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A FRAMEWORK TO PRIORITIZE ZONES FOR URBAN HEAT ISLAND (UHI) MITIGATION. A CASE STUDY OF KAMPALA, UGANDA.

CHIARA LUISA FERRARIO
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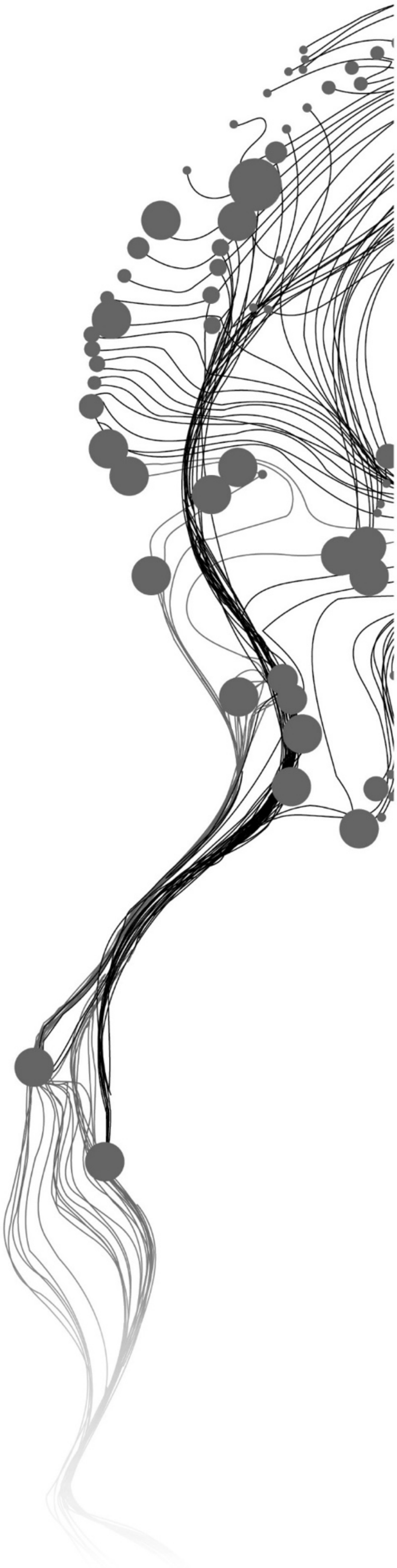

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A FRAMEWORK TO PRIORITIZE ZONES FOR URBAN HEAT ISLAND (UHI) MITIGATION. A CASE STUDY OF KAMPALA, UGANDA.

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Enschede, The Netherlands, June, 2021

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Spatial Engineering

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ABSTRACT

The problem of increasing temperature in urban areas compared to their rural surroundings, known as the Urban Heat Island (UHI) effect, also concerns fast-growing cities in the sub-Saharan region. These cities are commonly lacking mitigation and adaptation tools in the urban planning and design processes: this is also the case of Kampala, Uganda. Previous studies have shown a limited usage of zoning tools by municipalities to explicitly address climatic and environmental issues, in addition to the ones based upon socio-economic functionalities. One available zone-based analysis method which captures the variation of urban temperature is the Local Climate Zone (LCZ) classification method. Nevertheless, the LCZ framework alone is insufficient to help urban planners to identify priority zones for UHI mitigation. Therefore, the goal of this study is to demonstrate how a methodology framework can provide new means for urban planners to prioritize UHI mitigation targets, with the support of the LCZ scheme. The proposed methodology framework spans across multiple scales that starts from the city and gradually zooms into the neighborhood scale, and its backbone is the analysis of heat spatial risk. In parallel, LCZ classification is used as a support to identify contributing factors to the increase of temperature and, consequently, to select heat mitigation measures to be applied in the identified priority zones. We question to what extent the UHI effect concerns the city of Kampala by defining meaningful thresholds. Moreover, by analyzing the differences between mean Land Surface Temperatures (LST) in the different LCZs, showing that the warmest areas are the low-rise compact zones (LCZ 7, 2 and 3) which are mainly concentrated in the city center or in proximity thereof. Furthermore, we compare the mean LST of slums to medium-high income residential areas as a justification to select informal settlement dwellers as the vulnerable target group to analyze spatial heat risk in Kampala. A cross-section cutting through Kampala reveals additional insights regarding the complexity of the intra-urban variation of surface temperature. The final phase of the research focuses on how greenery interventions can be practically implemented for heat mitigation in the distinctive context of Kampala. Explicit attention is given to urban farming in informal settlement areas, by considering local initiatives and leveraging existing participatory planning tools to facilitate gradual integration into the local planning culture. Performance evaluation of the proposed methodology shows that in order to avoid overlooking any of the high heat risk zones, a more extensive input dataset is needed to calculate thermal comfort. However, it also highlights the availability of heat-related quantitative data produced by the methodology and the relatively straightforward approach based on open source software that can facilitate its implementation by municipalities in urban planning and design processes.

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1. INTRODUCTION

1.1. Background

1.1.1. Urban heat island effect in Tropical African Cities

Future exposure to extreme heat is expected to increase worldwide particularly in Africa, due to its unprecedented combination of high population growth and substantial changes in climatic conditions (Coffel, Horton, & De Sherbinin, 2018). This is particularly the case of African cities located in tropical areas where population growth is rapidly increasing and very hot and humid days are becoming more and more frequent (Rohat, Flacke, Dosio, Dao, & Maarseveen, 2019). Tropical-climate countries located in the African continent like Nigeria, Ethiopia, Tanzania, DRC, Niger, Zambia, and Uganda are in fact expected to have the largest populations in the world in the next decades, along with China and India (Canning, Raja, & Yazbeck, 2015). Additionally, these fast-growing countries also lack mitigation and adaptation tools and strategies to deal with increasing temperature, mostly due to limited financial, technological and institutional capacities to pursue climate-resilient development pathways (IPPC, n.d.).

The progressive conversion of larger amounts of vegetation covers into impervious surfaces due to rapid urbanization can significantly affect the evapotranspiration rates in urban areas. This means that the solar radiation absorbed by land surface cannot be released in the form of latent heat such as evapotranspiration and evaporation by large open green spaces (typical of the rural regions with soils and vegetation), but, on the contrary, remains trapped in between buildings (Torres Molina, Morales, & Carrión, 2020) and released in the form of sensible heat. This process generates an increase in the temperature which is further exacerbated by anthropogenic heat activities like excessive vehicle traffic and large use of air conditioners (Oke, 1982; Sodoudi, Shahmohamadi, Vollack, Cubasch, & Che-Ani, 2014). All these factors contribute to a substantial increase in atmospheric temperature in urban areas compared to their rural surroundings, known as the Urban Heat Island (UHI) effect (Figure 1).

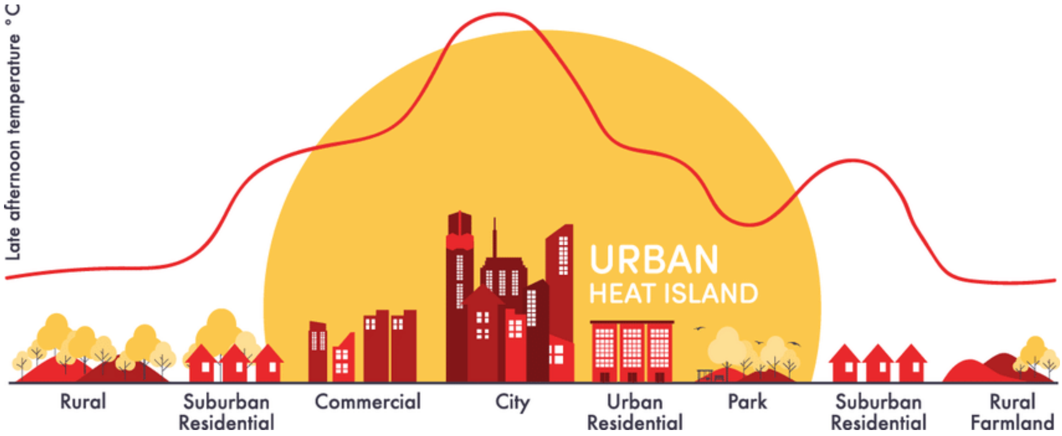


Figure 1 UHI generic profile: the effect is greatest in the city center (e.g. Central Business District) while local features such as parks can have a big cooling effect. Source: (Kamyar, Riza, & Ilkan, 2018).

Factors influencing the formation of the UHI could be the physical properties of the urban environment such as building forms, pavements, vegetation and water bodies and also could be anthropogenic activities generating heat such as heating and cooling system in buildings, and transportation (Oke, 1982; Sodoudi et al., 2014). The negative impacts of UHI on the environment and health include the increase in energy consumption and relative air quality deterioration (caused by elevated emissions of air pollutants and greenhouse gases); increased morbidity and mortality (respiratory diseases and excessive heat events that can result in heat strokes and above-the-range mortalities), and a decrease of water quality (US EPA, n.d.). The UHI effect has also been linked to the increase in the intensity of storms, which can lead to flooding (Torres Molina et al., 2020). The UHI effect on general and local temperature variations have been mostly studied in developed countries, especially in the northern hemisphere, while in tropical sub-Saharan cities research has been limited (Mensah, 2017). On the contrary, a wide range of mitigation measures has been identified for tropical cities. These are mainly related to vegetation (planting greeneries, parks and open spaces, green corridors), urban morphology (taking advantage of the regional climate and the airflow), water bodies & features, materials & surfaces (of streets, buildings and open spaces), shading, transport (traffic and fuel consumption reduction) and energy consumption (Ruefenacht & Acero, 2017). Furthermore, these strategies can carry multiple benefits in rapidly expanding cities like Kampala, Kinshasa and Accra by helping communities to become more inclusive and resilient to many of the damaging impacts of climate change, facilitate behavioural change and increase awareness of the importance of environmental issues (Kelbaugh, 2019). Although, these measures have not been efficiently integrated and adopted yet in existing policies (Codjoe & Atiglo, 2020).

1.1.2. Research gap

In order to effectively tackle their UHI, municipalities should mainstream the previously mentioned mitigation measures into spatial planning and across departmental policies and strategies. Urban planning tools typically entail actions at different scales from city master plans to site planning and design to control population densities, improve the allocation of resources and facilitate efficient transportation connections from place to place within the city (Climate Centre, 2019). These actions of planning and design are ultimately based upon zoning codes. Conventionally, this zone division is made according to socioeconomic functionalities, where the environmental and ecological dimensions are often not explicitly addressed. This could create unclarity since the user of the zoning map would not be sure what role the environmental and ecological issues may have played in defining the zones. To follow the convention of zoning while also considering the environmental and ecological purposes, we need to involve relevant information to examine how cities perform from a climatological perspective. Therefore, urban planners and designers require an equivalent tool of land-use planning for ecological and environmental purposes in order to have the greatest impact when addressing the UHI effect. To define what is the proper information at the suitable scale, the main causes of temperature increase at a block or neighbourhood scale have to be determined. Additionally, in this part of the world, part of the knowledge gap can be also attributed to the data scarcity and availability, like urban forms, functions of buildings, and spatial distribution of open spaces (Brousse, Wouters, et al., 2020).

1.1.3. Learning from the Local Climate Zones (LCZ) approach

Zone-based analysis of the climatic performance of cities can be found in the existing literature. In the case of studying temperature in urban areas, one way to capture the variation of temperature within urban areas in the form of zones is the Local Climate Zone (LCZ) scheme (Stewart & Oke, 2012a). This land classification method divides urban areas into zones that are expected to have homogeneous climatic behaviour including thermal patterns, such as the Land Surface Temperature (LST), which complements the conventional zoning that were only based upon socioeconomic functionalities. (LCZ classification scheme and its 17 standard classes can be found in Appendix 6.1). This zoning approach makes it easy to be adapted for urban planning purposes. Recently, climate and/or land surface products derived from satellite data boosted research in the field of urban climate (Brousse, Wouters, et al., 2020) enabling new opportunities for urban climate studies also in emerging-market cities (Perera & Emmanuel, 2018). For instance, the World Urban Database and Access Portal Tool (WUDAPT) framework (Bechtel et al., 2015) which employs Landsat 8 images to map the land cover in the form of Local Climate Zones (Stewart & Oke, 2012a) could help bridging over such data scarcity (Bechtel et al., 2015). The uniformity of zones is established by a considerable presence of physical properties of the urban environment in a certain area that may extend over hundreds of square meters to many square kilometres (Stewart & Oke, 2012a). Among the urban environment features considered: trees and building density, building height, materials and also imperviousness of surfaces. In the past years, the scheme made initially for heat island researchers, has been adapted also for city planning, landscape ecology and global climate change investigation uses (Stewart & Oke, 2012a). Recently, a European LCZ map has been created and shared by the World Urban Database and Access Portal Tool (WUDAPT), which is also currently working on the creation of a global database. Although, as previously mentioned, the scarcity of training data for regions of the world such as Africa hinders the creation of a global map which can serve the needs of global climate science (Demuzereid, Bechtelid, Middelid, & Mills, 2019).

The 17 classes of LCZ classification scheme (see Appendix 6.1) provide a wide range of urban and rural landscapes and a distinctive local thermal regime given by the unique combination of these physical properties (Stewart & Oke, 2012b). The nature of the LCZ approach is to select general properties of the urban and rural environments that can be found in any city of the world regardless of their latitude or altitude to facilitate intercity comparisons of heat island observations. Due to the high level of flexibility and adaptability of LCZ based approach to a wide variety of contexts, scopes and users, this land classification scheme is less data demanding compared to the intensive data input of a typical Urban Climatic Map (UCMap) (Perera & Emmanuel, 2018). LCZ classification scheme includes information derived from satellite data, in particular concerning characteristics of urban structure, fabric and cover, and information on the role of seasonality and phenology (Perera & Emmanuel, 2018).

The literature review conducted on several studies that entailed the use of LCZ classification demonstrates the frequent need to include extra input layers to complete and complement the information given by the standard LCZ classification. (Brousse et al., 2019; Edward & Chao, 2015; Perera & Emmanuel, 2018) This is also the case for the LCZ classification made for Kampala. For instance, in a recent study made to tackle health issues in Sub-Saharan cities that included the Ugandan capital, we see an extra LCZ class called 'Wetlands'. This choice was made due to their large presence in Kampala and because they are considered drivers of infectious diseases. Furthermore, because they could provide additional insight into the "spatial relation between their proximity to certain neighbourhoods and the urban health risk indicators." (Brousse et al., 2019). UCMap is a more popular tool used in the urban planning domain. This map is designed clearly for local planners to analyse and issue recommendations for UHI mitigation in targeted areas, and it has a richer input database compared to the LCZ framework. UCMaps typically include air temperature, airflow, land use, land cover, building structure, surface relief, and population density data layers (Edward & Chao, 2015). Local planners of the city of Kaohsiung in Taiwan decided to include population density as a key layer for the UCMaps so as to study its spatial relation with UHI indicators (Edward & Chao, 2015), it contributes to the intensity and location of anthropogenic heat activities (Oke, 1973, 1987).

After understanding the conventional approaches of how LCZs can be derived, and briefly introducing the UCMaps, it is important to reflect also on the practical significance of the LCZ scheme. Further to be a valuable tool to discover critical areas, it can also be beneficial as a support for the selection of effective mitigation and adaptation solutions in the spatial planning and design domain. Therefore, it's the intention of this research also to explore the extension of the original LCZ application into the mitigation and adaptation planning and design guidelines that have not been explored enough yet.

1.1.4. LCZ classification to mitigate UHI effect in Kampala: potentially missing layers

When it comes down to prioritize zones for UHI mitigation, information about high temperature alone does not lead to identification of targets for actions. It also requires information about who are in need of the actions and what needs to be done. Considering risk would imply analyzing information of exposed and vulnerable people to excessive heat; while mitigating effectively the UHI effect would entail recognizing the local factors influencing high temperature. LCZ scheme can help to identify the causes of temperature increase by acknowledging the physical features of the urban environment, while spatial (and temporal) information about people's densities who are exposed to higher temperatures is relevant to carry out a priority assessment.

Looking at building density as a representative indicator for population density can be very misleading. In fact, building density doesn't necessarily reflect population density: "If you look at new high-rise housing in the evening, you can find many apartments unoccupied. At the other extreme, internal crowding largely defines a slum. Building density does not mean population density." (Dovey, 2016). A relevant aspect if we consider that 49% to 64% of the total urban population of Kampala live in slums (Les Ateliers, 2019). This is a distinctive character of Kampala if, for instance, we compare it to an Asian mega-city located in a tropical climate. On one hand, we would have high density and high-rise buildings, while in a rapidly growing city like Kampala the built-up area would mainly develop horizontally, giving space to dense, low-rise buildings with a large percentage of informal settlements (Edward & Chao, 2015). Former research has shown that socio-economic stratification of wealth impacts the urban structure in Kampala, with consequences on the specific local climate. This is because typically wealthier neighborhoods are located at the top of the hills while low-income communities are mostly concentrated in slums located in the lower grounds next to the wetlands or on top of their original location (Vermeiren, Vanmaercke, Beckers, & Van Rompaey, 2016).

For the reasons described above, the additional required spatial layers are about:

a) Informal settlements residents and informal firms' workers;
b) Land use: to determine when and where people use certain spaces and consequently are exposed to high temperatures.

Moreover, in order to be able to assess priorities, areas with higher heat risk need to be calculated. This operation requires information about the hazard, exposure and vulnerability components that define heat risk (which will be explained in more depth in the next chapter).
In fact, the information provided by the LCZ scheme can be complemented by measurements of UHI intensity, to analyze and quantify the temperature patterns of LCZs. This can be done in different ways, including air temperature and land surface temperature (LST). Since there is insufficient data to measure the variation of air temperature between LCZ classes, a valid alternative could be the use of LST to allow a more comprehensive assessment of the effect of LCZ on local climatic conditions (M. Cai, Ren, Xu, Lau, & Wang, 2018). In the next chapters, we will see more in detail how and when these additional required layers can fit and be integrated into the proposed workflow.

1.2. Research Justification

1.2.1. Study case

The case study area was chosen considering fast growing cities in the sub-Saharan region, which are currently facing high temperatures. Therefore, Kampala), can be considered a suitable candidate for the purposes of this research work since it meets all the criteria. Uganda, with its capital city Kampala (Figure 2) , is a country within the tropical climate zone undergoing heavy urbanization and rural-urban migration. As a consequence, large parts of Kampala's vegetation and wetland systems (i.e. its green infrastructure) have been largely converted into formal and informal urban developments. The green infrastructure can potentially also be multi-functional green spaces that act as flood controllers, air pollutants dispersers and thermal comfort regulators (European Commission, 2015). The current urbanization practices have accelerated climate change, caused negative implications for public health, and limited work productivity due to thermal stress, leading to economic losses (Brousse, Wouters, et al., 2020). Kampala has already been identified as a study area for implementing climate adaptation strategies. For instance, recent projects undertaken by ITC have mainly focused on the flood management issue. Current and ongoing research in the field of UHI in Kampala shows particular attention in studying the effects of urbanization on the local urban climate (Brousse, Wouters, et al., 2020) as well as providing relevant insights on the unique lake-land breeze circulation activated by nearby Lake Victoria. Another soon-to-be-started project made for Kampala entails the installation of a smart-city-sensors network to detect the benefits of local vegetation on local urban climate that will be led by Dr. Peter Kabano starting from September 2021 until August 2022 ("netLabs - Projects," 2020). Therefore, it is meaningful to be inclusive so that multiple risks due to climate change can be considered and the power of the sensor network can be further leveraged. The rising temperature brings another dimension of the climatic risk, which brings the UHI into the scope of this research. However, Kampala is lacking tools to mitigate natural hazards, in particular, an actual zoning plan to mitigate the UHI effect.

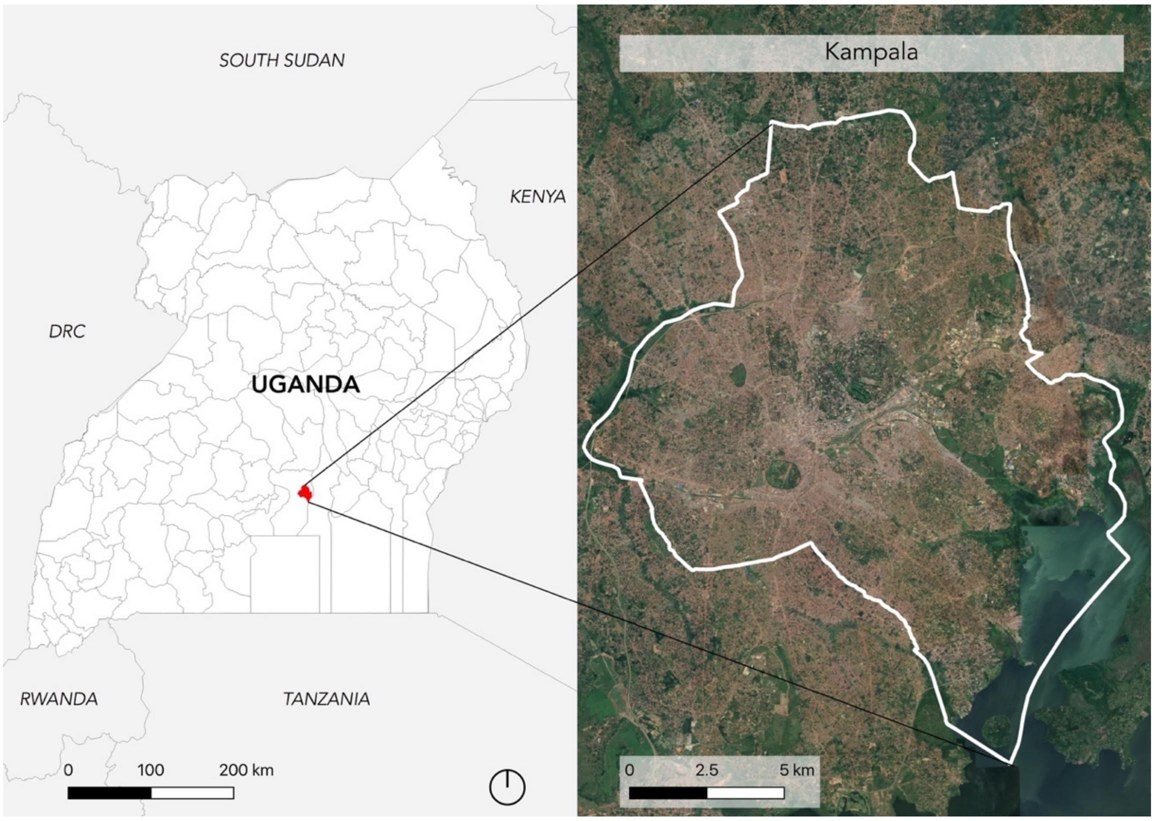


Figure 2 Geographical contextualization: Kampala. Source: ("Google Earth," n.d.)

1.3. Problem statement

- There are studies that tried to prioritize heat mitigation targets, but they did not fit into the planning convention;
- Maps produced with current LCZ classification are insufficient for spatial planning purposes to reduce UHI effects;
- The current LCZ framework alone does not help spatial planners to decide where and how to mitigate effectively UHI impact within the city.

For this scope, the information has to be more precise, both in terms of content (considering insights related to specific context) and in terms of scale in order to facilitate the process of choosing the most effective and suitable measure, applicable by spatial planners.

1.4. Research objective and research questions

The overall objective of this research is:

To demonstrate how a methodology framework can enable Urban Planners to select priority zones for UHI mitigation, with the support of LCZ classification. Moreover, to explore the potential of the LCZ scheme in urban planning and design context for mitigation and adaptation of urban heat. This framework can be adapted to the study case of Kampala and be further articulated. In this way, new insights concerning UHI in a tropical African city will be generated, while testing its implementation.

These are the sub-objectives and related questions:

A. **To analyze the heat hazard (or UHI effect) in Kampala**
   [1] "What are the thermal patterns of Kampala during the warmest period of the year?".
   [2] "What are significant threshold values to mitigate the UHI effect in Kampala?"
B. **To characterize the heat risk in Kampala, considering slum dwellers as vulnerable target group**
   [3] How to improve the LCZ classification of Kampala that fits into the local context, considering the overall objective?
   [4] What is the average temperature of the different LCZ classes?
   [5] What is the average LST of informal settlement areas compared to medium-high income residential areas?
C. **To prioritize areas for hazard mitigation interventions**
   [6] What is a suitable conceptual framework for identifying priority zones for UHI mitigation?
   [7] Which areas have a higher risk considered the targeted vulnerability groups?
D. **To propose UHI mitigation guidelines applicable by urban planners in Kampala**
   [8] Which mitigation strategies can be applied considering the LCZs of the identified priority zone?
   [9] How can the selected strategies be practically implemented?
E. **To evaluate the performance of the proposed methodology**
   [10] What are the strengths and weaknesses of the proposed methodology?
   [11] In which directions could further improvements be sought?

2. LITERATURE REVIEW

In the first part of this chapter, we reviewed the literature related to the prioritization approach while the second part focuses on the factors which contribute to the increase of temperatures in urban areas. The concept of priority in this research corresponds to areas with high risk and a large impact. Furthermore, the idea of treating the UHI effect as heat risk will be discussed more in-depth.

2.1. Heat risk, its components (H,E,V) and frameworks for mitigation prioritization

The process of identifying priority locations and targeted solutions for the implementation of planning and design guidelines demands a systematic approach. For this reason, this section focuses on two approaches: the first one is based on the spatial heat risk assessment and its variables, and the second one on a cross-scalar methodology framework that enables planners to detect areas where to implement green infrastructure solutions to decrease temperatures.

2.1.1. Priority as high heat risk

In order to allow a valuation of priorities, areas with higher risk have to be calculated. Risk is the product between hazard (H), exposure (E) and vulnerability (V) where H refers to the phenomenon that may cause health impacts; E corresponds to the people located in hazard-prone areas, while V represents the susceptibility of community groups to the impacts of the hazard (“Terminology | UNDRR,” n.d.).
In these two articles (Morabito et al., 2015; Tomlinson, Chapman, Thornes, & Baker, 2011), the UHI effect is considered as a hazard to calculate heat risk. The reason why these two articles have been chosen by the author is that the resulting high spatial hazard risk can be translated into zones of high priority. Both articles provide a methodology framework based on “Crichton's Risk Triangle” hazard-risk assessment methodology where risk is the result of the exact overlap of three variables of the triangle: Hazard (H), Vulnerability(V) and Exposure (E). If any of the three variables is zero, then the risk will not exist. The heat hazard corresponds to the LST increase, exposure to heat hazard is represented by the population affected above a certain threshold, the vulnerability by the spatial distribution of one of the targeted vulnerable groups. The final risk map is the result of the spatial interaction of all three components. Also, in this research, the hazard is represented by the LST and it is initially analyzed separately while the two other layers V and E are combined (here the vulnerability layer is the result of a filtering process of the exposed people). Thus, exposure refers to people, and vulnerability is the selection of categories of people that can be negatively affected by heat-related health risks. Areas with higher risk can be considered zones with higher priority for mitigation intervention. In the following section, more attention is given to the single components that constitute the new proposed methodology framework considering the context of Kampala.

2.1.2. Measuring UHI intensity: the hazard layer

Surface urban heat island (SUHI) and atmospheric urban heat islands (which we will continue to refer to as UHI) differ in the way they are generated, the techniques used to measure them and their impacts. As their prefixes suggest, atmospheric UHI intensity can be measured with in situ air temperature and mobile traverse measurements; they reach their peak after sunset due to the gradual release of heat from urban structures. The SUHI instead can be acquired from satellite-based sensors and it is more pronounced during the day when the sun is shining (Ur, 2011). Considering that meteorological stations measuring air temperatures are often located at the boundaries of cities (e.g. airports) which cannot cover urban morphologies variations and the requirement of relatively high spatial resolution data to address research purposes, measuring SUHI magnitude using Land Surface Temperature (LST) can be considered as a valid option, as demonstrated by several previous studies (Schwarz, Schlink, Franck, & Großmann, 2012). While LST and air temperatures are not equivalent, mitigating high surface temperatures in cities is a suitable target, as these reflect locations where both air temperature and absorbance of solar radiation is high, which impacts directly on human thermal comfort (Morabito et al., 2015; Norton et al., 2015; Tomlinson et al., 2011). Local authorities such as London Authority have used LST as a parameter to map heat hazards to support mitigation planning for decreasing the impact on the vulnerable communities (4 Earth Intelligence, 2020).

2.1.3. Heat exposure and vulnerability

After defining the hazard, it is necessary to understand where and to what extent this hazard threatens specific population groups. As already mentioned above, exposure and vulnerability have been combined, as done in the study carried out by (Tomlinson et al., 2011)UHI influences human well-being and human health, therefore the exposure refers to the population of Kampala while heat vulnerability corresponds to the susceptibility of urban residents to the negative effects of high temperatures (Z. Cai, Tang, Chen, & Han, 2019).

In previous research, multiple variables have been verified to change the correlation between heat and health outcomes. Among them, there are the demographic and socioeconomic variables. More specifically, age is a relevant factor since previous studies have proved that very young people and the elderly are more likely subjected to heat health risks. Also poverty and low level of education with consequent insufficient means to improve building structure, potential lack of AC and difficult access to basic services including green areas, have proved to be responsible for higher vulnerability rates to heat health risk (Reid et al., 2009). Slum residents and people working in informal businesses share the same difficulties such as (very) low income and education level, poor access to basic services like green areas. Therefore, they have been chosen for this study to represent a community group that is vulnerable to heat hazards. Furthermore, it has been demonstrated that large slums tend to be exposed to more intense locally high temperatures (Wang, Kuffer, Sliuzas, & Kohli, 2019). As reported by (Scott et al., 2017) it has been proved that slum residents in Nairobi are more susceptible to heat stress due to their warmer neighborhoods. Hot temperatures in residential communities can contribute to the spread of tropical vector-borne diseases since they are highly influenced by the local climate (Brousse, Wouters, et al., 2020).

2.1.4. Frameworks for prioritization

The study carried out by Norton (2015) provides a cross-scalar approach - from the city, to the neighborhood and to the street level – to facilitate the identification of locations for solutions to mitigate high urban temperatures. Their hierarchical decision framework prioritizes high-risk neighborhoods and selects the most appropriate Urban Green infrastructure (UGI) solutions according to the different contexts. Gaps still remain in defining the optimal planning of UGI in the urban landscape, but the proposed methodology framework is a starting point for local governments to prevent and start mitigating the UHI effect. As their framework was made for a study area in Australia, the main structure has been adapted to the goal and the context of Kampala (see Figure 3).

2.2. Studying the local context to identify potential causes of the UHI effect

Urban morphology, materials, buildings and open space functions and anthropogenic activities are all contributing to the increase of temperatures and have an impact on the local urban climate. Considering the research objective, in this section a deeper look is given to the potential role of LCZ scheme within the prioritization methodology framework and its relationship with human activities and land use is presented.

2.2.1. Urban geometry and materials captured by the LCZ scheme

It has been highlighted that one of the limits that previous studies had when tackling UHI consists in the use of administrative boundaries which do not consider the physical variation of the urban landscape – such as building density, height, materials - that have been demonstrated to influence the local climate of the city (Cai, Tang, Chen, & Han, 2019). Previous LCZ classifications made for other cities report some recurring patterns linked to building height. Even though the old areas of a Chinese megacity might differ very much aesthetically from the one of Kampala, some findings related to the relationship between LCZ classes and heat vulnerability of buildings can be still extended to the Ugandan settings. Low-rise buildings tend to be more vulnerable than mid-rise and high-rise buildings due to the fact that they are older and are often in poor condition due to years of scarce maintenance. Moreover, these low-rise buildings classes constitute one of the most vulnerable areas in the city during the extreme heatwave periods since they accommodate a large number of vulnerable people (e.g., elderly and low-income) (Z. Cai et al., 2019). The same argument can be applied to the informal settlements in Kampala. Additionally, studies made for other urban areas in China and the UK show that there was a correspondence between certain LCZ classes and higher LSTs (Z. Cai et al., 2019). In particular: LCZ classes with no or little vegetation, industrial areas, LCZ with old buildings and low-price housing. Unsurprisingly, classes with a high density of buildings (i.e. compact high-rise, compact mid-rise and compact low-rise) are usually more susceptible to heat compared to open class areas (open high-rise, open mid-rise, and open low-rise).

2.2.2. Anthropogenic heat

Anthropogenic heat contributes to the UHI effect. Sources of anthropogenic heat include heating and cooling of buildings, manufacturing, transportation, and lighting (Shahmohamadi, Che-Ani, Maulud, Tawil, & Abdullah, 2011). It is important to mention that in the context of Kampala and slums areas, many people make use of charcoal for cooking while the use of electric appliances is likely to be relatively rare. Road traffic and congestion are also significant problems in Kampala, but for the purposes of this study, the available time and the focus given to the physical features of the urban environment of the case study area, these factors will remain negligible.

2.2.3. Land use

In general land use cannot be fully described by the LCZ classes. If LCZ 10 provides information on the presence of industrial areas, low, medium high-rise buildings could widely differ in terms of functions (i.e. residential, commercial, etc.). In the case of parking lots and industries, it has been observed that the almost lack of vegetation and the mix of use of materials with critical thermal characteristics such as concrete register the highest heat levels (Portela, Massi, Rodrigues, & Alcântara, 2020). As already mentioned, the presence of green spaces in a community has been associated with a decreased risk of heat-related illness and death.

3. METHODOLOGY

3.1. Research design & framework

There are four major phases in this work, which have been addressed with both qualitative and quantitative approaches, as shown in Figure 3. The proposed methodology framework (Figure 3) spans across multiple scales that starts from the city and gradually zooms into the neighborhood scale. The aim is to propose a simple, logical methodology in order to intentionally avoid complicacies and facilitate communication with local authorities and other stakeholders. Before briefly describing the main steps/objectives of this study, it is important to remind the reader that this is entire desk-based research due to the travel limitations and restrictions imposed during the Covid-19 pandemic.

First sub-objective: "To analyze the heat hazard in Kampala"
This is a combination of quantitative and qualitative methods. First, an LST average map was created to determine the thermal patterns over the city of Kampala considering the warmest time of the year, for the period from 2018 to 2020. Furthermore, to measure the (S)UHI effect, and more in particular the heat hazard, meaningful thresholds have been identified by reviewing the literature. Afterwards, the (S)UHI thresholds for the case study of Kampala were calculated.

Second sub-objective: "To characterize the heat risk in Kampala"
The second sub-objective as well is a mix of qualitative and quantitative methods.
The LCZ classification was made with the LCZ generator online tool ("LCZ Generator," n.d.).
Temperature averages were calculated for each of the different LCZ. The choice to target a specific vulnerability group is supported by previous studies. Furthermore, the average temperature was calculated also for the areas with a high density of vulnerable communities.

Third sub-objective: "To prioritize areas for hazard mitigation interventions"
The selection of priority zones was based on the coincidence of the three components (H, E, V) that generated heat risk and the co-presence of two vulnerability groups.

Fourth sub-objective: "To propose UHI mitigation guidelines applicable in the context of Kampala"
Linking the local climate zones to possible mitigation strategies was possible after conducting a literature review. Solutions were assessed with a qualitative cost-benefit analysis. Finally, three scenarios have been considered to facilitate the implementation of mitigation solutions.

Fifth sub-objective: "To evaluate the performance of the proposed methodology"
The assessment was made following a SWOT analysis.

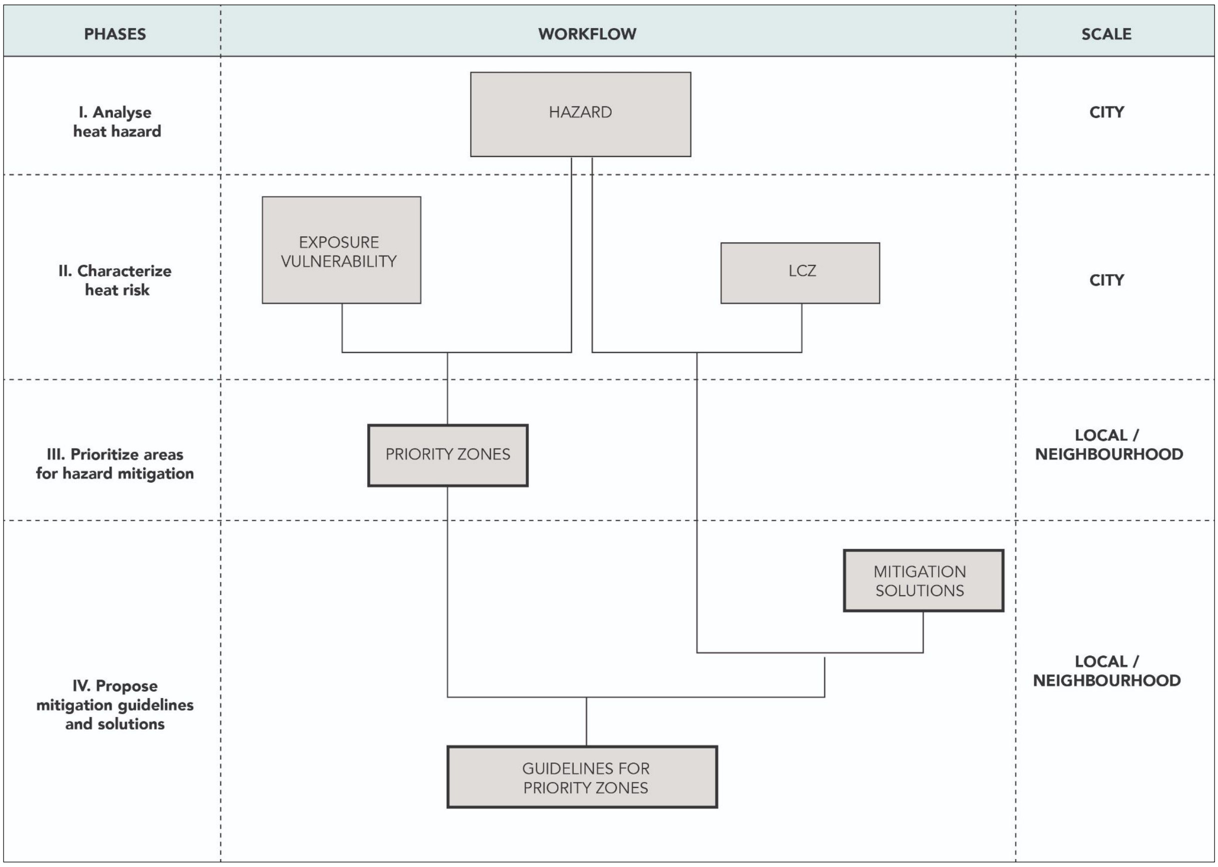


Figure 3 Proposed methodology-framework. Adapted version of "Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes". Source: the author

Figure 3 shows that the proposed interventions and guidelines are the result of a parallel analysis: defining the priorities (on the left side of the diagram) and studying the urban context to identify causes and contributing factors to surface temperature increase.

Table 1: Sub-objectives and related research questions

Sub-objective	Research question	Research method
A. To analyze the heat hazard (SUHI effect) in Kampala.	[1] "What are the thermal patterns of Kampala during the warmest period of the year?". [2] "What are significant threshold values to mitigate UHI effect in Kampala?"	-Literature review for the selection of appropriate threshold; -GIS-based method to create an average LST map;
B. To characterize the heat risk in Kampala, considering slum dwellers as vulnerable target group	[3] Which local information layers are required to make a more significant LCZ classification of Kampala, considering the overall objective? [4] What is the average temperature of the different LCZ classes? [5] What is the average LST of informal settlements areas compared to medium-high income residential areas? How about informal firms?	-Literature review to gain information of previous LCZ classification made for Kampala; -LCZ generator tool; -GIS-based methods to combine LCZ data layer and mean LST map to calculate spatial statistics.

C. To prioritize areas for hazard mitigation interventions	[6] What is a suitable conceptual framework for identifying priority zones for UHI mitigation? [7] Which areas have a higher risk considered the targeted vulnerability groups?	- Literature review; - GIS- based method, layering approach.
D. To propose UHI mitigation guidelines applicable in the context of Kampala	[8] Which mitigation strategies can be applied considering the LCZs of the identified priority zone? [9] How can the selected strategies be implemented considering the local context?	- Literature review and specific analysis of targeted LCZ to identify causes and mitigation strategy selection applicable in the priority zones; - Qualitative cost-benefit analysis: advantages, disadvantages and co-benefits are considered to select the best solution; -Scenario development;
E. To evaluate the performance of the proposed methodology	[10] What are the strengths and weaknesses of the proposed methodology? [11] In which directions could further improvements be sought?	-Literature review; -SWOT analysis.

3.2. Analysing the hazard

3.2.1. Average LST mapping

This study was carried out considering the warmest period in Kampala (January – February) over 3 years (2018-2020) also to create consistency with the other data layers. The selection of satellite images was made considering less cloud coverage. This is because previous studies demonstrated that UHI is greater during clear-sky conditions because during the daytime more solar energy is absorbed (Brousse, Wouters, et al., 2020). Data about the land surface temperature (LST) was retrieved by ("RemoteSensingLab," n.d.). The web application estimated the LST of the study area, which was derived from Modis, Landsat 8 images (Parastatidis, Mitraka, Chrysoulakis, & Abrams, 2017). To create one unique layer that could represent the thermal patterns of surfaces in Kampala, the three layers were combined in QGIS with the raster calculator by taking the average LST value for each pixel.

3.2.2. UHI Thresholds

UHI zones were identified using the following equation (Guha, 2017):

Equation 1 – UHI zone equation

$$LST>\mu+0.5*\delta,$$

while $0<LST\leq\mu+0.5*\delta$ referred to non-UHI zones,

where μ and δ are the mean and standard deviation of LST in the study area, respectively.
The spatial distribution of the UHI was applied to the average LST map.

3.2.3. Delineating the Urban Hot Spots

The LST mean map was used to analyze the Urban Hot Spots (UHS) over the entire study area. The expression used to delineate the UHS is the following (Guha, 2017):

Equation 2 - UHS zone equation

$$LST > \mu + 2 * \delta$$

These UHS refers to the warmest zones in an urban area. Usually, these areas correspond to zones with a large number of industrial buildings, busy transportation routes, or the concentration of thermal power plants (Guha, 2017).

3.3. Characterizing the risk

3.3.1. LCZ classification

Previous LCZ classifications made for Kampala were taken as references to make improvements (Brousse et al., 2020) Based on the weaknesses highlighted by the authors, small changes were made in the selection of training areas. In particular, more attention was given to the differentiation of LCZ 7 (lightweight compact low-rise buildings) from LCZ 3 (compact low-rise). This was done by taking into consideration the spatial distribution of informal settlements that are usually characterized by metal roofing sheets. Additionally, the LCZ 10 (industrial area) was introduced in the training areas (TA) due to the large presence of factories located in the central parts of the city. The new classification was created with the beta phase of the LCZ generator tool ("LCZ Generator," n.d.).

3.3.2. Thermal pattern analysis per LCZ

After obtaining the LCZ classification map of Kampala and the LST average map (2018-2020) the two layers were combined in QGIS to generate statistics. For each different LCZ class, the average LST was calculated. The first step consisted of resampling the LCZ raster map with the same pixel size as the average LST map of Kampala. Afterwards, the two maps could be merged. For each LCZ the mean LST was calculated considering its relative area on the total. The box plots created in excel show a five-number summary of the dataset: the minimum, first quartile, median, third quartile, and maximum.

3.3.3. LST intra-urban variation (cross-section)

The cross-section made for Kampala was generated using the Profile tool plugin QGIS. Two layers were selected: the LST average map and the resampled LCZ map. Subsequently, the excel file containing the spatial coordinates and the information about the temperatures were used in the Excel environment to recreate the profile of the intra-urban variation of the land surface temperature. The LCZ class section was visualized as a bar in Autocad. In the same environment, all the components were assembled to create a cross-section showing a simple skyline to emphasize the temperature variation between rural to urban land.

3.3.4. Heat Risk analysis and prioritization

In order to justify the choice of this thesis to focus on the UHI effect that is affecting informal settlement dwellers, a comparison with wealthier residential areas has been carried out. For this purpose, a similar approach to the one explained in the previous section was adopted. But, in this case, the informal settlements map and the residential areas with medium to high-income - acquired from Kampala Capital City Authority (KCCA) - were both provided in vector format. Therefore, the first step was to convert them in raster format with the same pixel size of the LST average map, so to compare the mean LST per category, based on the number of pixels. Since the LST average map was created by using three satellite images taken during the day, it was considered relevant to include in the comparison also the location of clusters informal businesses (World Bank, 2017). The original layer, provided in raster format, was first resampled according to the LST average map that allowed the calculation of its average thermal behavior.

The prioritization method to identify areas for UHI mitigation followed an adapted version of the approaches proposed in the "Spatial heat-risk assessment "by (Tomlinson et al., 2011) and (Morabito et al., 2015). Specific neighborhoods were identified by considering the largest coincident areas of the three components of heat risk (H, E, V). Where the Hazard is measured in terms of LST (°C) and it is represented by the UHS map, exposure is considered together with the vulnerability layer that corresponds to the informal sector layers.

3.4. Mitigating the hazard

In order to have a general overview of the possible heat mitigation strategies and refer to effective ways for their implementation, a literature review was conducted. This implied the consideration of typical main approaches implemented in different parts of the world, that aim to tackle a particular factor causing thermal increase (i.e. albedo rate). The identification, structuring of different strategies was made in the form of a table to facilitate the selection of the intervention. Strategies were firstly evaluated in terms of space, budget and sustainability. Subsequently, the advantages, disadvantages and main co-benefits were defined. After selecting the best solution(s) to address excessive heat in the identified priority zones, three scenarios - based on three different land tenure types - were investigated to allow a smoother implementation in the context of Kampala. This could be achieved by reviewing also studies and projects related to participatory planning experiences both locally and internationally.

3.5. Framework assessment

An evaluation of the proposed methodology framework was carried out with the SWOT analysis framework, where strengths, weaknesses, threats and opportunities were identified. This was based only on the personal experience of the author and the literature review, due to the impossibility of conducting additional evaluation with local experts.

4. RESULTS AND DISCUSSIONS

4.1. The heat pattern in Kampala

This section addresses research question 1: "What are the thermal patterns of Kampala during the warmest period of the year?". In order to accomplish that, an LST Average map of Kampala was created. The map shows the Intra-urban variation of the LST (°C) (Figure 4), with a temperature variation of 17°C.

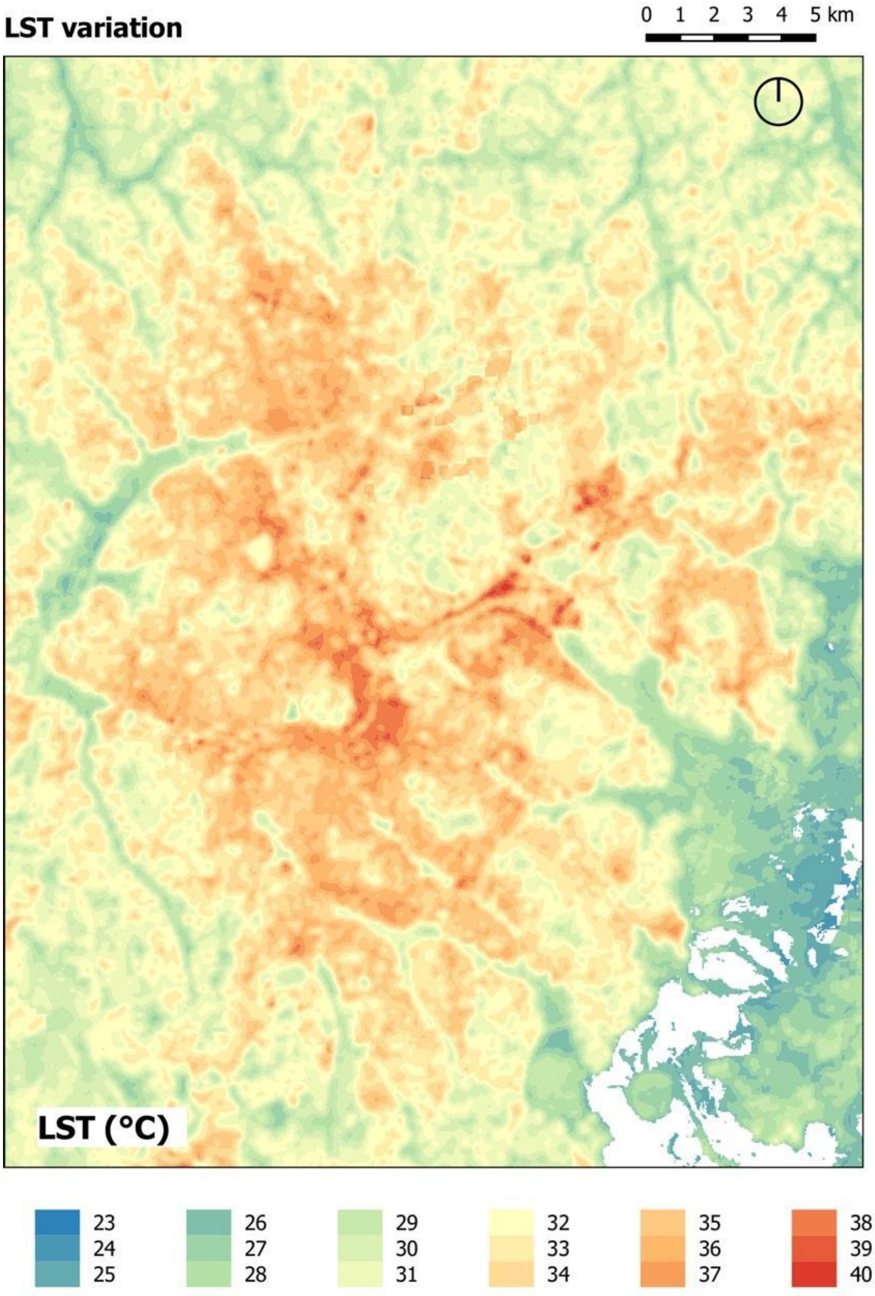


Figure 4 Surface temperature map of Kampala.

As expected, the coolest surfaces are registered in proximity to the shores of Lake Victoria and rural areas. The highest temperatures (38-40) are detected in the city center, and medium-high temperatures (35-37 °C) are widely spread across the city to further inspect the temperature variation please refer to Figure 2.

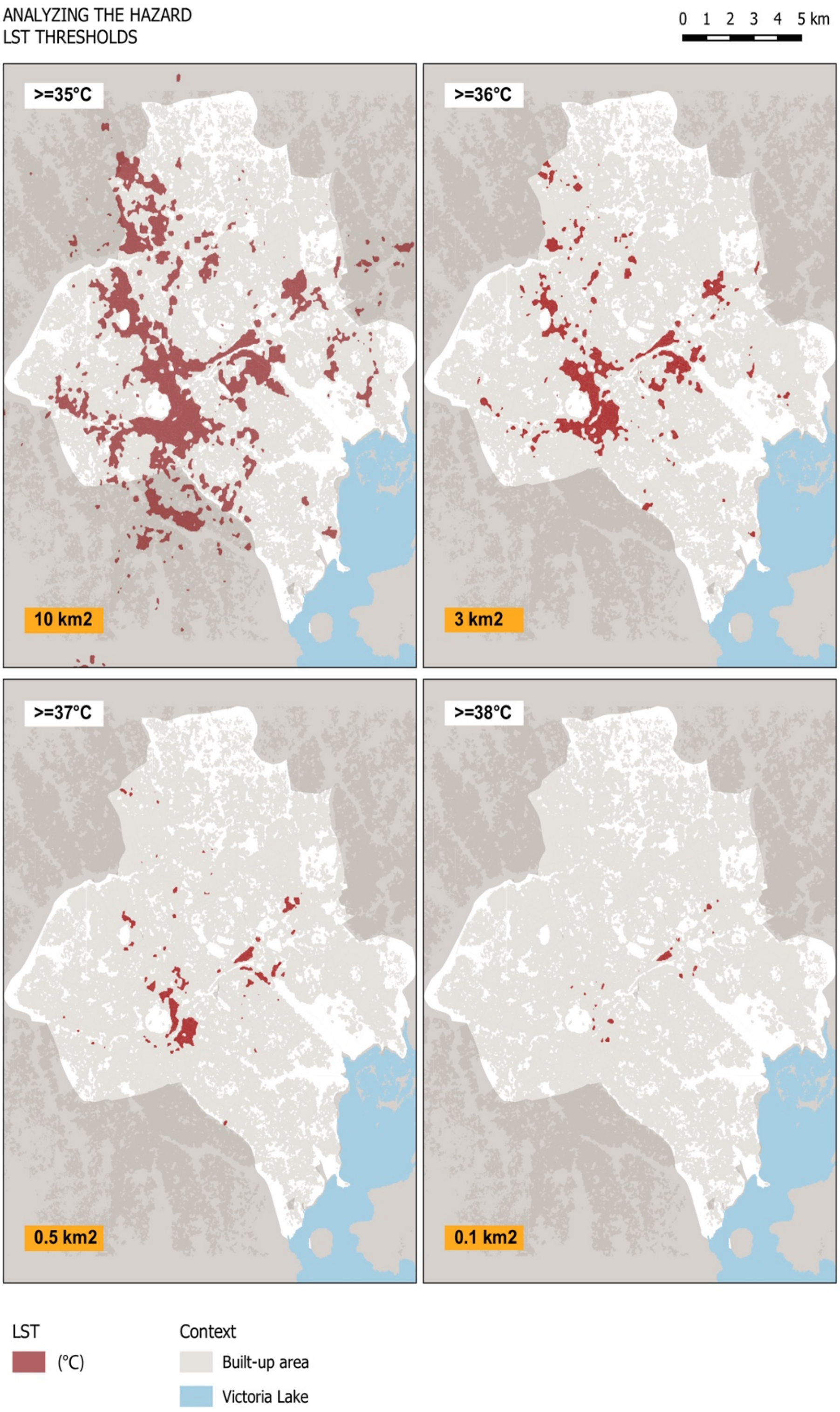


Figure 5 Comparison between different LST thresholds.

Figure 5 refers to one of the original LST maps used to generate the final average LST map (2018-2020). This comparison was made to highlight the different interpretations that could be given to the problem of UHI. Therefore, the importance of setting thresholds to assess excessive heat in cities, for example, Kampala, is essential to guarantee that zones located in high-risk areas are identified and then effectively addressed.

4.1.1. Setting the high temperature threshold

This section addresses research question 2: "What are significant threshold values to mitigate UHI effect in Kampala?"

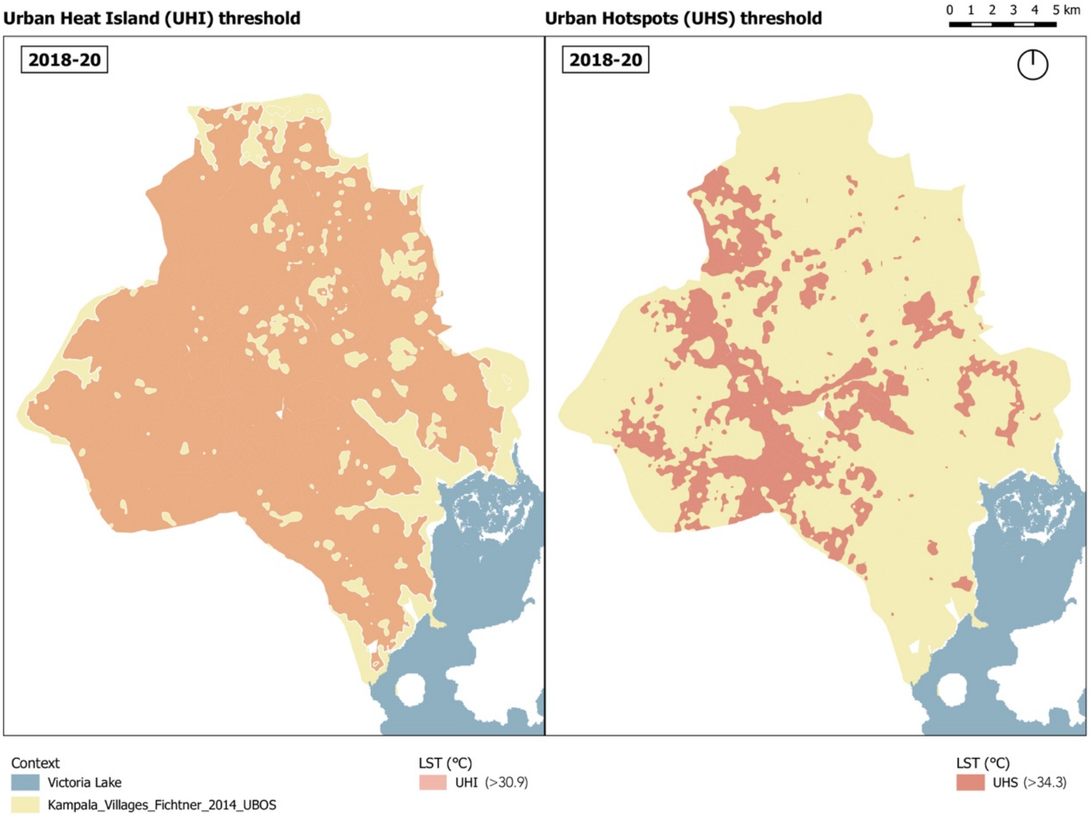


Figure 6 Comparison between UHI and UHS areas in Kampala.

Table 2 Values retrieved from the LST average map (2018-2020) and used to calculate UHI and UHS thresholds.

Years	mean LST	min LST	max LST	St. dev	UHI threshold	UHS threshold
2018-2020	29,8	22,7	40,3	2,3	30,9	34,3

The UHI threshold value based on the equation presented in section 3.2.2 corresponds to an approximated value of 31 °C. As shown on the left side of Figure 6, the area considered under the UHI effect (31-40°C) is almost covering the entire administrative area of Kampala Capital City. While the map on the right side shows the UHS layout (>34.3°C) which is contained in the larger UHI area. The highest surface temperatures in these hot spots correspond to areas with a high density of low and mid-rise buildings with a significant lack of vegetation. UHS are distributed mainly in the city center, around the Central Business District (CBD) and commercial hub, both very busy in terms of vehicle traffic.

If setting threshold values is a significant step to address excessive heat in cities, simultaneously it can be challenging to define it since the LST is a dynamic parameter that changes both in time and space. Both in terms of hours, day and night and between years. Due to the large presence of spatio-temporal values, it is important to remind the reader that the threshold values calculated in Table 2 are based on a limited selection of thermal images. Since the objective of the thesis is to present a potential workflow to effectively tackle the UHI effect in a sub-Saharan city, results should be considered more as representatives to demonstrate the logical flow and calculation of results rather than representing absolute precise results.

4.2. Characterising the heat risk (PART 1)

This section is divided into two main parts: the first one – here below - is focused on the analysis of the physical features of the urban context through the LCZ classification so to pave the way to effective mitigation solutions to tackle the UHI effect; while the second part is more centered on the spatial analysis of the vulnerability layer(s) to determine heat risk and consequently, priority zones.

4.2.1. LCZ classification

This section addresses research question 3: "Which local information layers are required to make a more significant LCZ classification of Kampala, considering the overall objective?".

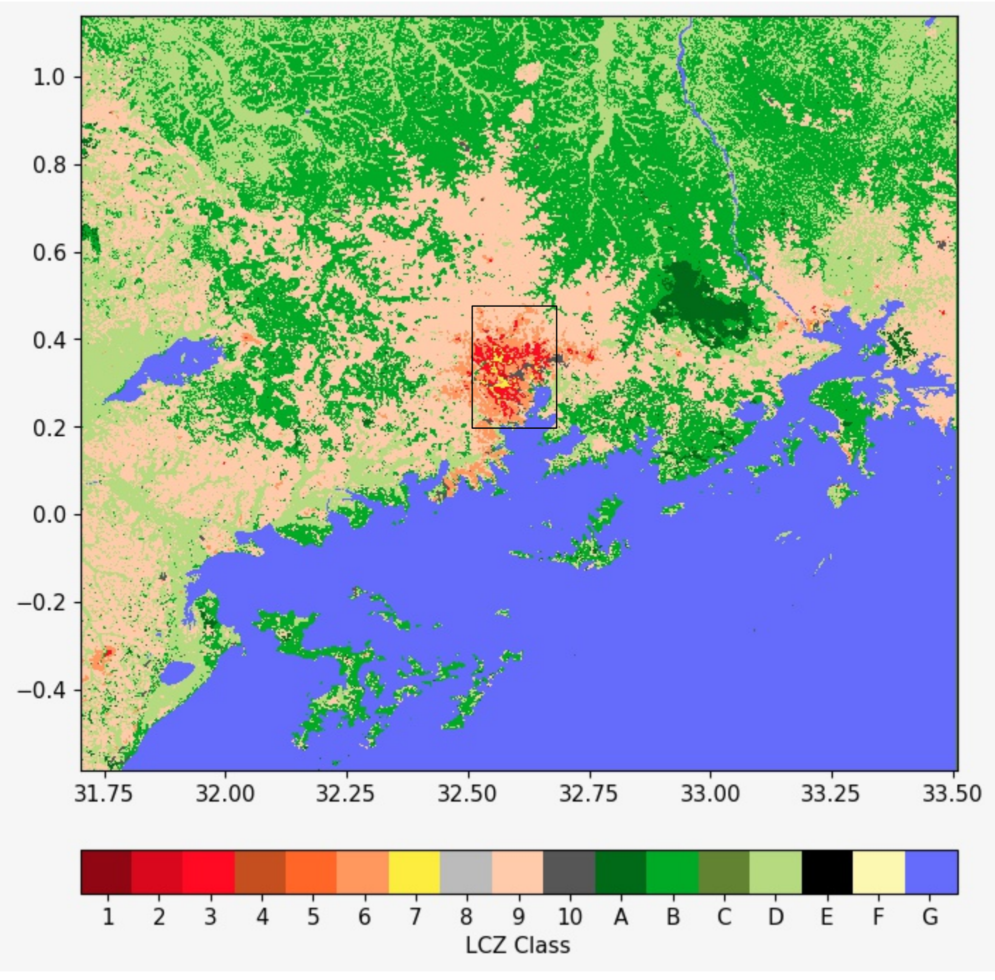


Figure 7 LCZ classification created with the LCZ generator tool, January 2021. A zoom on the content of the black frame is presented in the following figure. Source: ("LCZ Generator," n.d.)

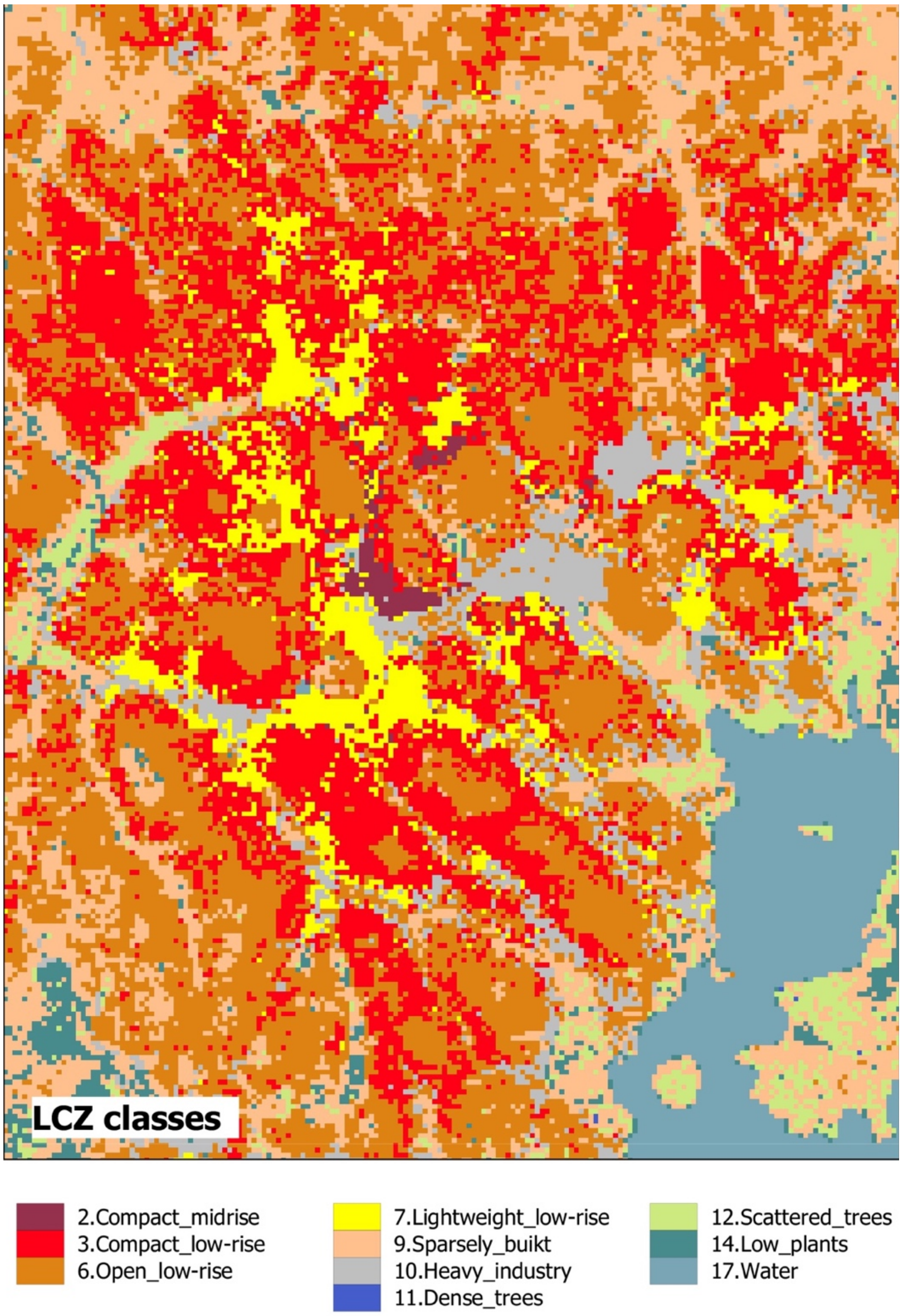


Figure 8 Zoom of the LCZ classification of Kampala city centre. Source: ("LCZ Generator," n.d.)

Compared to previous LCZ classifications made for Kampala (Brousse et al., 2020) some modifications have been made (upper map, Figure 7). Firstly, due to the high correlation between industrial areas and high LST values, training areas representing LCZ 10 (heavy industry) were added as a new information layer. As shown in Figure 8, a large number of factories are located near the city center of Kampala. Furthermore, another evident change is the increase of the total area of the LCZ 7 – representing zones with lightweight low-rise buildings- at the expense of LCZ3 (compact low-rise). This is due to the fact that a larger number of TA was traced and considered in the classification, by taking as a reference the Slum map. This choice was made because in general informal settlements are characterized by metal roofing sheets, easily detectable from bird view pictures. Additionally, as can be noted in the LCZ map, some classes are missing (e.g. large areas of high-rise buildings). This implies that a high percentage of buildings are 1-3 stories high. To conclude, the classification was carried out with a different tool compared to the one generated by (Brousse et al., 2020). The overall accuracy (OA) is 64% which is considered satisfactory since it is higher than the threshold of 50% set by Bechtel (Bechtel et al., 2019) for the classification to be allowed to be disseminated via the WUDAPT portal. A full overview of the LCZ results can be found in the appendix 0, including the average confusion matrix over all bootstraps. For a visual comparison of the two LCZ maps, please refer to Figure 9 and Figure 10.

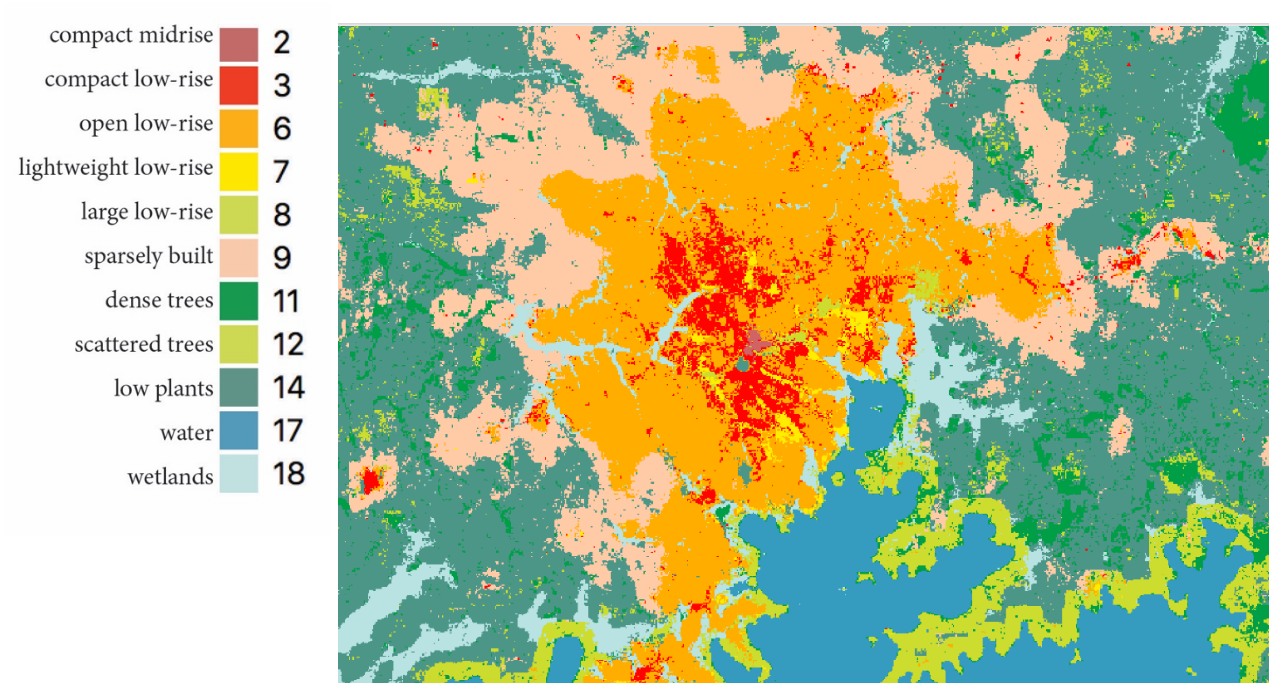


Figure 9 LCZ map published in the research paper: (Brousse et al., 2020).

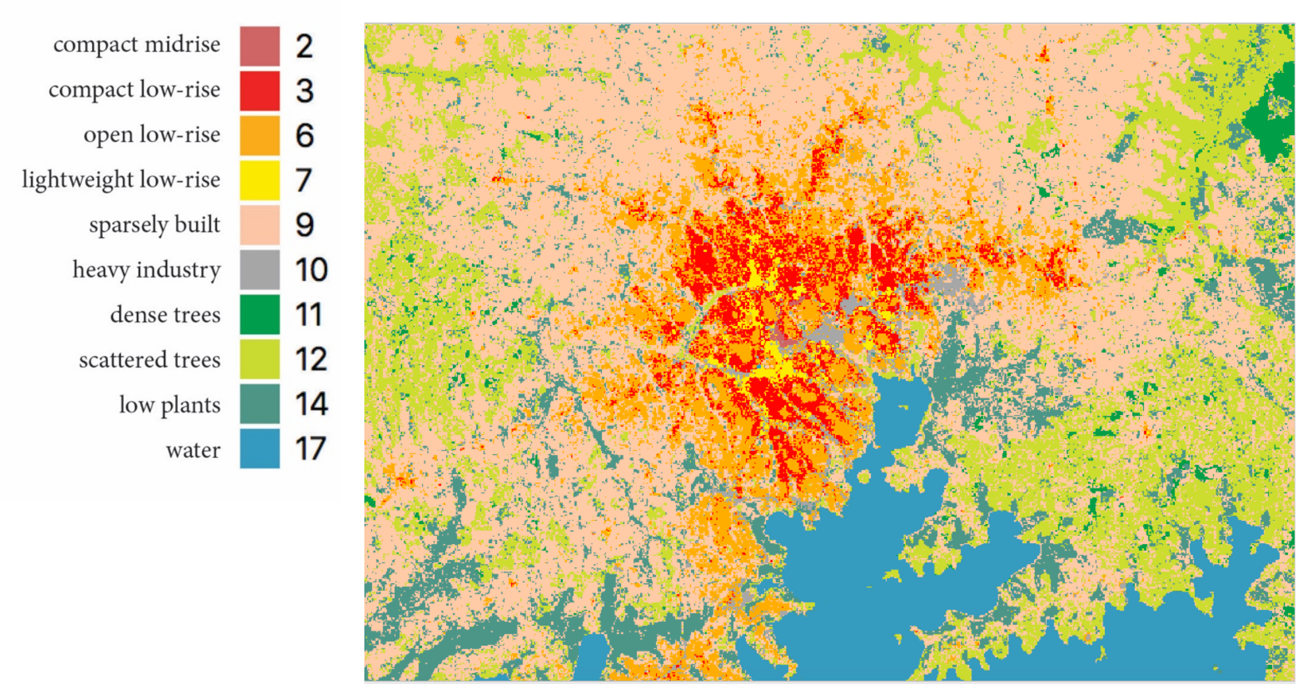


Figure 10 LCZ classification made by the author. Source: ("LCZ Generator," n.d.)

4.2.2. Average LST per LCZ class

This section addresses research question 4: "What is the average temperature of the different LCZ classes?"

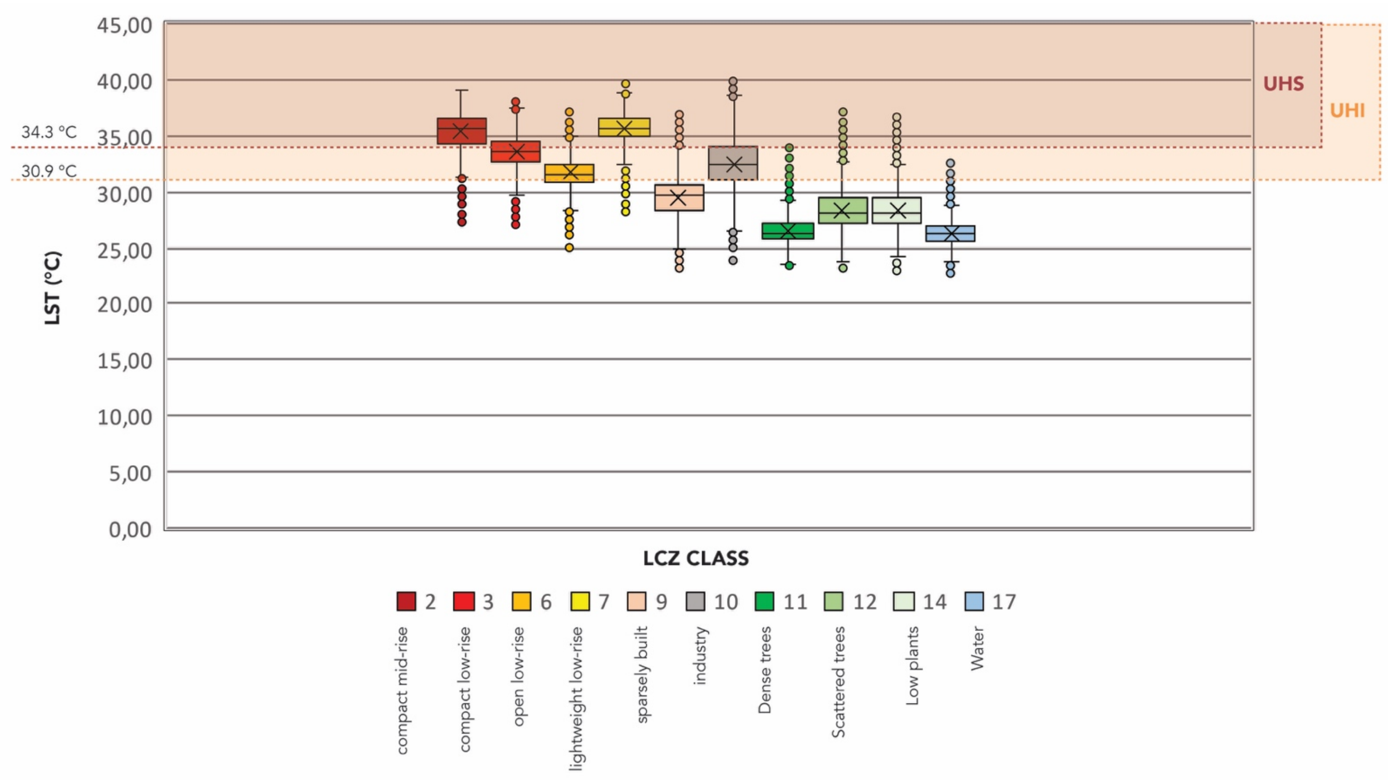


Figure 11 Mean surface temperature per local climate zone class.

Unsurprisingly, the results presented as box (Figure 11)show that high LSTs are located in the built types classes (from LCZ 2 to LCZ 10), while the landscape cover types (LCZ 11 to 17) have a lower average temperature that range between 26 to 28 °C. The box plot includes the UHI and UHS threshold values to have a reference of which classes have a higher tendency to reach higher temperatures, also due to their urban geometry. LCZ7 reaches the highest temperature (higher than the UHS value) together with LCZ 2. Also, LCZ3 results show an influence of compact low-rise building zones in terms of thermal increase. As already stated in the literature review chapter, there is a high correspondence between the presence of industrial buildings and LST increase. In general, it could be summarized that, in the case of Kampala, the results show a positive correlation between LST increase and high density and compactness of buildings (LCZ 2,3,7); additionally, a high correspondence between high surface temperatures and low-rise buildings is noticed (LCZ 7, 10); and to conclude the relationship between high LST and metal covers (LCZ 7, 10).

Table 3 A summary of the average LST per LCZ zones and their total areas. In the table below, more precise LST values for each LCZ can be found (highlighted, the highest values).

LCZ	Description	Ranking	Mean LST (°C)	Area (sqkm)
2	Compact mid-rise	2	35	3
3	Compact low-rise	3	33,5	118
6	Open low-rise	5	31,5	329
7	Lightweight low-rise	1	36	27
9	Sparsely built	6	29,5	115
10	Industry	4	32,5	55
11	Dense trees	9	26,5	20
12	Scattered trees	8	28	314
14	Low plants	7	28,5	214
17	Water	10	26	68

2	3	6	7	9	10	11	12	14	17
35,46	33,53	31,69	35,66	29,54	32,57	26,49	28,33	28,45	26,35

4.2.3. Intra-urban variation of LSTs and LCZs

Figure 12 shows a cross-section representation, cutting through the city center of Kampala to show the rural-urban and intra-urban LST variation, and its correspondence with the different LCZs. LCZ 7, 10, 3 and 2 are the ones that exceed the UHS threshold value, while the lowest temperature corresponds to a water body located in the core part of the city. Highlighted in yellow is the LCZ 7 that represents the presence of informal settlements dwellers (vulnerability layer).

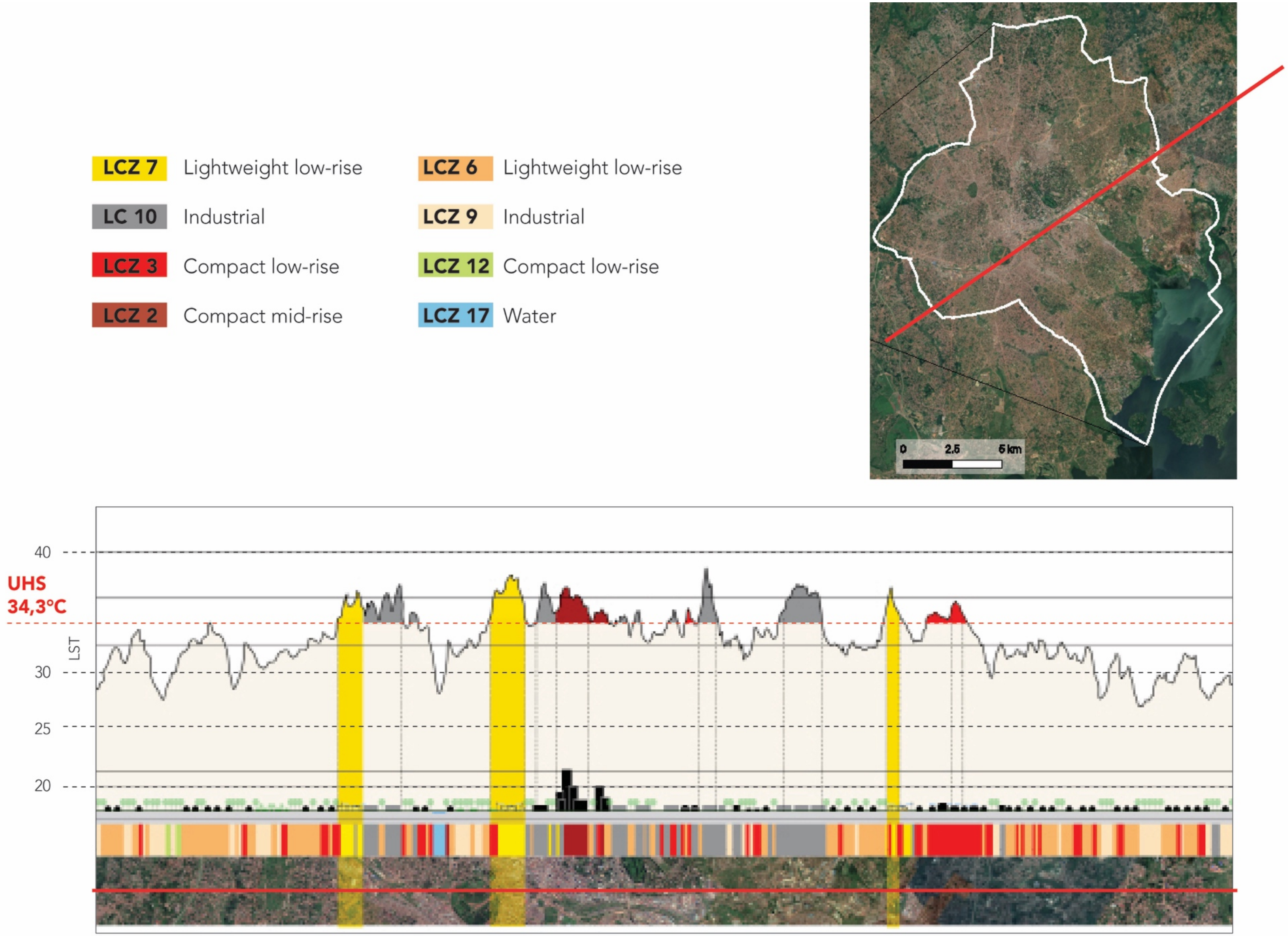


Figure 12 Cross-section showing LST variation and LCZ composition of the urban and rural landscape of Kampala. Source: ("Google Earth," n.d.) and the author

This cross section provides the opportunity to make a comparison and an observation on the relationship between air and surface temperature data measurements.

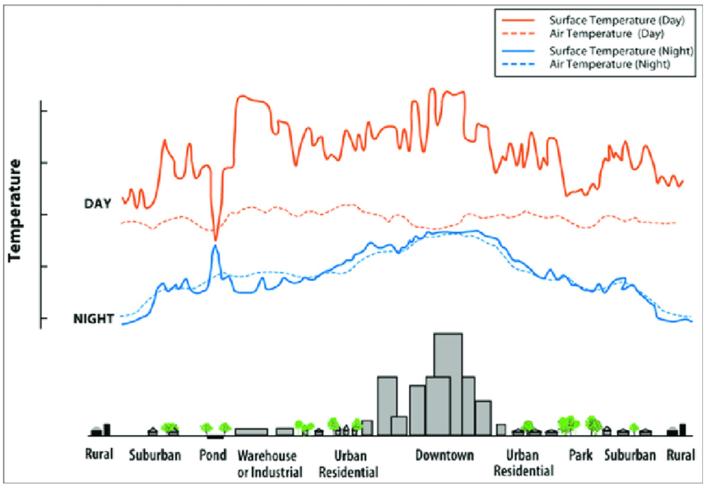


Figure 13 2D cross-section of surface and air temperature along rural-urban-rural transect for day and nighttime. Source: US EPA (2008) adapted from Voogt (2002)

As shown in the Figure 13, previous studies have revealed that the daily surface temperature dataset (used in this study) shows, in general, a greater intra-urban variability both compared to its night-time equivalent and to its corresponding air temperature version, which shows a smoother and more gradual change across the space. Even if it was not possible to create a similar cross-section with the air temperature measurements, the Trans-African Hydro-Meteorological Observatory (TAHMO) ("Projects and Partners - TAHMO," n.d.) provides open data about temperature, humidity and wind collected by numerous weather stations located in different sites of the world and in Kampala too. This free data service allowed us to make a simple comparison between surface and air temperature registered on the same day at a similar time in the same location. The comparison was made using the LST map acquired from Landsat 8 MODIS taken on 09/02/2020 ("RemoteSensingLab," n.d.) and the air temperature measurements registered at around 11 am of the same day by the weather stations displayed in the Figure 14.

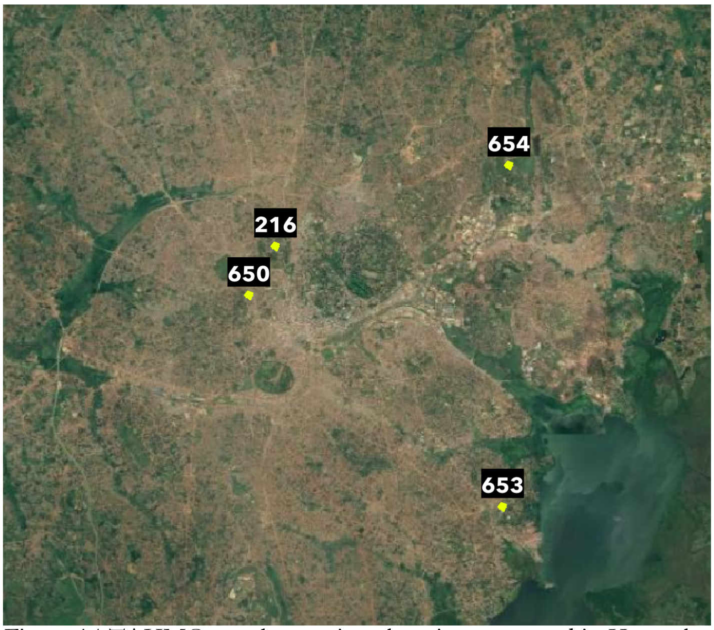


Figure 14 TAHMO weather stations locations near and in Kampala. Source: ("Google Earth," n.d.)

Table 4 Data retrieved from TAHMO weather stations.

STATION / LOCATION	AIR TEMPERATURE (°C) (TAHMO station)	SURFACE TEMPERATURE (°C) (Landsat 8 MODIS)	LCZ
TA00 216	29.8	30.5	6
TA00 650	29.8	32.4	6
TA00 653	28.6	31.7	6
TA00 654	29.8	28.6	6

Table 4 shows that the air temperature measurements registered for that day and time were almost all equal despite their location, with the exception of the one registered in the south (TA00 653) located closer to the shores of Lake Victoria. While the LST data express a greater variety of values. The lowest surface temperature measurement is recorded by the TA00 654 weather station located by the Kyambogo University. All the weather station sites are located in LCZ 6. Although it should be noted that station TA00 654, even if it falls in the LCZ 6, is surrounded by the more green coverage compared to the other stations. This might explain a lower LST measurement compared to its air temperature equivalent.

4.3. Characterising the heat risk (PART 2)

4.3.1. LST map + Vulnerability layers

This section addresses research question 5: "What is the average LST of informal settlements areas compared to medium-high income residential areas?"

In a similar way presented in the previous section, the box plot results can provide a clear comparison between the average temperatures. Looking at the first two boxes - in blue and orange - on the left side of Figure 15 representing the residential areas in Kampala, we can notice that both mean-values of LST of the two categories are affected by the UHI effect. Nevertheless, the informal settlements' average LST is above the UHS threshold. Furthermore, it was decided to include in the analysis also the results about informal firms. This is because since LST temperatures are higher during the day (and the LST map was created using daily thermal images), it was considered relevant to look at the relationship between LST and the informal businesses locations – to analyse the exposure of vulnerable groups during the day. Also, in this case, the resulting average temperature reached by high concentration of informal businesses is above the UHS Threshold value. These results prove a relationship between the targeted vulnerable community group and an increase of the SUHI magnitude, which can be translated into high risk.

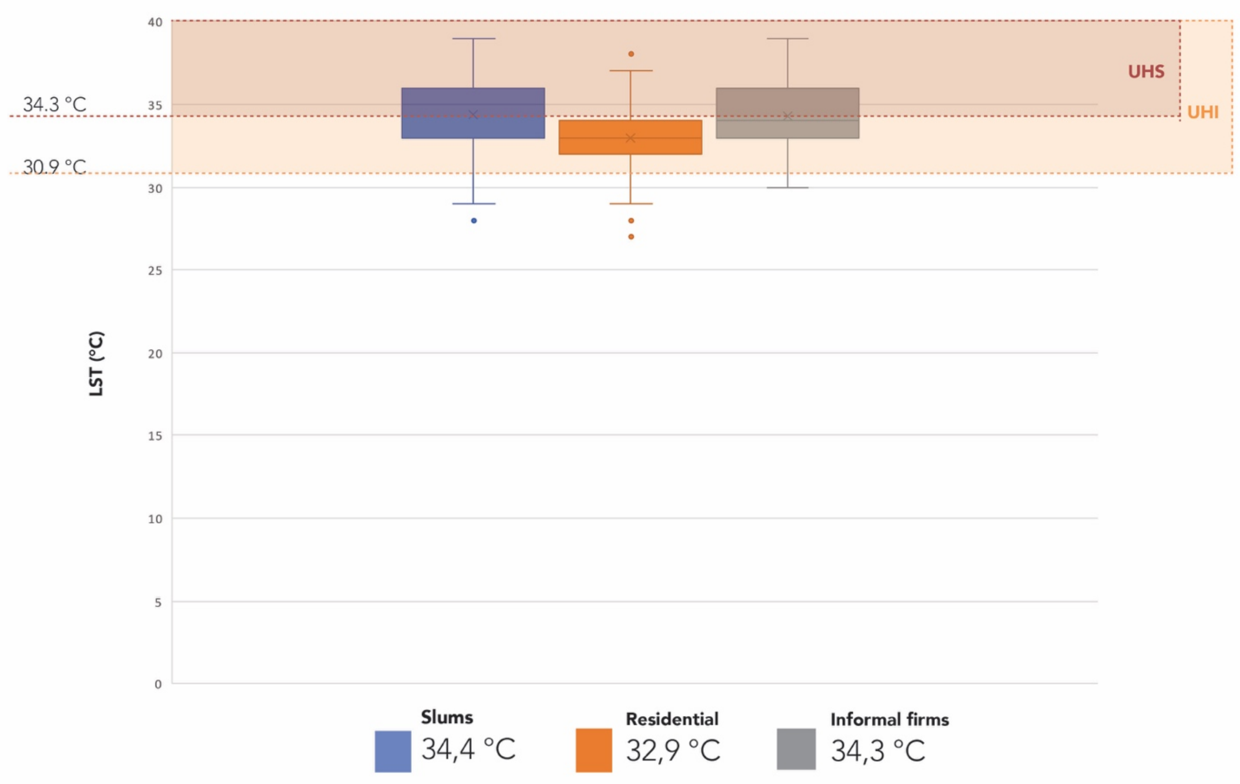


Figure 15 Box plot showing the comparison between the mean LST values registered for informal settlements, residential areas of medium-high income people and people working in informal firms.

4.3.2. Identifying priority zones (UHS + Informal sector)

The first part of this section answers the research question 7: "Which areas have a higher risk considering the targeted vulnerability groups?" by overlying the UHS map (hazard layer) and the informal sector maps represented by the informal settlements areas and the informal businesses density maps (exposure and vulnerability combined layers). Figure 16 shows three clear hotspots where the three components are largely superimposing. These three zones are all located in the central-western part of the city, in the proximity of the central business district. As already mentioned in the previous section, it is usual that informal shops are located and owned in the same areas where slums dwellers live (World Bank, 2017). The three identified squared zones (25 sqkm each) correspond respectively to the neighborhoods of 1. Kasubi; 2. Masaka road; 3. Katwe.

4.3.3. Every area is unique (1sqkm case study)

Before moving to the last stage of the proposed methodology framework that concerns the selection of UHI mitigation strategies and guidelines for their implementation- the last step of the prioritization phase is presented here below. It aims to gradually zoom into one of the three identified hotspot areas. At this stage, the spatial resolution increases, revealing the uniqueness of each targeted area that needs to be studied separately in order to choose solutions that could fit well in the existing urban context. Figure 17 compares the morphology of smaller areas contained in the three identified priority areas. Common features noticeable in all three areas (Figure 17) are the high density of small low-rise buildings with sheet metal roofs and a general low presence of vegetation. All three areas belong to LCZ 3 and 7, with an exception of the middle image that includes also an LCZ 10 (industrial buildings).

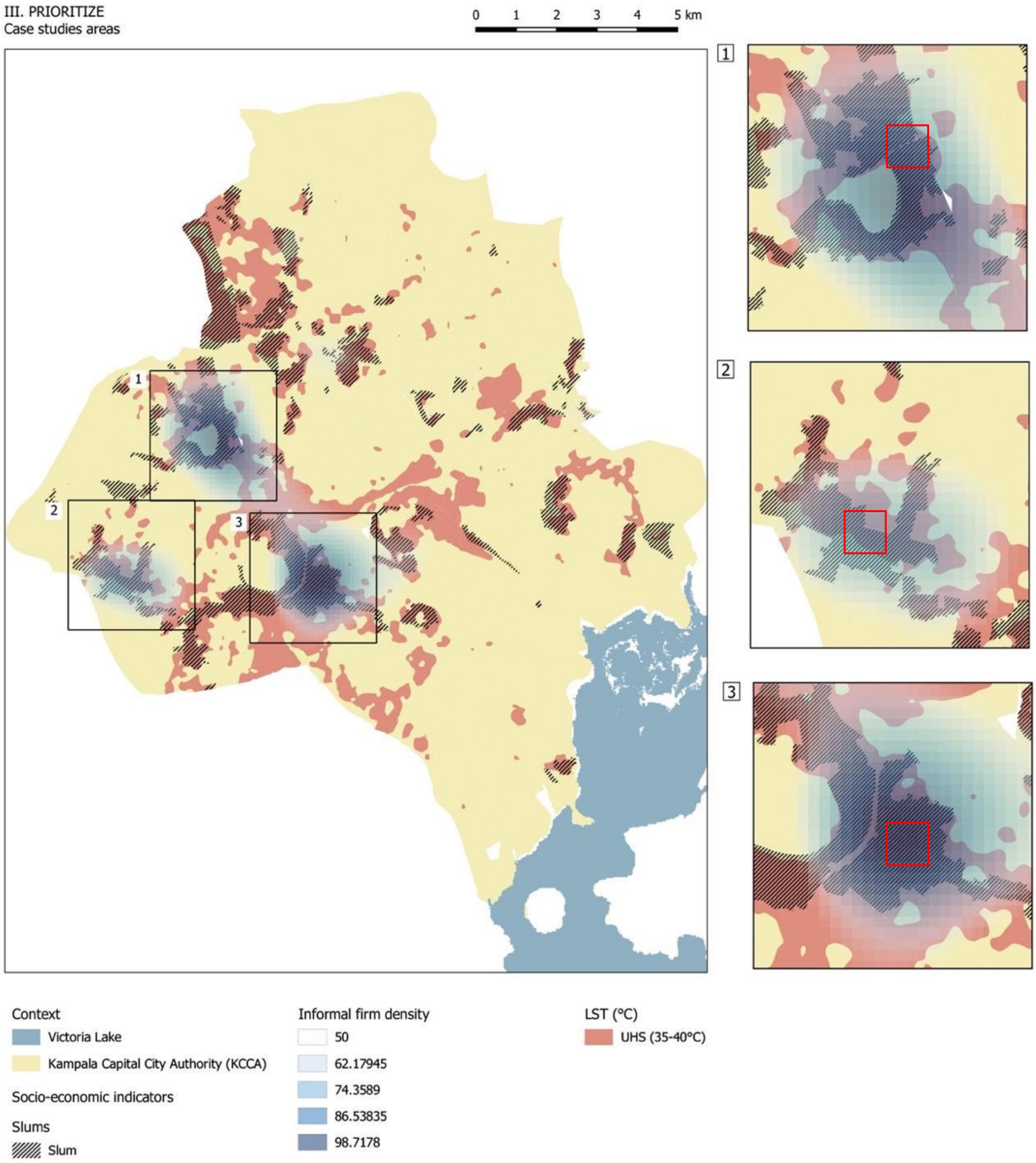


Figure 16 Identification of three priority zones in Kampala.

Figure 17 Smaller areas within the three identified priority areas. Source: ("Google Earth," n.d.)

Considering the research objective and time constraints, this study will use priority zone n° 3 (located in the Katwe area) as a representative small case study area, also because the common features described above fit better in the chosen square format. In Figure 18 a smaller area of just 1sqkm is selected from the original priority area (square 3, Figure 16). This allows a quick comparison with another 1sqkm area Figure 19 that is located just outside the priority zone of Katwe. The scope of this rapid evaluation helps to highlight the main differences in terms of spatial layout, green coverage and surface temperature. More than a 3°C difference is detected by the two average LSTs measured in the case study areas. As shown by the Google Earth street view pictures in Figure 19 the higher amount and space devoted to vegetation suggests a positive influence on the local climate (and a lower mean LST value). While in Figure 18 a limited presence of trees and green areas can be detected along the main and secondary roads, it is completely absent in the dense urban pattern that characterizes the slums area. This observation can lead to the choice of mitigation strategies that foresee the introduction of natural elements. However, the presence of a high density of buildings can hinder the feasibility of the project. Therefore, is it possible to propose mitigation strategies, maintaining the density and overcoming the limitations given by space, budget and time? The question is addressed in the next section.

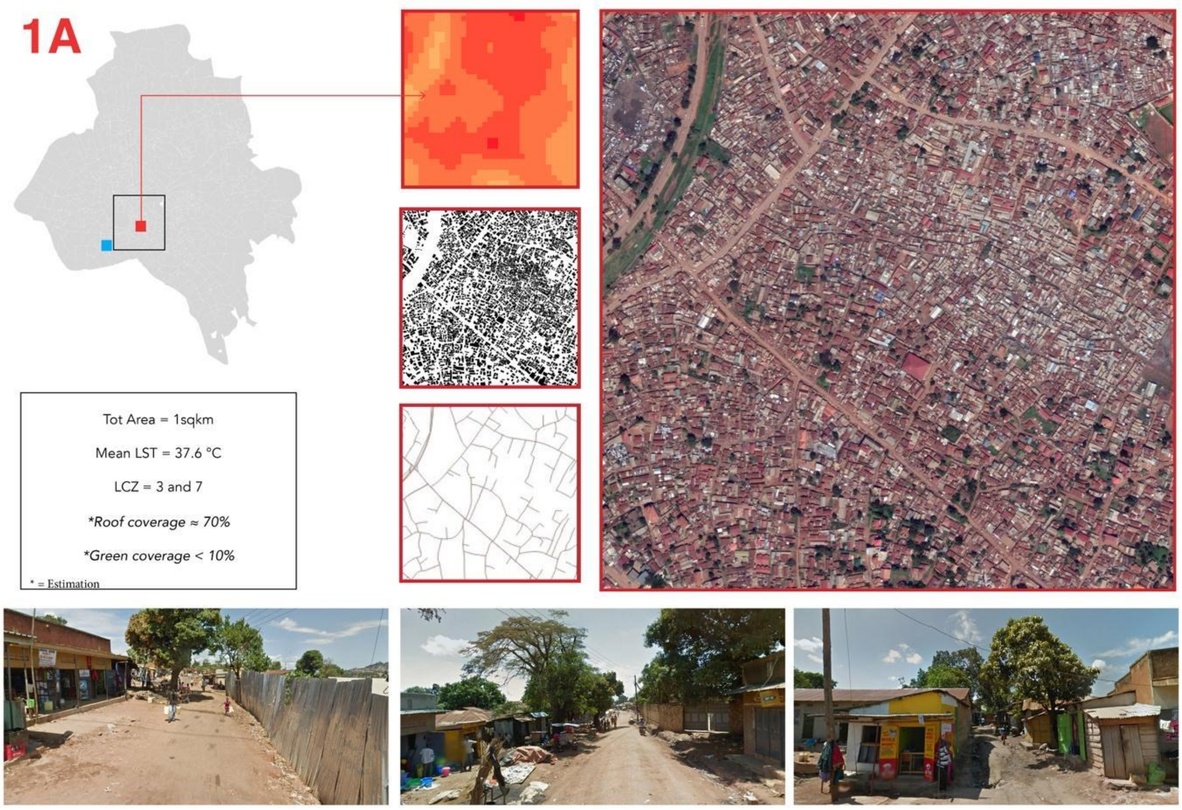


Figure 18 1 sqkm case study within priority zone 3, Katwe. Source ("Google Earth," n.d.)

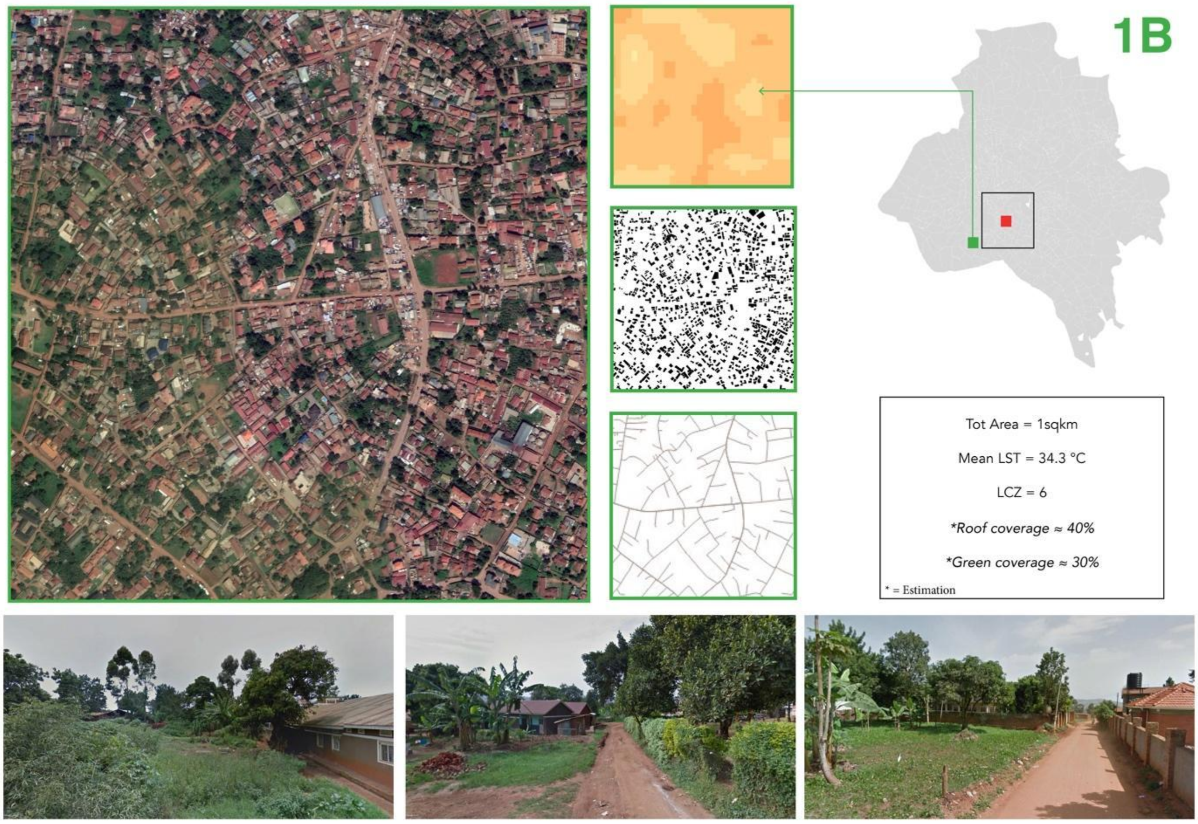


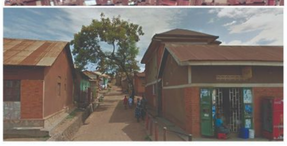
Figure 19 1sqkm case study representing LCZ6. Source: ("Google Earth," n.d.)

4.4. Proposed mitigations for the heat risk

This section answers the research questions 8 "Which mitigation strategies can be applied considering the LCZs of the identified priority zone?" and 9 "How can the selected strategies be implemented considering the local context?". Table 5 addresses research question 8 by highlighting the peculiarities of the LCZs encountered in the previous paragraph and connecting them to their corresponding mitigation solutions. The selection of proposed strategies derives from the atlas of heat mitigation interventions (Ruefenacht & Acero, 2017).

As already highlighted in Table 5, one of the main challenges of heat hazard mitigation is the very limited amount of free space available in the priority zones and in particular in the analyzed area in Figure 18. Another main constraint is the cost of such interventions together with the time required to implement strategies to reduce excessive heat. Therefore, there is a clear intention to focus on small-scale interventions in order to limit the possibility to relocate people from their original locations. It's important to stress the fact that in this section the author explores and makes suggestions of possible approaches and guidelines that would need to be tested, deliberated and reviewed with local stakeholders to prove their efficacy and success.

Table 5 Source for "Features": LCZ datasheets (Stewart & Oke, 2012a); traffic flow information (Google maps traffic); and (Dos Santos Cardoso & De Costa Trindade Amorim, 2018). Source used for selecting mitigation solutions in tropical climate regions (Ruefenacht & Acero, 2017). Source of images: ("Google Earth," n.d.). Table: own elaboration.

LCZ	FEATURES	AERIAL & STREET VIEW	CHALLENGES	STRATEGIES
3	**Geometry:** compact low-rise; **Form:** Relatively small buildings; Narrow streets; **Materials:** Heavy building materials (stone, concrete, brick) and roofs with ceramic tiles or metal sheets. **Land cover:** mostly paved with few or no trees. **Function:** Residential (single-unit housing); commercial (small shops) **Traffic:** medium-low	 	-Limited amount of free space; -High presence of parking lots.	**Geometry:** geometry of urban canyon; breezeway; surface coverage. **Form:** Shading (Building geometry; shelter design) Materials: streets and open spaces; buildings; **Land cover:** increasing vegetation coverage (planting greeneries, Parks and open spaces, green corridors); Water bodies and features. **Mobility:** green parkings, promote active mobility; decrease car use.
7	**Geometry:** compact lightweight low-rise; **Form:** Single-story buildings; compact arrangement; Narrow streets. Little or no consolidated infrastructure. **Materials:** Lightweight materials, thin walls and roofs with metal sheets. **Land cover:** mostly paved with few or no trees, bare soil. **Function:** residential, commercia (informal); **Traffic:** medium-low	 	-Very limited amount of free space; -Lack / absence of basic infrastructures; -Presence of informal settlements and informal economy.	**Geometry:** geometry of urban canyon; breezeway; surface coverage. **Form:** Shading (Building geometry; shelter design) **Materials:** streets and open spaces; **Land cover:** increasing vegetation coverage (planting greeneries, Parks and open spaces, green corridors); Water bodies and features.
6	**Geometry:** open low-rise; Form: small buildings, 1-3 stories tall. **Materials:** brick, ceramic tiles, concrete. **Land cover:** mostly pervious (abundant low plants cover, scattered trees). **Function:** mixed (residential, commercial) **Traffic:** medium-low	 		**Geometry:** breezeway; **Form:** Shading (Building geometry; shelter design); **Materials:** streets and open spaces; buildings; **Land cover:** Preserve and maintain existing green areas;

4.4.1. Selection of Heat mitigation strategies for Kampala - assessment and comparison

After a preliminary screening of possible mitigation solutions previously presented in Table 5, the author selected three different approaches (shown in Table 6) applicable for LCZ 7, considering space, time and costs. The table here below is a summary of the advantages and potential challenges that each strategy might entail, together with possible external factors and co-benefits. More detailed information about the single solutions can be found in appendix 6.3.

Table 6 Sources : ("Masterclass: Understanding, Modeling, and Mitigating Urban Heat Islands | Global Heat Health Information Network," n.d.)("What Are the Hidden Co-Benefits of Green Infrastructure?," n.d.) | (Ruefenacht & Acero, 2017).

Strategy	**Solutions**	**Advantages**	**Disadvantages**	**Co-benefits**
1. Vegetation	• Microscale urban greening (i.e. pocket parks and street trees) • Urban farming through community gardens (or 'backyard gardening')	• Vegetation cools the environment through evapotranspiration; • Trees provide shade which reduces heat load on human body; • GI reduces LST under tree Canopy.	• Maintenance costs;	• Air purification; • Water quantity mitigation; • *Improves aesthetics of the urban environment;* • Creates social interaction; • Improves mental health and wellbeing; • Food production / food supply for low income groups; • reduce unemployment and promote economic growth and empowerment; • Enhanced access to fresh fruit and vegetables • Reduces environmental impacts through less transport
2. Materials	• Changing the color of roofs, pavements to a lighter / more reflective color	• Changes the thermal properties of materials that can be found in cities (increase of albedo) • LST decreases since the energy from the sun is reflected back to the atmosphere	• High albedo surfaces lower LST but increase mean radiant temperature	•Can improve *aesthetics of the urban environment;*
3. Shading	• Buildings overhangs; arcades.	• Has a direct impact on temperature, and thermal comfort.	• Shades improve daily thermal comfort but longwave trapping / heat retention at night;	NA

Considering the high rate of co-benefits that in general urban greenery approach generates and the additional external factors that urban farming might imply, it was decided by the author to further investigate the feasibility of the implementation of such solutions. This choice was also supported by an acceptable estimation in terms of costs, time and space. Although, in order to move from a more theoretical approach to a more practical one based on the local context, the identification of required steps to implement the selected solutions is demanded. The feasibility of the targeted solutions can be assessed by starting to consider the physical built-up environment (Figure 20) and the current administration settings.

Figure 20 Open spaces, within the analysed priority-zone, highlighted in green. Source: ("Google Earth," n.d.). Own elaboration.

In the majority of cases, three-quarters of the area of the informal settlements belongs to a small minority of residents. Results of a study conducted on four East African cities including Kampala show that most of the dwellings in slums are offered by non-state providers, but rather by individuals who are in the same social networks as the (future) residents (IHS, 2019). Tenure security can provide slum residents with the incentives to invest in the land they occupy and the community in which they reside and diminish littering of "no man lands". (Richmond et al., 2018). In Kampala's slums, it is common that the landowner, building owner and residents are all different people, which would make the process of engagement with local stakeholders more complex and slower (The Independent, 2019) Recently, the government started a stakeholder's engagement process in Katwe (one of the priority locations identified in this study) to see how an upgrade of slums can be developed. One potential approach would be the drafting of a comprehensive plan to acquire land in slums and develop them with the co-participation of current residents (The Independent, 2019). This type of approach is supported by the local NGO ACTogether which acts in Kampala. The process of 'upgrading slums' pursues the goal of improving the residents' lives reducing vulnerability for those who are working and inhabit these spaces. So, slum improvement through tenure security and participatory planning can provide a better environment for the people who are currently living and working in these areas at risk.

4.4.2. Participatory planning approaches, a brief overview

Designing public spaces through placemaking

As already mentioned in the previous paragraph, every area is unique, which means that even if we are importing successful solutions from elsewhere this is not enough to guarantee a successful outcome. "Each community has its own unique local conditions that must be accounted for". Local knowledge needs to be listened to and valued in order to have a positive aftereffect. Placemaking is a bottom-up approach that empowers and engages the "users" of a certain place and can be combined with the knowledge of the "experts" that is also needed to act effectively (Symbiocity Kenya, 2018).

Bridging geospatial knowledge to citizens' knowledge

A recent European project called Smarticipate demonstrated that bridging geospatial knowledge to citizens' knowledge is possible and can be achieved with digital platforms ("Smarticipate – Opening up the smart city," n.d.). Smarticipate encourages citizens to take an active part in the decision-making process by providing them with access to the data of their city in an intuitive and simple manner. In this way, municipalities can gain valuable inputs and feedback and guarantee a more democratic and dynamic planning and decision-making approach. The geospatial data can be enriched also by the citizens themselves. Additionally, citizens can be informed with insights into the process of planning and decision-making processes by providing them with easy-to-understand information about legal frameworks and relevant policies ("Smarticipate – Opening up the smart city," n.d.).

The implementation of significant environmental regulations can be strengthened by creating public awareness and by supporting community/self-policing. Organizations can embark on communication campaigns to summarize their mandates, responsibilities, assessment methods and publish public guideline documents supported by the use of illustrations to facilitate the conveyance of information to the general public. Nevertheless, it is equally necessary to target the management team in each organization and the local leaders first, to guarantee a shared view, so as to communicate it more effectively to the public. (World Bank Group, 2015). As a general consideration, transparency during the decision-making process and inclusion of all the involved actors, particularly the local community, is fundamental to minimize the intensification of feelings of marginalization, exclusion and distrust, in addition to impoverishment risks of local informal settlements dwellers (Nikuze, Sliuzas, & Flacke, 2020).

4.4.3. Local urban farming initiatives

This brief overview shows that already a number of urban farming initiatives are already taking place in and near Kampala, at different scales. Some of them are the result of a collaboration between educational institutions and community gardens, like the initiative involving the University of Makerere (Figure 21). One of the Agriculture for Health and Wealth (AHW) cofounders highlighted that the knowledge produced by universities most of the time does not reach the envisioned users that are local farmers. Technical and technological information produced within the University environment could really make a difference and improve agricultural production and consequently the community's lives, and urban farming and microscale gardening can be the opportunity where the youth can tap into (Nabatte, 2019).

Figure 21 Urban farming by Agriculture for Health and Wealth (AHW). Source: (Nabatte, 2019)

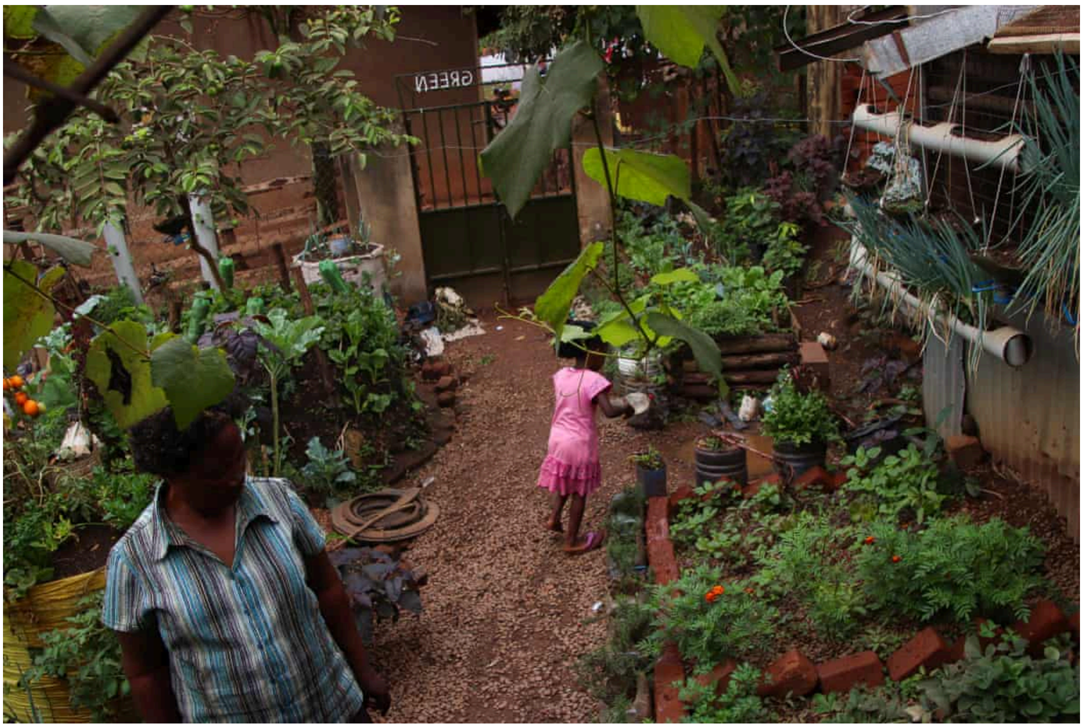


Figure 22 Harriet Nakabaale's urban farm in the Kawaala district of Kampala is popular among locals who want to learn how to grow crops in their urban spaces. Photograph: Nils Adler; Source: (Adler, 2018)

Figure 23 Kwagala farm – Backyard farming, Kampala. Source: (AVSI & @TheSAYproject, 2016)

Figure 24 Urban farms in Kampala, Uganda, make the most of their limited space. Photograph: Nils Adler ; Source: (Adler, 2018)

Urban farmers in Uganda are venturing into vertically stacked wooden structures, in order to respond to the limited available space (Figure 25).

Figure 25 Vertical and micro gardening initiatives (Bettis, 2020).

4.4.4 Three Scenarios

The potential stakeholders involved in the process would be:

1.Tenants; 2. Resident structure owners; 3. Non-resident structure owners; 4. Landowners and 5. support institutions (national/local governments, Civil Society Organizations (CSOs), the private sector and multi/bilateral development partners) (Syagga, 2012); 6. NGOs 7. Educational institutions like Universities and schools.

The scenarios are based on the information described in section 4.4.1 and consider the measures that are usually used for "slum upgrading", which are the following:
1. Installation or improvement of basic community infrastructure;
2." Regularization of tenure and housing rights": by surveying and titling plots. Minimum installation or improvement of existing infrastructure is provided;
3.Comprehensive upgrading: Includes both approaches where environmental conditions are very poor (Syagga, 2012). The three scenarios based on land ownership (public or private) are presented in the Table 7, here below.

Table 7 Three scenarios based on different land ownerships.

I.Public	I.Private (option 1)	II.Private (option2)
Direct implementation of micro-scale green infrastructure projects by the local government. Two options: A. Pocket parks or street trees; B. Urban farming; For option A, municipality is asked to cover expenses for installing the green community infrastructures. In order to guarantee a correct and functional maintenance of these new community spaces, the task of maintaining vegetation in a good condition can be assigned to local residents as a paid job. Potential locations for micro green interventions are initially identified and proposed by planners and local community members are invited to provide feedback and suggest new ideas. --- For option B, slum residents have the possibility to access to microfinance or community saving schemes so to be able to cover initial expenses of urban farming tools.	Comprehensive upgrading: In this case the land does not belong to the municipality. Therefore, the local government has to first arrange the land tenure regularization and then starting with the implementation of the small-scale GI projects described in scenario 1. This scenario, compared to the third one, mainly differs in requiring longer time to implement the comprehensive upgrade process due to uncertain length of time to achieve land regularization. However, this option would be more beneficial in the longer term, since residents would be more inclined to invest and care for their own plots in the future. This could also be an important step towards gradually changing this fragile environment by developing dialogue between inhabitants and local authorities. It would also be beneficial to citizens' empowerment enabling them to slowly move away from poverty situations and to deal with other pressing issues that slums are currently facing.	Only vacant land, suitable for green interventions and urban farming, is leased out by private owners to the local government. Local dwellers can buy urban farming equipment by microfinance and community saving schemes. Collaborations with local NGOs, schools and University are encouraged to educate the local community on the urban farming topic and knowledge sharing on both directions can be achieved.

4.5. Performance Evaluation of the proposed methodology

This section answers the research question 10: "What are the strengths and weaknesses of the proposed methodology?" and question 11: "In which directions could further improvements be sought?" by describing the Strengths (S), Weaknesses (W), Threats (T) and Opportunities(O) of the proposed methodology-framework.

S. Strengths of the proposed methodology are the use of open-source software (i.e. extensive use of QGIS) to facilitate reproducibility. Also, the choice to rely on existing free tools like the RSlab tool for the LST estimation and the LCZ generator tool to make an LCZ classification was made to guarantee a relatively simple and fast workflow. Furthermore, the value of quantitative outputs and maps showing the conditions across the landscape to support policy making. The cross-section, for example, shows how the reality of heat surfaces and exposure is more complex than the general model (Figure 1) suggests.

W. As previously mentioned in the document, the impossibility of carrying out fieldwork has limited the work just to desk research, leading to numerous assumptions that could have not been validated by ground truth. Furthermore, even if the proposed hazard mitigation solutions consist in small-scale interventions that aim to minimize significant changes to the inhabitants of the priority zones, there is still the risk that some relocation might be involved. Moreover, the size of identified priority zones is rather large (25 sqkm) making it more challenging to precisely determine contextual factors to choose and focus on consequent implementation obstacles that should be considered. Therefore, the choice to focus on a smaller representative area. Additionally, green is just a small part of upgrading slums. Other pressing issues need to be included in this fragile and poor context.

O. Since health risks posed by prolonged exposure to high temperature are among the most relevant reasons for conducting this research, it would be highly beneficial to consider thermal comfort in future studies, by leveraging scientific progress and research to overcome data scarcity of sub-Saharan cities. Collecting and calculating information about heights, sky view factor (SVF), wind speed, humidity, etc. would allow estimating thermal comfort (i.e. Physiological Equivalent Temperature). If not possible, air temperature patterns made with mobile measurements can be included.

T. Focusing just on the LST variation without considering thermal comfort might imply that areas with higher heat risk can be overlooked. This could also be the case of spatial clusters of heat vulnerable groups of the population (the elderly, the young and the people with weak health conditions) that might also need to be included among the mitigation priorities zones. Furthermore, another threat might consist in the triggering of an "environmental gentrification" that can contribute to an increase of land and home prices and the consequent relocation of current informal settlements inhabitants. Therefore, the local community must be directly involved in the 'green' upgrade which simultaneously generates an income for the informal settlements' inhabitants.

4.5.1. Dealing with wickedness

Different strategies can be adopted to decrease the wickedness of a problem: these include the structuring and the analysis of the problem and stakeholder engagement. Defining the main problem and key stakeholders is the first step to facilitate the structuring of the problem. In this particular project, the increase of knowledge about the problem (UHI effect and how to mitigate it) was achieved by answering research questions that enabled us to pinpoint locations at risk. While the stakeholder consensus can be improved by sharing the geospatial findings with citizens. Public awareness and participatory planning are all key strategies to increase consensus among actors. Moreover, increasing awareness of direct and indirect health impacts of excessive heat is crucial and should be extended to different stakeholder groups and not limited to only decision-makers nor to just some vulnerable community groups. Since reducing health complicacies (i.e. cardiovascular and respiratory disorders, heat exhaustion, cramps and strokes) and its consequences (i.e. altering human behaviour, the transmission of diseases, health service delivery, air quality, and critical social infrastructures such as energy, transport, and water) (World Health Organization, 2018) are the primary motivation of this whole research work.

To conclude, bringing stakeholders in the methodology and finding suitable mitigation solutions. Even if the solutions are small-scale interventions, it's important to consider that every policy intervention would not purely be just positive but also other unexpected externalities will be triggered. For example, creating opportunities for increased greening in a community may require the relocation of some houses and residents, which is in itself a very wicked problem that is fraught with difficulties and challenges (Nikuze et al., 2020; Nikuze, Sliuzas, Flacke, & van Maarseveen, 2019; Patel, 2016; Patel, Sliuzas, & Mathur, 2015).

5. CONCLUSIONS AND RECOMMENDATIONS

The main objective of this research was the design and demonstration of a relatively simple and fast methodology framework that could enable urban planners to identify priority zones for UHI mitigation, with the support of the LCZ classification. The identification and calculation of meaningful thresholds (UHI and UHS) helped to determine the extent of the heat problem concerning the city of Kampala and to provide potentially useful information for policymakers. The analysis of thermal patterns of LST values, during the warmest period of the year, revealed that the UHI effect impacts the entire administrative area, while UHSs (>34.3 °C) are more concentrated in the city center around the Central Business District (CBD) and commercial areas which are also among the busiest places in terms of vehicle traffic. Furthermore, the results of the analysis confirmed a high correlation between compact LCZ classes with low vegetation coverage and high surface temperature (LCZ 2,7,3), as already stated in a previous study (Z. Cai et al., 2019). Concerning the heat risk analysis, results disclosed an extensive overlap between the informal settlement areas (mainly belonging to LCZ 7 and 3) and high LST values, showing that the vulnerable target group of slum residents is exposed to higher temperature compared to dwellers in other residential areas. Furthermore, the cross-section (fig.12) revealed a much more complex rural-urban and intra-urban variation of surface temperature compared to the general profile (fig.1). However, it confirmed the evident cooling effect of water bodies and green areas, as already mentioned in previous paragraphs.

The proposed prioritization framework followed a cross-scalar approach which allowed the identification of three major priority zones for UHI mitigation. Subsequently, the methodology required a further selection of a representative smaller area. Although every project area is unique, findings offered general insights about implications for slum residents.

Insights provided by the LCZ classification, led to the decision to introduce urban greenery measures, as considered the most appropriate and beneficial intervention for the identified priority zones. Urban greenery was chosen as a general strategy, both public and private greenery. Subsequently, small-scale urban farming was also included as a solution because of its potential contribution to the improvement of local livelihood, health, and well-being. Additionally, this small-scale intervention can reduce the chances of relocating informal settlement dwellers.

As a general consideration, all the proposed suggestions would need to be tested, deliberated, and reviewed with local stakeholders and especially residents. Potential concerns on the limited amount of input layers used for hazard analysis (LST maps) are understandable, though it is important to remember that the primary objective of the research is the design of a system that connects different existing approaches in a logical way, in which the specific input layers are of lesser importance. There is also a reason for concern about the identification of priority areas based exclusively on land surface temperatures instead of considering thermal comfort. This choice would entail looking at the microscale where issues like wind, ventilation would also be important as well as considering the local cooking systems that are often charcoal-based. So far, the magnitude of thermal stress remains unknown. This would require more data about several information layers including heights (i.e. terrain, vegetation, buildings), sky view factor, humidity, wind speed, to also calculate available shading areas together with assumptions on physical parameters referring to a standard human being. Therefore, there is room for adaptation and enrichment of the proposed methodology in Kampala or other sub-Saharan cities which have access to the data of the previously mentioned variables. This would enable spatial planners to detect hotspots of heat stress more precisely. Future studies can imply the comparison between the resulting thermal patterns with the night-time UHI effect based on air temperature measurements.

In this case, the intra-urban variation of land and air temperatures, at the same spatial resolution, would require measurements with mobile devices.

The outcome of this thesis provides a tool aiming to improve the quality of life in a sub-Saharan city like Kampala. In order to speed up and automate the identification of priority zones, it would be useful to explore the possibility of translating the first three phases of the workflow (figure 3) into a standalone programming script, providing support to the local team of policy makers and urban planners. In this way more focus can be given to communication and involvement efforts of local stakeholders, to the benefit of Kampala and the local community.

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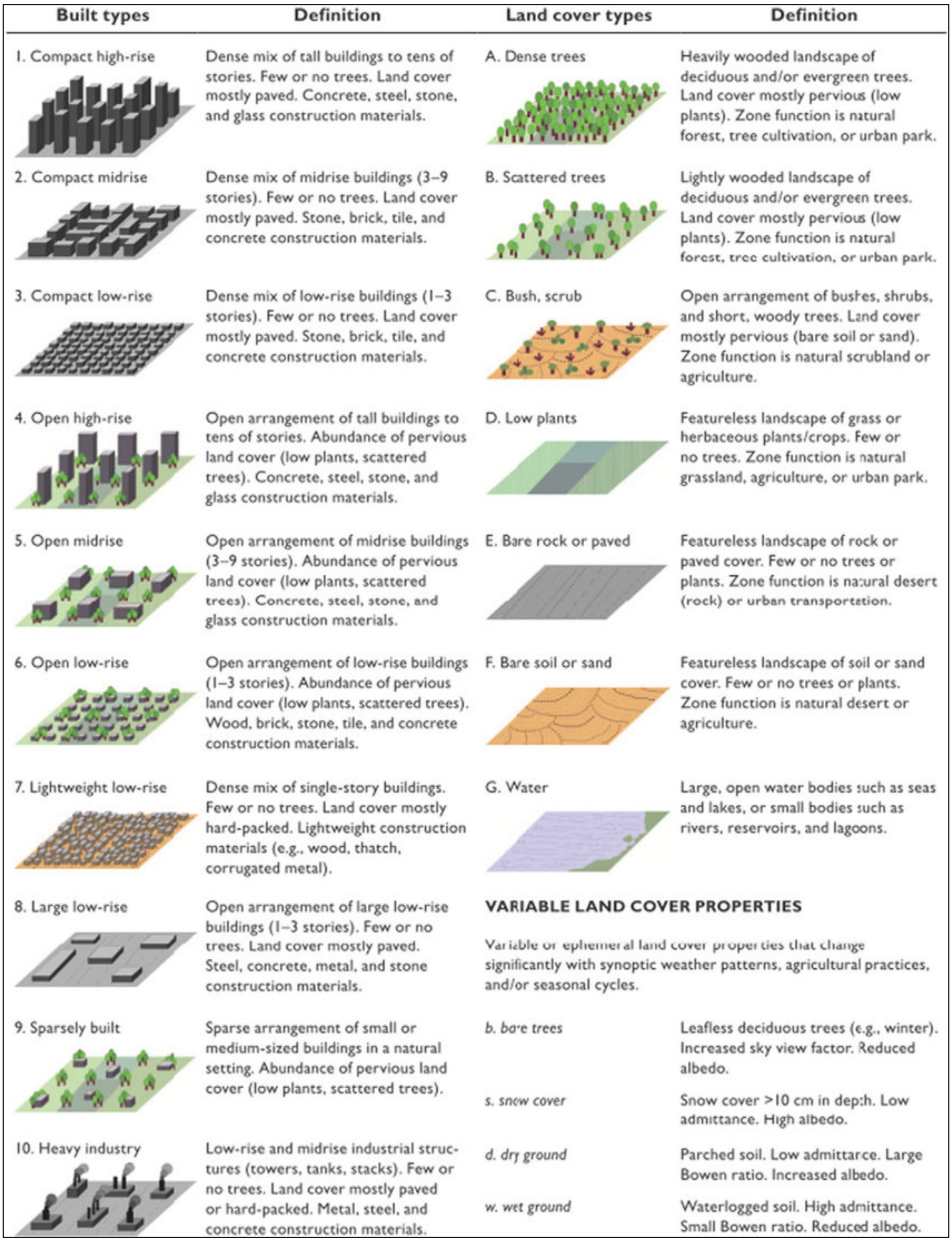
6. APPENDIX

6.1. LCZ classes



Built types	Definition	Land cover types	Definition
1. Compact high-rise	Dense mix of tall buildings to tens of stories. Few or no trees. Land cover mostly paved. Concrete, steel, stone, and glass construction materials.	A. Dense trees	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
2. Compact midrise	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	B. Scattered trees	Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
3. Compact low-rise	Dense mix of low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	C. Bush, scrub	Open arrangement of bushes, shrubs, and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.
4. Open high-rise	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	D. Low plants	Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.
5. Open midrise	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	E. Bare rock or paved	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.
6. Open low-rise	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.	F. Bare soil or sand	Featureless landscape of soil or sand cover. Few or no trees or plants. Zone function is natural desert or agriculture.
7. Lightweight low-rise	Dense mix of single-story buildings. Few or no trees. Land cover mostly hard-packed. Lightweight construction materials (e.g., wood, thatch, corrugated metal).	G. Water	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.
8. Large low-rise	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.	**VARIABLE LAND COVER PROPERTIES** Variable or ephemeral land cover properties that change significantly with synoptic weather patterns, agricultural practices, and/or seasonal cycles.	
9. Sparsely built	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).	*b. bare trees*	Leafless deciduous trees (e.g., winter). Increased sky view factor. Reduced albedo.
		s. snow cover	Snow cover >10 cm in depth. Low admittance. High albedo.
10. Heavy industry	Low-rise and midrise industrial structures (towers, tanks, stacks). Few or no trees. Land cover mostly paved or hard-packed. Metal, steel, and concrete construction materials.	*d. dry ground*	Parched soil. Low admittance. Large Bowen ratio. Increased albedo.
		w. wet ground	Waterlogged soil. High admittance. Small Bowen ratio. Reduced albedo.

Figure 26 Definitions of LCZ classes (Stewart & Oke, 2012a)

6.2. LCZ classification Results

Submission information

- Continent: Africa
- Country: Uganda, Republic of
- City: Kampala
- Reference:
- Remarks:
- Representative date: 2021-01-08
- Submission date: 2021-01-10 15:22
- Software version: 0.0.0b5

LCZ class	Count	Avg. area (km2)	Total area (km2)	Perimeter (km)	Shape	Vertices
2	6	0.22940089694387034	1.376405381663222	1.9471275449597465	1.4408973509091345	6.6666666666
3	18	0.5318789144855012	9.573820460739022	2.831911090433066	1.3163884781568262	6.444444444444445
6	19	1.2860293652022112	24.434557938842012	4.3262863768367605	1.2987489124537681	6.684210526315789
7	15	0.3113579838109353	4.67036975716403	2.286951236223427	1.4586022851757934	10.4
9	20	1.4001405345365348	28.002810690730694	4.739801139716369	1.3626427922333009	4.2
10	7	0.761154221157445	5.3280795481021155	4.180038499059548	2.16707911543431	13.285714285714286
11	5	9.772685935337247	48.86342967668624	12.337351125834564	1.33205512993679	4.0
12	14	1.5011044628494385	21.01546247989214	4.865294116229328	1.3120287628262808	5.0
14	15	1.863938714269175	27.959080714037626	4.964982712873057	1.354223422683306	4.866666666666666
17	11	246.89449017030586	2715.8393918733645	57.56373552407911	1.331521935964977	5.363636363636363
19	16	7.995660530021032	127.93056848033652	12.179984500261412	1.8136672197433077	5.75

- ID: c2ac7ce8b901537962dbb597b2c72db009f9ca0e

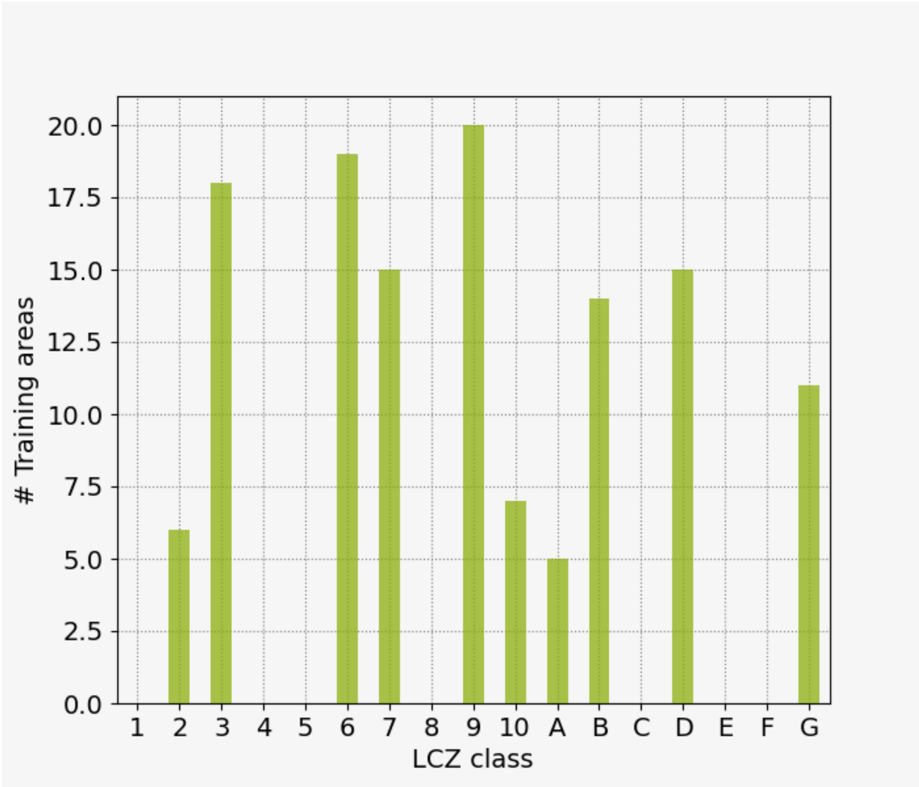


Figure 27 LCZ classes and training areas statitistics

The final filtered LCZ map is produced using all training areas and input features. Corresponding overall accuracies are:

- OA: 0.64
- OA_u: 0.71
- OA_{bu}: 0.85
- OA_w: 0.89

Here below the average confusion matrix over all bootstraps.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Total	UA (%)
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
2	0.0	23.0	2.0	0.0	0.0	0.0	12.0	0.0	0.0	11.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	48.0	47.9
3	0.0	5.0	171.0	0.0	0.0	139.0	28.0	0.0	1.0	23.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	367.0	46.6
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
6	0.0	0.0	59.0	0.0	0.0	190.0	2.0	0.0	10.0	13.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	274.0	69.3
7	0.0	17.0	11.0	0.0	0.0	4.0	175.0	0.0	0.0	27.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	234.0	74.8
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
9	0.0	0.0	0.0	0.0	0.0	60.0	0.0	0.0	356.0	0.0	6.0	53.0	0.0	55.0	0.0	0.0	0.0	530.0	67.2

10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	53.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	53.0	100.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	113.0	0.0	1.0	184.0	0.0	82.0	0.0	0.0	0.0	380.0	48.4
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	2.0	0.0	27.0	0.0	94.0	0.0	0.0	0.0	128.0	73.4
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	113.0	113.0	100.0
Total	0.0	45.0	243.0	0.0	0.0	393.0	217.0	0.0	485.0	129.0	7.0	264.0	0.0	231.0	0.0	0.0	113.0	2127.0	
PA (%)		51.1	70.4			48.3	80.6		73.4	41.1	0.0	69.7		40.7			100.0		63.9

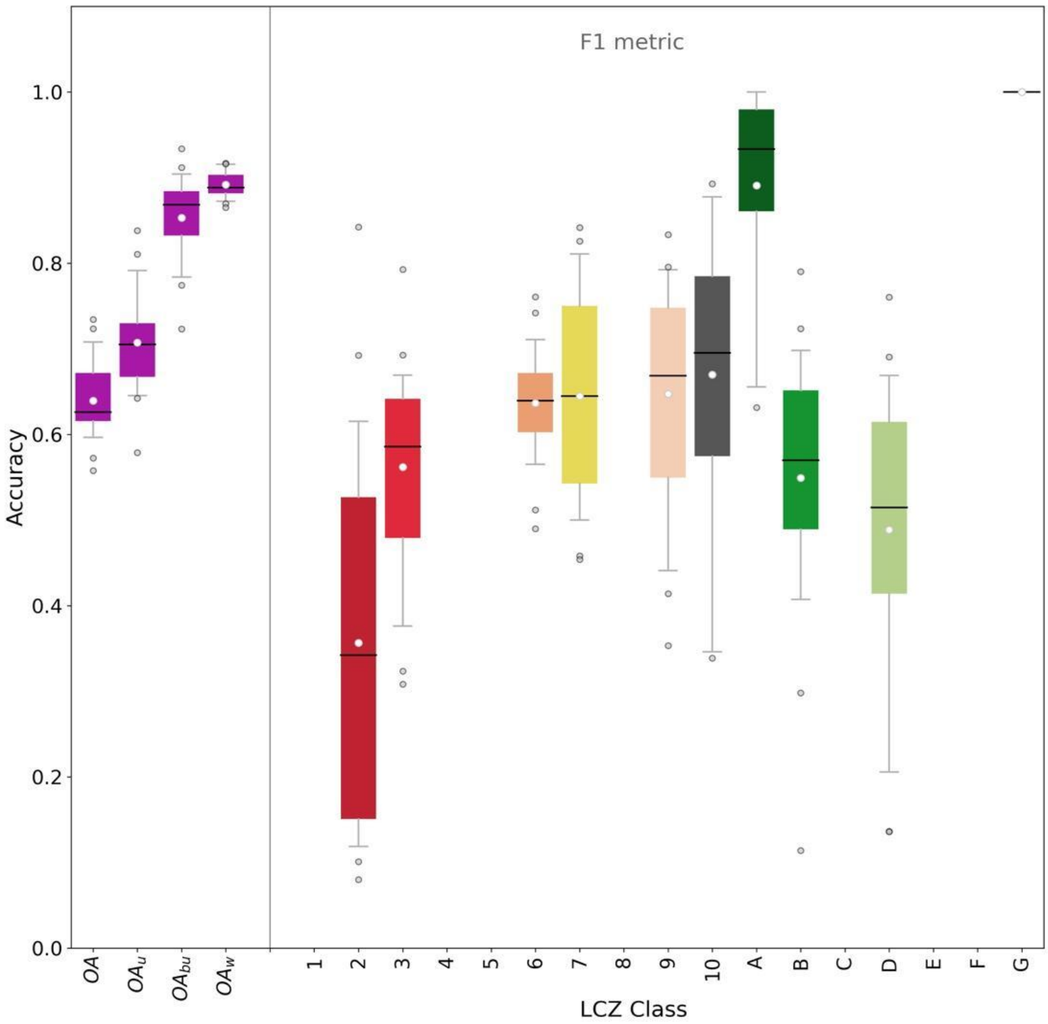
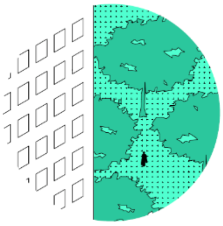


Figure 28 LCZ classification: the boxplot figure with accuracies.

Additional datafiles like the original training areas and suspicious training areas (polygons/points) are also available on request.

6.3. Strategies for cooling cities



PARKS AND OPEN SPACES

LOCAL URBAN GREENING

Local urban greening involves the increase of the presence of midsize parks inside the urban area to provide areas of thermal comfort for leisure and recreation. They are commonly located close to residential areas or along sea shores with a compact or linear shape.

UHI & OTC effect
Urban greening in local contexts are expected to provide thermal comfort within them, but little effect is expected far away from their boundaries. The combination of vegetation, shadowing and adequate ventilation can increase significantly the outdoor thermal comfort with respect to the nearby artificialised area.

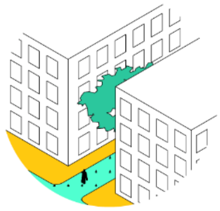
Tropical climate
Similar to other vegetation strategies, the shadowing effect of local urban greening can be used with clear benefits in thermal comfort. In humid tropics mostly all year through, the vegetation is in suitable condition to provide benefits of thermal comfort.

Urban planning
The implementation of local urban greening should be carefully considered and in relation to the urban extension. These areas should be considered as providing thermal comfort inside them. They could be developed within specific urban development guidelines that enforce their presence in every new planning/project.

State of the art
The performance of these parks is similar to big nature parks, but their effects are expected to be more localised. Numerous studies have proven their benefits (Robitu et al. 2006; Feyisa et al. 2014; Klemm et al. 2015).

PARKS AND OPEN SPACES

MICROSCALE URBAN GREENING



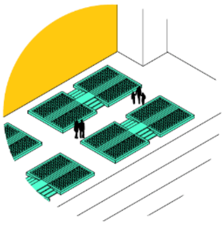
Microscale urban greening can be used to increase small vegetation presence inside the urban area. In addition to having vegetation around buildings, other uses can be pocket parks and green courtyards.

UHI & OTC effect
Despite the benefits on OTC can only occur in a small area when implemented adequately and/or interconnecting different microscale greening along the city, the effects on UHI could actually increase.

Tropical climate
Similar to other vegetation measures, the shadowing factor presents clear benefits in improving OTC. Additionally, it can prevent the overheating of surface materials.

Urban planning
There can be two kinds of implementation: first, in developed areas where urban retrofitting is possible to improve the thermal comfort along pedestrian paths and in other pedestrian areas; second, in new urban areas to interconnect parks and bigger vegetation areas to create suitable thermal comfort pathways along the whole urban area.

State of the art
A study compared two streets in Rio De Janeiro, Brazil where one had aligned trees and the other no trees. The results showed that 69 per cent of the people surveyed had a neutral thermal sensation on the street with trees while fewer people (18 per cent) experienced the same sensation on the street without trees (Drach et al. 2014). The finding was that the number of people with discomfort increased significantly on the street without trees and vegetation (microscale greenery).



PARKS AND OPEN SPACES

URBAN FARMING

Urban farms concern the practice of growing or producing food within urban areas. It can be installed in under-utilised urban spaces including rooftops, abandoned buildings and vacant lots. Urban agriculture has different climatic opportunities and constraints compared to rural agriculture that need to be understood.

UHI & OTC effect
Urban farms can serve as green islands within the urban landscape that can offer shade and protect impervious surfaces from the effects of solar radiation. Like other urban greenery, urban farms can produce similar local thermal comfort benefits and if highly extended to a relevant part of the urban area, it can lower the UHI effect and thus reduce building energy consumption for cooling.

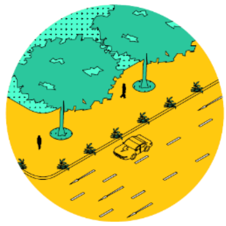
Tropical climate
The climate in Singapore is conducive to integrating urban farming within urban areas due to the frequent rain precipitation. This makes water access possible, which makes the implementation affordable, possibly even more effective than in other regions of the world.

Urban planning
Urban farming presents many benefits and opportunities, particularly to Singapore. It helps to green the city, increase the amount of food grown and produced locally, thus preventing CO2 emissions in food transport from distant producers, and improving food security for this land-scarce island city. Suitable building codes, guidelines for new/retrofit areas and/or economic policy can help develop green farming spaces.

State of the art
The thermal comfort and UHI benefits of urban farming could be similar to other mitigation measures based on the extension of vegetation elements inside the urban area. Additionally, the production of crops could be likely supported in cities with appropriate microclimate combined with UHI effects that would not grow successfully if these extra warming would not occur (Waffle et al. 2017).

GREEN CORRIDORS

TRANSPORT CORRIDORS



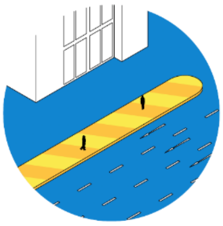
The vegetation arrangement along transport corridors can provide shade to the infrastructure surface. The effect can vary depending on the vegetation density, height and species. But it is also key to combine the reduction on incoming solar radiation with the natural ventilation capacity of these spaces.

UHI & OTC effect
Vegetation can absorb incoming solar radiation and thus reduce heat accumulation in urban materials. At the same time, it provides shadowing (in the case of trees). Thus, considering local pedestrian OTC, an increase in the number of trees makes sense. However, transport corridors are often open spaces that can be used as ventilation paths to introduce fresh air into the urban area and/or help remove the accumulation of heat. Thus, these transport corridors should be carefully designed with respect to UHI and OTC.

Tropical climate
Adequate use of transport corridors can be useful in reducing the heat trapped in the urban surfaces in the whole urbanised area of Singapore.

Urban planning
In planning for arranging vegetation along transport corridors, the exposure to direct solar radiation and wind enhancement should be considered carefully. A combination of different heights of vegetation elements together with their strategic location can allow for suitable airflow inside the transport corridor and thus pose higher benefits for this mitigation measure. These planted trees along ventilation areas should not form dense windbreaks.

State of the art
It is important to be aware that good ventilation leads to positive effects in terms of temperature and air quality (Ng and Ren 2015). Additionally, cooler surfaces with low roughness such as grass may allow air to move gently along corridors, thus avoiding turbulent vertical air movements produced by hot surfaces.



STREETS AND OPEN SPACES

COOL PAVEMENTS

Cool pavements are made of materials that reduce their surface temperature by reflecting a significant percentage of solar radiation and releasing thermal heat into the environment. These surfaces are usually a light colour, or white.

UHI & OTC effect
Cool pavements are characterised by high albedo (high solar reflectance) and high thermal emittance. Consequently, this reduces the urban heat accumulation responsible for UHI phenomena, especially in hot climates. However, this measure could worsen local OTC. The main positive effects of these materials are two-fold: one, reducing solar radiation absorbed by the pavements during the day, and two, releasing absorbed thermal heat into the atmosphere readily.

Tropical climate
This measure has special significance for Singapore because of the elevated position of the sun throughout the year, and the potential for lowering the outdoor temperature to improve liveability in the city.

Urban planning
Cool pavements could be obtained by implementing lighter coloured asphalt on streets and roads and also by the use of cool tiles or special coatings on urban pavements. An incorrect implementation of this measure, especially in high urban density areas such as urban canyons, could cause outdoor visual and thermal discomfort for pedestrians and drivers as well as an increase of cooling loads in surrounding buildings. Nonetheless, cool pavements could be developed in both public and private spaces.

State of the art
Conventional dark pavements absorb 80-95 per cent of sunlight, and thus show higher surface temperatures compared to cool pavements. The heat accumulated by the pavement surface throughout the day is then released into the air when the sun goes down and can affect urban night temperatures. This results in a warming of the surrounding air, and a contribution to the UHI effect (US Environmental Protection Agency 2008). Cool pavements, on the other hand are able to keep urban temperatures lower overnight (Asaeda and Ca 1993; Santamouris 2013). Other studies have also investigated the benefits of cool pavements using different high-albedo materials (Santamouris 2016) and the effect of ageing phenomena on their performance (Kyriakodis and Santamouris 2017).

BUILDINGS

RETRO-REFLECTIVE MATERIALS

Retro-reflective materials are directionally reflective surfaces (non-diffusive surfaces) characterised by high albedo and the ability to reflect solar radiation back towards its source.

UHI & OTC effect
Retro-reflective materials contribute to the mitigation of extreme local overheating and UHI effects by lowering building cooling loads and electricity consumption (Synnefa et al. 2006). The decrease of building and urban surface temperatures, and consequently urban ambient temperatures, influence pedestrian thermal comfort in a positive way.

Tropical climate
This measure has a large potential benefit in Singapore because of the sun's intensity and the significant demand for resultant cooling.

Urban planning
Suitable applications in dense urban environments need to consider the negative effects such as overheating and glare in nearby buildings. Implementation should be focused on roofs, façades, and pavements paying attention to the directionality of the reflected radiation.

State of the art
Innovative technologies, policies and programs have been established internationally to encourage the use of such a solution for its effectiveness when applied within different climate boundary conditions (Akbari and Matthews 2012). The effect of directionally selective reflector materials on the decrease of buildings and urban surface temperatures and therefore on urban ambient temperatures has been largely demonstrated over the course of the years. They are able to maintain lower surface temperatures, around 45˚C, especially in extremely hot climate conditions compared to materials with low solar reflectance and thermal emittance (Parker and Sherwin 1998). The benefits deriving from their application over built urban surfaces can be accounted at single-building, inter-building, and global scale (Santamouris et al. 2001). At single-building level, annual energy savings up to 19 per cent were calculated for 14 kWh/m^2 of reflective roofs area in the metropolitan context characterised by a humid tropical climate (Xu et al. 2012). At inter-building scale (district scale), this solution can have a non-negligible positive impact on the local microclimate generating a strong reduction of the UHI phenomenon. Its application at a wider urban scale has the potential to improve the environmental air quality because less cooling energy demand means less power plant emissions released into the atmosphere (Rosenfeld et al. 1995).

SHELTER DESIGN

PERMANENT SHADING DEVICES

Permanent shading devices are solid and fixed structures. They are horizontal or vertical shades that protect people from harsh sunlight all day. Some types of fixed devices are urban pergolas, shade sails, framed canopies, shelters, or even solar cells applied on façades. They are mainly permanent structures.

UHI & OTC effect
Shading devices can control the intensity of solar radiation, but should not obstruct the breezeway and allow a refreshing sensation to guarantee comfort. The effect of this measure depends on the material, geometry, dimension and location of the device. It is imperative to study the sun-path to define the type and properties of the shading device.

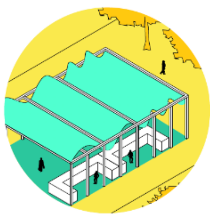
Tropical climate
Horizontal shading devices are especially important in Singapore to protect pedestrians and urban surfaces from the high sun angles during the solar noon. The size of the device can be determined by the shadow length needed.

Urban planning
Fixed devices can be applied to protect walkways, transport stops, park accesses, fixed urban furniture, or playgrounds. It is important that the design of fix shading devices can balance the amount of shade and natural light.

State of the art
Shading affects the experience and thermal perception of people in outdoor spaces. In hot and humid climates, it is key to assess the thermal sensation and adaptation of users in order to provide sufficient shading options. Emmanuel et al. (2007) studied the effect of urban shading in the tropics and concluded that horizontal shading is a necessary means to protect both pedestrians and urban surfaces especially around solar noon. The study also presents that shaded outdoor spaces can reduce the energy consumption of buildings. Nevertheless, Wong (2003) argues that while shading devices can give protection from solar radiation, they can also affect the availability of light and ventilation of urban spaces.

SHELTER DESIGN

MOVEABLE SHADING DEVICES



Moveable shading devices are operable, manual and automated shades. They allow users to adjust the spatial properties according to personal needs. Some types of mobile devices are autonomous canopies and temporary tents.

UHI & OTC effect
This measure fulfils similar purposes as the fixed shading device. It can adapt to the sky conditions, solar angle and time of the day, reducing direct sun exposure during extreme weather conditions. Additionally, it offers spatial and temporal flexibility, but is limited in the sense of dimension, material and durability. It can have a positive impact on the thermal comfort, especially in areas where permanent structures are not allowed or needed.

Tropical climate
Due to Singapore's proximity to the equator and the sea, its climate can vary within a day, offering clear or cloudy sky conditions. Therefore, moveable devices can serve as alternative shading structures that can adapt to the sun path, shading patterns and sky conditions to provide shading where it is needed at a particular time of the day.

Urban planning
Mobile devices are commonly light and simple to install. They can be applied in areas where additional shading is needed during the daytime, for example in parks, sports fields, or temporary public spaces. During night-time they can be removed. This allows flexibility and variety of shaded and sunlit areas all-day round.

State of the art
An option to improve the thermal comfort at street level is to modify the urban geometry by compromising the Sky View Factor (SVF). Instead, Swaid (1992) suggested having adjustable urban shading devices that can be attached to existing buildings when needed and retracted anytime. During day-time the street canyon can be reduced, providing more shading. This way the SVF during night-time will not be compromised, enabling sufficient ventilation. Moveable shading devices can adapt to different solar angles, providing shading where it is needed. Hyde (2000) recommends that horizontal shading devices be oriented towards the north and south, while vertical shading devices be oriented towards the east and west.

Figure 29 From the atlas of heat mitigation solutions. Source: (Ruefenacht & Acero, 2017)

6.4. LCZ and LST cross sections

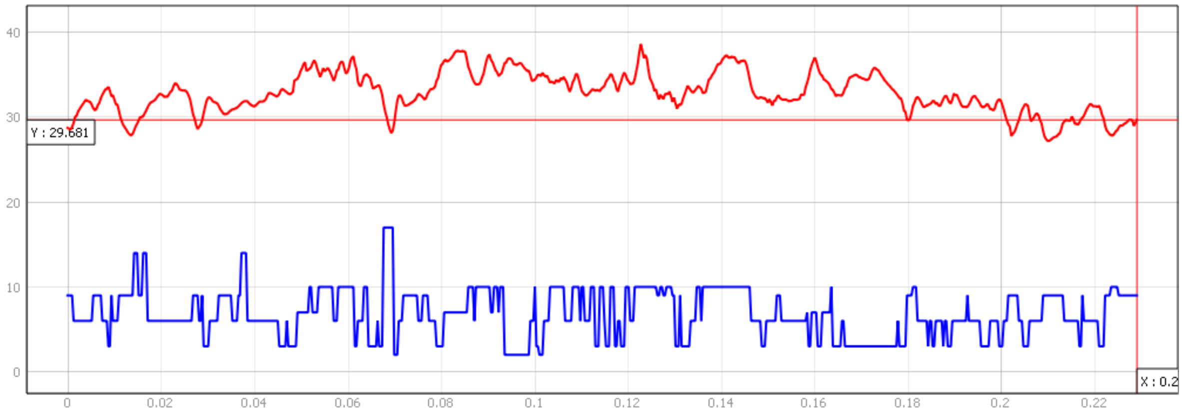


Figure 30 The cross section made for Kampala was generated using the Profile tool plugin QGIS. In red the LST variation, in blue the corrisponding LCZ classes.