m buffer of schools as the most crucial parameter for outdoor Environmental Education practice leading to better health and well-being of the students. The SCI based UGM framework combines the concept of Person-Environment Interaction Model (PEI) for pro-environmental behaviour development and elements of Attention Restoration Theory (ART) for positive impact on school going students. Connection with local green areas as idyllic places for 'Being away' and 'green corridor' as 'Trails' and 'Pathways' for extent is considered for vice-versa effect on dwellers and the environment (Kaplan & Talbot 1983; Kaplan

1995). The model is a contribution to the research gap about 'how' EEP based urban green management framework can contribute to local green management considering schools as a center for sustainable development. For EEP establishment, the SCI based UGM framework allows policymakers to identify districts with schools with similar high or low SCI scores, which can lead to 'Eco-Schools District' development with common regulations for district specific and school specific interventions.

The proposed School Criticality Index (SCI) shows 'how' school neighbourhoods can be evaluated for EEP establishment potential considering the context specific morphology and natural elements. The extent to which the schools can enhance local climate following the proposed SCI model-based Urban Green Management Framework (UGMF) needs further research. Future scope of studies can be: analysing the impact of SCI based UGM on enhancing school neighborhood micro-climate, developing transportation system of the school neighborhoods, and reducing urban flooding.

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15

Semi-Automated Workflow for Multi-Scale Analysis of Heatwaves

A Case Study of Lyon, France

Globally, the frequency, severity, and length of heatwaves have intensified and are expected to increase. While many methods for estimating heatwave risk and mapping methodologies have been developed; a comprehensive, harmonized multiscale assessment of the most impacted areas remains absent. Currently, heatwave risk assessments are either too generic and do not adequately represent the heterogeneous urban landscape, or require a large amount of data, are computationally intensive, and take a long time at the microscale level. This research developed a novel semi-automated approach to analyze heatwaves at two different scales: city and neighborhood. Thirteen of the most frequently used machine learning algorithms and seventy factors were tested for heatwave hotspot identification. The workflow combined city-scale analysis into neighborhood-scale analysis by examining the most severely affected areas in more detail, and greening scenarios were applied to simulate the appropriate heatwave mitigation threshold. It is crucial for decision-makers to quickly explore hotspots at different scales to efficiently allocate emergency operations promptly and plan future mitigation strategies to reduce the effect of a heatwave in the most impacted areas.

1 Introduction

Airborne remote sensing data is commonly utilized before a severe event to map the regions most susceptible to heat exposure and mortality and provide an effective alert system. The city-scale temperature reference based on meteorological station data is overly generalized for heatwave risk and does not designate the heterogeneity of the urban environment (Jedlovec et al. 2017). Efficient resource management necessitates concise data processing as well as assimilation at specific scales, with the core principle being that the larger the area of interest, the more aggregate data that can be considered at the expense of thematic differentiation and spatial accuracy of the map components (Weiers et al. 2004). Even though various approaches have been used to estimate heatwave risk and mapping procedures, a complete standardized multiscale evaluation of the most impacted areas remains absent (Zhou et al. 2018). Therefore, a new workflow that requires limited data sources that can also resolve the feature selection challenges and define heatwave risk concerning an urban environment in a more thorough method is urgently required.

In recent years, research into mitigating the impact of Urban Heat Island (UHI) has risen in popularity. In the literature, a variety of urban mitigation techniques have been suggested, including the use of highly reflecting construction materials, attention to building geometry, improving urban vegetation proportions, and the use of green and cool roofs (Akbari et al. 2016; Santamouris 2013; Yang et al. 2018). Most research suggests that increasing the percentage of green spaces and using higher reflectivity materials in metropolitan areas can assist cities in mitigating UHI. Microscale mitigation solutions rely on a wealth of data from a range of sources, including meteorological and detailed urban morphology dynamics (Akbari et al. 2016). The process is usually computationally intensive, time-consuming, and requires proprietary software to simulate scenarios.

1.1 Aims & Objectives

Based on the current situation, this research intends to:

1. Assess the efficiency of thirteen machine learning algorithms in identifying the most vulnerable areas in a heatwave-affected region.
2. Test various climate, land use/land cover, topographic, socio-demographic, and urban morphology metrics to determine the factors that contribute most to the model.
3. Create heatwave risk maps that decision-makers can easily interpret with little to no GIS/technical expertise.
4. Simulation of greening scenarios to mitigate the effects of most impacted areas.
5. Package the workflow with minimal user input while rapidly quantifying the most vulnerable areas.

Ultimately, this study aims to answer the resulting important questions: 1) Which machine learning model produces the best results in heatwave hotspot identification? 2) What factors contribute the most to the model prediction? 3) How are the factors correlated to heatwave risk? 4) What are the connections between hazard and vulnerable populations, and how are heatwave risk hotspots distributed spatially? 5) How much greening is required to sufficiently reduce heatwave risk? The answers to these questions will impact emergency response efforts during a heatwave and future urban planning efforts in mitigating the effects of a heatwave in Lyon, France.

2 Background

2.1 Heatwave Overview

Climate change-related hazards have increased in recent decades, particularly in heatwave severity and frequency, and are anticipated to persist throughout the twenty-first century. The Intergovernmental Panel on Climate Change (IPCC) has identified heatwaves as one of the extreme weather events associated with climate change (Smith et al. 2009). Worldwide, the frequency, intensity, and duration of heatwaves have increased and will continue to increase. Heatwaves are one of the deadliest natural hazards, yet they get limited attention since their fatalities and damage are not usually immediately apparent (Mushore et al. 2018). Climate change is increasing the vulnerability of communities globally to heat, and this trend will continue. In the 19 years between 1998 and 2017, around 166,000 individuals have died from heatwaves. During the 2003 European heatwave, more than 70.000 people died in Europe (World Health Organisation 2017).

2.2 Urban Heat Island (UHI)

Heat has been exacerbated as a result of urbanization and the increased number of people living in cities (Sultana & Satyanarayana 2020). Heatwaves significantly have a negative impact on urban areas due to the large area of rough artificial surfaces, regional and local climatic conditions, and a lack of vegetation and green space, resulting in variations in air temperatures and the development of intense urban heat islands (Cui et al. 2016). The UHI signifies the temperature difference between urban and rural areas, and the magnitude of the UHI in urban areas is positive. Numerous studies have established a strong link between heatwaves and human mortality due to their intensity, frequency, and duration (Akhtar 2020; Arsenović et al. 2019; Stafoggia et al. 2006). Death from heat-related illness is among the most severe public health threats identified in these findings. Elderly, children, socially marginalized, and chronically ill individuals are among the demographic categories most vulnerable to heatwaves. According to one study conducted in China, the urban heat island effect contributes around 30% to global warming (Huang & Lu 2015).

2.3 Classification

The ability to automatically classify urban structures has dramatically improved over the previous decade due to better classifiers and the availability of more detailed data sets (Bechtel & Daneke 2012). Urban surface and structural analyses using Synthetic Aperture Radar (SAR), thermal, hyperspectral, and high-resolution optical data are among the most common applications (Li & Guo 2016). More deaths are due to heatwaves than by any other natural phenomenon, and so, many researchers examined the temperature threshold that might have more adverse health impacts on the population (Wilhelmi and Hayden 2010). Gosling, McGregor, and Páldy 's (2007) findings are based on a thorough examination of specific thresholds and accompanying death rates. Mortality increased as a result of not only the occurrence of extreme heat events but also owing to the increased intensity and duration of the heatwave exposure. Farhan, Pattipati, Wang, and Luh (2015) tested multiple machine learning algorithms using environmental and physiological factors to predict individual thermal comfort with support vector machines (SVM) obtaining the highest accuracy of 77%. Although this exposure has severe health implications, it is also a result of other factors, including population sensitivity to temperature, their ability to tolerate and react to a temperature increase (Wilhelmi & Hayden 2010). These groupings have been mainly defined qualitatively, integrating utility and structure characteristics. As a result of this variation, there is limited transferability and inconsistent outcome comparability (Bechtel & Daneke 2012).

2.4 Heatwave Mitigation

In recent years, research into mitigating the UHI impact has risen in popularity. In the literature, a variety of urban mitigation techniques have been suggested, including the use of highly reflecting construction materials, attention to building geometry, improving urban vegetation proportions, and the use of green and cool roofs (Akbari et al. 2016; Santamouris 2013; Yang et al. 2018). All of this research suggests that increasing the percentage of green spaces and using higher reflectivity materials in metropolitan areas can assist cities to mitigate UHI. However, most models require large amounts of data spanning several years to predict greening situations correctly. Data gathering and processing takes time, requires constant data input from numerous sources at an extremely high spatial resolution over a long period, and is often tailored to a particular city (Santamouris & Osmond 2020).

2.5 Mapping Challenges

The fact that urban and microclimate simulations have higher resolution and more precise data does not exclude their spatial distribution throughout a city because of their high processing costs and the complexity of the elements that are vital to their operation (Demuzere et al. 2014). The results of mesoscale systems have yet to be conclusive in terms of the UHI's large-scale consequences. Although they have some capabilities, they are not effective in explicitly assessing and defining a heterogeneous urban environment (Zhao et al. 2019). To create spatially and computationally viable frameworks, more research is needed to address this unsettling challenge. Current geographical and temporal data are typically captured over a variety of time intervals when data is collected from several sources. Future studies should collect spatiotemporal data over the same time period, and researchers should eventually develop models that incorporate meteorological and urban texture components (Scott et al. 2014). The lack of a workflow connecting extreme temperature analysis from different scales is severely lacking.

Furthermore, while the amount of information available for decision-making has increased, the ability of humans to properly comprehend and utilize this information in disaster management has dropped. Humans are at a disadvantage in instances where actions must be made instantly. A challenge currently observed in the field is the successful incorporation of analysis into a format that is easily interpreted and accessible to the decision-maker (Sultana & Satyanarayana 2020).

3. Methodology

The study proposes a new semi-automated approach for analyzing heatwaves at various scales depicted in Figure 1. Data from Landsat 8 satellite imagery and auxiliary data on socio-demographic, topographic, and environmental factors are clipped to the area of interest and preprocessed to normalize the data due to its multi-source origin. Preprocessing data is a critical stage in machine learning. The quality of the data and the valuable information obtained from it directly affect the model's learning capacity; the data needs to be calibrated and preprocessed before feeding it to the model. Preprocessing is the methodical process of assimilating data into a standardized product via filtering, integration, reduction, and transformation (Pant 2019). The preprocessed data is then routed to the city's lowest level divisions, referred to as "blocks" (or "IRIS" in French), which are analogous to census block groups in the United States of America or the United Kingdom's lower super output areas. The IRIS blocks containing information about 70 factors are then fed into 13 machine learning algorithms for classification. Individual model definitions and hyperparameter adjustment are performed to optimize the accuracy of each model. The relevance and weight of each element contributing to each model are then examined coupled with principal component analysis (PCA) to determine the most significant factors contributing to the prediction of the LST, which is utilized as the premise for defining heatwave hazard.

Zonal statistics is applied on the LST using IRIS boundaries and the result is classified into four groups based on intensity: Low, Moderate, High, and Extreme. The machine learning model with the highest overall accuracy and accuracy within the "Extreme" class, which represents the most severely affected areas by heatwaves, is then chosen, along with the factors that contributed the most to the model using the magnitude of feature attributions. Multi-criteria analysis (MCA) is performed on the resulting machine learning output, demonstrating the heatwave's hazard in conjunction with the factors affecting the most vulnerable population. The MCA-created map will highlight the most severely affected locations, allowing emergency responders and decision-makers to plan and prioritize crucial assistance when resources and time are limited. Next, lidar data for the most afflicted neighborhoods is retrieved to study the areas further. Lidar data provides a more detailed three-dimensional depiction of the site, allowing for additional study of the variables contributing to the higher temperature of the IRIS blocks. After converting the 3D analysis to model-compatible data, it is used to run several simulations for heatwave mitigation. The most severe IRIS blocks are examined using several scenarios involving green roofs and increased vegetation cover to understand better the implications of various mitigation techniques and their overall effect on temperature. The results will assist city planners in determining the amount of effort necessary to mitigate the areas in the future successfully. Natural disaster management necessitates the rapid integration and dissemination of knowledge; consequently, an online interactive map will contain the research findings, allowing for simple distribution and revision of information with all parties involved.

The workflow is divided into five distinct stages:

1. Preprocessing and Zonal Statistics
2. Evaluation of the Machine Learning Model and Feature Importance
3. Multi-Criteria Analysis and Production of Heatwave Risk Map
4. Simulations of Heatwave Mitigation Strategies
5. Interactive Online Map

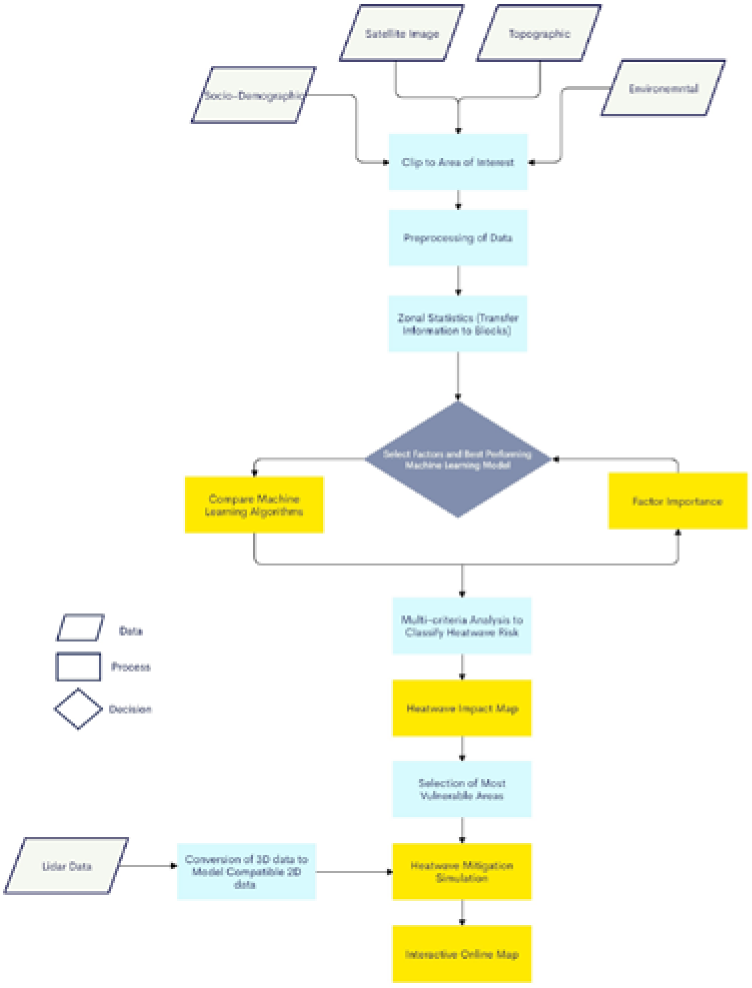

Figure 1. Overview of Semi-Automated Workflow (Figure: Popal 2021)

4 Results

4.1 Model Evaluation

The accuracy results for the thirteen machine learning algorithms are depicted in Figure 2. Most models had an accuracy between 70% to 94%, except for AdaBoost (ADA) Classifier, which performed poorly. Models constructed using linear regression (LR), logistic regression (LDA), support vector machine (SVM), naive bayes (NB), k-nearest neighbors (KNN), and neural networks (MLP) all performed well, with accuracies ranging from 70% to 80%. The models demonstrated the most significant degree of confusion between the intermediate classes. Confusion may arise due to the models being calibrated to be extremely sensitive to the Extreme class, resulting in the incorrect classification of the intermediate classes. The decision tree (Tree) and ensemble (CART, GBC, RF, and XGB) learning algorithms had the highest accuracy scores, ranging around 90%. Tree-based algorithms facilitate predictions with high accuracy, consistency, and interpretability. In comparison to linear models, tree-based and ensemble algorithms can accurately map nonlinear relationships. The best performing model was the XGBoost (XGB) classifier, with an accuracy of 94%. Gradient boosting algorithms are highly effective classifiers/regressors that work exceptionally well on structured data.

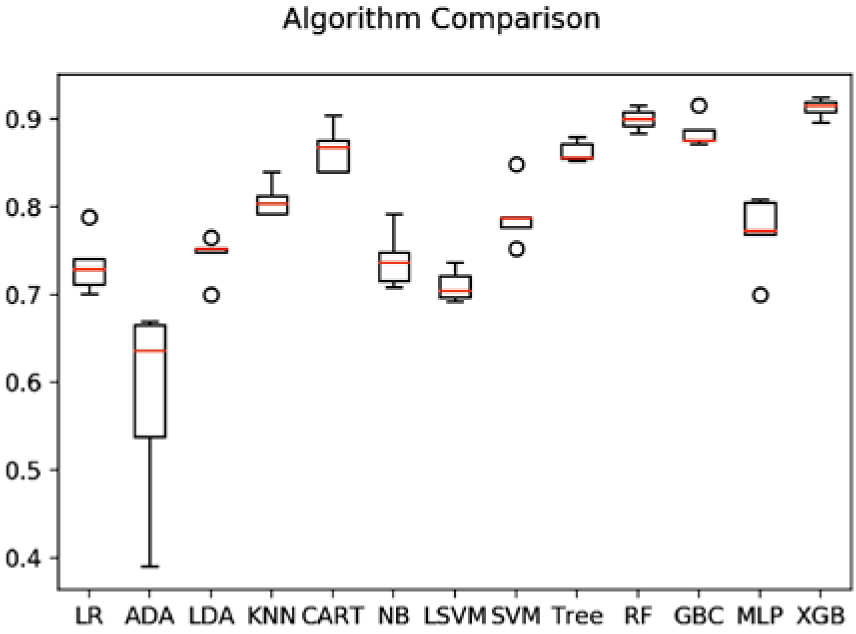

Figure 2. Machine Learning Model Accuracy for Predicting Heatwave Hotspots (Figure: Popal 2021)

4.2 Feature Importance

Figure 3 depicts the top 20 results of SHAP feature importance for the machine learning models. The feature importance is plotted in decreasing order of importance, and the predictor significance diagram illustrates each predictor's relative value and relationship to the outcome. The six most significant factors selected for the heatwave hotspot identification model were normalized difference built-up index (NDBI), enhanced vegetation index (EVI), digital elevation model (DEM), albedo, percent of industrial area to IRIS area (Industrial_A_P), and percent of low-skilled workers living in the IRIS (Workers_P). The correlation with temperature and the overall influence on the model help understand the underlying relationship among the factors in predicting heatwave risk. The factors were selected based on importance in the model encompassing all 70 factors as well as the PCA analysis, which indicated which combination of factors worked in cohesion. NDBI and the percent of low-skilled workers positively correlate with temperature, whereas EVI and DEM negatively correlate with temperature. Percentage of industrial area and albedo both have a very weak varying correlation with temperature. As for influence, NDBI has the most significant influence with around 30%, followed by percent of industrial area and EVI accounting for 18%. Albedo is next with 14% and finally, DEM and percent of low-skilled workers follow close behind.

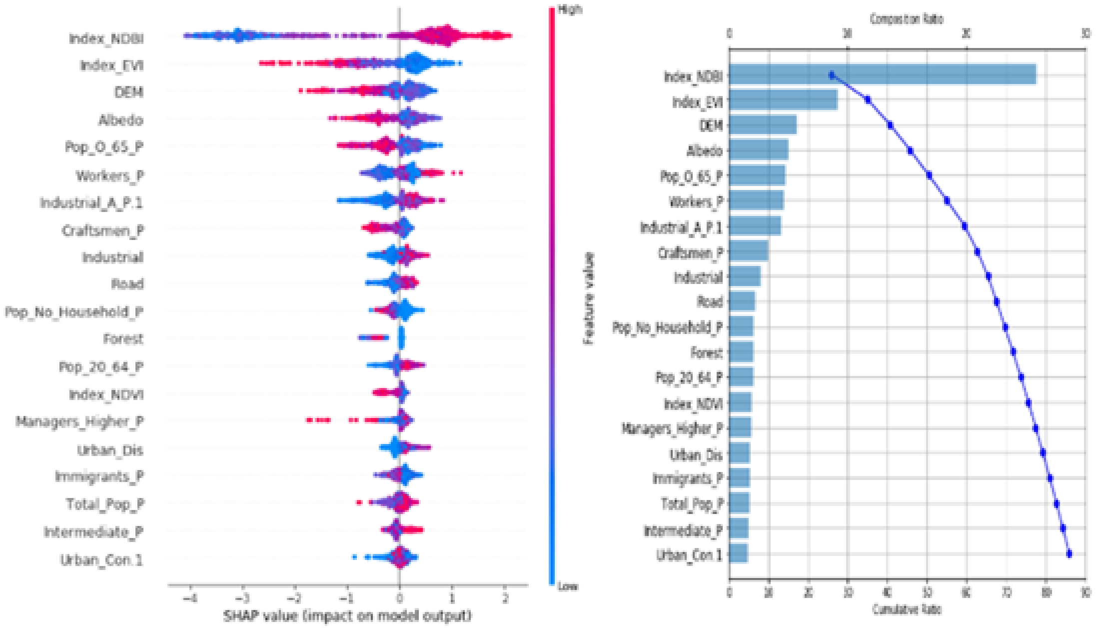

Figure 3. Feature Importance Analysis for Top 20 Factors: Feature Correlation with Temperature (Left), Feature Contribution to the Model (Right)) (Figure: Popal 2021)

4.3 Heatwave Risk Map

Figure 4 depicts the final heatwave risk map. The combined vulnerability and hazard map reveals a distinct pattern of the most susceptible IRIS boundaries. In the central and eastern areas of Lyon, the highest risk is concentrated. Three IRIS limits are categorized as Extreme in total. The combined map reduced the Extreme class to three from about twenty IRIS zones on the individual hazard and vulnerability maps. Limiting the IRIS to a smaller number of possibilities will assist emergency responders and decision-makers allocate scarce resources to the most impacted regions during a heatwave. The results show that Lyon heatwave risk is not solely influenced by the most urbanized areas but rather a mix of a few factors. The IRIS zones with high NDBI values in the proximity of industrial buildings or zones are most at risk, evident by the eastern part of Lyon being at higher risk due to the higher proportion of industrial activity. The anthropogenic heat and increase in greenhouse gas emissions caused by industrial zones could have a major negative effect on the microclimate of the zone. The three IRIS regions with the highest risk of heatwaves will be examined further on a larger scale to develop mitigating solutions.

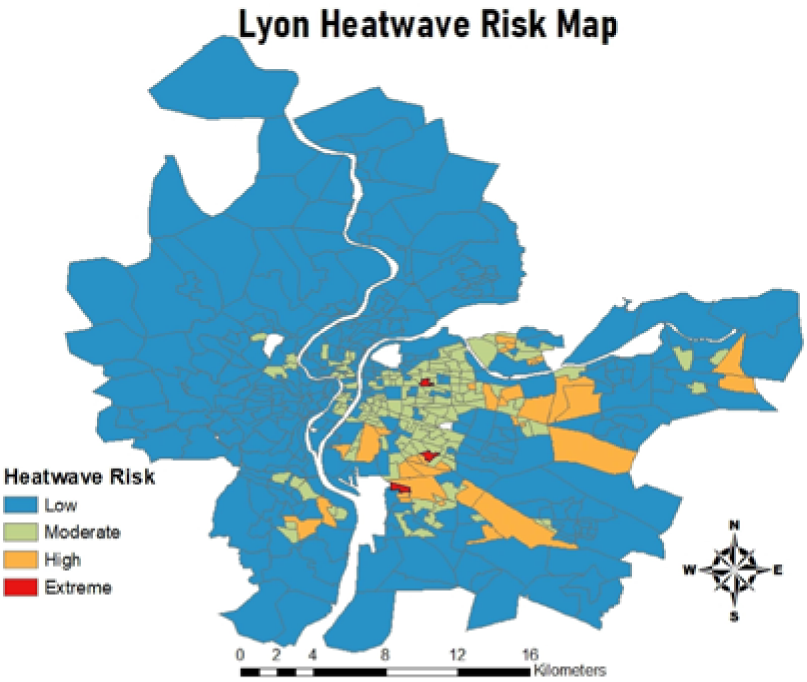

Figure 4. Heatwave Risk Map for Lyon (Figure: Popal 2021)

4.4 Heatwave Mitigation Scenarios

The three most affected areas were simulated into three different greenifying scenarios: 25%, 50%, 75% of the available area. The outcomes of the situations are shown in Table 1. The result of the scenario is provided in terms of temperature and heatwave risk categorization. The heatwave risk classification will indicate if the change was sufficient to shift the categorization from Extreme to High or away from the top 2.2% of overall risk. In essence, it would indicate if the scenario had sufficiently decreased the risk for the IRIS by not being categorized in the most extreme class.

	Villeurbanne	Lyon 8E Arrondissement	Saint-Fons
Original Temperature	40.64	40.83	40.28
Original Risk Class	Extreme	Extreme	Extreme
25% Green Roof & Vegetation (Temp)	40.42	40.52	39.97
25% Green Roof & Vegetation (Class)	Extreme	Extreme	Extreme
50% Green Roof & Vegetation (Temp)	40.22	40.31	39.80
50% Green Roof & Vegetation (Class)	High	High	High
75% Green Roof & Vegetation (Temp)	40.16	40.13	39.43
75% Green Roof & Vegetation (Class)	High	High	High

Table 1. Results of Simulation of Greening Scenarios (Table: Popal 2021)

Overall, the simulations demonstrate that mitigating the effects of a heatwave on an IRIS that is more densely inhabited with more structures is significantly more challenging than mitigating the impact of a heatwave on a more balanced IRIS. Even with greater greening intensity, the benefits appear to be diminished, compounding the difficulty of mitigating the effects of UHIs in an urban context. Greening 25% of the available areas for all three areas resulted in a minor change in the total temperature and heatwave risk class, with the model continuing to classify all three areas as Extreme risk. By greening 50% of the available space, all three locations were lowered to High risk, indicating that the mitigating actions were partly successful. The temperature reduction between 0.42°C and 0.52°C was similarly substantial. The importance of other factors contributing to the model can also be seen in Saint-Fons, where a temperature of 39.97°C was classified as Extreme after 25% greening. In contrast, Villeurbanne and Lyon 8E Arrondissement had temperatures of 40.22°C and 40.31°C, respectively, after 50% greening and were classified as High risk. The higher elevation may explain the classification discrepancy, which correlates negatively with temperature and the higher concentration of low-skilled workers in Saint-Fons compared to Villeurbanne and Lyon 8E Arrondissement. The 75% greening scenario had a negligible effect on Villeurbanne, a mediocre effect on Lyon 8E Arrondissement, and a significant influence on Saint-Fons, but not enough to classify any of the areas to a lower overall risk class.

5 Conclusion and Discussion

The research developed a novel semi-automated approach to analyze heatwaves at two different scales: city and neighborhood. Thirteen of the most frequently used machine learning algorithms were used in this research to determine which algorithms delivered the best results for heatwave hotspot identification. XGBoost classifier provided the highest accuracy of 94% and was chosen as the algorithm to base the model on predicting heatwave hotspots. NDBI, EVI, Industrial_A_P, Albedo, Workers_P, and DEM are the factors that contributed the most to the projection of heatwave hotspots. NDBI was the most significant factor in the model, accounting for 30% of the total. NDBI, Industrial_A_P, and Worker_P had a negative correlation to temperature whereas EVI, albedo, and DEM had a negative correlation with temperature. The workflow combined city-scale analysis into neighborhood-scale analysis by examining the most severely affected areas in more detail, and greening scenarios were applied to simulate the appropriate heatwave mitigation threshold. Greenifying 50% of the three most impacted IRIS was sufficient to reduce the risk from Extreme to High, resulting in a temperature decrease of 0.42°C to 0.52°C. The model's capacity to forecast heatwave hotspots in other locations was not confined even though it was trained on a heatwave event in Lyon, France. Heatwave intensity was classified using standard deviation statistics based on relative measures rather than absolute temperature readings. When applied to Glasgow, UK, the model produced an accuracy of 81% during the 2018 heatwave that swept throughout Europe. It is crucial for decision-makers to quickly explore hotspots at different scales within a heatwave-affected region to efficiently allocate emergency operations promptly as well as plan future mitigation strategies to reduce the effect of a heatwave in the most impacted areas.

Additionally, the study had several limitations. First, due to a lack of data, the factors included in the analysis may have been incomplete, decreasing the prediction performance. The factors used in the model came from various data sources from different times, sometimes spanning over 10 years which is not representative of the latest ground data. Second, the model was trained on one heatwave event in one city, to facilitate processing time. The research data set consisted of two satellite images obtained around a heatwave, which was relatively brief in comparison to other climate studies. Deriving LST from a single heatwave event might be influenced by various meteorological conditions such as precipitation and wind speed, therefore further case studies in several urban settings and seasons can validate and improve the results of the research. Cities in various climate zones and data collected over extended periods would expand the data range and representation. Third, various medical incident data from the heatwave and crowdsourced Twitter data can be used to conduct a complete analysis since the data can display exactly where the vulnerable population is located. Finally, the accuracy of existing predicting models is exclusively predicated on LST values derived from satellite images, with no ground-based verification.

This study demonstrated a method for rapidly evaluating the IRIS with minimal resources and established a framework for incorporating the method into a more comprehensive methodology for analyzing heatwaves at the neighborhood level. Although the cooling effect of vegetation is significant, based on the findings of this study and previous literature, future research could include vegetation attributes including canopy height, flora species, and biomass, because the cooling effect is reliant on not just the presence of vegetation but also on its type, shape, and size. Additionally, wind is inextricably linked to urban morphology characteristics and can significantly impact UHIs, which was not examined in this study. As a result, it is advised that future research incorporate wind circulation and wind velocity. Locality considerations may assist enhance the methodology in the future by integrating variables such as the kind and location of the intervention since various mitigation actions will have varying degrees of efficacy when considering urban morphology indicators. Also, the results of in situ data regarding greenifying change can be incorporated into the model to calibrate the weights and produce more realistic results.

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The second MUrCS (Master in Urban Climate and Sustainability) proceedings introduces 15 articles by students graduated from the programme in 2021. The articles are classified under the main themes Climate change adaptation in different urban contexts and Urban Heat Island (UHI) in connection with urban overheating mitigation. Three articles represent cross-cutting studies: mobility emissions, environmental education and analysis of heatwaves.

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ISBN 978-951-827-400-4 (PDF)

LAB University of Applied Sciences

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