A Critical Evaluation of Different Methods of Urban Climate Mapping: A Case Study of Glasgow City

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A thesis submitted for the Joint programme of
Master in Urban Climate & Sustainability

August, 2021

<table>
<tr><td rowspan="2">Author
Begum Rabeya</td><td>Publication type
Thesis</td><td>Completion year
2021</td></tr>
<tr><td colspan="2">Number of pages: 92</td></tr>
<tr><td>Supervisor I
Prof. Rohinton Emmanuel</td><td colspan="2">Supervisor II
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<tr><td colspan="3">Title
A Critical Evaluation of Different Methods of Urban Climate Mapping: A Case Study of Glasgow City</td></tr>
<tr><td colspan="3">Degree: Master in Urban Climate & Sustainability</td></tr>
<tr><td colspan="3">Abstract
The urban climate is a modified urban atmospheric phenomenon shaped by urban morphology and land use pattern. Urban Heat Island (UHI) is an emerging urban climatic concern that increases the heat risk likelihood in urban settings together with the global climate change effect. This dissertation has undertaken an urban climate mapping exercise with available climatic, socio-economic, and terrestrial datasets to visualize the urban heat risk (UHR) analysis in a spatial framework for Glasgow city, largely evaluating the methodological processes for several alternative features. With an abductive approach, simple mixed-method research is designed to integrate both qualitative and quantitative secondary data. This study has used nine base indicators for hazard, exposure, and vulnerability components to synthesize UHR with both map algebra and weighted overlay techniques in ArcGIS. The resultant UHR maps identify the climate-sensitive hotspots in the highly built environments including the city center alongside the river Clyde. Moreover, the thesis demonstrates that both GIS techniques provide a similar overarching results, but map algebra gives heterogeneous spatial UHR distribution at a smaller scale. As for two alternative hazard components (Land Surface Temperature and Air Temperature), this study found that LST-based maps give a detailed and pragmatic reading compared to air temperature as air temperature data is coarse and of poor quality. This study infers that the selection of the number and type of indicators and risk components, and spatial analysis technique affect the UHR outputs spatially. It is concluded that climate-cautious priority intervention can be identified through UCM which is further dependent on the mapping’s methodological choices. Thus, the local government should pay careful attention to the mapping methods to attain desired UCM results. As for implication, based on the Urban Climate Planning Recommendation Map, the study recommends to preserve the green spaces that provide cooling benefits and take immediate actions for climate-sensitive hotspots by incorporating urban green infrastructure at both local and city scales.</td></tr>
<tr><td colspan="3">Keywords
Urban climate mapping, Urban heat risk analysis, Green infrastructure, Glasgow city, Ecosystem service mismatch, Sustainable urban planning, Comparative analysis</td></tr>
<tr><td>Originality statement. I hereby declare that this Master’s dissertation is my own original work, does not contain other people’s work without this being stated, cited and referenced, has not been submitted elsewhere in fulfilment of the requirements of this or any other award.</td><td colspan="2">Signature</td></tr>
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ACKNOWLEDGMENT

I would like to express my gratitude to Professor Rohinton Emmanuel to guide me with patience throughout the thesis project period. I also want to thank Dr. Jose Dueñas for supporting me regularly. The biggest support system of my personal life is my spouse, Md. Zakir Hossain, who has encouraged and supported me at the same time to persist in good work and complete the thesis on time. Moreover, the immense support from my family helped me to overcome the personal issues and be strong psychologically. Besides, all my MUrCS colleagues played a key role by being in touch and helping in need.

I would like to thank Evan Mushfiq for teaching and explaining the GIS technique hand in hand that helped me to have a good command of ArcGIS. Besides, I want to thank my friends and well-wishers in different corners of the world to give me mental peace throughout the thesis period.

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CHAPTER 1: INTRODUCTION

This chapter introduces the thesis by enclosing the context and rationale of the research topic, aim and objectives, a briefing of methodology, and an outline of the report.

1.1 Rationale of the Study

Urban areas, as the nucleus of a country, are contributing to the country's economic growth. According to United Nations (2019), about 80% of global Gross Domestic Product came from cities, and approximately 55% of the world's population were urban inhabitants in 2018 that was projected to be nearly 68% by 2050. Rapid urbanization influences the near-surface urban atmosphere by transforming the landscape with intense urban forms and associated urban functions (Ren, 2015; Mills, 2015). Urban Heat Island (UHI) and air pollution are two of many urban climatic anomalies, which challenge human 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 (Henríquez & Romero, 2019; Larsen, 2015). Sustainable urbanization can address these urban problems (Knudsen et al., 2020) for which urban planners and decision-makers are the key levers. Sustainable urban planning can maintain and balance social, economic, and environmental sustainability, and provide a comfortable, affordable, and healthy urban environment (Parsee et al., 2019; Knudsen et al., 2020; CUHK, 2012). Thus, sustainable town planning needs climatic knowledge incorporated into planning and decision making (Ren, 2015).

However, researchers repeatedly highlighted the reasons for the lack of climatic context in the urban planning scheme. 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 climatology 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 researches followed the same fundamental concept (CUHK, 2012). However, evaluation of the UCM research methodologies is rarely seen. Thus, this thesis has attempted for an urban climate mapping exercise in form of urban heat risk (UHR) analysis for Glasgow city by using multiple processes. This study aims not only to carry out a UHR analysis

but also evaluates the synthesizing processes to test the practical application of available data, identify the climate-sensitive hotspots, and inspect the methodological factors affecting UHR mapping outcomes. Finally, the research findings will provide insights to Glasgow City Council (GCC) to improve its spatial planning and climate change adaptation strategies.

1.2 Aim and Objectives

This thesis aims to generate urban climate analysis maps in form of urban heat risk maps and planning recommendation maps for the City of Glasgow by incorporating socio-economic, terrestrial, and climatic parameters, which will contribute to the city's climate-sensitive urban planning.

The objectives of this dissertation are to:

1. Investigate the state-of-the-art for urban climatic maps (UCMaps) and their implication in city planning by identifying the link between urban features and urban climate.
2. Obtain and justify the relevant urban and climatic features required for urban heat risk mapping.
3. Identify the inflection points as well as barriers and opportunities in existing climate change adaptation plans and strategies of Glasgow city
4. Construct urban heat risk maps by using multiple methods and alternative approaches.
5. Scrutinize and critically evaluate the resultant atlases and the methods used to derive them along with delivering a planning recommendation map based on the findings.

1.3 Outline the Methodology

This study, primarily, intends to generate urban heat risk maps with several combinations of the relevant indicators in multiple processes. The research has processed the secondary datasets of various formats to prepare a homogenous raster dataset by using different tools of ArcGIS 10.6.1. Then, the processed dataset is divided into three risk elements (hazard, exposure, and vulnerability) which are, then, combined to create Glasgow city's heat risk maps through two popular spatial analysis techniques such as Weighted Overlay and Map Algebra. Tools like Google Earth, ArcGIS, and Microsoft Excel are used to carry out the research.

1.4 Outline of the Dissertation

The novelty of this dissertation is six-fold. The first chapter unfolds the rationale, aim, objectives, and outline of the thesis. The backdrop and published literature of the research topic are discussed and understood critically along with the reasoning of this study in the second chapter. The third chapter provides an overview of the study area, Glasgow city, and clarifies the process of data collection, data preparation, and requirement of chosen indicators and methods for the heat risk analysis. Chapter four delivers the heat risk maps along with a comparative analysis of resultant atlases. Chapter five brings in a critical discussion of the key findings in respect of published literature of the subject topic, and the implication of the study outcome. Chapter six will enclose the concluding remarks, limitations of the thesis, and scopes of further research.

CHAPTER 2: LITERATURE REVIEW

To attain the first objective of this dissertation, this chapter provides the background of the research topic along with identifying the gaps of existing studies and the motivations for this thesis.

2.1 Link between Urban Features and Urban Climate

Urbanization enforces urban inhabitants to engage in non-agriculture activities and transformation of natural landcover into the manufactured surface (Mills, 2015). Waste materials and energy produced through urban functions and metabolism affect the cities' thermal balance and air quality (Mills, 2015). Urban form is defined by cities' 2D and 3D features and their materials composition controls energy exchange in between the surface and its overlying atmosphere (Mills, 2015; Henríquez and Romero, 2019). In addition, urban geometry, an interface of three-dimensional urban form, influences ventilation route, shadow cover, and openness of the city (CUHK, 2012; Mills, 2015). Consequently, the near-surface urban atmosphere becomes very complex and diverse that generates urban microclimate at a local scale and urban climate at a macro scale.

Other factors like historical background, cultural context, and local government's decisions also affect the urban environment. Geospatial location determines access to the amount of annual and diurnal solar radiation and prevalent wind type and partly influences urban climate. The city's topography influences the local air circulation system by providing sheltering and/or creating an airflow channel (Mills, 2015; Ren, 2015). Thus, even though few climatic parameters such as precipitation and sunlight cannot be controlled, human-built urban areas affect other climatic features like temperature and wind pattern due to heat retention and discharge capacity and soil capping proportion (CUHK, 2012; Urban Climate Stuttgart, 2021). All these aspects together result in an urban climate, a modified climate overlying the urban territory (Henríquez and Romero, 2019; Mills, 2015).

2.2 Rise of UCM Studies

Long after the industrial revolution, only in the late 1950s, the rise of environmental awareness led to policy reformation and new regulations regarding environmental sustainability (Glasson et al., 2005). The scientists gathered evidence and proved that anthropogenic intervention gave

rise to global warming and induced global climate change (IPCC, 2014). On another side, 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 and Meseguer-Ruiz, 2019). Scientists and researchers also established the reciprocal relationship of urban warming (i.e., UHI) and climate change effect and their impacts on urban inhabitants' quality of life (Henríquez & Romero, 2019; Larsen, 2015; Emmanuel & Krüger, 2012; Mills, 2015; Oke et al., 2017; Ren, 2015; CUHK, 2008; Ashie et al., 2015; TMG, 2005). Krüger and Emmanuel (2013) stated that temperate regions face fewer consequences than tropical regions because UHI intensity is subject to vary spatially and temporally (Oke et al., 2017). Moreover, climate change worsens air pollution and intensify weather events like a heat wave, flood, 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 pointed out the role of UHI hit by extreme climatic events (Conti et al., 2005). Kalkstein et al. (2011) found that 1300 additional deaths occurred per year between 1975 to 2004 due to excessive-heat events in 40 cities of the USA. Even though cold-related death cases still supersede the heat-related deaths, UK Climate Projection 2018 estimates an increase of heat wave frequency due to climate change impact and thus, more death cases projection in the region (Lowe et al., 2018; Met Office, 2021f). Thus, sustainable urban planning is very crucial to ensure the health and safety of the world's majority population. In this regard, UCM research creates a bridge to convey climatic information in urban planning languages to contribute to sustainable urbanization (Mills, 2015; Ren et al., 2013; Ren, 2015; Henríquez and Romero, 2019; Knudsen et al., 2020). Urban Climate Mapping can play a key role in addressing urban climatic problems like extreme heat, air pollution, and flood through identifying climate-sensitive zones. Therefore, different cities tried to understand and address different climatic problems through urban climate mapping.

2.3 History of UCM

Urban climate mapping is a fifty-year-old concept that got initiated by Germany in the 1970s (Ren, 2015) after the rise of the environmental sustainability movement. Knowledge and information of the IPCC report stimulated the decision-makers to investigate the correlation of urban climatic parameters to urban problems. The first UCMap was created for the city of

Stuttgart of Germany to mitigate air pollution (Ren, 2015, Urban climate Stuttgart, 2021; Matzarakis, 2005). Till 2019, approximately 40 countries adopted them to enhance urban development without compromising the urban climate and quality of life of the inhabitants (Henríquez and Romero, 2019).

UCMap contains two key components: Urban Climatic Analysis map[1] (UC-AnMap) and Urban Climatic Planning Recommendation map (UC-ReMap) as shown in fig 2.1 (Ren, 2015). UC-AnMap visualizes and evaluates urban climate science data and land data in a spatial framework and discovers climatopes[2] (Ren, 2015). Moreover, UC-ReMap demonstrates planning instructions for climate-sensitive areas.

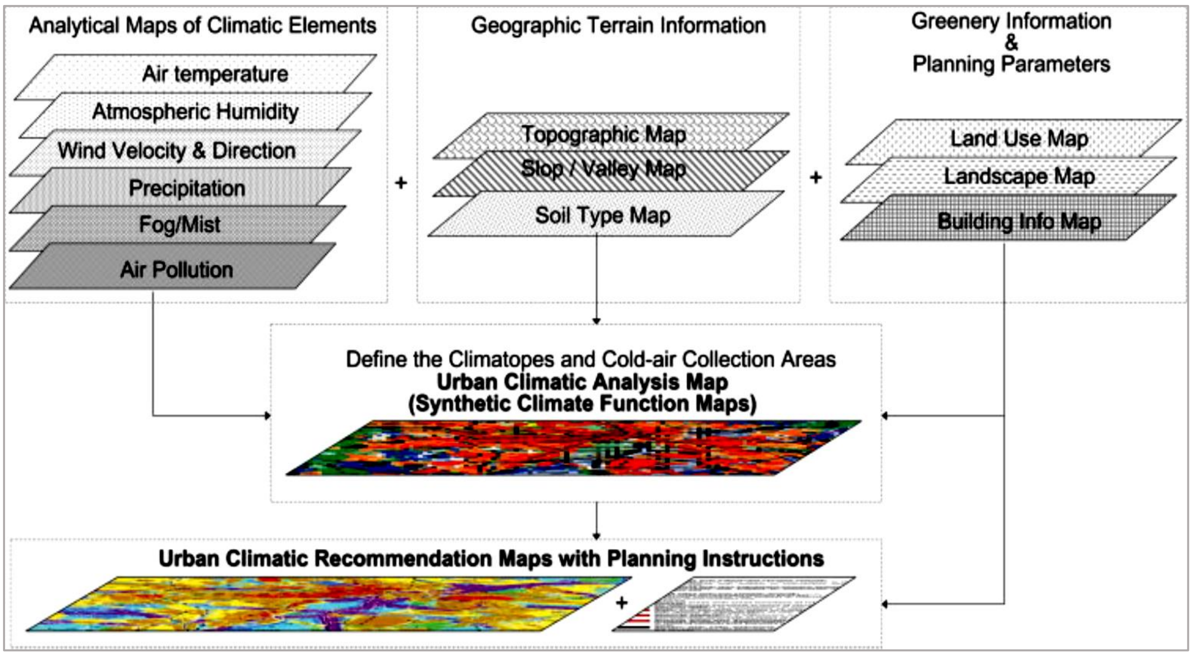


Figure 2.1: The general structure of urban climatic map system (Ren, 2015)

UCMap presents an overall picture of urban climate in a spatial framework and provides guidance to carry out a suitable development plan and revise it. There are no strict rules for creating urban climate mapping except a must consideration of climatic parameters. Although many cities adopted UCM studies by name, the process followed by each city is usually not identical because the selection of parameters depends on the purpose of doing the UCMs as

[1] Urban Climatic Analysis Map is also called as Synthetic Climate Function Map (Ren, 2015)
[2] The spatial units that distinguish areas with similar near-surface atmospheric characteristics (Oke et al., 2017; Ren, 2015)

shown in table 1.1. All these UCM examples imply that one or more climatic data is merged with land cover and land use information to inspect various urban phenomena through UCM analysis in cartographic form. Besides, after the development of GIS, most of the UCM research is done in GIS along with statistical analysis as seen Xi'an case.

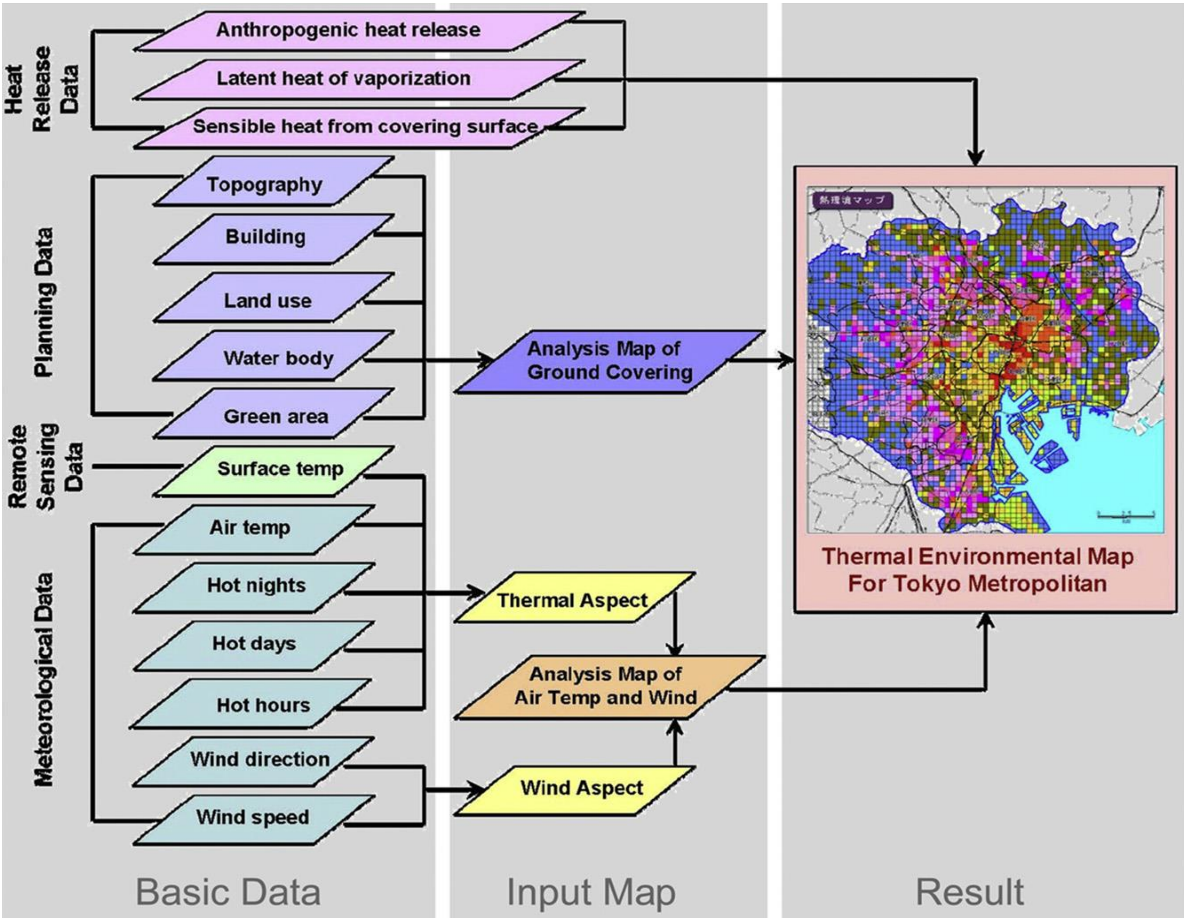


Figure 2.2: : Workflow of creating Tokyo Thermal Environment Map (TMG, 2005)

Researchers of Hong Kong had wide access to vast observational and simulated datasets such as 40 station's wind data. Again, Xu et al. (2020) collected field-based climatic data for three years. Readily available data was used in the case of Kaohsiung city (Ren, et al., 2013) which motivated the author of this thesis to perform a UCM analysis for Glasgow city with freely available data as thesis project is a time constraint work.

Table 2.1 Published case studies about UCM

City & Country	Purpose	Indicators	Reference
Stuttgart, Germany	To understand air quality and to mitigate air pollution	Infrared aerial photographs showing instant radiation temperature along with other climatic elements (ground temperature, humidity, and wind), topographic map, city map, land use plan, and aerial picture plans of the entire territory and air-hygiene data.	Urban climate Stuttgart, 2021; Baumeller and Reuter, 2015; Ren, 2015;
Tokyo, Japan	To understand how to reduce the UHI effect	17 indicators into major four classes as shown in figure 2.2	CUHK, 2008; TMG, 2005; Ashie et al., 2015
Hong Kong, China	To improve thermal comfort and reduce heat stress through facilitating more wind penetration	Building volume, elevation, greenery index, ground coverage, natural landscape, and proximity to openness are used to map thermal load and dynamic potential as well as wind information	CUHK, 2008
Kaohsiung, China	To encourage the use of urban climatic knowledge in planning	Topography, population intensity, land use, UHI index, natural landscape, water bodies, and wind information	Ren, et al., 2013;
Greater Manchester, the UK	To measure heat stress effect	Land cover, building density, building height, and anthropogenic heat flux, socio-spatial vulnerability index, and temperature data	Smith, Cavan, and Lindley, 2015
Xi'an, China	To analyze the variability of urban thermal comfort spatially and temporally	Air temperature, wind speed, relative humidity, land cover, land use, building density, building height, greenspaces, and population density	Xu, et al., 2020

2.4 Collation of UCM and UHR

The Majority of UCM studies are limited to spatial and climatic aspects only and ignore socio-economic and governance context (Parsee et al., 2019). UCM without considering the complex nature of urban systems such as expectations, capabilities, and management can turn into an arbitrary and subjective recommendation that has less possibility to adopt into urban planning and actions (Parsee et al., 2019). Thus, the urban climate risk analysis approach can fill the gap by incorporating socio-economic parameters because sustainable urban planning needs not only urban climate analysis but also what risks it put on people's livelihood. In other words, it is an urban climate analysis that also considers intangible parameters like demographic status, population density, etc.

Smith, Cavan, and Lindley (2015) coincide UCM with urban climatic risk analysis in the case of Greater Manchester. The authors performed a risk analysis by merging hazard, vulnerability, and exposure components to measure heat stress and flooding effect based on climatic parameters like rainfall and temperature consecutively as given in figure 2.3. It pinpoints that urban climatic events alone cannot jeopardize the urban inhabitants unless accounting for the physical exposure and socio-economic vulnerability scenario of the city (Georgiadis, 2017).

Urban Climatic Planning Recommendation Map

Urban Climatic Analysis Map		
Type of risk	Component	Data in each Layer
Risk map for flooding	Hazard: Climatic elements	annual rainfall
	Exposure: Physical elements	surface cover
		soil type
		flood risk zones (river)
		flood risk zones (surface)
	Vulnerability: People at Risk	socio-spatial index
Risk map for high temperature	Hazard: Climatic elements	summer temperature
	Exposure: Physical elements	surface cover
		building density
		building height
		anthropogenic heat flux
	Vulnerability: People at Risk	socio-spatial index
	Air Quality	air pollution emission
		background air quality

+ Land use data

Figure 2.3: : UCM study in Manchester (Smith, Cavan, and Lindley, 2015)

Likewise Greater Manchester, this study has designed a UCM study in form of urban climate risks, specifically urban heat risks to minimize the drawbacks of typical UCM studies. Due to the limitation of research scope and time, this study has only focused only one component of urban climatic phenomena. Besides, Glasgow city's plans and policies lack detailed urban heat analysis that is further described in Chapter 3.

2.5 Risk Perception and Urban Heat Risk Analysis

It is crucial to comprehend the overarching risk analysis framework before reviewing urban heat analysis methods. Risk originates from a combined effect of interaction among social, physical, and climatic processes (Cardona et al., 2012). According to IPCC (2014), the risk is a function of hazard, vulnerability, and exposure. Hazard is defined as an incident that possesses a potential threat; however, hazard alone cannot cause any damage unless some elements or assets are exposed to it. For example, a tornado is a hazard regardless of its location, but it is not risky if it occurs in a barren desert instead of a city. Exposure denotes the presence of people, environment, resources, etc. that could be affected by the hazard. Yet again, hazard and exposure cannot decide the risk intensity without the vulnerability component. For example, a young and an aged person exposed to the same hazard is not equally endangered. Thus, vulnerability indicates the propensity or degree of harm an exposed element/person can get for a certain hazard. That is why, vulnerability is often defined by a function of sensitivity and lack of adaptability (IPCC, 2014; Dickson et al., 2012; and Leis and Kienberger, 2020).

GIS-dependent spatial risk assessment is a process-based and bottom-up study. From preparation of fundamental indicators to final risk analysis may require several steps that depend on risk perception as shown in figure 2.4. Ideally, the five definitions of figure 2.4 are adapted from one another and carry the same core concept, but spatial mapping outputs may be changed as each processing step alters the weightage factors of the indicators. As per the literature review, no study was found to find out the influence of different risk perceptions on the spatial analysis outcome. Thus, this thesis has adopted a novel approach to perform the urban heat risk analysis from different risk perspectives.

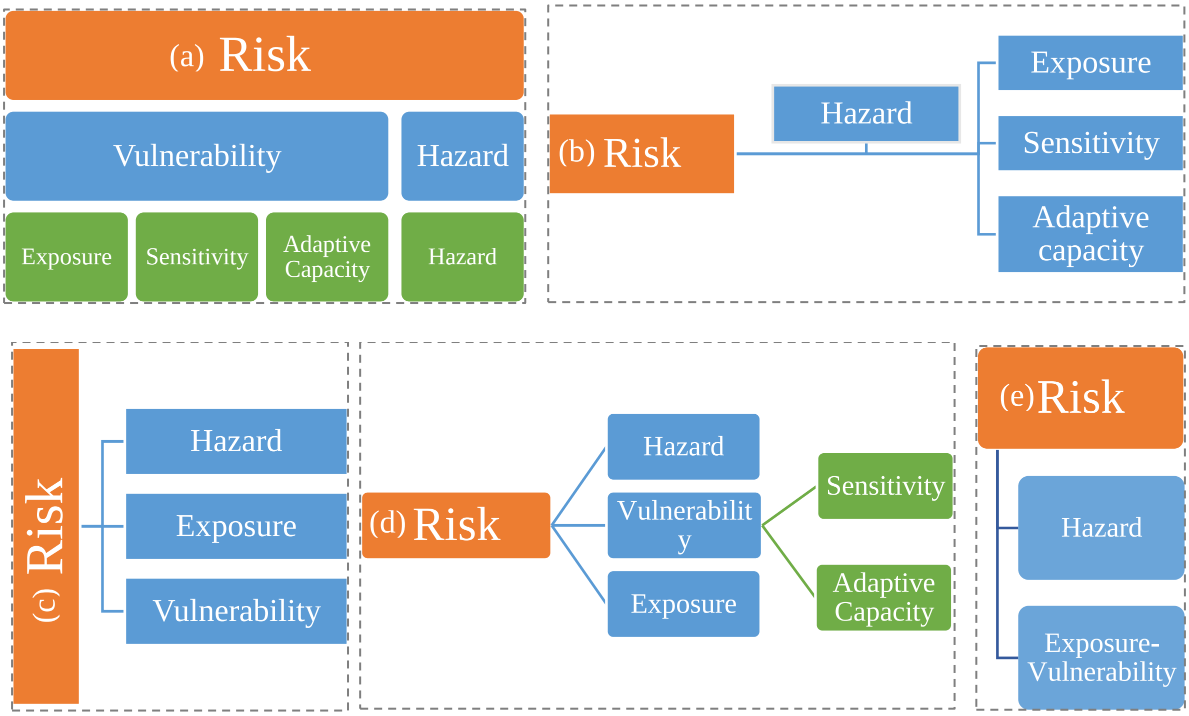


Figure 2.4: Different perceptions of risk definition [(a) Yu et al., 2021; (b) World Bank, 2021 [adapted from IPCC]; (c) Smith, Cavan, and Lindley, 2015; (d) Tapia et al., 2016; IPCC, 2014; (e) Buscail, Upegui, & Viel, 2012]

To estimate heat risk, different indicators are assigned to hazard, exposure, and vulnerability mapping by using either Map Algebra or Overlay application in GIS (Tomlinson et al., 2011; Smith, Cavan, and Lindley, 2015; Greater London Authority, 2021). As it is heat risk analysis, thus, usually climatic factors such as LST, Air temperature data is used alternatively as hazard component (Arup, 2014; Sun, Sun, & Chen, 2020; Tomlinson et al., 2011; Azevedo et al., 2016; Estoque et al., 2020; Buscail, Upegui, & Viel, 2012; Liu, Song, & Yu, 2017; Ho, et al., 2014; Schwarz et al 2012). For exposure analysis, generally physical and demographic indicators such as buildings, greenspace, population age, etc. play the key role (Chen et al, 2018; Arup 2014). Vulnerability is assessed based on the degree of damage that may happen to infrastructure, resources, and populations which are exposed to a particular hazard. Thus, vulnerability accounts for the intangible nature of the people and resources (Estoque et al., 2020). Arup (2014) conducted a study to discover the reasons for urban heat risk in London and visualize the risk. The study considered the characteristics of the people, buildings, and locations of London city to map the urban heat risks. A typical structure of the UHR study is given in figure 2.5 that shows step by process of the analysis. Besides, indicators are either positively or negatively correlated to heat risk. Some indicators such as LST, Population density, etc. are positively linked whereas other parameters like NDVI, DEM is negatively

correlated to heat risk. (CUHK, 2012). Räsänen et al., (2019) pointed out that the uncertainty and discrepancy are created by choices of different weighting and zoning factors of risk and vulnerability mapping. The selection of relevant indicators for each risk element is highly significant to do the proper mapping. Besides, studies apply only one method either overlay or map algebra to map the heat risk, but comparative studies are not found. Thus, this thesis attempted to carry spatial urban heat risk assessment with both methods to investigate whether there is any discrepancy found or not.

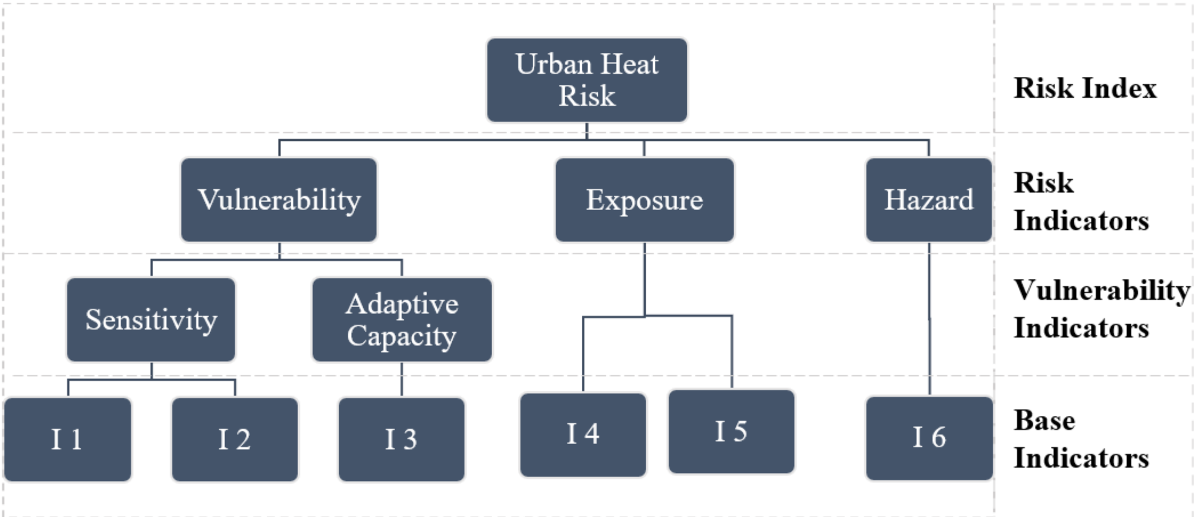


Figure 2.5: A typical framework of urban heat risk mapping (adapted from Estoque et al., 2020)

The difference between UCM and UHR mapping is that UCM divides the study area into climatopes whereas UHR divides into risk levels. Based on the intensity of the risk level, suitable measures are recommended in UC-ReMap such as Nature-based solution (NbS). Urban green infrastructure (UGI) promoted through NbS provides many ecosystem services/benefits from nature to the society to fight against climate change (Sebastiani, Marando, & Manes, 2021). Woody vegetation in form of ES can address UHI and air pollution problems and enhance climate change adaptation (Dursun and Yavas, 2015; Marando et al., 2019). UGI contributes to urban temperature regulation with its cooling effect which ultimately helps in lowering summer temperature and heatwave intensity (Majekodunmi, Emmanuel, and Jafry, 2020; Filho et al 2021; EPA, 2021;). However, the application of UGI needs a successful urban planning strategy for which understanding the supply by ES and demand from the human sphere is very crucial. ES mismatch estimation comes in many forms considering both spatial and temporal dimensions (Geijzendorffer, Martín-López, and Roche, 2015). Areas with high demand but poor supply are prone to extreme temperature. Thus, the ES mismatch calculation

helps in the spatial intervention of heat risk by identifying the disadvantaged area (Sebastiani, Marando, & Manes, 2021) and hence, contributes to recommendation planning.

Vegetation is a key indicator for identifying the overheating led risk and the quality of ecosystem services. Urban greenspaces help to model near-surface energy exchange and thus, modulate the surface temperature and surface runoff (CUHK, 2012). Not all types of vegetation contribute in the same manner. Thus, knowing the health of the vegetation is more relevant to this study. Therefore, NDVI was considered as a representative for vegetation for mapping urban heat risk (CUHK, 2012; Peng et al., 2020; Mehrotra, Bardhan, & Ramamritham, 2019).

Many UCM studies incorporated both building height and building area density to map the thermal load of the study area (Xu et al 2020; Smith, Cavan, and Lindley, 2015). Other studies considered building volume to carry out thermal load mapping of UCM studies (CUHK, 2012). In this study, the building volume layer was prepared by using two different layers: Building height and horizontal building density. Areas with high horizontal and vertical building density are more exposed to heat compared to a sparsely building density area. Besides, high building volume with tall buildings has more heat storage capacity and causes low sky view factor (CUHK, 2012). Even though they also provide a shadow effect and reduce LST (Mehrotra, Bardhan, & Ramamritham, 2019), they obstruct the dismission of longwave heat radiation at night and prompts canopy layer urban heat island (CUHK, 2012). High building volume does not mean the area has tall and large buildings. For example, a 100m building coverage with 3m building height will have the same volume of 10m area having 30m height. Thus, our target is to identify zones with both tall buildings and large building area density values. Furthermore, studies found that building height is an important variable to assess heat risk in the urban area (Tomlinson et al 2011) because people in high-rise building are more exposed to heat risk (Buscail, Upegui, & Viel, 2012).

2.6 Research Questions and Reasons of this Study

The urban climate mapping process is improving day by day. This study will also contribute in the UCM methodology improvement. Based on the literature review, three novel approaches are adopted in this thesis. Firstly, this study endeavored an urban heat risk mapping exercise with limited available data. It has sought a different combination of climatic and planning parameters through both overlay and map algebra (raster calculation) to test different UHR analysis approaches. Thus, the thesis will critically evaluate the synthesizing process to identify

the influencing factors of mapping outputs. Moreover, this research will help the local government to understand the spatial distribution of heat risk levels in Glasgow city and the contribution of different indicators for risk mapping. Furthermore, this study's findings will provide insights into the importance of urban climate sensitivity in climate resilience plans. A climate-resilient urban environment needs both scientific knowledge and planning skills. This study helps by reviewing the synergies and barriers that exist between climate change action plans and urban climate mitigation plans to enhance the uptake and usefulness of UCMs. Thus, this thesis will develop a planning recommendation map to identify the prior interventions. Overall, this dissertation will help to evaluate the existing urban settlement and future development plan of Glasgow city to help the decision-makers in making sustainable urban spatial planning.

CHAPTER 3: METHODOLOGY

This chapter provides an overview of the study area, Glasgow City council, and the research philosophy and approaches. Moreover, data sources and data processing are illustrated along with justification of the chosen parameters and methods to derive the urban heat risk maps.

3.1 Study Area Profile

Glasgow is the biggest city in Scotland with a surface area of approximately 176.4 square kilometers (Glasgow City Council, 2017a; Ordnance Survey Mastermap, 2020). River Clyde is flowing through the heart of the city, carrying the history of culture, heritage, and economic growth and a great source of ecosystem services (Glasgow City Council, 2017a).

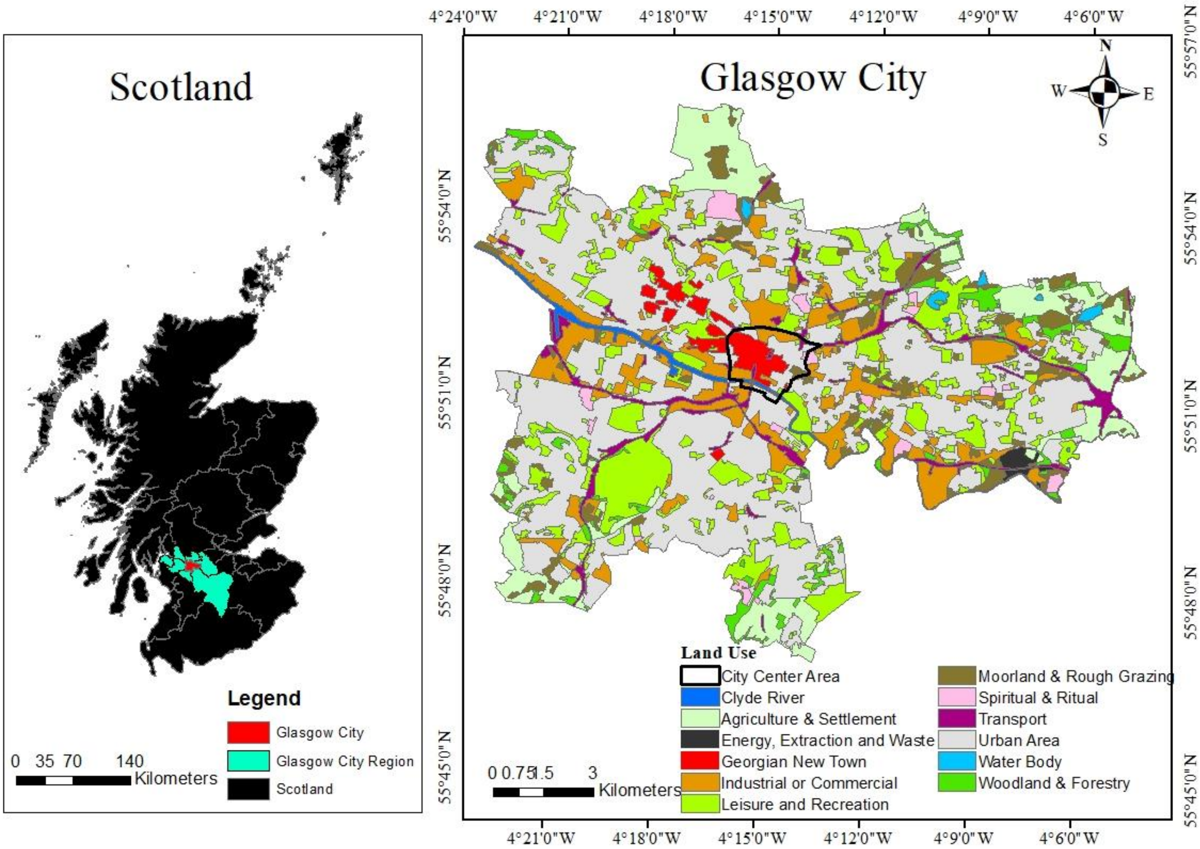


Figure 3.1 Location and land use of Glasgow city (HLAmap, 2017)

It is located at 55.8642° N, 4.2518° W (Google Earth, 2020) at a low-lying area in the south-western part of Scotland as shown in figure 3.1. The average elevation is only 40m approximately from the sea level which put a great impact on its wind speed and direction and temperature pattern.

Glasgow city is the most populated city in Scotland with a population density of 3,590 persons per square kilometer which is increasing day by day. As of 30 June 2019, there was a total of 633,120 inhabitants in the city where 22.7% are from Black, Asian, or Minority Ethnic groups (Sniffer, 2020a; Understanding Glasgow, 2021). Besides, one study in 2012 report that the city's 50% citizen resides in the 20% most deprived locality and 33.3% children lives in poverty (Glasgow City Council, 2017b).

The city is highly urbanized along with agricultural lands in the periphery and limited water bodies as shown in figure 3.1. There are only 16 hectares of greenspace per 1000 inhabitants which is the lowest among 8 councils of Glasgow City Region (Sniffer 2020a). Greenspaces are used for leisure and recreational purpose mostly (HLAmap, 2017). Furthermore, figure 3.2 highlights the areas with ecological and economic values. Overall, both figure 3.1 and 3.2 give a preview of the study area's urban environment that influences its urban climate.

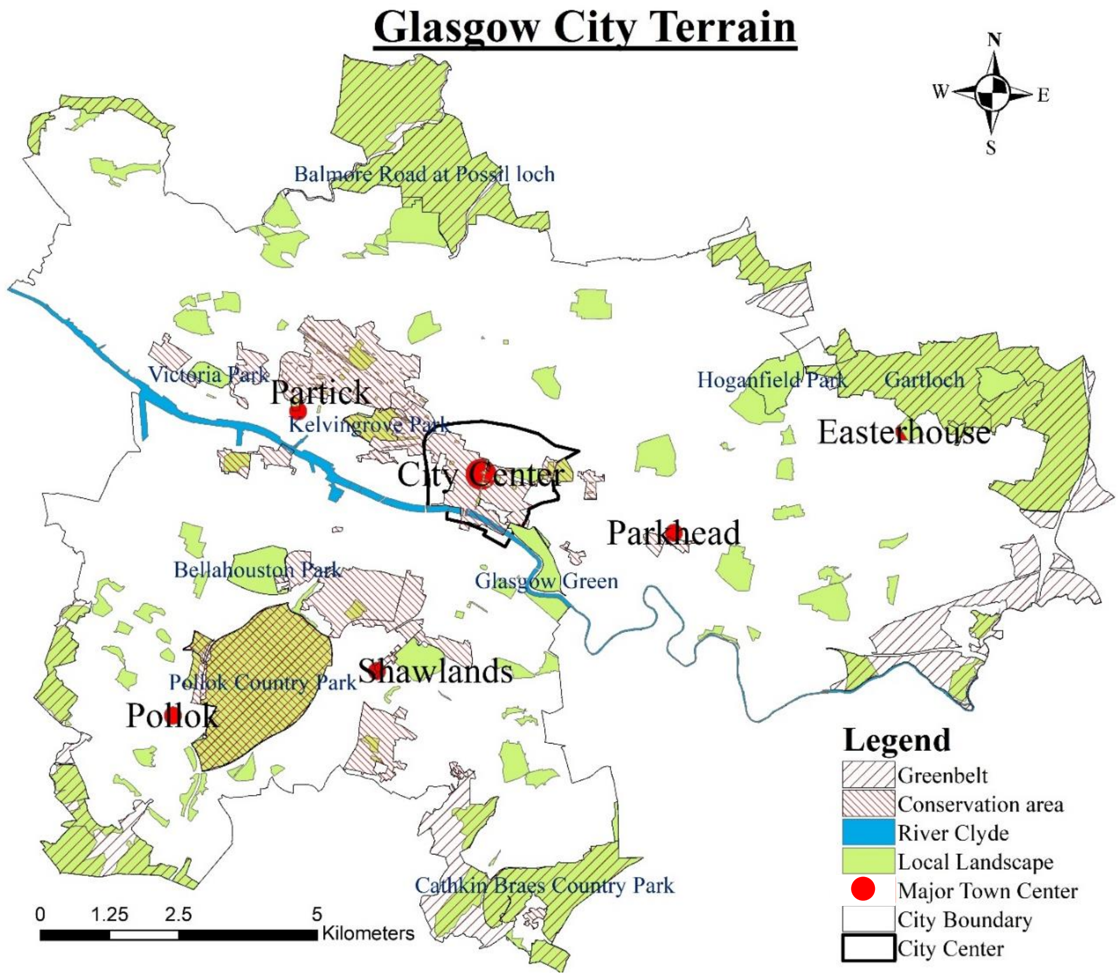


Figure 3.2: Special terrestrial features of Glasgow City (Digimap Ordnance Survey, 2020)

3.1.1 Urban Climate

Western Scotland including Glasgow city contains a temperate maritime climate that usually gives cool summer, mild winter, and rainfall round the year (SEPA, 2014) due to the influence of the sea and warm Gulf Stream. The mean annual temperature is approximately 9.5°C that is slightly higher than its surrounding area due to the UHI effect (Met office 2021b).

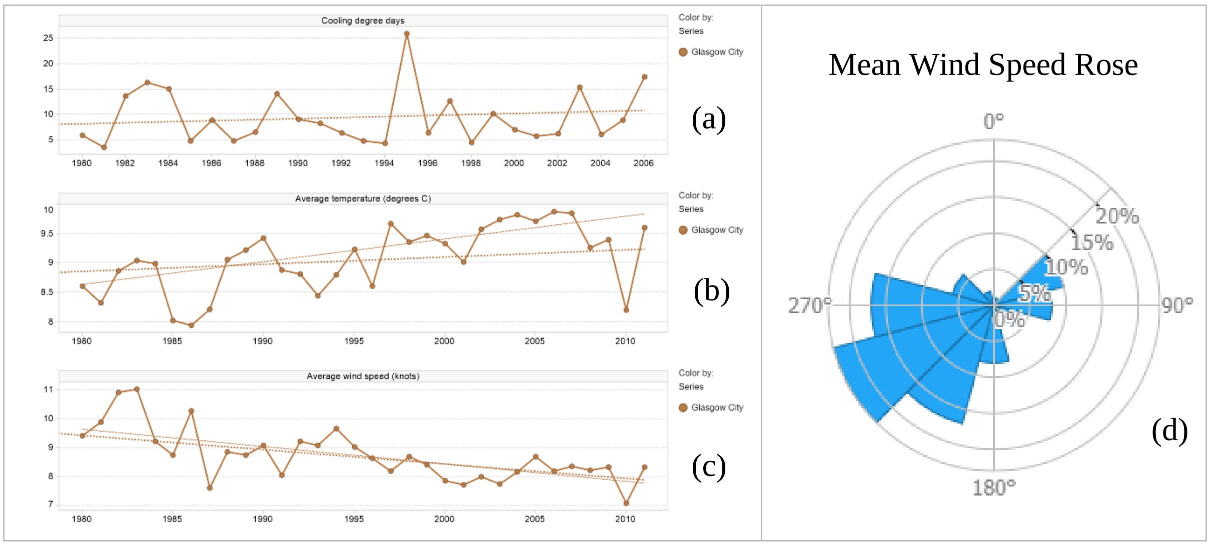


Figure 3.3: A glimpse of 30 years' climate trend of Glasgow city (SEPA, 2021; Global Wind Atlas, 2021). (a) Trend of cooling degree days, (b) mean temperature (°C) trend 1980 to 2010, (c) average wind speed (knot) trend, and (d) Mean wind speed rose at 10m height.

The prevailing westerly wind blows over the city typically from west, southwest, and south. Autumn and early winter (October to January) is the wettest period whereas Spring and Summer (April to June) is the driest period in western Scotland. Similarly, the wind is also strongest during winter and early spring and the lightest during summer (Met office 2021b). Graphs a, b, and c in Figure 3.3 exhibit the climatic trend in Glasgow city that infer a gradual rise in air temperature and fairly steep fall in wind speed. Cooling degree days trend sighted the more energy need on cooling technologies due to rising air temperature.

3.1.2 Climate Projection and Overheating concern

UK Climate Projections (UKCP) 2018 projection reveals an increase in temperature and precipitation and their corresponding impacts such as increasing sea level, more extreme weather events like flooding, heat waves, etc. in Scotland (Scottish Government, 2019). Glasgow city has already witnessed a record temperature of 31.9°C on 28 June 2018 (The

guardian, 2018). It is also forecasted that there is a 50% chance of recording a similar high temperature by 2050 (The guardian, 2021).

Kruger, Drach, and Rohinton (2018) found that the UHI effect of Glasgow city is approximately 3°C on average which might go up to 4°C under certain conditions. UHI effect along with rising air temperature will cause extreme temperature and increase heatwave frequency in Glasgow city. O'Neill & Tett (2019) reported that Glasgow City Region will experience 5 to 10 and 10 to 50 heatwave days per decade in the 2050s and in the 2070s respectively compared to the baseline period (1981-2010). Thus, Glasgow City Council (GCC) should pay attention to growing overheating problems as rainfall and wind will be reduced in the summer season, but the temperature will get higher in the city (The Guardian, 2021).

3.1.3 Inflections and Gaps of Existing Climate Change Policies and Plans

The vision of the sustainable city, eco-city, climate-resilient city, etc. is gaining popularity due to anthropogenic induced global climate change effect (IPCC, 2014). Likewise, the Glasgow city council (GCC) is taking proactive plans and actions to cope and adapt to climate change. That is why it set its carbon neutrality target by 2030 fifteen years earlier than Scotland's national net-zero GHG target (Climate Ready Clyde, 2021). Concurrently, GCC holds several strategic plans to improve its climate change adaptability and mitigate climatic risks such as:

i. Strategic Plan 2017-2022 (Glasgow City Council, 2017c)
ii. City Development Plan 2017-2022 (Glasgow City Council, 2017a)
iii. Climate Adaptation Strategy and Action plan 2020-2030 (CRC, 2021)
iv. Glasgow Open space strategy 2020 (Glasgow City Council, 2017b)

However, current policies and plans are not sufficient to address the projected heatwave events in Glasgow city. The climate risks and opportunities assessment of Climate Ready Clyde pointed out valuable notes and the thematic aspects of climate-induced risks and benefits in the Glasgow City Region (England et al., 2018). Table 3.1 presents a SWOT[3] analysis of the current strategies from a heat risk management perspective.

[3] SWOT stands for Strengths, Weaknesses, Opportunities, and Threats

Table 3.1: SWOT analysis of current climate change adaptation policies and plans from a heat risk perspective

Strengths	Weaknesses
• Long-term goals and targets for a sustainable and climate-resilient city (i, ii, & iii) • Political willingness and supportive mindset of local government (i, ii, & iii) • Strong commitment from stakeholders[4] • Initial thematic plans and policies(iii) • Plan in hand to conserve green belt and enhance green network (ii)	• Lack of research and understanding on spatial heat risk analysis currently (ii) • Lack of heat risk management plan i.e., early warning system (iii). • Existing socio-economic equalities (i) • Insufficient greenspaces as per inhabitants' expectation (iv) • No strategic plan specific for heat stress mitigation (i, ii, iii) • No concrete plan on green & blue infrastructure improvement for cooling effect (iv) •
Opportunities	**Threats**
• Cross-cutting collaboration with neighboring municipalities (i & iii) • Innovation and resources such as available researchers, experts, academicians, and scientists as stakeholders (iii) • Green financing (iv) • Scope of public participation and community-based risk management (iv) • The relatively colder and wetter climate[4] • COP 26 platform	• Impending heatwave • Uncontrolled population density • Disasters like flash-flood, drought, etc. • Economic recession • A pandemic outbreak like COVID 19 • Political instability • Unrest and protest

Therefore, all these policies and strategies are interlinked and help each other to grow and develop as they all point at a common goal called "sustainable and climate-resilient Glasgow city". These dissertation findings will provide insights on priority interventions solely focused on heat risks to minimize socio-economic inequalities and attain climate resilience.

3.2 Explanation of Research Onion

3.2.1 Research philosophy

To develop knowledge in the sustainable urban planning field, this study has followed a pragmatic research philosophy. The urban climate is a complex phenomenon that influences and is influenced by many factors. Thus, we need to focus on the study from a practical point

[4] England et al., 2018

of view. Interpretivism view rooted in pragmatism philosophy helps to constantly question the reality and requires constant interpretation (Saunders et al., 2019).

3.2.2 Research approach

The abduction approach is the best fit for the nature of this study as the research sways in between deduction and induction. This study will examine existing theories and will also add new insights to existing theory through the best guess and analysis based on available evidence and the addition of new elements to the study. The new result will improve the current understanding of the subject topic.

3.2.3 Methodological choice

The research design chooses a simple mixed method where both qualitative and quantitative research are integrated. The study used content analysis and literature review to derive a certain set of results whereas numerical data were used to generate other sets of results by following statistical and spatial analysis and using different tools. Besides, PPGIS (public participation GIS) is used for data visualization through mapping.

3.2.4 Strategy

Research strategy sets plans of actions to achieve the aim and objective of the study. Thus, this study adopted a case study strategy to achieve the research goal. Saunders et al., (2019) stated, “A case study is an in-depth inquiry into a topic or phenomenon within its real-life setting” where understanding context is vital to this kind of research. Urban climate mapping of Glasgow city about deriving empirical description of the urban climate-sensitive hotspots to identify what is happening and why.

3.2.5 Time horizon

This study predominantly follows a cross-sectional time horizon which is Summer 2019. However, it also briefly touches longitudinal time frame to analyze certain sections such as climatic data (temperature, wind, rainfall, etc.) over 20 years.

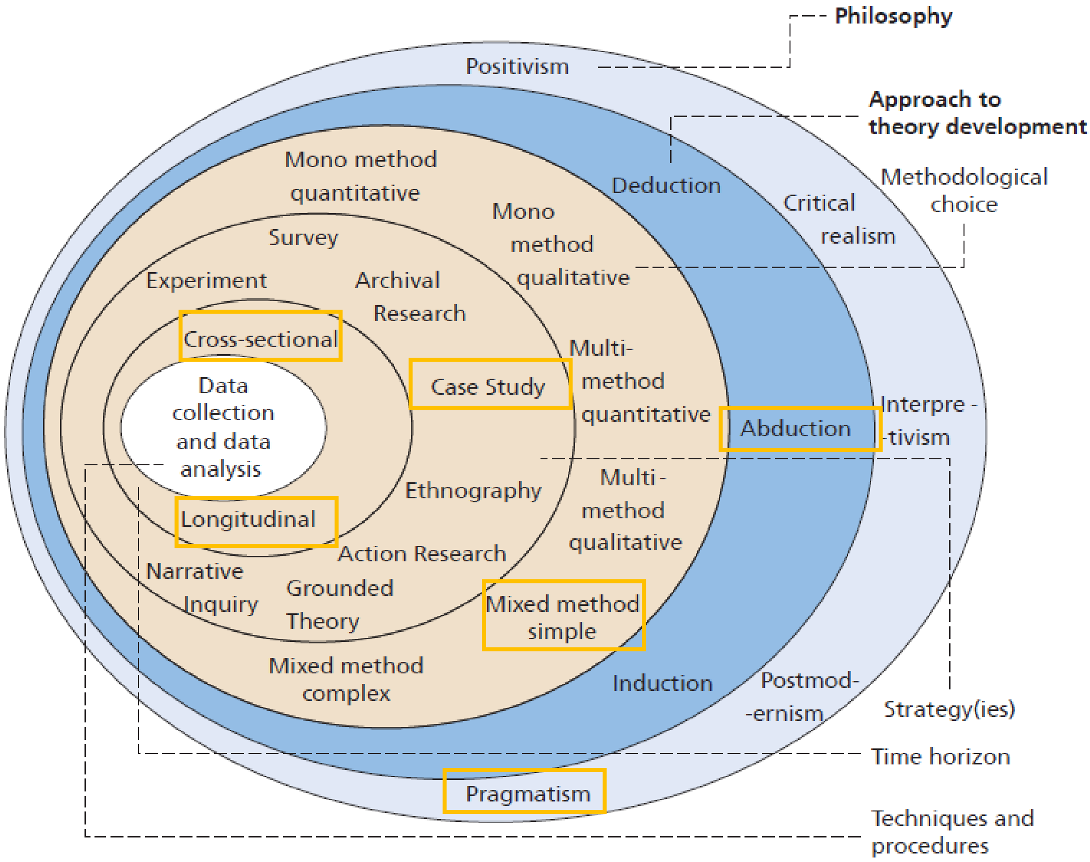


Figure 3.4: Selected research methods from research onion for this study (Saunders et al., 2019)

3.3 Overall Study Framework

The overall framework in figure 3.5 gives an overview of the core steps of this research. Urban climate analysis for heat risk consists of three key components hazard, exposure, and vulnerability where several indicators are combined to generate each component layer. NDVI is used in different layers to generate a different combination of maps which is marked as (*). The UC-ReMap will comprise principally UCAn-Map and Ecosystem service mismatch map along with other valuable feature like old homage, hospital etc. (Improvement Service, 2020).

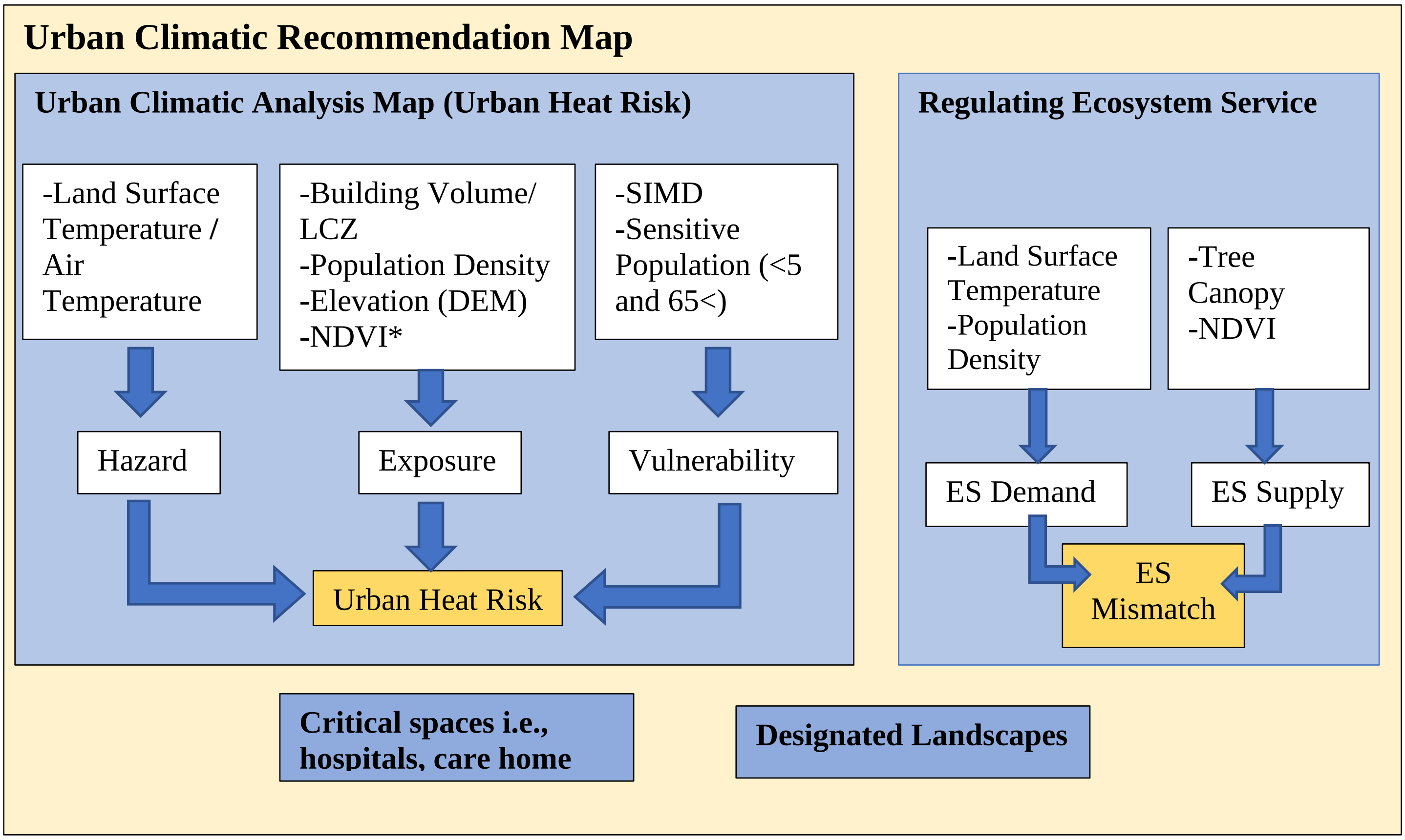


Figure 3.5: Overall Framework of the study

3.4 Data collection and Sources

Available relevant datasets and information needed to assess and visualize UHR are obtained with different formats such as shape, raster, excel, NetCDF etc. as given in Table 3.2.

Table 3.2: Sources, formats, and uses of dataset in this research

Category of Data	Dataset Type (Year)	Source	Format & Spatial Resolution	Risk Element
Socio-economic	Population density (2017)	Scottish Government	Excel	UC-AnMap: Exposure; Ecosystem Services
	Sensitive Population	Scotland's Census	Excel	UC-AnMap: Vulnerability (Sensitivity)
	Scottish Index of Multiple deprivation (2020)	Scottish Government	Shape file	UC-AnMap: Vulnerability (Sensitivity)

Climatic	Wind speed (1980-2010)	UK Met Office (HadUK Grid)	NetCDF; 1km	UC-ReMap
	Air temperature (1980-2010)	UK Met Office (HadUK Grid)	NetCDF; 1km	UC-AnMap: Hazard
	Wind speed and direction (2018-2020)	UK Met Office	MS excel;	Study area Background analysis
	Land surface temperature (28 June 2019)	Landsat 8 from USGS: Earth Explorer	Raster file	UC-AnMap: Hazard; and Ecosystem services
Planning	Land use (2017)	HLAmap	Shape file	UC-ReMap
	Building height and building area (2019)	Digimap: Ordnance Survey	Shape file	UC-AnMap: Exposure
	Digital Terrain Model (2003)	UBDC	Raster file	UC-AnMap: Exposure
	NDVI	Landsat 8 from USGS: Earth Explorer	Raster file	UC-AnMap: Vulnerability; Ecosystem Services
	Tree Canopy from PAN65 (2008)	Glasgow City Council	Shape file	Ecosystem Services
	LCZ	Zala, 2020	Shape file	UC-AnMap: Exposure

3.5 Data Preparation- Indicators

The raw data of different formats and different scales are simplified and reclassified to get homogenous datasets before using ArcGIS. Based on the literature review, figure 3.6 summarizes the correlation of heat risk intensity and each indicator. For example, high LST and low NDVI values increase heat risk. All the maps are produced in British Coordinate System at the data zone level. Data Zone (DZ) refers to a small unique geographical area enough for statistical representation in Scotland (Scottish Government, 2013). Nine available indicators are used to generate urban heat risk maps in this study that are described in the following section.

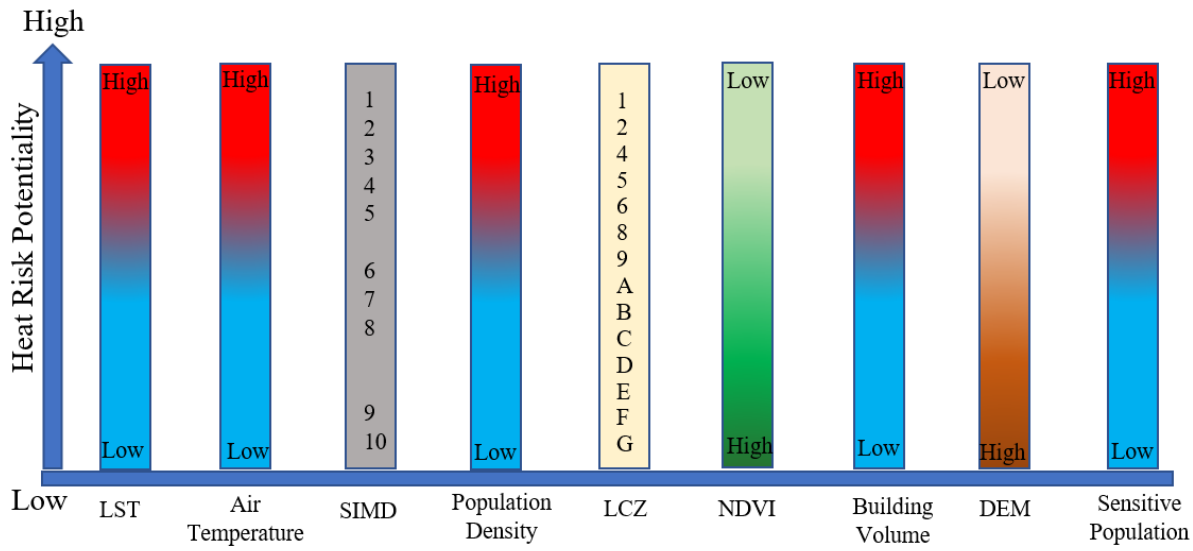


Figure 3.6: Link between heat risk potential and chosen indicators of this study

3.5.1 Land Surface Temperature (LST)

LST is highly regarded as a hazard component in heat risk assessment because of its strong correlation to UHI (Arup, 2014; Sun, Sun, & Chen, 2020; Tomlinson et al., 2011; Azevedo et al., 2016; Estoque et al., 2020; Buscail, Upegui, & Viel, 2012; and Liu, Song, & Yu, 2017). LST also helps to understand the area of the pervious areas like greenspace and impervious area such as built environment (Arup, 2014; Azevedo et al., 2016)

LST map of 30m resolution is retrieved from Landsat 8 satellite image of 28 June 2019 daytime with less than 5% cloud cover by following the guidelines of USGS website, publications, and YouTube tutorial (Chen et al., 2018; Mustafa et al., 2020; USGS, 2021a; Made4Geek, 2018).

Tools such as Project Raster, Zonal Statistics, and Reclassify are used to derive LST at the DZ level. Low, medium, and high categories are assigned based on the standard deviation (SD) value of the raw data distribution as presented in Table 3.3 along with other indicators. The calculation is explained in Appendix B.

3.5.2 Air Temperature

UHI is measured based on air temperature (Ta) disparity that turns it to be the primary indicator in UHR analysis (Schwarz et al., 2012). Sometimes, LST replaces Ta when there is a lack of Ta data (Ho et al., 2014).

Mean Air temperature data for 30 years (1981 -2010) at 1.5m height were collected from HadUK-Grid datasets of Met Office in 1km Gridded raster data format. Ta data from HadUK-Grid discloses a similar spatial pattern except for values regardless of seasons, so mean Ta is used only in this study. The raster data is resampled and reclassified into high, medium, and low categories as shown in Table 3.3.

3.5.3 Normalized Difference of Vegetation Index (NDVI)

Urban greenspaces help to model near-surface energy exchange and reduce the surface temperature through their cooling effect (Handley and Carter, 2006). NDVI which reflects vegetation health is certainly a vital indicator to visualize the spatial variation of heat risk (CUHK, 2012; Peng et al., 2020; Katzschner, & Burghardt, 2015; Mehrotra, Bardhan, & Ramamritham, 2019). NDVI is perceived either as an exposure component (Smith, Cavan, and Lindley, 2015) or a vulnerability element (Estoque et al., 2020; Buscail, Upegui, & Viel, 2012) in different studies. Thus, this study has assigned this parameter in both exposure and vulnerability layers alternatively.

NDVI was also calculated with band 4 (Red) and band 5 (Near Infrared) of Landsat 8 satellite data for 28 June 2019 daytime by following the below formula (Made4Geek, 2018; USGS, 2021c).

$$NDVI= \frac{(NIR-RED)}{(NIR+RED)} = \frac{(Band\ 5-\ Band\ 4)}{(Band\ 5+\ Band\ 4)}$$

NDVI range is from -1 to +1 where -1 refers to water and +1 refers to dense tree forest. A value close to zero means urbanized area, ranges from 0.2 to 0.5 in suburbs and grasslands, and above 0.5 corresponds to medium to dense vegetation (USGS, 2021b). The derived NDVI data was cross-checked with Google Earth satellite image, Ordnance Survey’s Greenspace data, and Planning Advice Note (PAN) 65 data of Glasgow city council.

3.5.4 Building Volume (BV)

In this research, BV comprises both building height and building area density to estimate the thermal load of the study area (Xu et al., 2020; Smith, Cavan, and Lindley, 2015, CUHK, 2012). Tall buildings retain heat by reducing sky view factor and obstructing longwave

radiation at night (CUHK, 2012) although their shadow effect reduces LST (Mehrotra, Bardhan, & Ramamritham, 2019) while building area fraction compromises evapotranspiration cooling capacity through soil capping (CUHK, 2012) and air ventilation route (Acero, and Katzschner, 2015). Building height data is cross-matched with the Digital Surface Model of Lidar data and through physical observation.

3.5.5 Socio-economic Index

One or more socio-economic parameters are sighted to be the core indicators to measure spatial variation of heat vulnerability in all UHR studies. Parameters such as chronic disease (Lindley et al., 2006), income (Estoque et al., 2020), education (Buscail, Upegui, & Viel, 2012), crime (Arup, 2014; Heilmann and Kahn, 2019), number of people in the household, and accessibility to medical and other necessary services (Chen et al., 2018) are considered as a heat vulnerability factor in different studies. Scottish Index of Multiple Deprivation (SIMD) 2020 incorporates all the above-mentioned parameters necessary to represent the socio-economic index of Glasgow city for heat vulnerability assessment. Therefore, this study has considered SIMD 2020 ranks to define the socio-economic status of inhabitants where all the above-mentioned socio-economic factors were incorporated. Each factor is highly relevant to heat vulnerability (Scottish government, 2020). For this study, the defined decile value of SIMD was categorized into three classes where low ranked data zones are more susceptible to heat risk than high ranked zones.

3.5.6 Sensitive Population

Based on literature review, this study has determined population below 5 years and above 65 years as a heat-sensitive population group in Glasgow city (Understanding Glasgow, 2021; Estoque et al., 2020; Buscail, Upegui, & Viel, 2012; Chen et al., 2018; Yu et al., 2021). The population data were obtained from the 2011 Census result (Scotland’s Census, 2011). This study considered the ratio of sensitive population to total population in each data zone.

3.5.7 Population Density

There will be no risk if no elements (like buildings and people) are happened to be present. Thus, high population density increases the heat exposure level as well as anthropogenic heat flux (Ren et al 2013; Estoque et al., 2020; Tomlinson et al 2011; Buscail, Upegui, & Viel, 2012; Chen et al., 2018; Xu et al., 2020).

3.5.8 Elevation

Consistent with the environmental lapse rate concept, the air temperature decreases with altitude (Ren et al., 2013). Besides, high elevated places are exposed to more windspeed that helps to dissipate the heat from the area (MET office 2021c; Mehrotra, Bardhan, & Ramamritham, 2019; CUHK, 2012; Ho, et al., 2014; Wong et al, 2015). Reclassification categories are chosen with the insights from published literature (Ren et al., 2013; CUHK 2012; Andrade et al., 2015). The elevation data was obtained from Lidar data supplied by Urban Big Data Centre (2021) and cross-checked with interpolation of the absolute mean height of the ground from OS building height data.

3.5.9 Local Climate Zones (LCZ)

LCZ data is derived from the Landsat 8 satellite image of 27th Feb 2019 by following the WUDAPT protocol (Zala, 2020). As LCZ divides the city into different zone based on urban form and characteristics, the reclassification is done based on each LCZ's thermal admittance and anthropogenic heat flux characteristics (Stewart, 2011). In this study, LCZ classification is complimentary to building volume classification as they both are defined on urban physical characteristics and their contribution to thermal load.

Table 3.3 summarizes the assigned reclassified value of all nine indicators as the base layers of heat risk analysis of Glasgow city. Tomlinson et al. (2011) indicated that all the layers should be on the same scale. This study reclassified all the base indicators at 1 to 3 scale to minimize the complexity of the study that consists of a large number of indicators.

Table 3.3: Assigning reclassified value to each indicator

Reclassification		**Original Value of each indicator**								
Heat Risk Potential	New Value	LST	Air temperature	Building Volume	Population Density	Elevation	NDVI	LCZ	SIMD	Sensitive Population
Low	1	20.68 - 22.86	8.58 - 8.90	1, 2	0 - 3500	100 - 130.51	0.39 - 0.46	9, A, B, C, D, E, F, G	1 to 5	0.015 - 0.132
Medium	2	22.86 - 26.79	8.90 - 9.50	3,4	3500 - 10,000	42.82 - 100	0.21 - 0.39	4, 5, 6, 8	6 to 8	0.132 - 0.267
High	3	26.79 - 28.32	9.50 - 10.01	6, 9	10,000 - 52,389.4	5.56 - 42.82	0.04 - 0.21	1, 2	9 to 10	0.267 - 0.390
		Standard Deviation	Standard Deviation	Insights from published studies	Insights from published studies	Insights from published studies	Standard Deviation	Anthropogenic Heat Flux and Thermal Admittance	Expert opinion	Standard Deviation

3.6 Layer preparation: Risk Element

3.6.1 Risk Definition Perspective

Based on the literature review, this study adopted the below two perspectives by following IPCC's risk definition where perspective 2 is an adapted version of perspective 1.

Perspective 1: Risk = f {hazard, exposure, vulnerability}

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

3.6.2 Risk Analysis Method

Table 3.4 provides a full picture of risk elements, selected indicators, and methods used to create the different risk components. When NDVI is used in the exposure layer, it is not considered in the vulnerability layer. Moreover, while the GIS overlay technique is widely used to assess UHR (Buscail, Upegui, & Viel, 2012; Tomlinson et al., 2011), map algebra is also found in several UHR studies (CUHK, 2012; Smith, Cavan, and Lindley, 2015; Greater London Authority, 2021). Thus, this study used both weightage overlay and raster calculator sum to carry out urban heat risk mapping.

Table 3.4: Selection of indicators for each risk component.

<table>
<tr><th>Risk Element</th><th>Layer Type</th><th>Indicators of each layer</th><th>The method used to prepare the Risk components</th><th>The method used to create the risk maps</th></tr>
<tr><td rowspan="2">Hazard</td><td>Hazard 1</td><td>LST</td><td>Not applicable</td><td rowspan="6">1.Weighted overlay (equal weightage)
2.Map Algebra (raster calculator-sum)</td></tr>
<tr><td>Hazard 2</td><td>Air Temperature</td><td>Not applicable</td></tr>
<tr><td rowspan="2">Exposure</td><td>Exposure 1</td><td>1.Building Volume
2. Population Density
3. DEM
4. NDVI*</td><td rowspan="3">1.Weighted overlay (equal weightage)
2.Map Algebra (raster sum)</td></tr>
<tr><td>Exposure 2</td><td>1. LCZ
2. Population Density
3. DEM
4. NDVI*</td></tr>
<tr><td rowspan="2">Vulnerability</td><td>Sensitivity</td><td>1.SIMD
2. Sensitive Age (<5 & >65)</td></tr>
<tr><td>Adaptation Capacity</td><td>NDVI*</td><td>Not applicable</td></tr>
</table>

Table 3.5: GIS weightage for risk assessment of existing studies

Topic	Country	Hazard	Vulnerability	Exposure	Reference
Urban Heat Risk	Great Manchester	33.3%	33.3%	33.3%	Smith, Cavan, and Lindley, 2015
Heat Health Risk	Philippines	22%	33% (Adaptive Capacity 56% and Sensitivity 44%)	45%	Estoque et al., 2020
Heat Health risk	China	33.3%	33.3%	33.3%	Chen et al., 2018

However, there is no consistency found in choosing the weightage factor of mapping risks through weightage overlay. Table 3.5 gives three research examples for weightage factor decisions. Therefore, this study followed an equal weightage factor for the sake of simplification of the study with the insights of the literature review.

3.7 Ecosystem Service Mismatch Calculation

Ecosystem service mismatch indicates the extent of services urban dwellers receive from nature in Glasgow city. ES supply and ES demand value of temperature regulation are calculated by following the study done in Italy (Sebastiani, Marando, & Manes, 2021) with available data such as LST, population density, NDVI, and Tree canopy. ES mismatch is obtained by subtracting ES supply intensity from ES demand intensity.

3.7.1 Tree canopy layer

Revised PAN65 data (H1, H2, H3, H4 (without water), M3, M4) is employed to calculate the tree canopy index for Glasgow city. Google Earth satellite data was used to cross-check the availability of trees in those selected PAN65 categories. Tree canopy is calculated as the percentage of ground area covered by trees which is vital to determine temperature regulating ecosystem service (ES) quality (Sebastiani, Marando, & Manes, 2021).

CHAPTER 4: RESULT AND ANALYSIS

This chapter presents and describes the empirical results with the methodology described in chapter three to fulfill the objective 4 and 5 of this dissertation. At first, the climatic features of Glasgow city and individual base indicator layers are described. Then, the final heat risk maps are presented and analyzed.

4.1 Study Area's Climatic Features

Glasgow city's climate can be comprehended from 20 years of data (2000 - 2020) of two nearby Met Office's meteorological stations; Bishopton and Salsburgh. It is found that Bishopton is approximately 9km far on the northwest side of Glasgow city at an elevation of 59m altitude, and Salsburgh station is about 12.5km far on the eastern side (as shown in figure 4.1) at 277m elevation.

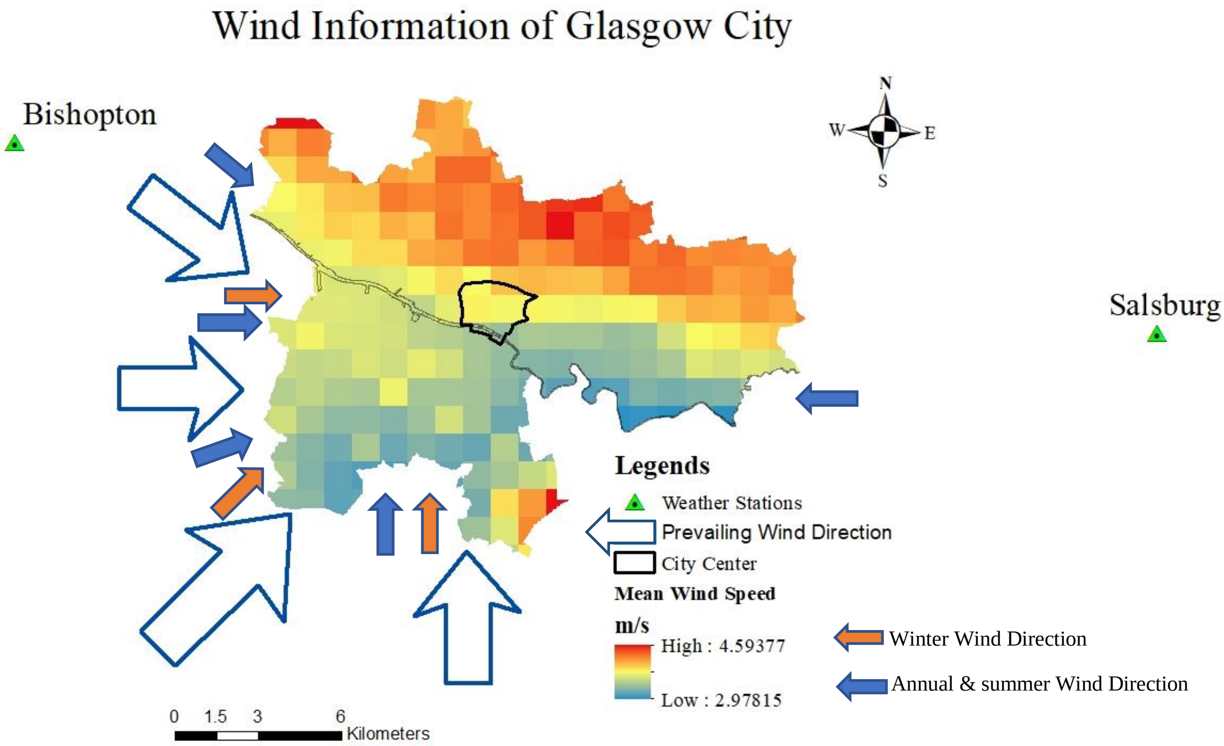


Figure 4.1: Wind Speed and direction of Glasgow city

The mean temperature at Bishopton and Salsburgh is 9.3°C and 8.04°C respectively. The average daily maximum and minimum temperature is 12.8°C and 5.8°C at Bishopton and 11.14°C and 4.93°C at Salsburgh correspondingly. However, no significant trend was found in

temperature data although both graphs in figure 4.2 present an oscillation of temperature anomaly over the years at both stations. Both stations recorded June, July, and August as the warmest months, and December, January, and February as the coldest months as displayed in figure 4.3.

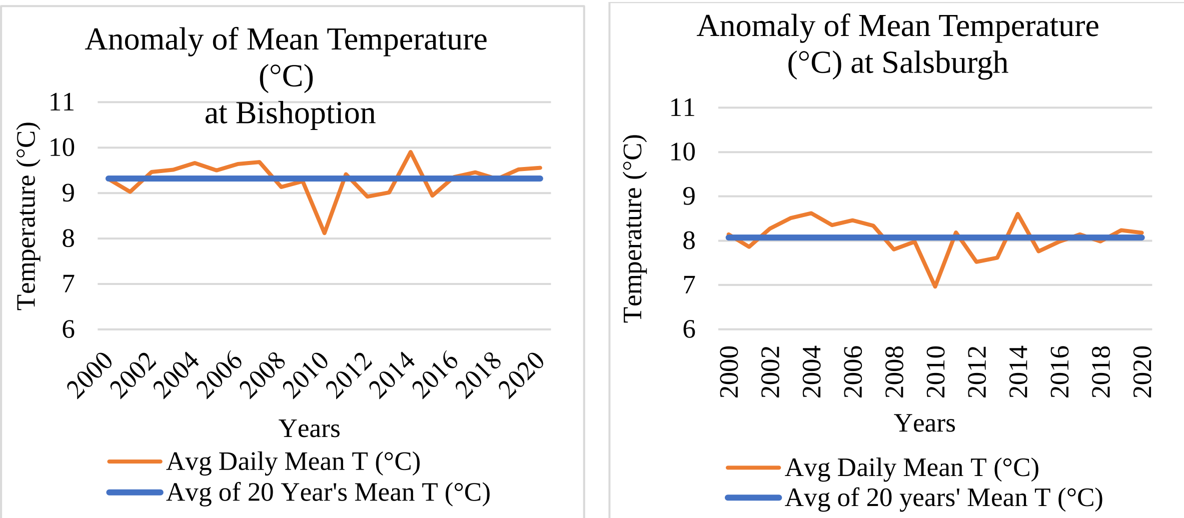


Figure 4.2: Mean Temperature anomaly graphs of Bishopton and Salsburgh

As per figure 4.3, on average, a total of 116.5 mm and 91.75 mm monthly rainfall is observed at Bishopton at Salsburgh within the last 20 years. Bishopton station records a daily mean wind speed of 7.5 knots whereas Salsburgh records 11.67 knots. The average daily maximum gust comes around 22.7 knots at Bishopton and 26.5 knots at Salsburgh.

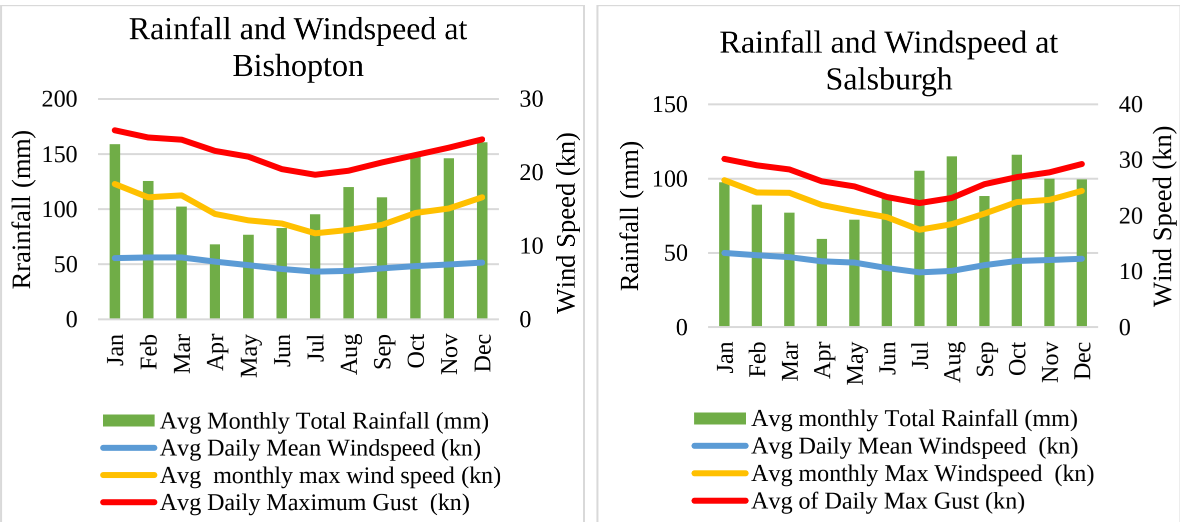


Figure 4.3: Rainfall, windspeed, and gust speed pattern at Bishopton and Salsburgh

As presented in figure 4.4, the western wind is predominant during summer and throughout the year followed by eastern and northwestern wind at Bishopton station. In another hand, the

southern wind is prevalent throughout the year at Salsburgh. A holistic picture of Glasgow's wind profile is presented in figure 4.1 by merging both stations' recorded data.

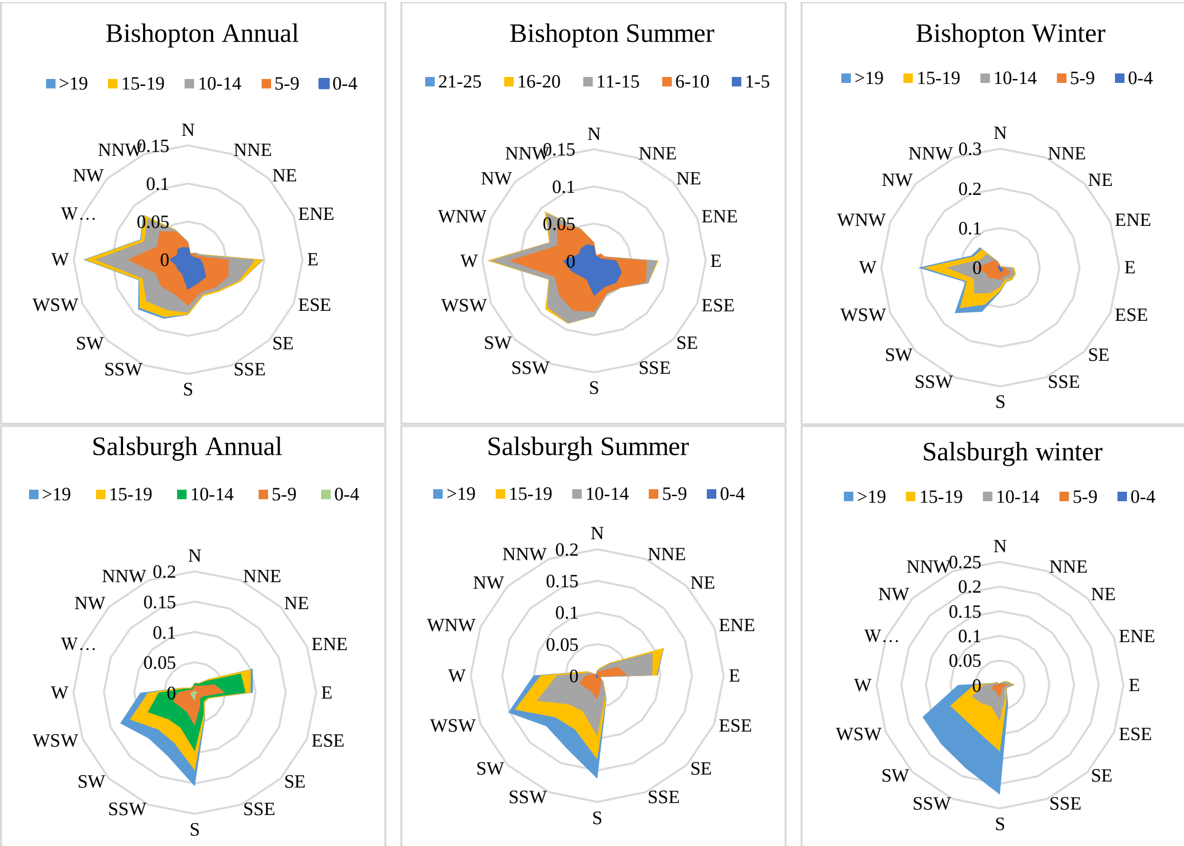


Figure 4.4: Annual, summer, and winter windspeed rose at Bishopton and Salsburgh

Overall, it is noticed that the north side of the city receives more wind speed than other parts. As Salsburgh station is located in hilly areas, it records lesser temperature and more wind speed data compared to Bishopton station.

4.2 Base Layers of Heat Risk Assessment

LST and air temperature are two alternative hazard layers presented in figure 4.5. As per the LST map, the built environment reflected high surface temperature (highlighted in red color) which was 33.13 °C at maximum and dispersed throughout the city. Based on the land use profile, it is understood that urban green and blue spaces such as parks, agricultural lands, and water bodies manifested low surface temperature (highlighted in blue color). The highest Ta is evident in and around the city center that gradually gets reduced in the outskirts.

LST and Ta data are not comparable as they represent two separate time horizons; nonetheless, there is a resemblance in their spatial distribution that signifies green belts as cool places and the central part of the city as a warm place relatively.

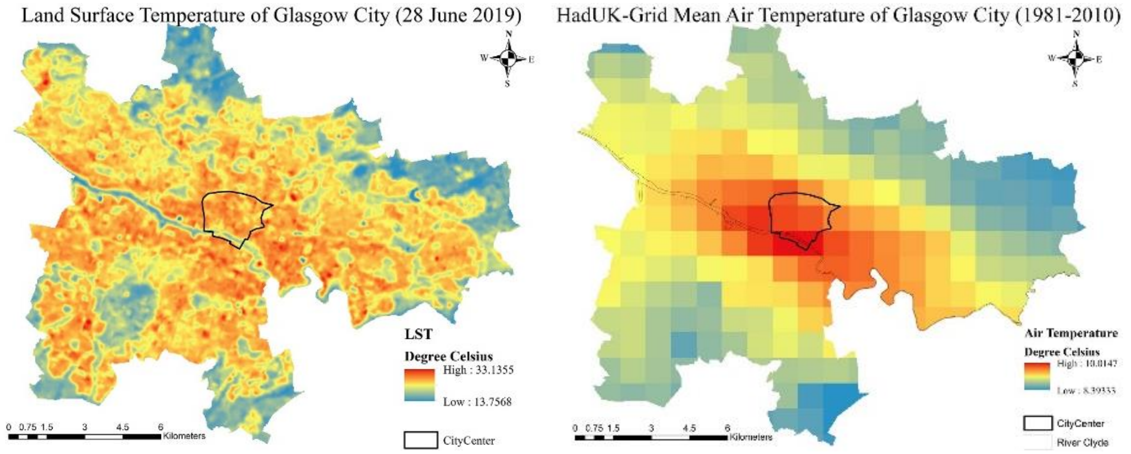


Figure 4.5: LST (left) and air temperature (right) maps of Glasgow city

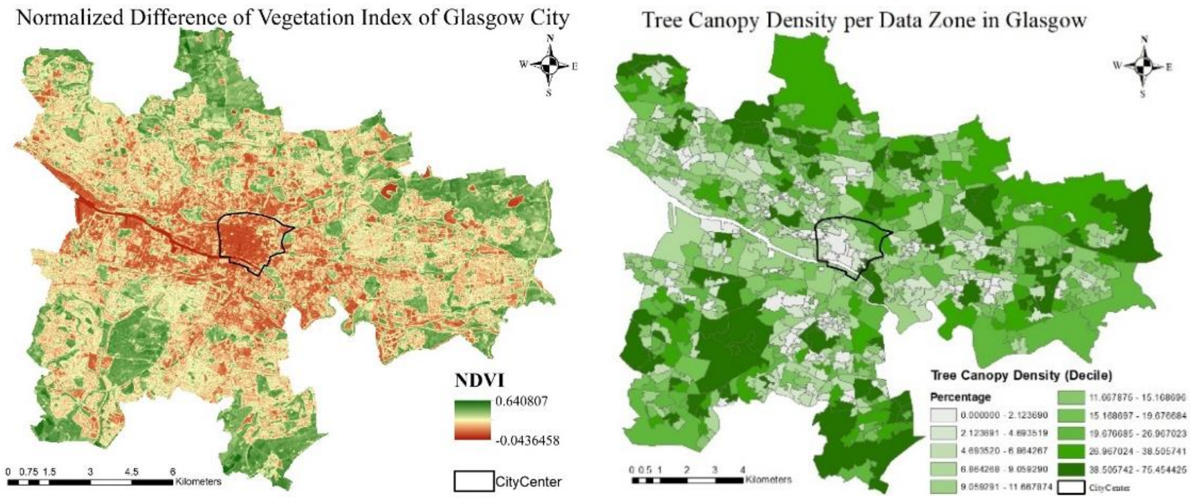


Figure 4.6: Maps of NDVI (left) and tree canopy density per DZ (right) of Glasgow city

NDVI map in figure 4.6 implies that the city center contains limited to no vegetation. The map also reveals that only 19% of areas comprise moderate to high dense trees which are mostly found in green belts and parks. At maximum, roughly 75.45% of a DZ is covered by tree canopy whereas the city center encompasses only less than 2.12% tree canopy on average. Both NDVI and tree canopy maps provide similar images of Glasgow city's greenspaces. If the NDVI map is compared to the LST map, it is found that a low LST value is reflected in the high NDVI zones (highlighted in green color in figure 4.6).

The tallest building in the city is 99m in height but the highest average building height of a DZ is 34m as displayed in figure 4.7(a). On average, the city center encompasses tall buildings, but still, some discrete DZs in the fringe got tall buildings. Additionally, the city center uncovers high building area density that can be up to 63% area of a DZ as seen in figure 4.7(b). Together building height and area density marks the high BV in dark red color in figure 4.7 (c) in the city center followed by Partick and Shawlands town area. LCZ map in figure 4.7(d) reveals that LCZ 8 mostly containing large low-rise buildings is prevalent in the city that covers almost 25% of the city followed by LCZ 9 with the sparsely built zone.

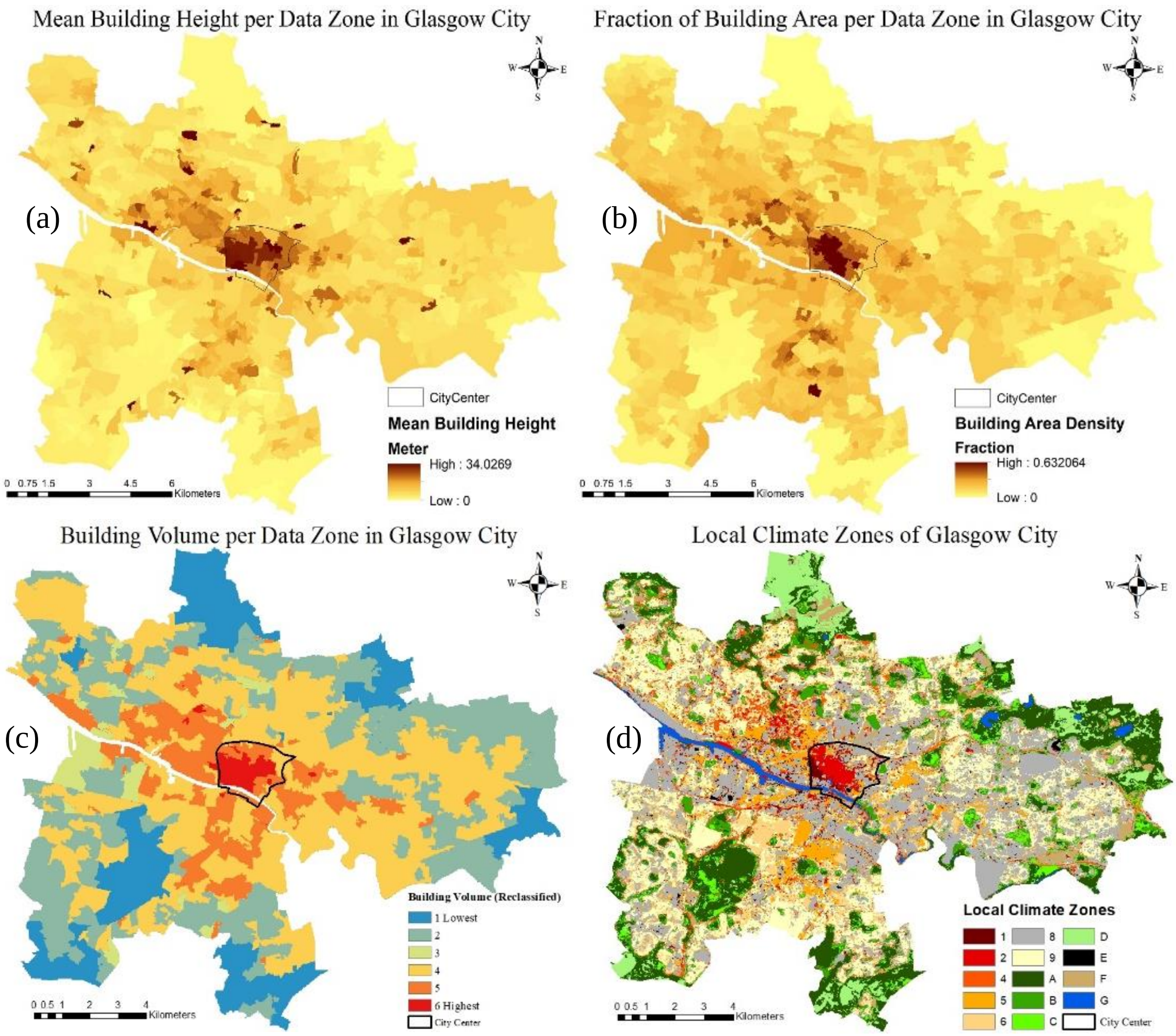


Figure 4.7: Maps of (a) building height, (b) building area density, (c) building volume derived from building height and area density, and (d) Local Climate Zones of Glasgow city

Through map analysis, it is observed that areas with the highest BV value overlay the joint areas of LCZ 1 and 2 which is evident in the city center. Furthermore, areas with low BV overlay the zones of LCZ A, B, C, and D that mainly contain medium to high vegetation cover.

Thus, both BV and LCZ are seemingly presenting similar information on Glasgow city's urban form.

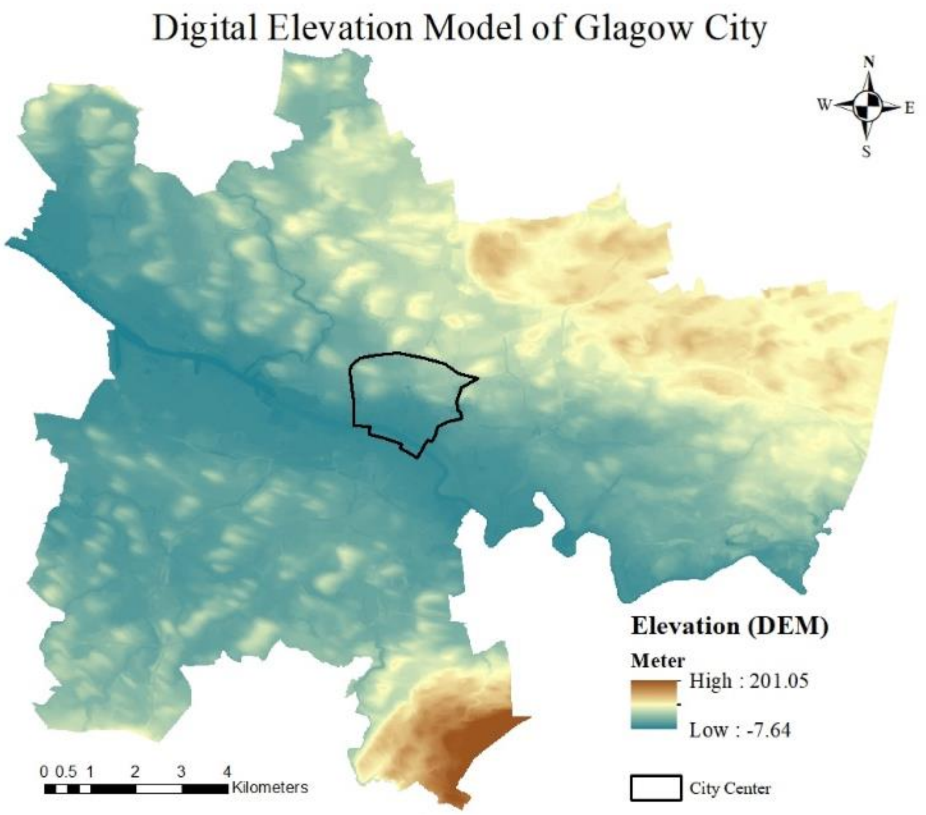


Figure 4.8: Digital Elevation Model (DEM) of Glasgow city

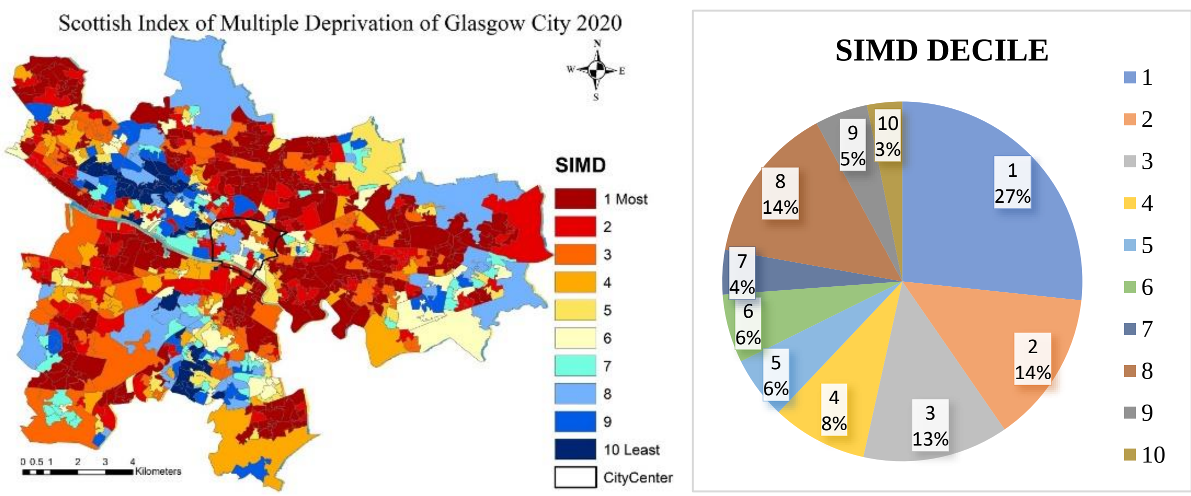


Figure 4.9: Map (left) and pie chart (right) of SIMD decile

Digital Elevation Model in figure 4.8 infers that the city lies in a low-lying area with a mean height of 41.8m above sea level. Besides, according to the DEM map, only 3% area is located above 100m of sea level which is largely found in the northeast and southern part of the city.

If we compare the DEM map to the wind and temperature map in figures 4.1 and 4.5 respectively, it is obvious that hilly areas are exposed to high wind speed that reduces the heat intensity of those zones. Overall, it can be assumed that heat intensity depends on many factors such as topography, wind speed & direction, and surface permeability together with vegetation cover, etc.

SIMD pie chart in figure 4.9 displays that nearly 68% area of Scotland's largest city is facing high deprivation. Approximately 27% of Glasgow city area falls under the most 10% deprived zones of Scotland whereas only 3% of the area is the least deprived. SIMD map portrays that low-deprived communities (highlighted in blue and dark blue) are living in Partick town along with part of the city center and southside of Shawlands town center. On the contrary, the other three towns such as Easterhouse, Parkhead, and Pollok face high socio-economic deprivation.

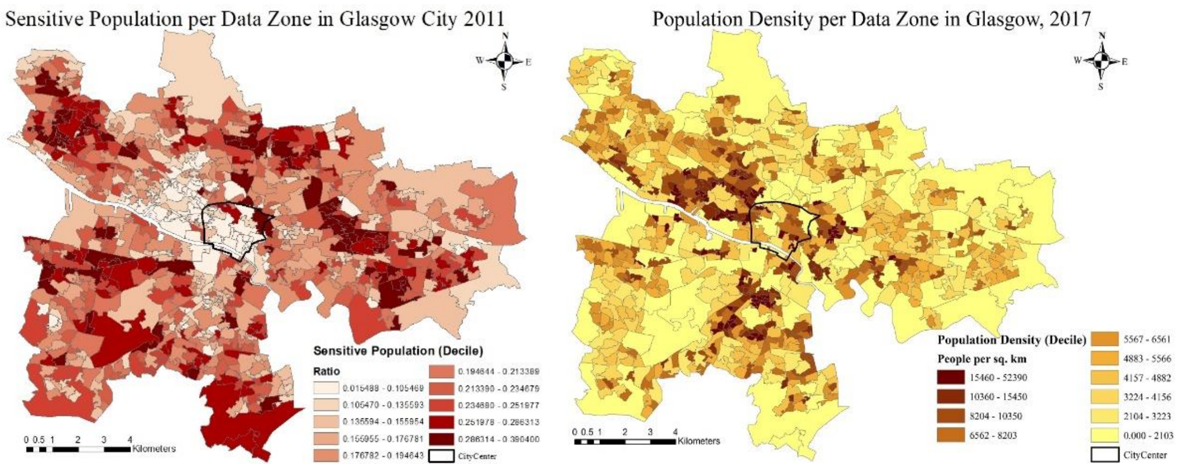


Figure 4.10: Sensitive population ratio (left) and population density (right) maps of Glasgow city

Partick town along with part of Shawlands town contains medium to high population density that can be up to approximately 52,390 inhabitants per sq. km. per DZ. Meanwhile, the sensitive population ratio is evident in the suburbs that is about 0.39 at maximum in a DZ. Population density and sensitive population density reveals two opposite pictures as presented in figure 4.10. If we compare figures 4.9 and 4.10, it is established that Partick and Shawlands are prosperous areas that have low deprivation indices despite having high population density.

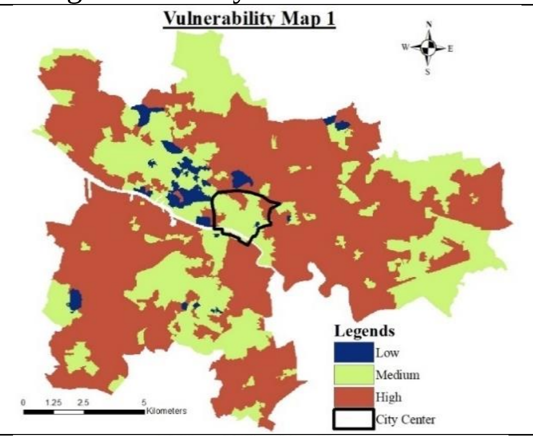
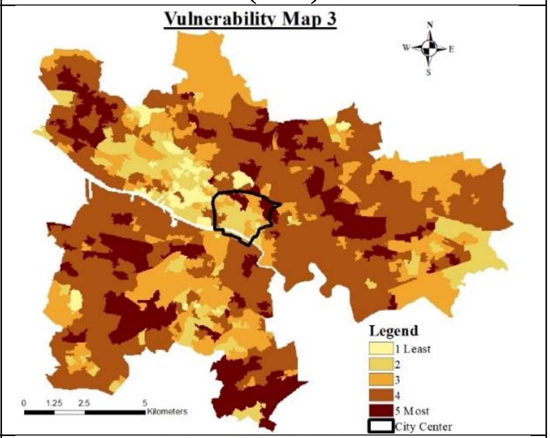
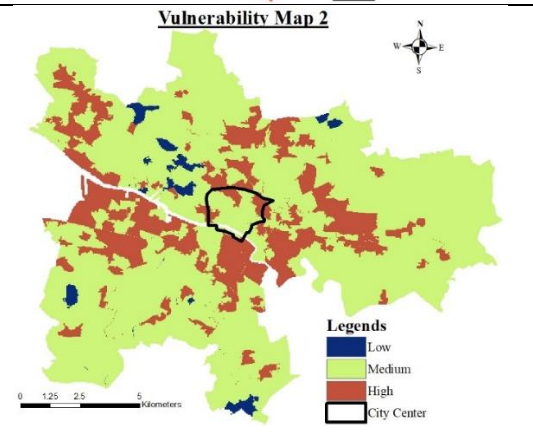
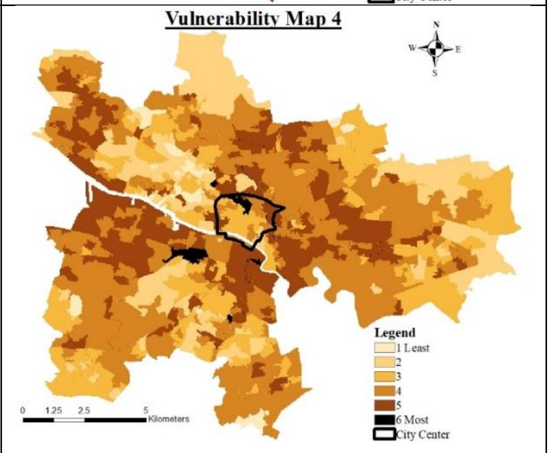
To sum up, the images of all base indicators give immediate hints on high and low heat risk magnitude based on their positive or negative correlation.

4.3 Risk Components: Vulnerability Maps

Based on the methods explained in chapter three, four vulnerability maps (VM) are generated in the thesis, given in table 4.1. The detailed process is given in appendix C.

In common, four VMs define Partick town as low heat vulnerable and city center as moderate. This thesis found that the vulnerability scenario changes drastically when the NDVI parameter is merged, largely because of its negative correlation to heat intensity. For example, VM 1 without NDVI designates about 64% area as highly vulnerable to rising temperature while VM 2 with NDVI displays only 21% area.

Table 4.1: Heat vulnerability maps (1 to 4)

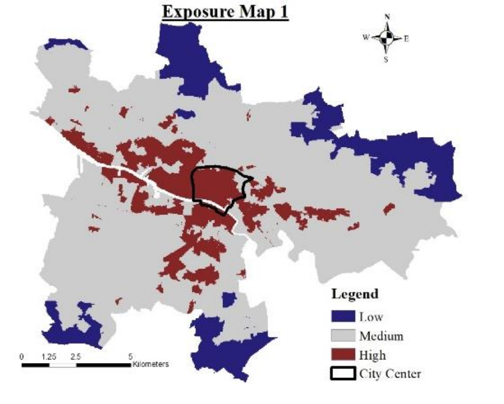
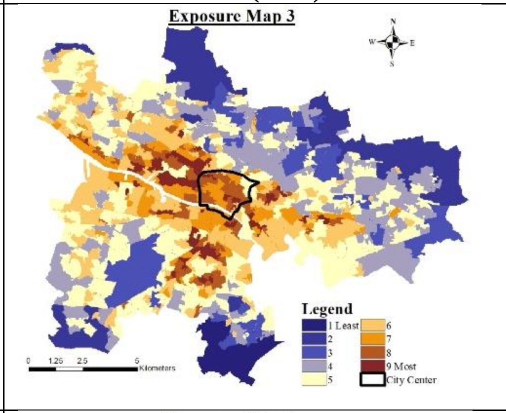
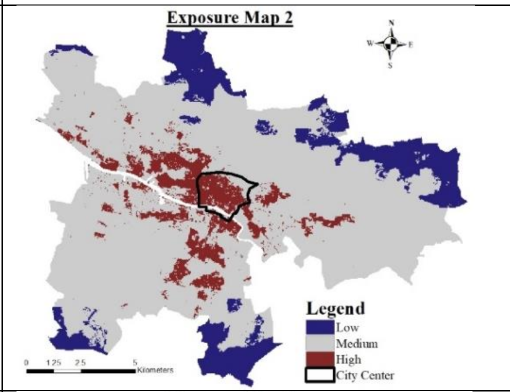
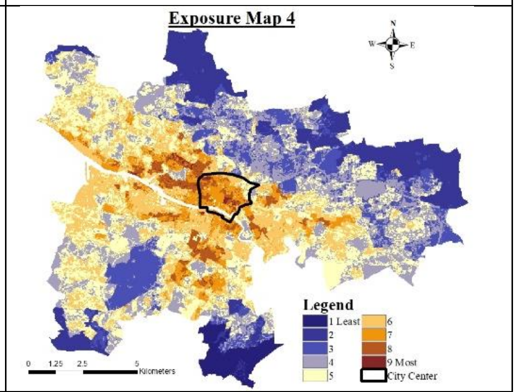
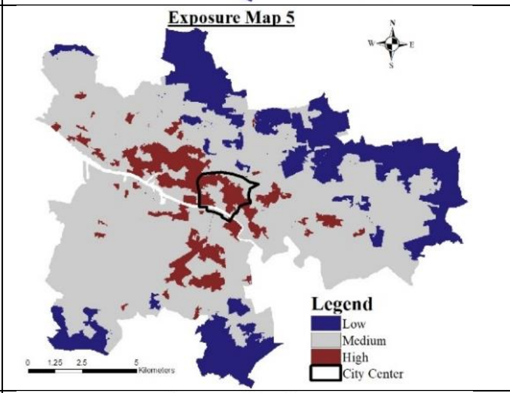
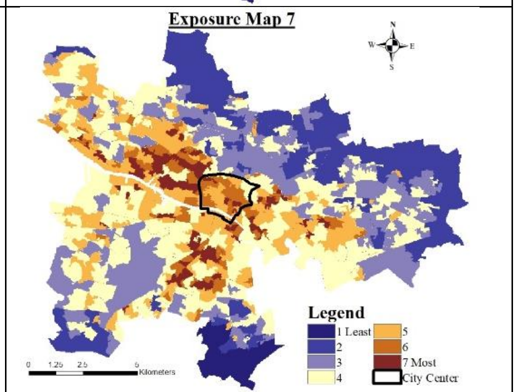
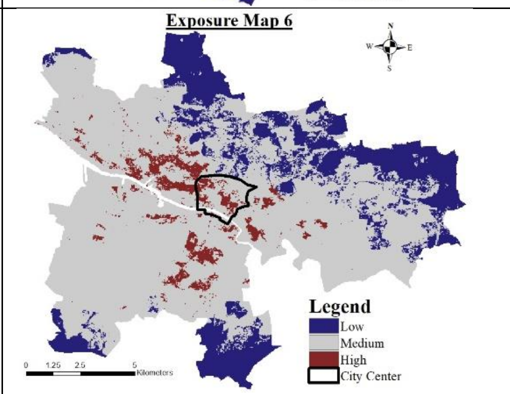
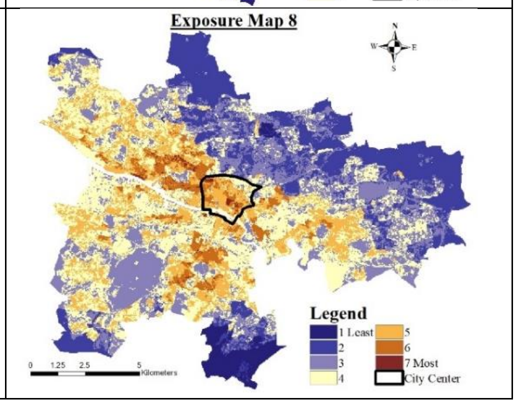
<table>
<tr><th>Parameters</th><th>Weighted Overlay</th><th>Raster Calculator (sum)</th></tr>
<tr><td>SIMD
Sensitive
Population</td><td>
</td><td>
</td></tr>
<tr><td>SIMD
Sensitive
Population
NDVI</td><td>
</td><td>
</td></tr>
</table>

4.4 Risk Components: Exposure Maps

As presented in table 4.2, a total of eight exposure maps (EM) are derived from different combinations of Building volume, LCZ, elevation, population density, and/or NDVI by

applying both weighted overlay and raster calculator methods in ArcGIS. The detailed process is given in appendix C.

Table 4.2: Heat exposure maps (1 to 8)

<table>
<tr><th colspan="2">Parameter</th><th>Weighted Overlay</th><th>Raster Calculator (sum)</th></tr>
<tr><td rowspan="2">With NDVI</td><td>Building Volume based maps</td><td>
</td><td>
</td></tr>
<tr><td>LCZ based maps</td><td>
</td><td>
</td></tr>
<tr><td rowspan="2">Without NDVI</td><td>Building Volume based maps</td><td>
</td><td>
</td></tr>
<tr><td>LCZ based maps</td><td>
</td><td>
</td></tr>
</table>

EM varies with GIS techniques. For example, Pollok Country Park is found as a moderately exposed area with the weighted overlay method, but less exposed with map algebra. Moreover, unlike vulnerability maps, the city center is found as high heat exposed zone partially or fully. The statistical analysis graph presented in figure 4.11 implies that the absence of NDVI in exposure analysis (EM 5 & 6) increases low exposed zones and decreases high exposed zones.

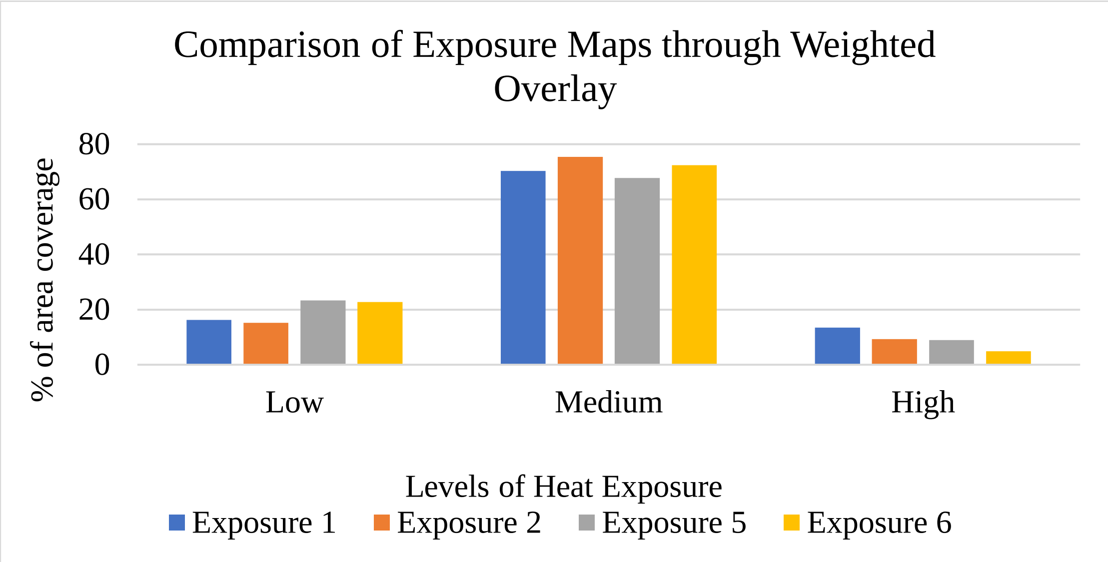


Figure 4.11: Statistical analysis of exposure maps with weighted overlay

4.5 Urban Heat Risk Analysis

This study created a total of 40 urban heat risk maps by using 2 hazards, 4 vulnerability, and 8 exposure components with both weighted overlay and map algebra techniques as explained in appendix D. Figure 4.12 gives a general framework of generating these 40 maps.

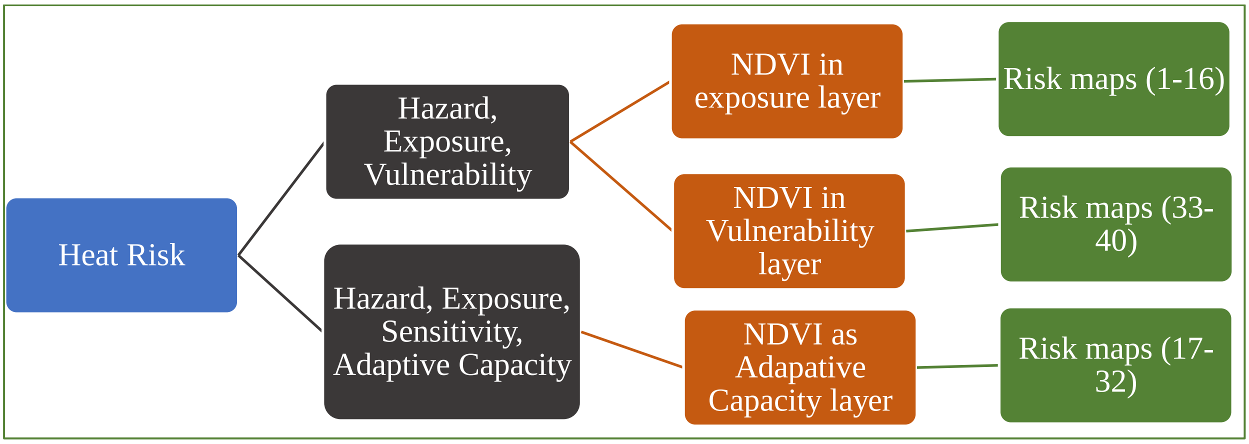


Figure 4.12: A chart of heat risk analysis process

4.5.1 UHR Maps with Weighted Overlay Technique

Twenty heat risk maps created with the weighted overlay method divide the study area into three risk categories only. According to figure 4.13, on average 76%, 17%, and 7% surface area of Glasgow city is susceptible to moderate, high, and low heat risk respectively. However, the percentage fluctuates tremendously based on the number of risk elements and the number of indicators of those elements. Notably, when NDVI is used to create the vulnerability layer (such that risk no. 33 to 36), the % of low heat risk area is increased and high heat risk zones decreased as shown in figure 4.13. Besides, four risk elements result in the highest high-risk zones. The spatial distribution given in appendix E, F, and G, 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.

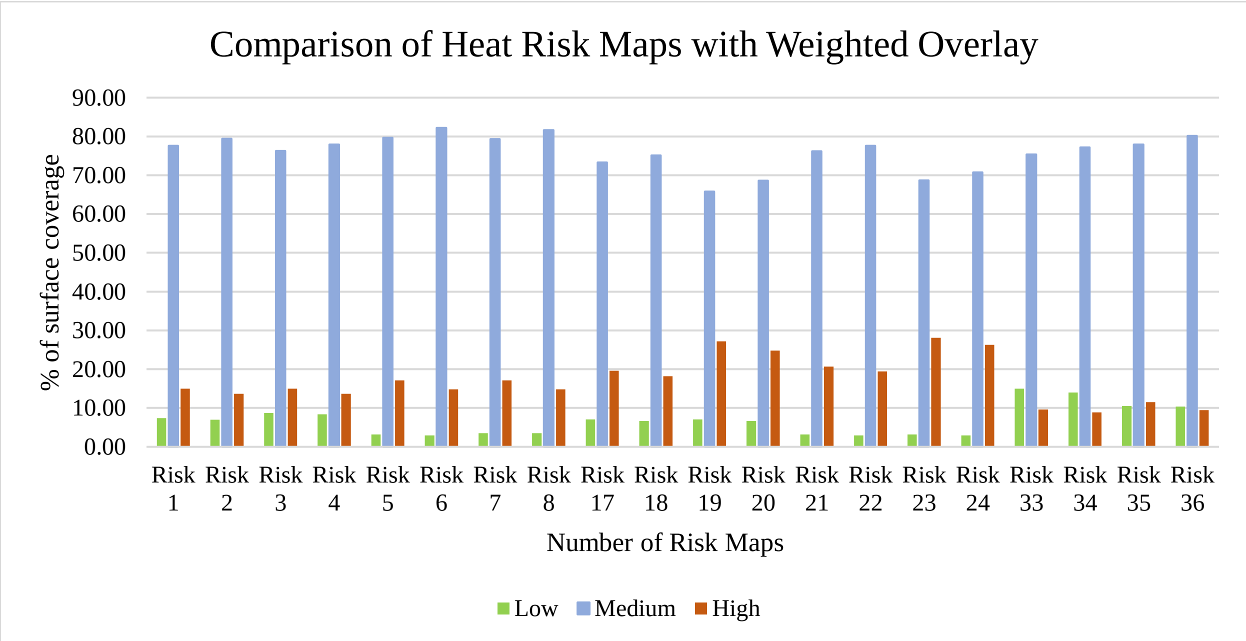


Figure 4.13: Comparison of all heat risk maps with weighted overlay (equal) technique

4.5.2 UHR Maps with Map Algebra Technique

Another twenty heat risk maps are derived through Raster calculation (sum) that divides the study area into more than six classes. However, as for the raster calculator, the number of classes differs based on the number of risk elements and the numbers of indicators for each element as presented in Figures 4.14, 4.15, and 4.16. Risk analysis with four risk components divides the study area into the maximum risk classes.

All the twenty maps show a normal distribution pattern in statistical analysis graphs as explicitly shown in figure 4.16. It infers that the percentage of high and low heat risk zones is little compared to moderate heat risk zones. On average, the map algebra technique discovers 5% of areas as the least and less than 4% of areas as the highest heat risk susceptible zones.

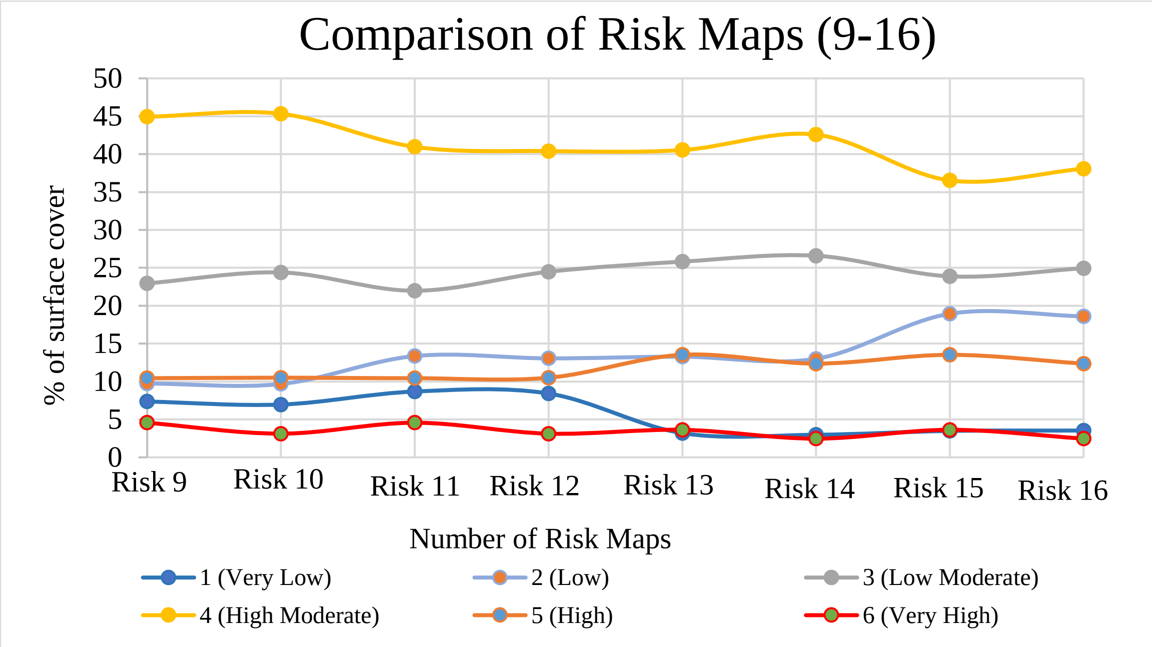


Figure 4.14: Comparison of heat risk maps (9 to 16) considering NDVI in exposure layer

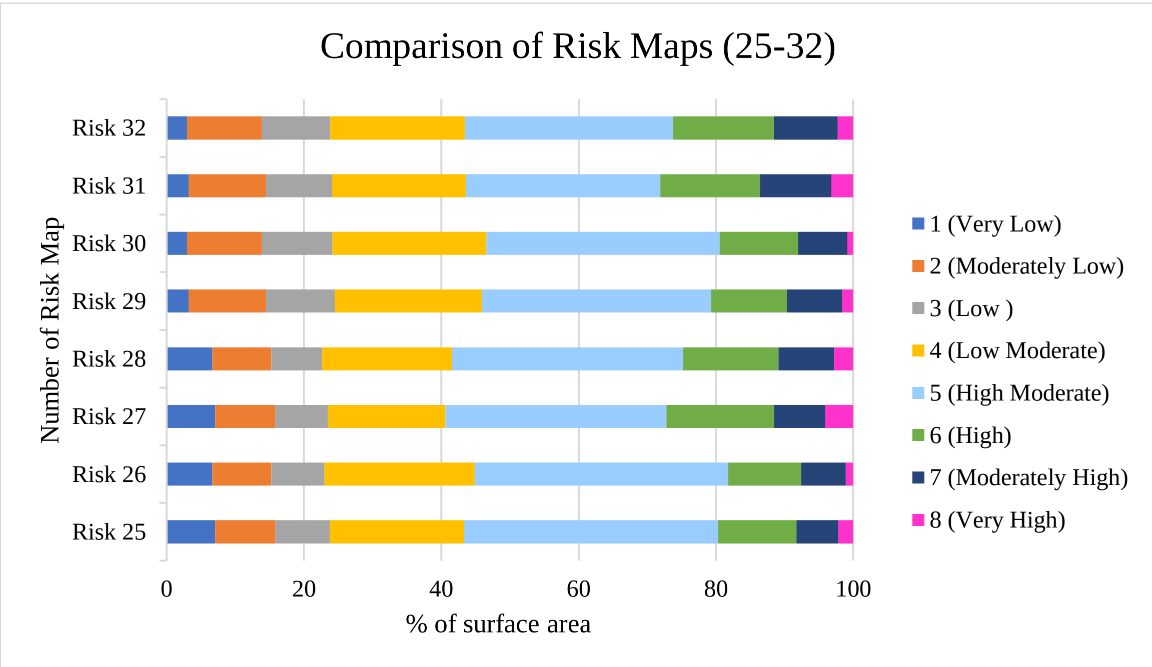


Figure 4.15: Comparison of heat risk maps (25 to 32) considering NDVI as the adaptive capacity layer

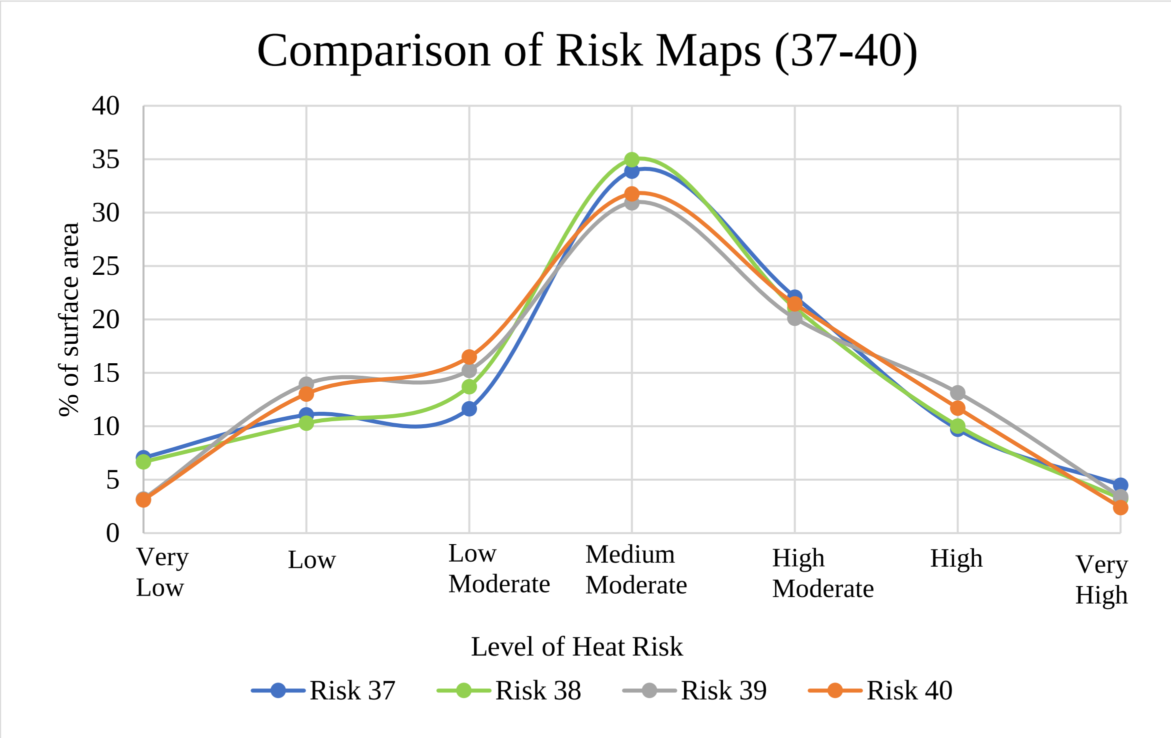


Figure 4.16: : Comparison of heat risk maps (37-40) considering NDVI in vulnerability layer

4.5.3 Description of Climate-sensitive Hotspots

This research appraised four raster calculator-based UHR maps (36 to 40) as the best fit to portray Glasgow city's heat risk mapping statistically and spatially. The rest of the map algebra-based maps (9 to 16 and 25 to 32) are given in appendices E and F.

According to this study, six climate-sensitive hotspots are containing high to very high heat risk potentiality are denoted as A, B, C, D, E, and F as shown in figures 4.17 and 4.18. Table 4.3 presents the background summary of all nominated hotspots. Hotspot A designates the city center which is highly exposed but with a 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. Hotspot C is also located near to Parkhead town center containing similar physical characteristics to B and relatively with a high vulnerability index. Hotspot D is a bulky climate-sensitive area with high deprivation and high LST. Hotspot E is a small hotspot pocket with a high vulnerability index. Lastly, F is a hotspot alongside the river Clyde bank entirely used for industrial or commercial purposes and highly exposed to heat risk. UHR

map numbers 38 and 40 shown in figure 4.19 also reveals the similar spatial distribution of UHR 37 and 39 correspondingly.

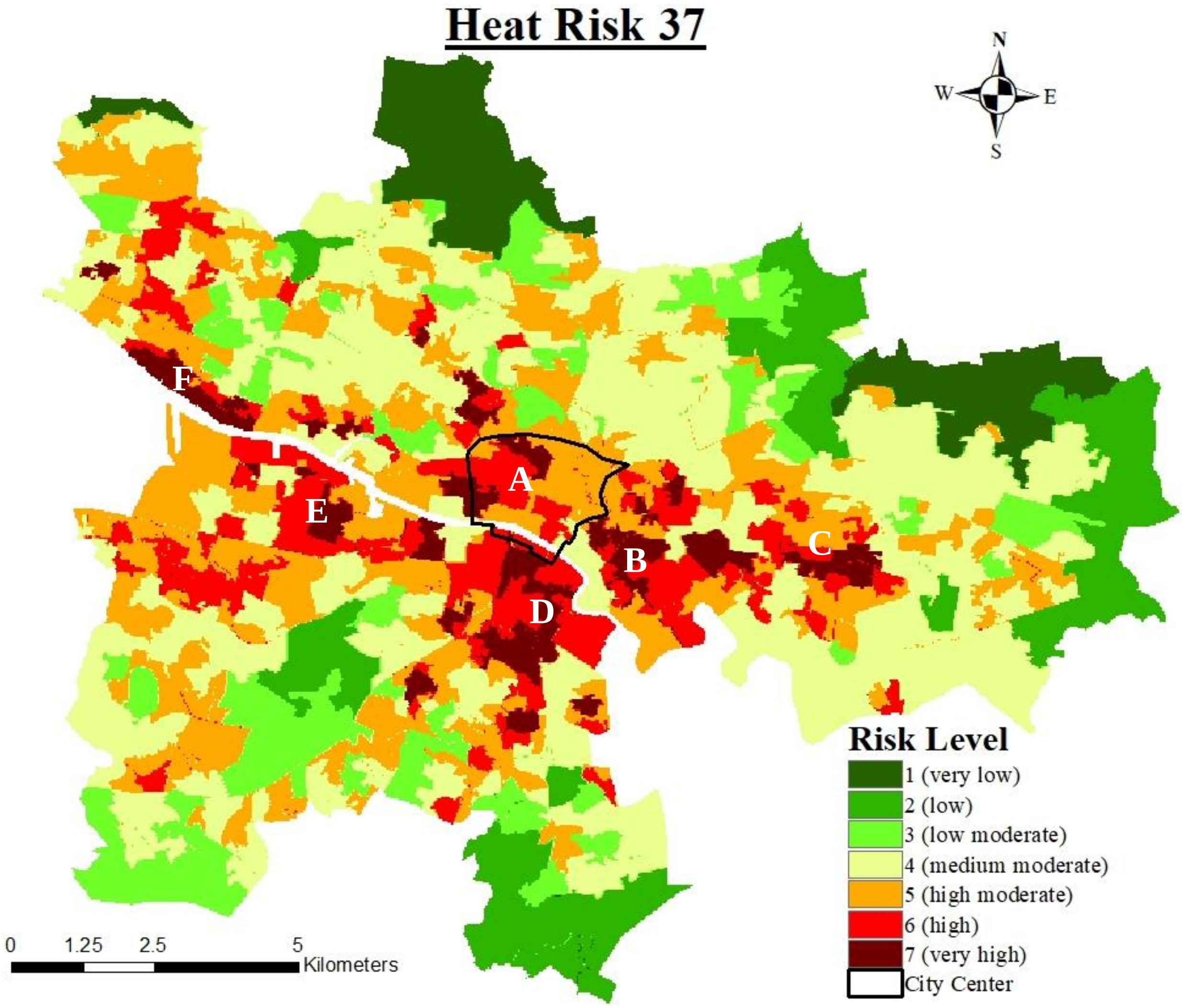


Figure 4.17: Building volume-based heat risk map for LST hazard

The key finding of this study is that five out of six hotspots are located within the River Clyde Development Corridor, a prospective development area under the City Development Plan. Besides, these high-risk zones are found either under Strategic Economic Investment Locations (SEILs) or Economic Development Areas (EDA) of GCC. 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 including Pollok and Easterhouse town

area. Therefore, it is deduced that an area can be susceptible to heat risk due to a combined effect of climatic, physical, socio-economic urban features.

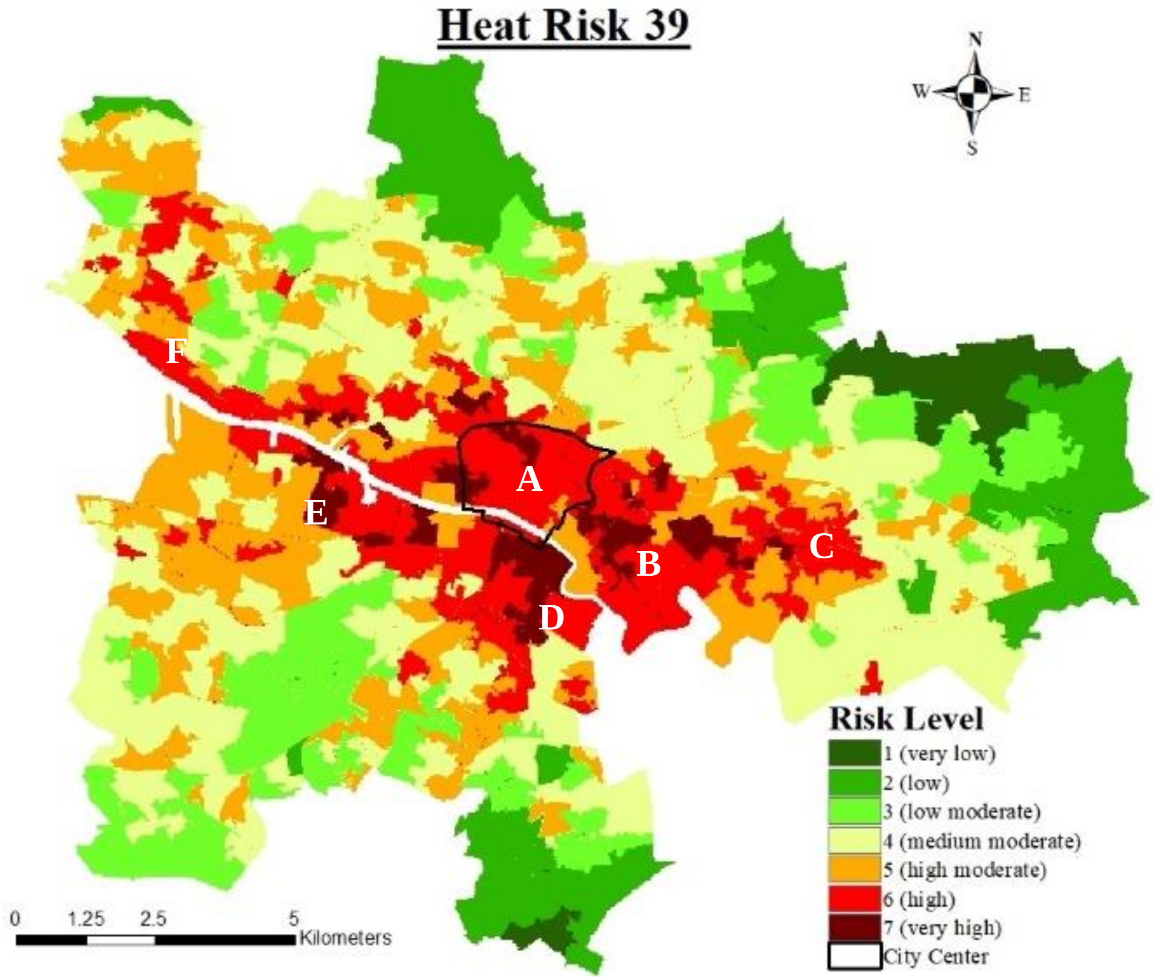


Figure 4.18: Building volume-based heat risk map for air temperature hazard

Table 4.3: Background status of six hotspots

	LST	Air Temperature	Elevation	Building Volume	LCZ	Population Density	Sensitive Population	NDVI	SIMD	Land use
A	High	High	Low	High	1, 2	Medium	Low	Low	6 to 8	Georgian New Town
B	High	High	Low	High	5, 8	Medium	Medium	Low	1 to 5	Urban area; Industrial or commercial;
C	High	Medium	Low	Medium	5, 8	Medium	High	Medium	1 to 5	Urban area
D	High	High	Low	Medium	8	Medium	Medium	Medium	1 to 5	Urban area; Industrial or commercial;
E	High	Medium	Low	Medium	5, 8	Medium	Medium	Low	1 to 5	Industrial or commercial; Urban area;
F	High	Medium	Low	High	8	Medium	Medium	Low	1 to 5	Industrial or commercial;

4.5.4 Description of Comparative Analyses

Regardless of GIS spatial analysis techniques, the majority surface area of Glasgow city is prone to moderate heat risk. Both techniques show a normal distribution pattern of the ordinal risk classes where both low and high classes have low percentage and moderate class has a high percentage. A risk-class-based statistical comparison is not possible as the raster calculator provides more classes in contrast to only three classes of the overlay method. However, detailed information on spatial heat-risk distribution can be gathered with the map algebra method duo to more risk classes at a small scale. Besides, both techniques spotted the low and high heat risk zones in similar locations.

As for the two hazard components, all LST-based maps with both techniques generate about 3% - 4% more low UHR zones than Ta-based maps, but similar percentages of high UHR areas as also shown in figure 4.16. Besides, the extent and magnitude of six climatic hotspots vary spatially between LST and Ta-based maps. Ta-based risk map discloses the whole city center as highly climate-sensitive while LST-based map designated only numerous data zones under Georgian New Town part. However, both hazards assigned a greater part of Partick town as medium risk zones even after its high population density and the densely built environment. Overall, this study appraises LST-based UHR mapping over Ta-based UHR mapping.

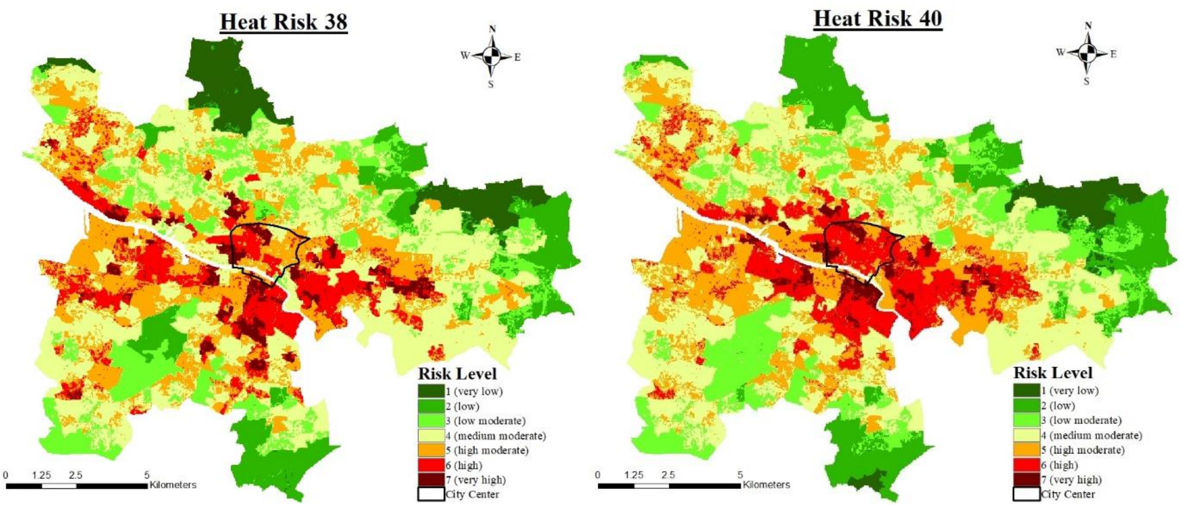


Figure 4.19: LCZ- based heat risk map for LST (left) and air temperature(right)

Selection of the number of risk elements changes the assignment of NDVI to different risk components in this study, which influences the percentage of high and low heat-risk areas in the case of overlay-based mapping. Four components derive a bigger percentage of high-heat risk zones in contrast to the three components. However, the number of risk elements affects the number of risk classes only in map algebra-based UHR mapping while keeping the percentage of low and high heat-risk areas relatively similar.

Comparison of UHR maps no. 37 and 38 revealed a parallel result spatially and statistically, which infers that the LCZ map is a good alternative to the building volume map.

CHAPTER 5: DISCUSSION AND RECOMMENDATIONS

By using the established concept of urban climate mapping, this thesis has conducted an urban spatial heat risk analysis to visualize the zones of Glasgow city likely to be affected in case of overheating (Smith, Cavan, and Lindley, 2015). To accomplish objective no. 6 of this dissertation, this chapter encompasses a critical evaluation of the thesis's findings with published literature.

5.1 Risk Perception and Number of Risk Elements

Risk mapping is a step-wise process where each step shapes the weightage of base indicators. This study is the first of its kind to generate heat risk maps with a different number of risk elements. 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% only for each component when risk is a function of four risk elements. In this thesis, risk maps with four elements consider Sensitivity and Adaptive Capacity separately instead of one vulnerability layer; hence, NDVI's contribution outstrips other parameters except for the hazard component. As a result, perception of risk definition plays a key role by essentially changing the contributing factor of each base layer in the statistical and spatial risk outputs, similar to the discussion raised by Andersson-Sköld et al. (2015).

5.2 GIS Spatial Analysis Tools

Among many GIS spatial analysis tools, Map Algebra and Weighted Overlay are commonly used in both UCM and UHR studies. This study adopted a novel approach to compare these two techniques for the subject topic. Published literature used either overlay technique (Smith, Cavan, and Lindley, 2015; Tapia et al., 2016; Estoque et al., 2020; Chen et al., 2018; Tomlinson et al., 2011) or map algebra (Greater London Authority, 2021; CUHK, 2012) for urban climate analysis without giving an insight on the logic for choosing the method.

Even as the overarching statistical pattern is similar, the raster calculator helps to understand heat risk intensity at micro-scale by contributing more risk classes. However, limited information can be gathered from the three heat risk classes extracted through the weighted overlay method. Technically, the overlay method is designed to conduct suitability or susceptibility analysis of a location in GIS (ESRI, 2021). Considering the depth of interpretations of the maps, the raster calculator delivers better results in this thesis. As seen in overlay-based risk analysis studies, preparation of base layer with larger scale such as 1 to 5

(Tomlinson et al., 2011) and 1 to 10 (Smith, Cavan, and Lindley) could improve the overlay-based risk maps of this thesis.

5.3 Evaluation of UHR Maps for Hazard Components

LST and Air temperature are used alternatively as the hazard element, but readable information is obtained from LST-based risk maps rather than Ta-based maps. LST mapped the heat risk at the local scale and thus, delivered detailed knowledge about Glasgow city's geospatial heat risk condition. Meanwhile, air temperature data is clustered at the city center and thus, seemingly looks biased. The discrepancy lies in the base layer data quality. Air temperature data was collected with poor resolution (1km x 1km) from the HadUK-Grid dataset of Met Office. HadUK-Grid project retrieved the mapping version of Ta through inverse distance weighted interpolation method with the observed climatic data of the Met Office's meteorological stations (Met Office, 2021d). As indicated in figure 4.1, there is no Met Office station within the city boundary. Thus, the interpolation might have taken data from the nearby stations. Thus, Ta is coarse and not a good representative of Glasgow city's air temperature at 1.5m height. Rather, satellite-based LST data reflects urban surface temperature at 30m grid size, highlighting the nature of urban land cover such as building, water, vegetation, etc. Hence, the LST map represents a better heat load scenario at a smaller scale than Ta in this thesis. As a result, LST-based UHR maps are more sophisticated, realistic, and heterogenous than Ta-based UHR maps in this study.

5.4 Evaluation of NDVI as an Indicator of UHR Mapping

As enlightened by Räsänen et al. (2019), this study also infers that changes in weightage factor affect the final risk map production. Placing NDVI in different risk component layers allocates different weightage factors to it such as 8%, 11%, and 25% in exposure, vulnerability, and adaptive capacity layer respectively, and thus, resulted in different mapping scenarios statistically and spatially. NDVI has been used either in the vulnerability layer (Tapia et al., 2016; Maragno et al., 2021; Estoque et al 2020; ARUP 2014) or the exposure layer (Smith, Cavan, and Lindley, 2015; Greater London Authority, 2021) in different studies. UHR maps with NDVI in the vulnerability layer highlighted low UHR zones in the cooling zones like the study findings of Majekodunmi, Emmanuel, and Jafry, (2020). Besides, as studies such as Andersson-Sköld et al. (2015), ARUP (2014), and Mehrotra, Bardhan, & Ramamritham, (2020) consider NDVI is just one of the many indicators for UHI estimation and heat risk

analysis; thus, 25% weightage for NDVI is an exaggeration, which might cause overestimating result. Therefore, it can be deduced that allocation of NDVI in the vulnerability layer gives better results.

5.5 Evaluation of UHR Maps' Spatial Distribution in Glasgow City

The study found a spatial clustering of high heat risk potentiality in the Glasgow City Center, similar to the study findings of Wolf & McGregor (2013) for London and Smith, Cavan, and Lindley (2015) for Greater Birmingham. Many other studies also highlighted that city centers are likely to be hit by high heat risk intensity in the whole city (Tomlinson et al., 2011; Buscail, Upegui, & Viel, 2012). Like the findings of Arup (2014) for London city, this thesis also observed a decreasing pattern of heat risk intensity from the city center toward the peripheral zones along with pockets of low UHR in large parks such as Pollok Country Park (Buscail, Upegui, & Viel, 2012). Besides, other heat risk hotspots are also evident near the city center and alongside the river Clyde except for Partick town. Despite having high exposure index, Partick town is strong socio-economically which resulted in low UHR intensity. Comparison of SIMD and sensitive population maps demonstrate that the least deprived data zones have the least sensitive population. However, those least deprived areas have high population density which claims that those areas are well off and have more ability to cope up with heat risk. Areas covered with high vegetation has low population density but more sensitive population such as in Pollok and Easterhouse town area. Thus, these town areas are moderately heat-risk potential. Parkhead town area is one of the top deprived zones which is under LCZ 8 (low large building) and contains less vegetation. Table 4.3 infers that high heat risk zones are spotted mostly in the heavily built-up area serve for industrial or commercial purposes parallel to the UCM study for Greater Manchester (Smith, Cavan, & Lindley, 2015). However, unlike Greater Manchester, all these spots are not high for all risk components. Some of the hotspots are attributed to less exposure, but high vulnerability. 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.

More indicators can be used to conduct UHR mapping as found in different kinds of literature. It should be kept in mind that all these parameters are interlinked. For example, one study found that population density above 14,500 inhabitants/km2 may cause intra-urban temperature difference of 1°C and means have more building volume to accommodate these

large populations, reduce SVF, and leave limited surface area for vegetation (Ramírez-Aguilar and Souza, 2019). Some parameters may substitute the others. For example, NDVI can replace impervious surface index (Kaspersen, Fensholt, & Drews, 2015), LCZ for Building volume, and LST for Ta.

5.6 Evaluation of CDP in Respect to UHR findings

The reflection of the climate change effect is visible through atmospheric phenomena such as temperature, rainfall, etc. that lead to secondary urban problems like overheating, flooding (England et al., 2018). Projected temperature rise together with UHI intensity will put urban inhabitants in danger (Maragno et al., 2021). Besides, urban morphology, social and economic factors, and spatial planning decide who are more affected than others. Thus, this study answered the question of detecting hotspots to intervene on a priority basis. This study found that a significant part of the city's conservation areas falls under Medium to high-risk level including Hotspot A in the city center. Besides, 5 out of 6 risk hotspots are observed in the River Clyde Development Corridor as shown in CDP 2. Besides, a comparison of risk map 38 and CDP 3 maps reveals that hotspot B and D are found in the Strategic Economic Investment Locations (SEILs). These critics give insights to review the city development plan by conducting an in-depth study on the hotspots. Considering the economic loss due to the prospective damage from overheating, it is high time to improve climate change adaption and mitigation measures along with controlling the UHI sources.

Overall, this study highlights the risk of overheating risk in a two-dimensional spatial framework at mesoscale. Instead of the conventional UCM approach, the risk-based approach enabled to fill the gap between socio-economic inequalities, a major drawback of traditional UCM study as stressed by Parsaee, et. al. (2019). This study's findings encourage climate-proof planning and resilience design for overheating in Glasgow city which is pressed by Emmanuel (2021).

5.7 Recommendation at City Scale

Even after being climate neutral, climate change will not go off overnight as there are no administrative boundaries of the atmosphere. However, 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) too.

5.7.1 Strategic intervention

As existing urban set-up is expensive to transform, so Glasgow city council can incorporate the urban geometry factors such as optimum H/W ratio, sky view factor, street orientation, etc. for the regeneration projects (Dursun & Yavas, 2015). Besides, compact neighborhoods along with public open spaces should be kept in mind during redevelopment and regeneration planning (Johansson & Yahia, 2010). Increasing surface permeability is necessary to control both day and nighttime indoor and outdoor heat stress whereas the shading effect with building density is equivocal. Compact tall buildings reduce to keep the daytime outdoor cool but exacerbate night-time heat stress (Andersson-Sköld et al., 2015). Thus, the shading effect from trees should be considered to have a cooling effect in Glasgow city. The shading and evapotranspiration effect of green spaces can cut the LST and Ta by between 2 –8°C (Arup, 2014). Reference of UGI development is evident almost in all UCM studies as a heat stress mitigation strategy (Tokyo Metropolitan Government, 2005; Ng, 2015; Watkins, Palmer, and Kolokotroni, 2007). These studies also highlighted the importance of cooling albedo effect, minimizing surface sealing, and increasing air ventilation in UHI mitigation. The study conducted by a research group of Glasgow Caledonian University has already emphasized the need for green infrastructure to adapt to overheating trend in Glasgow City (Rohinton & Loconsole, 2013). Dursun and Yavas (2015) further recommended deciduous trees i.e., Pine trees in an enclosed form for cold climate cities so that they produce shade in summer and retain the heat in winter. Besides, the cooling effect of vegetation cover varies with the anatomical features of the trees, positioning, and size of the greenspaces (Doick & Hutchings, 2013). UGI development in Glasgow city should prioritize the above-mentioned facts.

Besides, public participation in climate-sensitive community development can help to improve the microclimate. Small measures together can have a greater effect on the urban environment as a whole. Arranging for design competition brings in innovative solutions and is found effective in urban retrofitting (Djukic, Vukmirovic, & Stankovic, 2016). Other measures like heatwave forecasting (CRC, 2021), Heatwave Management Guideline development like England[5], and designated local cooling centers (Arup, 2014) can be established beyond the existing policies and plans. Moreover, developing economic activities and reducing socio-economic equalities should be prioritized too. Partick town area should be taken as an example

[5] https://www.gov.uk/government/publications/heatwave-plan-for-england

which is a highly populated area with compact mid-rise buildings and having low heat risk potential due to its least SIMD index.

5.7.2 Spatial Intervention

The benefits of nature-based solutions are also highlighted in different policies and strategies of the Glasgow city council (CRC, 2021) for improving urban climate resilience. Therefore, the improvement of green infrastructure as a tool of ES services (Naylor et al., 2017; Marando et al., 2019) is a key strategic point for Glasgow city's heat risk mitigation. To help in identifying spatial intervention zones for the GCC, this study constructed an UCRe-Map by overlaying the map of ecosystem service mismatch for temperature regulation (34% weightage) as shown in figure 5.1 and the UHR map number 38 (66% weightage). ES mismatch map is derived from ES demand and ES supply map as shown in appendix H. The UCRe-Map divided the study area into five planning zones as displayed in figure 5.2.

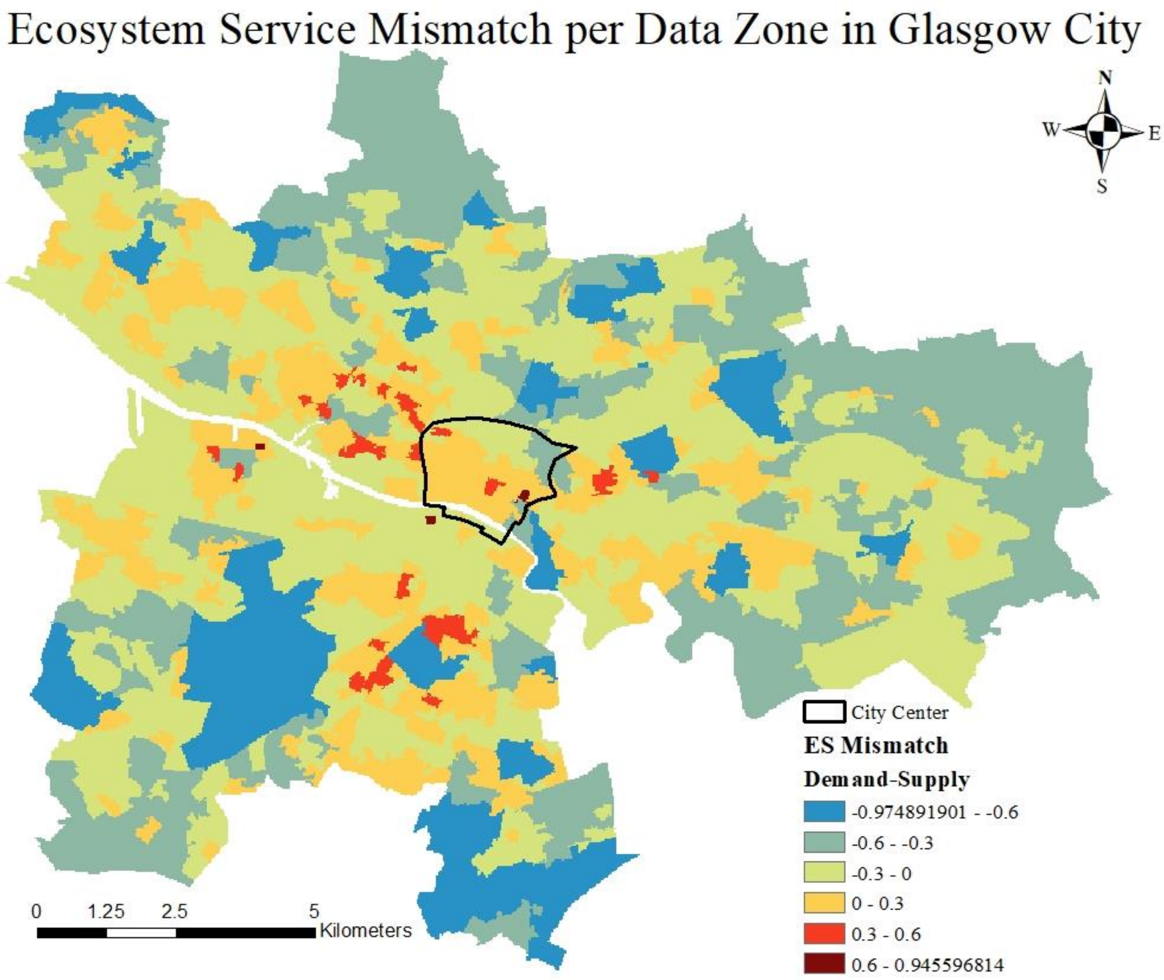


Figure 5.1: ES mismatch of Glasgow city

UPZ 1 consists of green spaces like parks and woodlands providing low to high cooling effects. Some of these areas are found in the designated Greenbelt zones such as Pollok Country Park which is also a Local Landscape area and conservation area. Areas discovered under UPZ 1 are climatically valuable areas that need to be protected.

UPZ 2 is mostly found in greenbelt zones used as agricultural land. These pervious surfaces have an NDVI index of more than 0.2. Besides these places are at high elevations and get the most windspeed in the whole city. Attention needs to be given to preserving these zones and their functionality to mitigate climate risks.

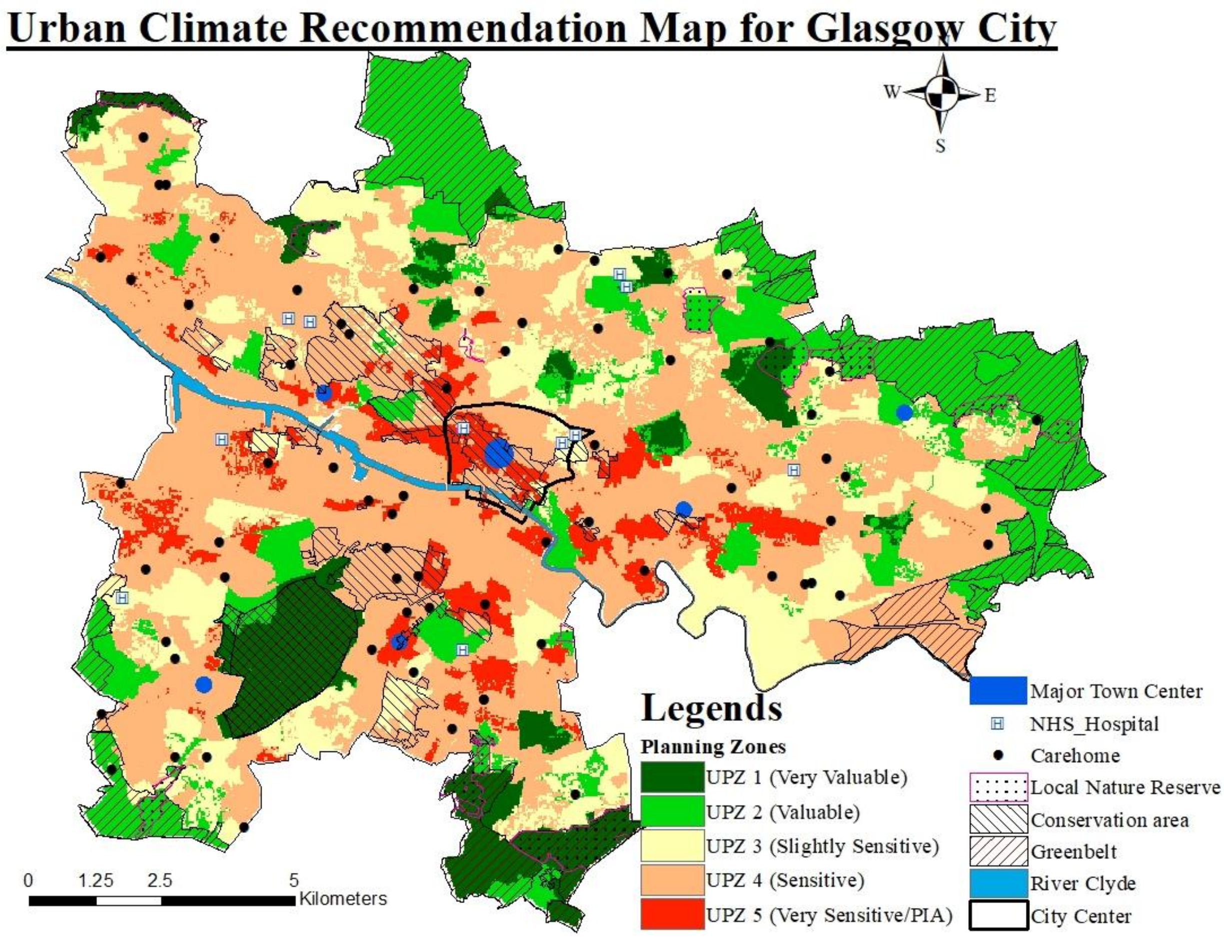


Figure 5.2: UC-ReMap for Glasgow City

UPZ 3 are slightly sensitive zones that are mostly used for industrial or commercial purposes along with urban areas. They need continuous monitoring so that they do not turn into more sensitive areas.

UPZ 4 covers the majority of areas of the city which are used as urban areas and industrial or commercial areas. Some conservation sites also fall under this planning zone. Most of the old homes are found in this category. This is a climatically sensitive area because of its high ecosystem service demand but poor ES supply. Thus, the above-mentioned strategic measures should be incorporated wherever possible.

UPZ 5 is the most sensitive zones that need priority intervention by the local government. Five major town centers including the city center are found in this category. Besides, a significant portion of Georgian new town is covered by UPZ 5. The only hospital in the city center is located in UPZ 5 too. Glasgow Green Park is under stress as its surrounding area is highly sensitive to overheating. These zones have very high demand and very little ES supply. Therefore, necessary climate change adaptation measures must be applied to get immediate benefits by reducing the UHI effect.

5.8 Recommendation for Glasgow City Center

Addition of ES Mismatch map to UHR map partially or fully nullified majority climate-sensitive hotspots except for city center as seen in the UPZ 5 of figure 5.2. To position the Glasgow City Center as a commercial and cultural hub of Scotland, it is needed to be a sustainable, livable, and enjoyable destination. The City Center Strategy and Action Plan 2014 – 2019 has already recommended an integrated green infrastructure development encompassing trees, green roofs and façade, rain gardens, and swales to mitigate floods, improve urban cooling, and enhance the quality of life (GCC, 2013). According to this thesis, Sauchiehall, Blythswood, Central, Broomielaw, and Merchant City districts of the city center are relatively more prone to heat risk than other districts. Thus, this study has provided several implications on how to make the city center a vibrant and sustainable place:

- The city center is a compact and highly built environment, so a feasibility study should be done to map the scope of the green space of more than 0.5 ha for greater cooling benefits (Arup, 2014). The distance between two greenspaces (small or large) should

not exceed 300m for optimum cooling effect at a neighborhood scale (Doick and Hutchings, 2013).

- Improving shading effect with tree canopies instead of buildings and temporary structures like pergolas, retractable canopies, etc. should be planned.
- To reduce air pollution and anthropogenic heat flux, radical actions like traffic diversion or traffic-free days can be introduced (Arup, 2014).
- Roof refurbishment with white paint or extensive green roof[6] (i.e., a thin layer of substrate, pocket habitat, etc.) should be done to improve the existing building's insolation that will cool down the building in summer but keep warm in winter (Arup, 2014).
- Considering 'Greening the Gray'as a useful tool, strategic measures for IGGI7 should be taken (Naylor et al., 2017).
- A scheme like the 'Green Flag Award'[8] to encourage both public and private corporations for developing accessible UGI should be embraced.

Overall, the city should aim to increase adaptive capacity and achieve climate "just" resilience by using the suggested measures and focusing on UCRe-Map coupled with SEPA's flood mapping[9] at different spatial scales.

[6] Ecological Master Plan in London. https://www.betterbuildingspartnership.co.uk/ecological-master-plan-london
[7] IGGI – Integrated Green Grey Infrastructure (Naylor et al., 2017)
[8] https://www.greenflagaward.org/

[9] SEPA- Scottish Environment Protection Agency in collaboration with Met Office works to forecast the flood. https://www.sepa.org.uk/environment/water/flooding/

CHAPTER 6: CONCLUSION, LIMITATION, AND SCOPE OF FURTHER STUDIES

6.1 Conclusion

Urban forms and functions together with socio-economic and planning aspects greatly influence the overlying urban atmosphere and its associated climatic risks. It is anticipated that the climate change effect will exaggerate the urban climatic risks, which puts pressure on urban decision-makers to reinforce the climate change adaptation strategies. Urban climate mapping is an excellent mechanism to integrate multi-disciplinary knowledge into a 2D spatial framework to visualize the climate change-induced problems such as overheating likelihood. Through a literature review of many UCM case studies, it is understood that urban climate mapping, simply, means a process of integrating climatic parameters such as temperature, rainfall, humidity, wind, etc. with planning and terrain parameters in a cartographic format. UCM outputs can be found in many forms such as thermal maps, heat risk maps, emission maps, climatic analysis maps, and planning recommendation maps. A risk-based approach is applied in this study to create UCMaps with readily available data for the whole Glasgow city. Besides, UCM processes are not identical among the existing studies but based on common ground. It created the curiosity to test different climatic risk mapping processes. Unlike any existing studies, the methodological processes are being questioned in this study to identify the key factors throughout the risk synthesizing process that may affect the mapping outcomes. From the indicator selection for each risk component to the risk synthesizing stage, this research developed unique methods grounded on the UCM concept. This thesis used two alternative climatic parameters (LST and air temperature) as hazard elements, two alternative GIS spatial analysis tools (raster calculator and weighted overlay), and two risk definitions. Several conclusions can be drawn from the research findings such as:

- Any of the two GIS techniques are useful to produce urban climatic maps but map algebra has provided detailed risk information compared to weighted overlay in this study. The quality of overlay maps can be improved if a larger scale is chosen while reclassifying the base layers.
- The LST-based process gives better mapping outputs than the air temperature-based process as the air temperature data is coarse and lacks spatial detail at the local scale. It is also learned that LST data is sufficient to analyze the urban heat risk if Ta data is unavailable or with poor resolution.

- 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. In other words, the selection of multiple indicators for each risk component can overrule the influence of an individual indicator and thus, reduce the tendency of overestimated results. This study also infers that NDVI is better placed as a component of heat vulnerability analysis as this combination gives a seemingly realistic spatial distribution of heat risk intensity in Glasgow city.
- From the appraised maps, this thesis concludes that climate-sensitive zones are prevalent within the boundary of the River Clyde Development Corridor having mixed land use characteristics. High heat risk spots are either urban areas or industrial or commercial areas or a mix of both. The city center is detected as a heat risk hotspot regardless of any changes in the mapping processes, which calls for a prior action by GCC to control the sources of UHI effect in the city center.
- The planning recommendation map highlights the zones that need priority interventions including the city center as these places have high ES demand but get very less supply. There is no better alternative than the development of urban green infrastructures such as extensive green roofs for a compact built environment like Glasgow city center. However, the right species and optimum distance of the green spaces should be taken into consideration. Besides, the conservation of open spaces that have a high cooling effect is also emphasized.

The implications of climate-cautious measures for priority intervention needs proper spatial UCM mapping which is even further dependent on the UCM synthesizing processes. Thus, special attention needs to be paid off on the methodological choices of UCM mapping when the decision makers determine to identify the spatial intervention for climate change adaptation plan and strategies. Overall, this study's findings provide insights to the local government and planner for climate-proof planning and resilience design for anticipated overheating effect.

6.2 Limitation

This study used only secondary datasets collected from diverse sources, which were produced on different dates and years. For example, sensitive population data is taken from the 2011 census data whereas SIMD presents the deprivation index for the recent year, 2020. Besides, DEM is from 2003's Lidar data and population density data is from 2017. Thus, there is a large

span found between the datasets. Some data are quite old which might be different from the current scenario. Combining all these data with a long-time gap may lead to unlikely research findings.

The building height data did not match when cross-checked physically and compared with Lidar Digital Surface Model data. Thus, validated building information might be different than the data used in this study. LST and NDVI data are collected for a single day only. The average value of multiple dates will improve the data quality and validity. Besides, SIMD data is very coarse because some people in the most deprived zone might not experience deprivation. Thus, the vulnerability index might not be the true reflection of the real heat vulnerability scenario in Glasgow city.

Even though the exclusivity of this research is performing UCM with available data, it is important to assume that other relevant data used in previous UCM studies might give unlikely results. For example, good air ventilation mitigates thermal load in a city for which detailed wind information is needed. This study could not incorporate this valuable parameter due to a lack of data. Besides, relative humidity and proper tree canopy data are highly relevant for heat risk mapping could not be found for this study. The impact of blue infrastructure is not incorporated in this study. Thus, adding the cooling effect of river Clyde might result in different mapping analyses.

This study has tested several methodological approaches to find the causes of different mapping results. However, no validation is done for the findings. Usually, UCM study requires a longer time frame, even up to three years, and high expertise. Here, the knowledge of this dissertation's author on the subject topic is not comparable with previous UCM researchers. Thus, time constrain nature and knowledge gap might be a drawback of this thesis.

It is crucial to notify that the risk mapping exercise is highly dependent on the raw data processing, particularly the reclassification process to create the homogenous datasets. In this regard, the author's input is reflected in the new classification. Thus, this research might have some human errors.

6.3 Further Study recommendation:

Urban climate mapping is a developing concept, and being advanced and sophisticated with new researches. There is still further research scopes in this subject topic as pointed below:

- A new study can be conducted for Glasgow city by adding more relevant and latest data, probably after the next census.
- As there is no Met Office station within Glasgow city, a long-term UCM study plan can be taken to collect and use temporary station-based data.
- Microscale heat risk analysis can be performed for the climate-sensitive hotspots identified in this study by using computational models like CFD and simulation tools like ENVI-met.
- Validation of the best approach identified in this study with in-depth analysis
- A comprehensive study on the type and placement of GI in Glasgow city can be done by considering the soil characteristics and temperate climate.
- A different approach can be taken to perform UHR analysis by selecting different weightage factors of the indicators and risk elements.
- Blue infrastructure effect in Heat Risk analysis can also be studied.
- Integrated UCM study approach by merging flood and heat risk mapping for Glasgow city will improve the urban climate-resilient design.
- Mapping of Glasgow city's tree canopy to calculate the ecosystem service mismatch with high accuracy is a new scope of research.
- Evaluation of climate-sensitive measures based on priority and efficacy.

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APPENDICES

A. Abbreviations

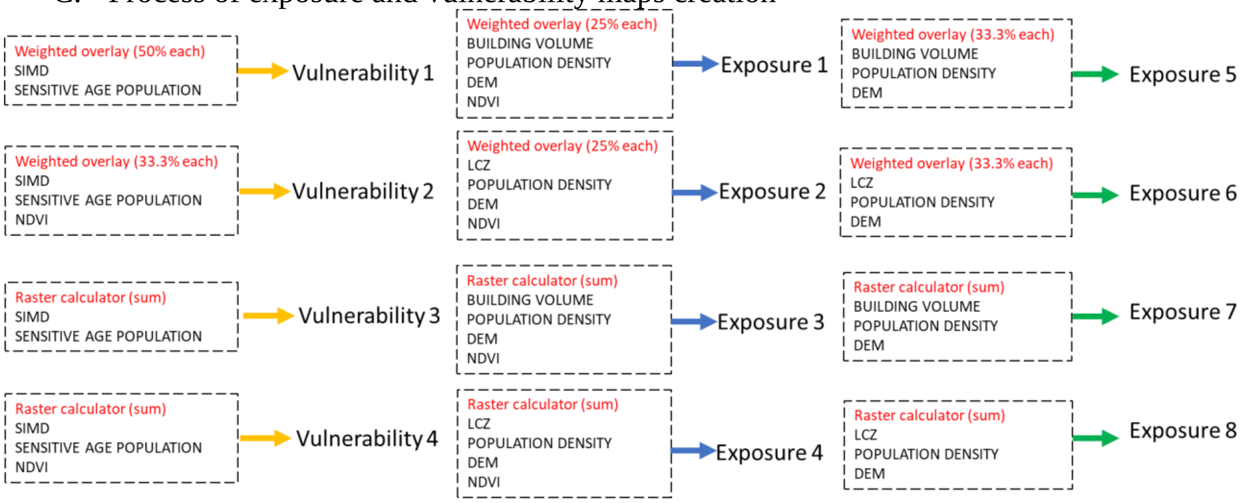
BV- Building Volume
CDP – City Development Plan
CUHK - The Chinese University of Hong Kong
DEM – Digital Elevation Model
DZ – Data Zone
EM – Exposure map
ES – Ecosystem service
GCC – Glasgow City Council
GI – Green Infrastructure
GIS – Geographic Information System
IPCC- Intergovernmental Panel on Climate Change
LCZ – Local Climate Zone
LST – Land Surface Temperature
NDVI – Normalized difference vegetation index
OSS – Open Space Strategy
PAN – Planning Advice Note
SD – Standard Deviation
SEPA – Scottish Environment Protection Agency
SIMD – Scottish Index of Multiple Deprivation
SWOT - Strengths, Weaknesses, Opportunities, and Threats
Ta – Air Temperature
TMG- Tokyo Metropolitan Government
UCM – Urban Climate Mapping
UCMap – Urban Climatic Map
UC-AnMap - Urban Climatic Analysis map
UC-ReMap - Urban Climatic Planning Recommendation map
UGI – Urban Green Infrastructure
UHR – Urban Heat Risk
UHI – Urban Heat Island
UK – United Kingdom
UKCP - UK Climate Projections
UPZ- Urban Planning Zone
VM – Vulnerability Map

B. Typcial example of classification

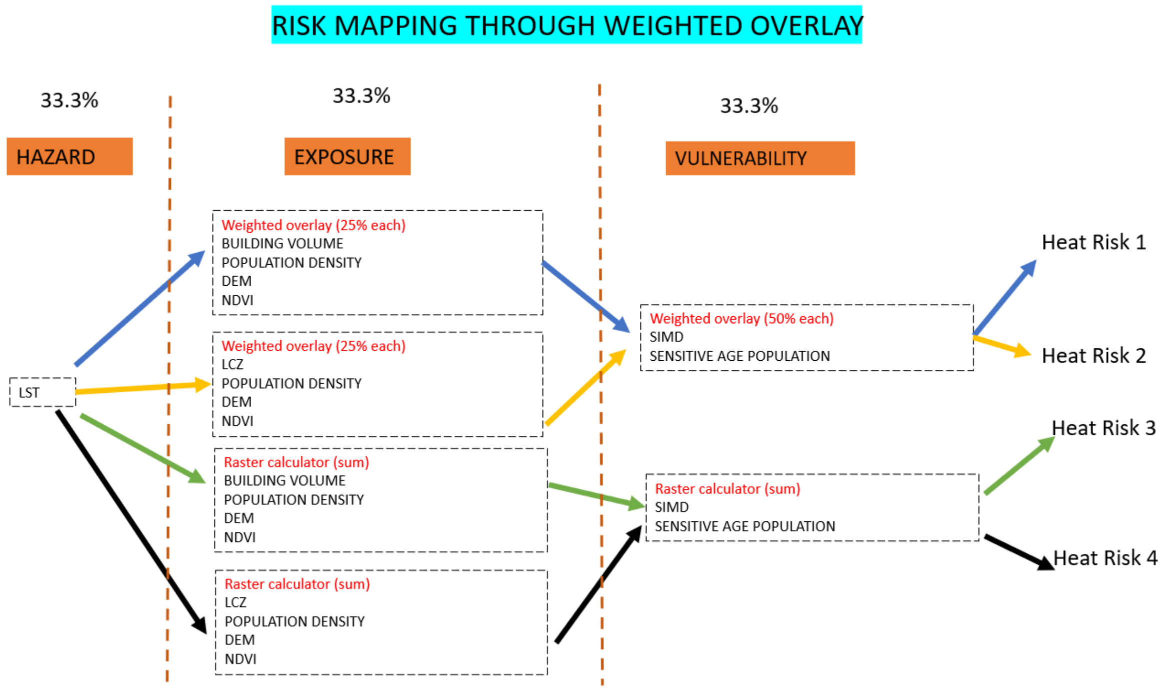
If the raw data of any indicator provides normal distribution statistically, the classification is done based on standard deviation values. For example, the minimum LST value is 20.68°C, mean is 24.83°C and the maximum value is 28.32°C and the standard deviation is 1.968.

Low = Minimum value, 20.68°C to 22.862 (Mean minus 1 standard deviation value
Medium = 22.862 to 26.798 (Mean plus 1 standard deviation value)
High = 26.798 to maximum value, 28.32°C

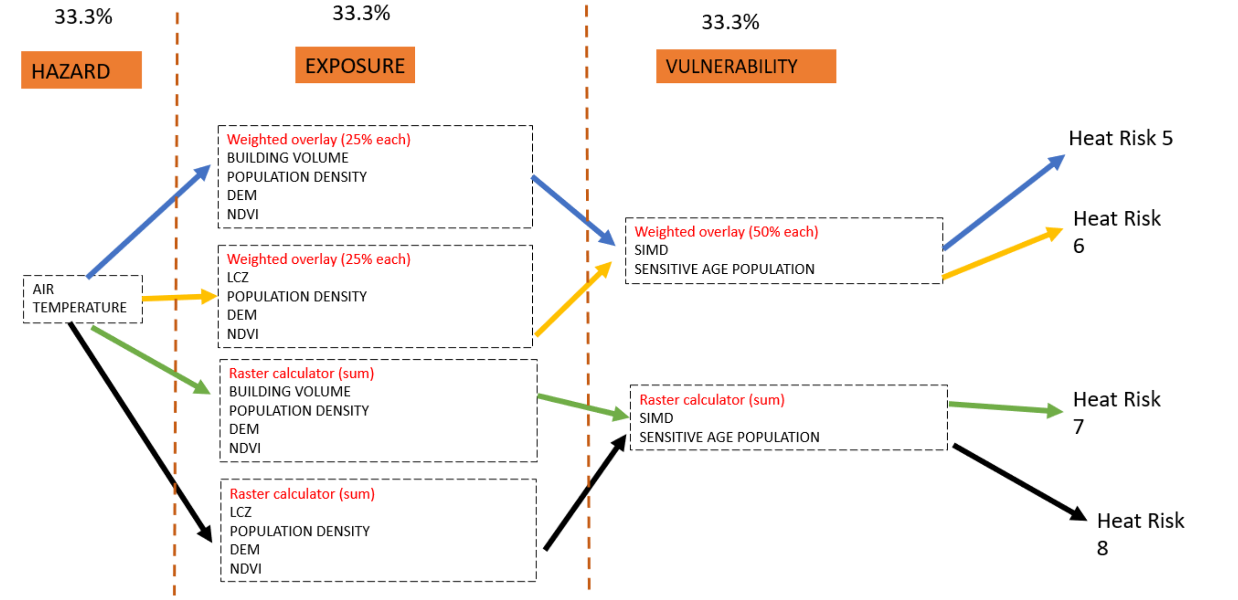
C. Process of exposure and vulnerability maps creation



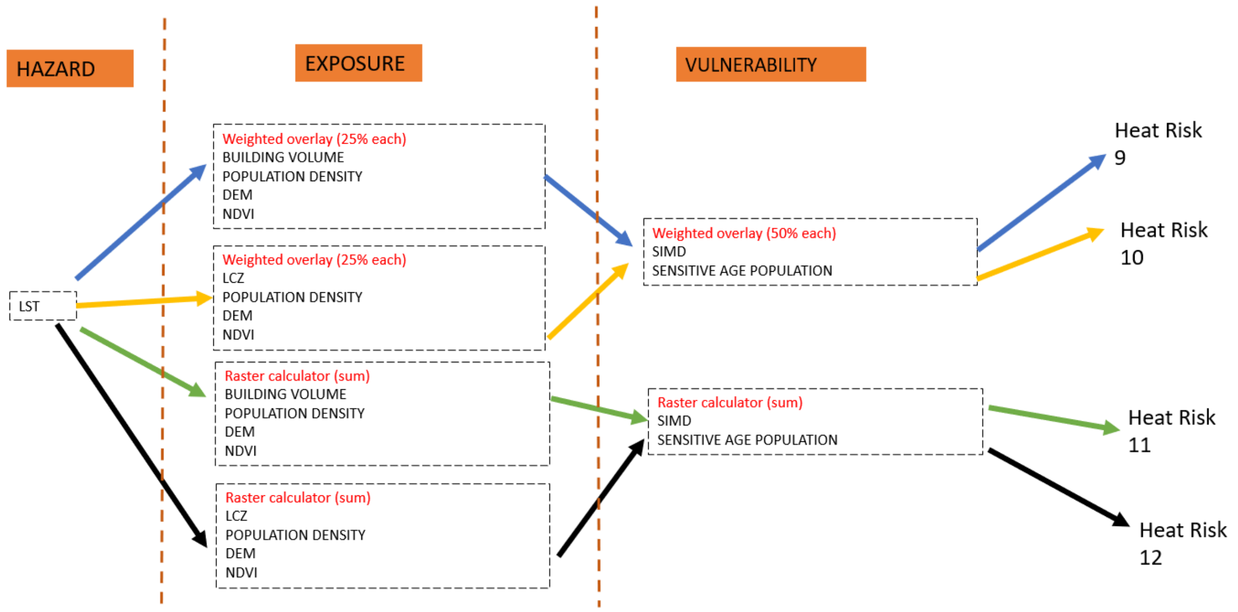
D. Process of each heat risk map formulation



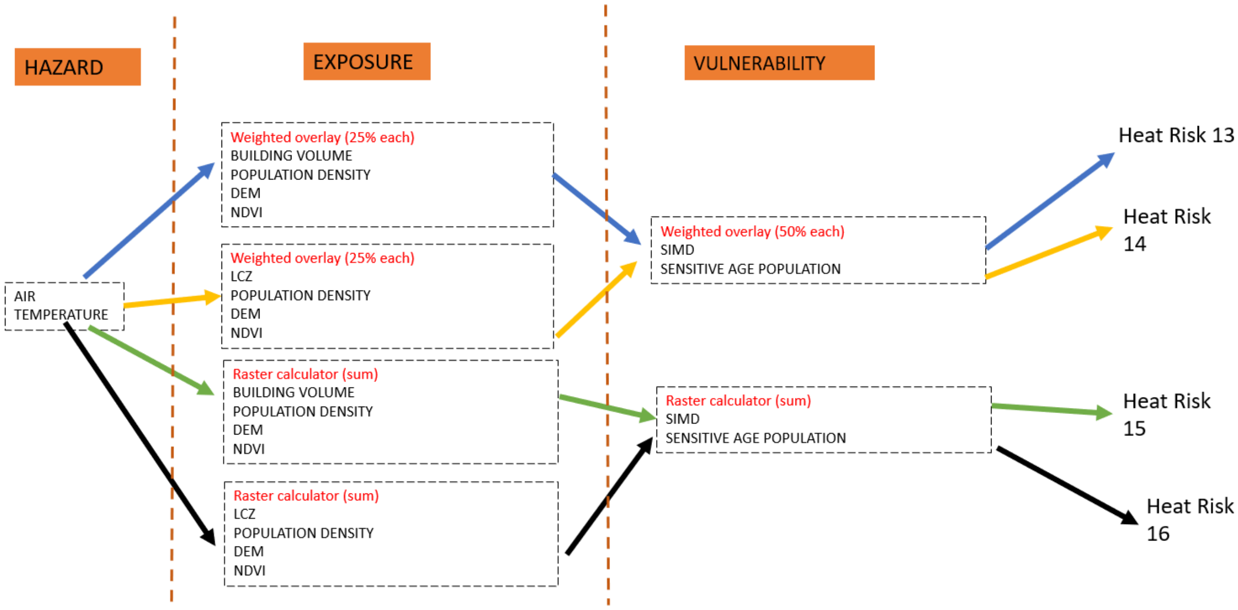
RISK MAPPING THROUGH WEIGHTED OVERLAY



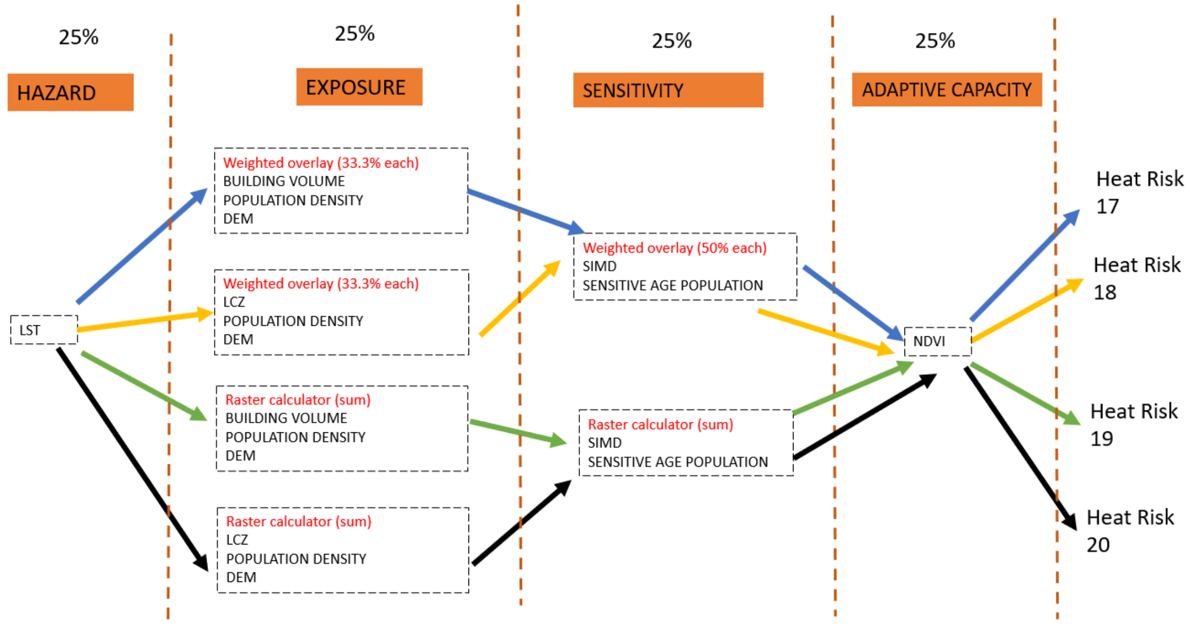
RISK MAPPING THROUGH RASTER CALCULATOR (SUM)



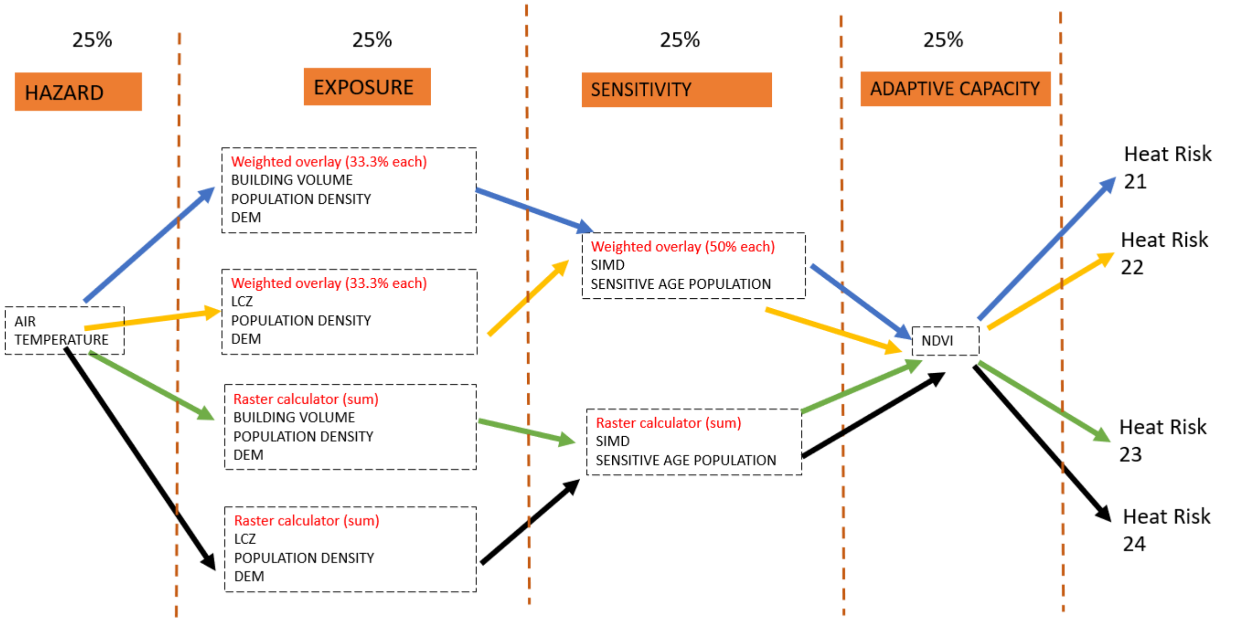
RISK MAPPING THROUGH RASTER CALCULATOR (SUM)



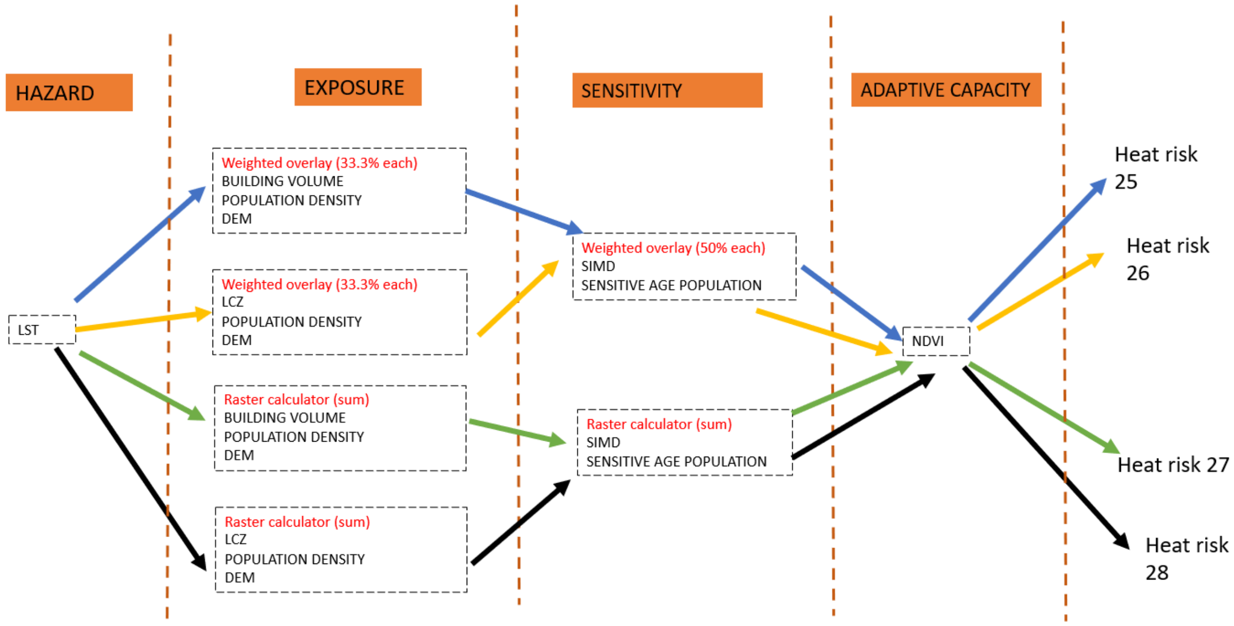
RISK MAPPING THROUGH WEIGHTED OVERLAY



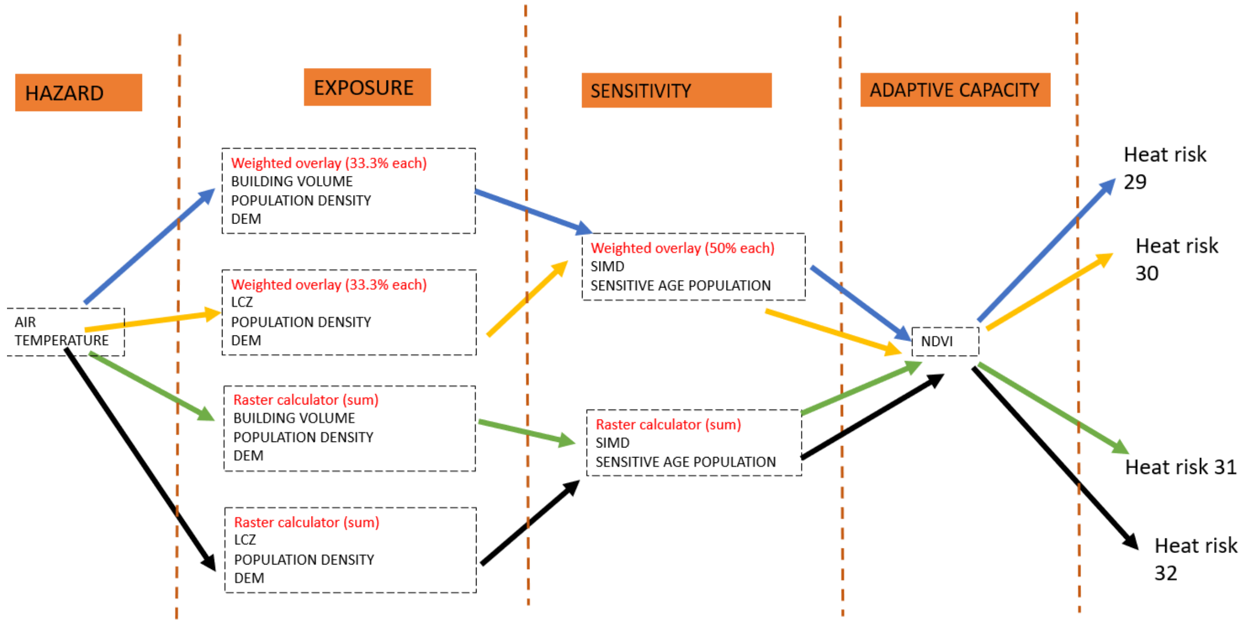
RISK MAPPING THROUGH WEIGHTED OVERLAY



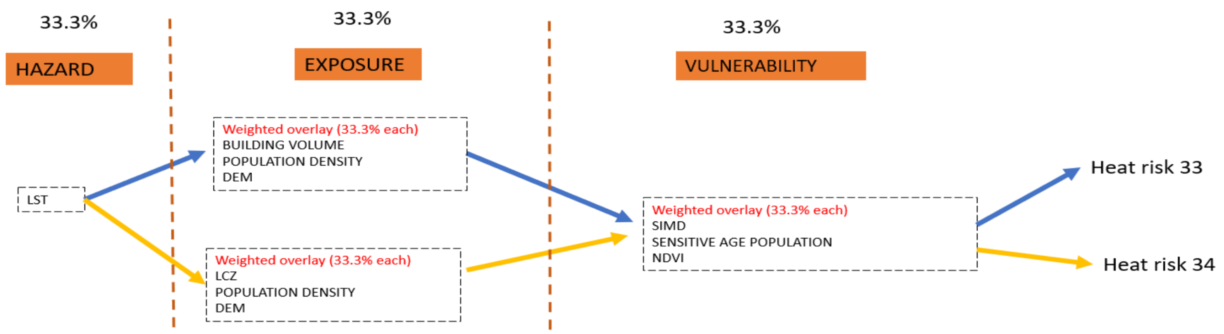
RISK MAPPING THROUGH RASTER CALCULATOR (SUM)



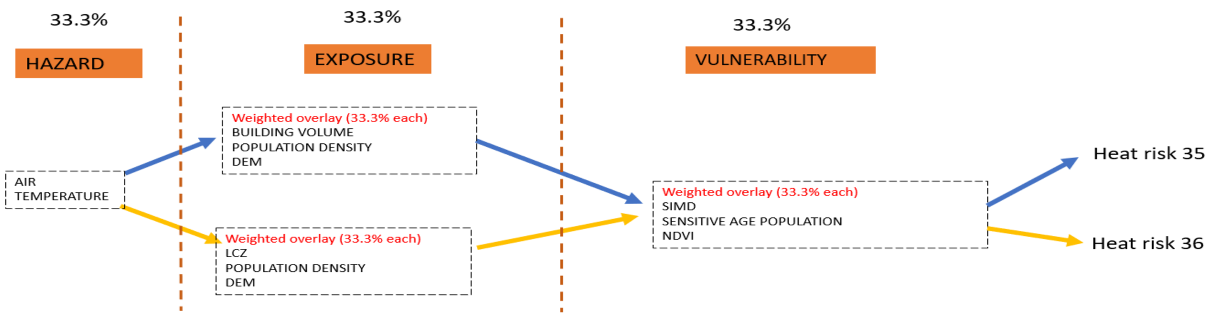
RISK MAPPING THROUGH RASTER CALCULATOR (SUM)



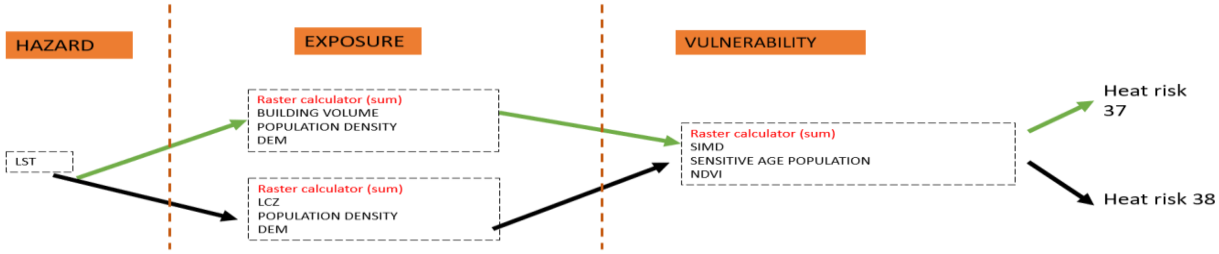
RISK MAPPING THROUGH WEIGHTED OVERLAY



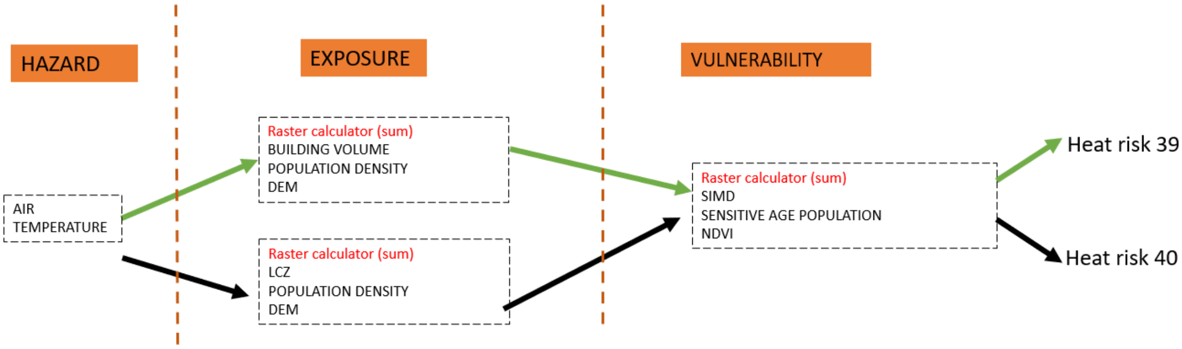
RISK MAPPING THROUGH WEIGHTED OVERLAY



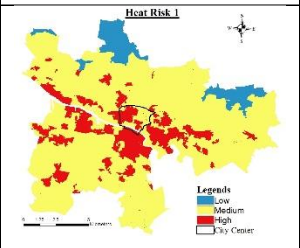
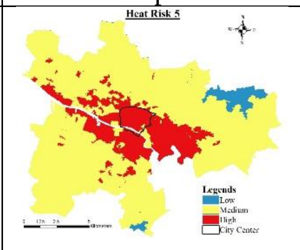
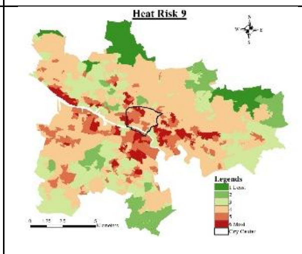
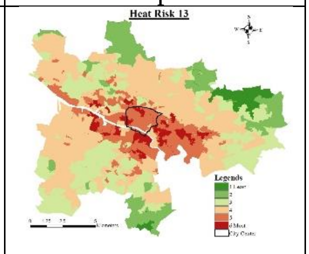
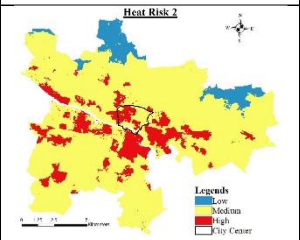
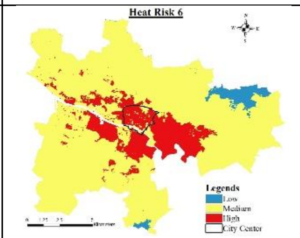
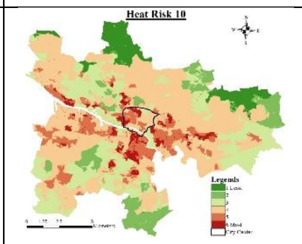
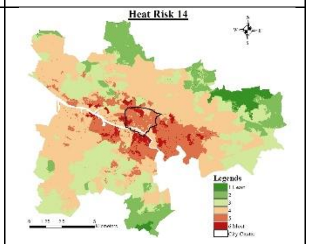
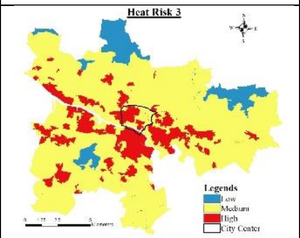
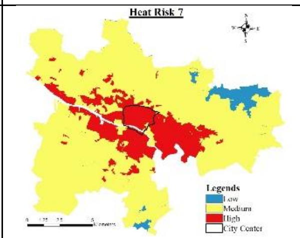
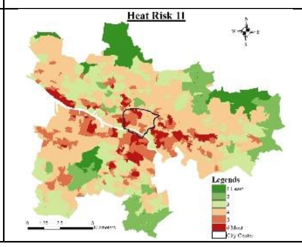
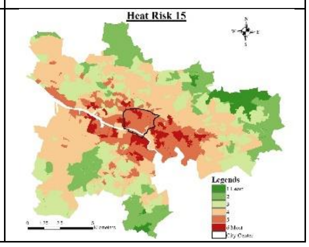
RISK MAPPING THROUGH RASTER CALCULATOR (SUM)

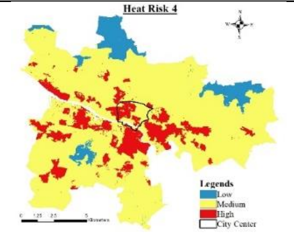
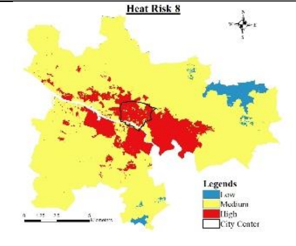
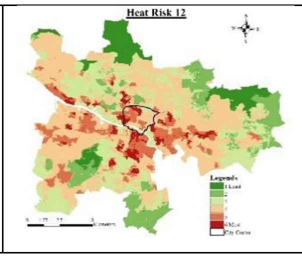
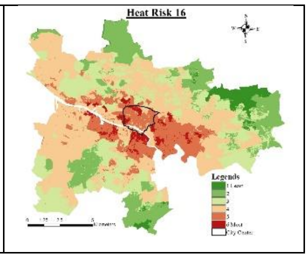


RISK MAPPING THROUGH RASTER CALCULATOR (SUM)

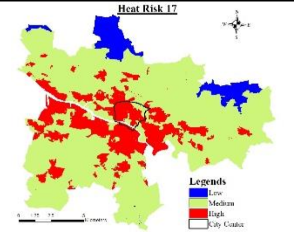
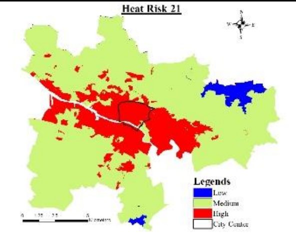
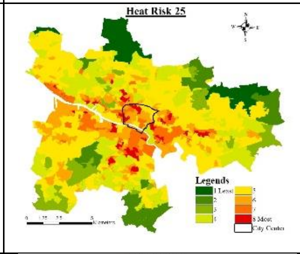
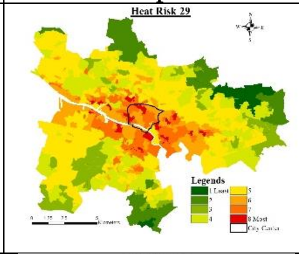
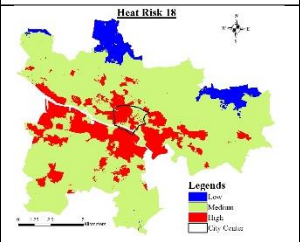
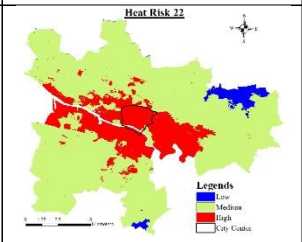
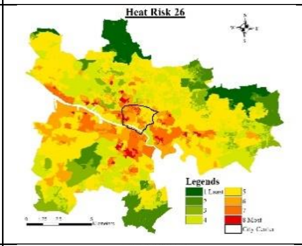
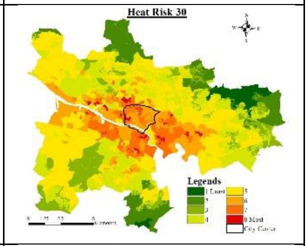
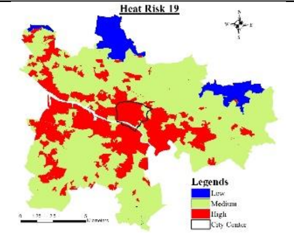
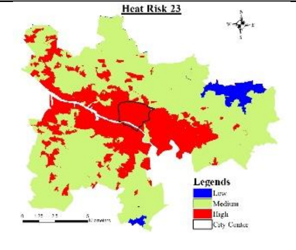
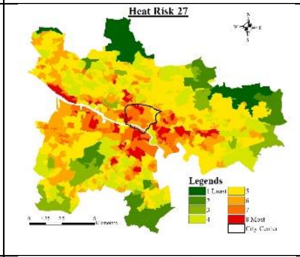
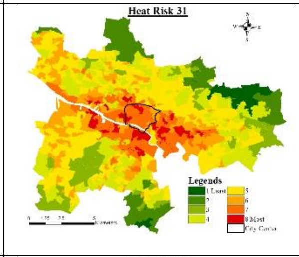
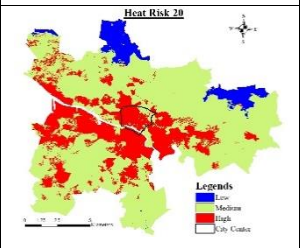
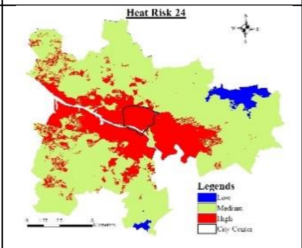
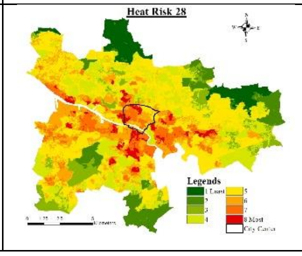
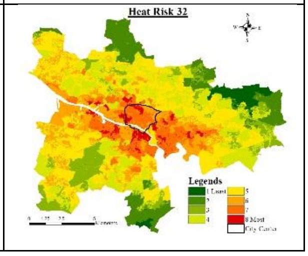


E. Urban heat risk maps from 1 to 16

		Weighted Overlay in Risk Analysis		Raster Calculator (Sum) in Risk Analsyis	
		LST	Air Temperature	LST	Air Temperature
Weighted Overlay in Risk Element Analysis	Building Volume (Weighted				
	LCZ (Weighted Overlay)				
Raster Calculator in	Building Volume (Raster				

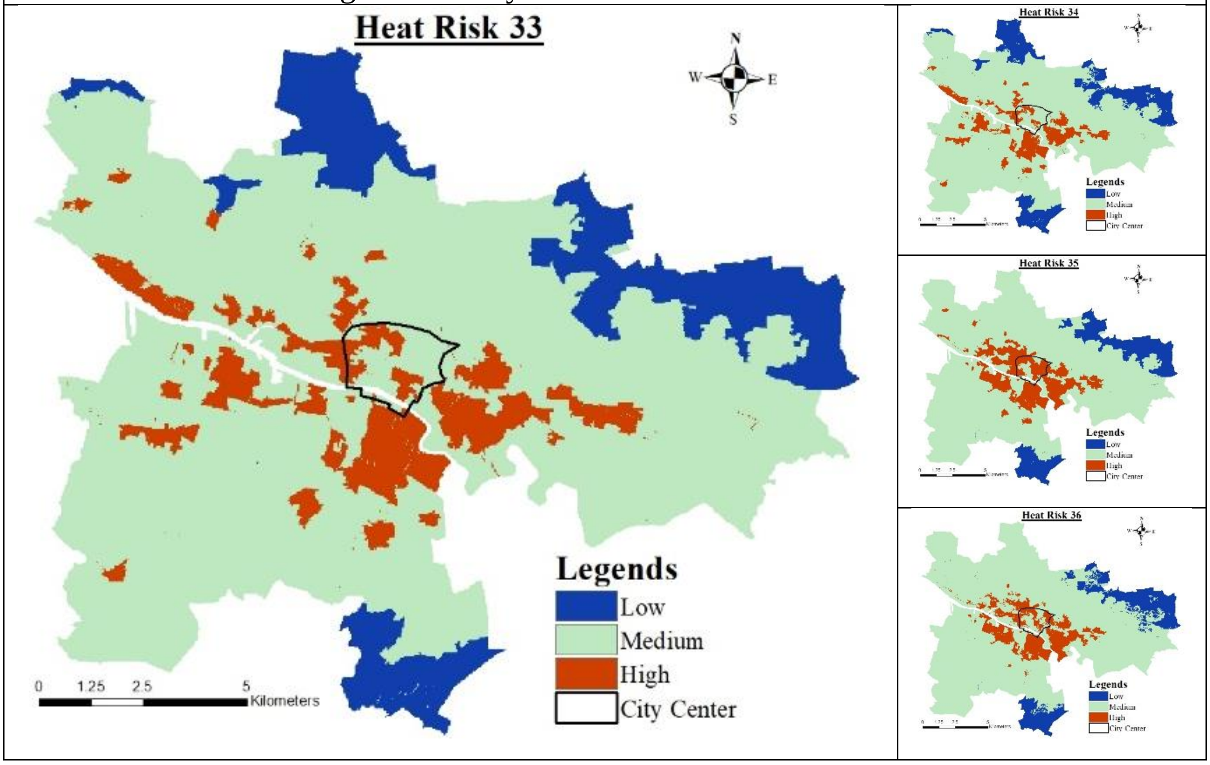
	LCZ (Raster Calculator)				

F. Urban heat risk maps from 17 to 32

		Weighted Overlay		Raster Calculator (Sum)	
		LST	Air Temperature	LST	Air Temperature
Weighted Overlay in Risk Element Analysis	Building Volume				
	LCZ (Weighted Overlay)				
Raster Calculator in Risk Element Analysis	Building Volume (Raster				
	LCZ (Raster Calculator)				

G. Urban heat risk maps from 33 to 36

Heat Risks based on Weighted Overlay



H. Ecosystem Services supply (left) and demand (right) map