The challenge of heat stress in urban areas: A case study in the Merwede Canal Zone, Utrecht

Adaptive cooling strategies to efficiently reduce the urban heat island effect for the Merwede Canal Zone in Utrecht.

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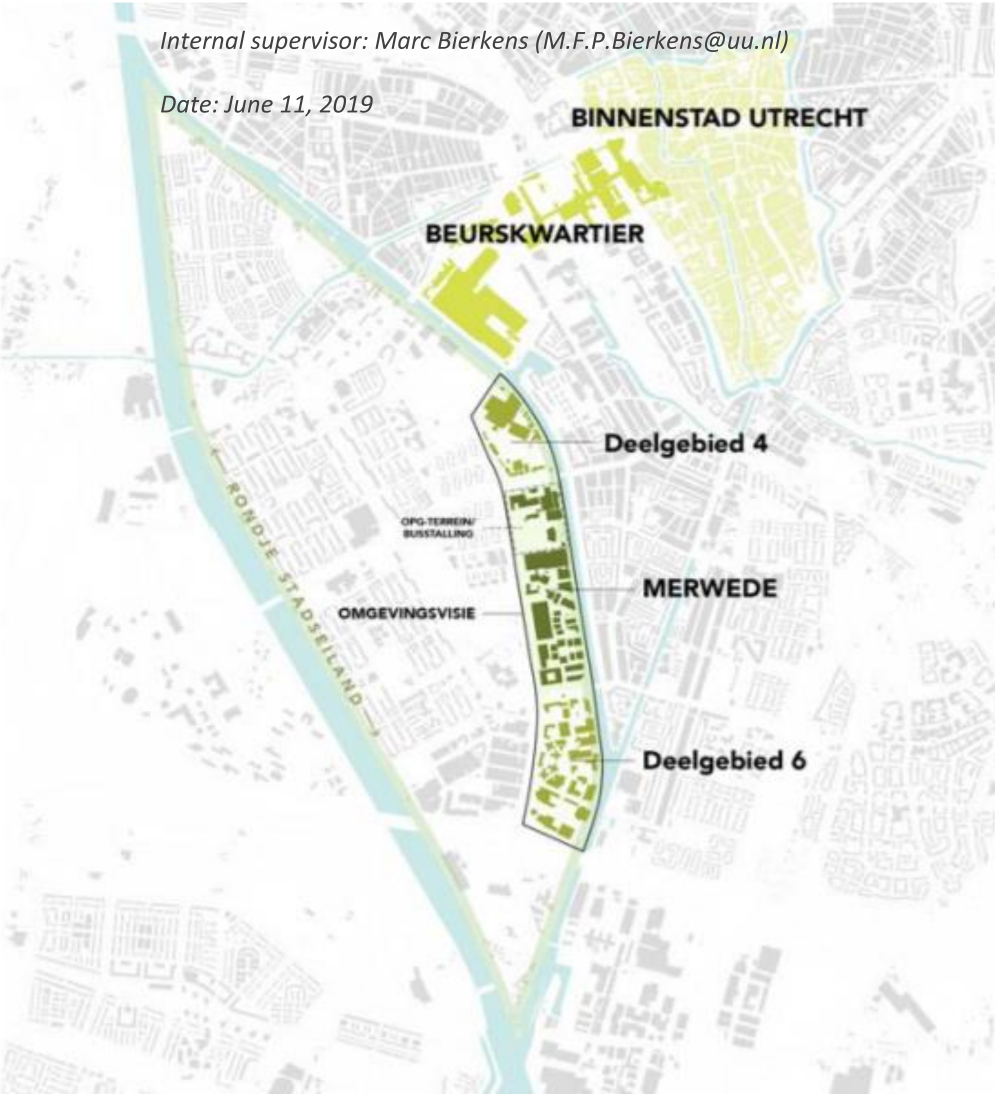

Abstract

Global warming has increased the global surface temperature with 0.8°C since pre-industrial values. The increase in surface temperature is not linear over time as two third of the warming has occurred since 1975. Moreover climate change is expected to increase both mean and extreme temperatures as heat waves become more intense, longer lasting, and occur more frequently.

Urban areas are more sensible to the temperature increase during heat waves due to the Urban Heat Island (UHI) effect. The UHI effect acts invigorative as temperatures in urban areas are significantly higher compared to rural areas. This effect is mainly due to urban characteristics; therefore this master thesis research project aims to efficiently reduce the heat stress in the Merwede Canal Zone in the city of Utrecht.

However there is no formal way to express heat stress in urban areas as there is no commonly used standard for heat stress. This research uses a new approach by the use of UHI_{24h} and UHI_{max}. The UHI_{24h} represents the average urban heat island effect over one day cycle (24 hours). Where, the UHI_{max} represents the massive heat at night which is the maximum value of the urban heat island effect in a 24 hour cycle. The heat stress in urban areas has been assessed by creating recommended scenarios with different adaptive cooling strategies. The different adaptive cooling strategies focus on the implementation of more green area and on changing the albedo of roofs, walls and roads. The adaptive cooling strategies are created within the UCAM (Urban Climate Assessment & Management) method which enables to simulate both the UHI_{24h} and UHI_{max} on a spatial scale.

The multiple adaptive cooling strategies are combined with an SCBA RAS (Social Cost-Benefit Analysis Rotterdam Climate Adaptation Strategy) in order to add a financial dimension to the strategies and to conclude which strategy is most efficient to reduce heat stress in urban areas.

This research showed that the implementation of green area mainly impact the urban heat island effect at night-time. While the implementation of different albedo types more likely change the urban heat island effect during the day. Hereby the most efficient strategy is the implementation of green measures as it is the most climate-robust solution which impacts on multiple levels at relative low costs. This research contributes to the current risk dialogue on what value is ''acceptable'' for heat stress as it uses a new approach with the use of two components to express heat stress in urban areas.

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1. Introduction

1.1 Background information

The global surface temperature has been increasing since the beginning of the last century. The NASA's Goddard Institute for Space Studies (GISS) conducted a temperature analysis to analyse the ongoing global average temperature increase (Hansen et al., 2010). Since 1880 the global average temperature has increased with 0.8°C, where two third of the warming has occurred since 1975 (Hansen et al., 2010). This implies that the rate of this increase is roughly 0.15-0.20°C per decade (Hansen et al., 2010). Moreover the rate of temperature increase nearly doubled in the last 50 years (Fig. 1). As climate change is a global concern the United Nations Framework Convention on Climate Change (UNFCCC) introduced the Paris agreement in December 2015. Here 195 UNFCCC members, including the Netherlands, have signed an agreement to undertake ambitious efforts to combat climate change and adapt to its effects (Schleussner et al., 2016). The central aim of this agreement is to limit the temperature increase well below 2°C above pre-industrial levels (Schleussner et al., 2016).

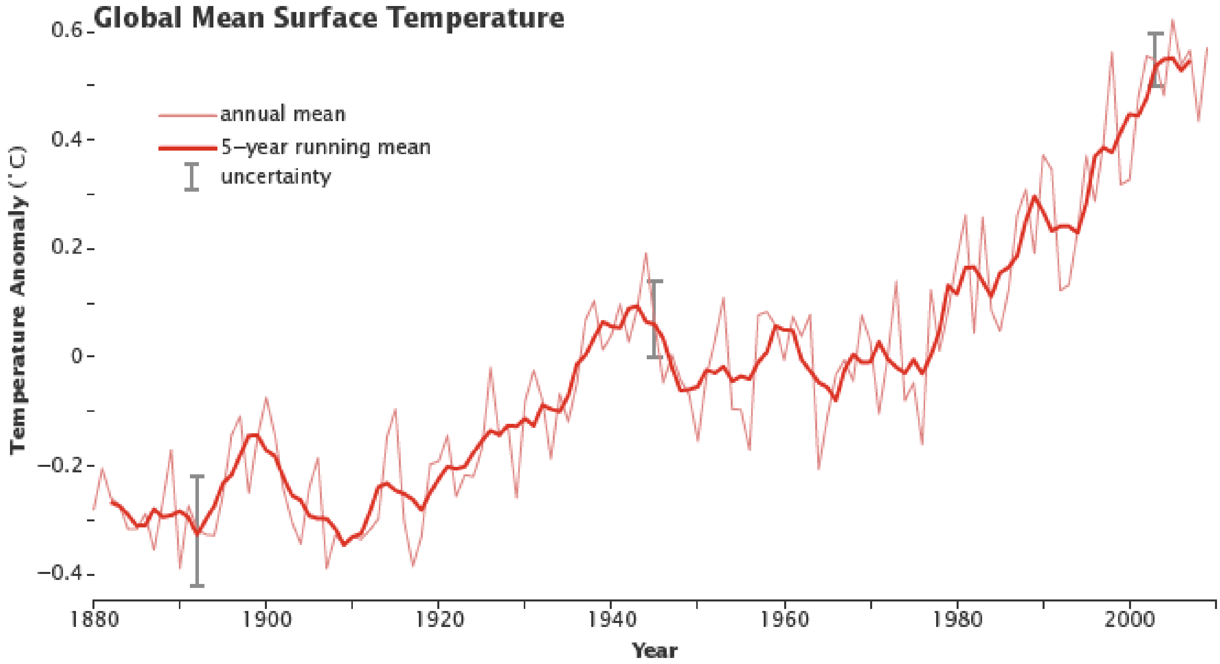

Figure 1: The increase in global mean surface temperature since pre industrial values (1880) up to 2010 (Hansen et al., 2010)

While a global temperature increase of 2°C may sound small, the impact on extremes is considerable. A global coupled climate model shows that there is a distinct geographic pattern to future changes in heat waves (Meehl & Tebaldi, 2004). Over the coming century, climate change is projected to increase both mean and extreme temperatures as heat waves become more intense, longer lasting, and more frequent (Hayhoe et al., 2009). Moreover heat waves are more intensive in urban areas compared to rural areas (Tan et al., 2010). This phenomenon is called the Urban Heat Island (UHI) effect (Fig. 2). This UHI effect causes temperatures in urban areas to be significantly higher than the temperatures in the surrounding rural areas due to the high density of buildings and material which absorb the heat and emit as long wave radiation (Rovers et al., 2014) (Fig. 2).

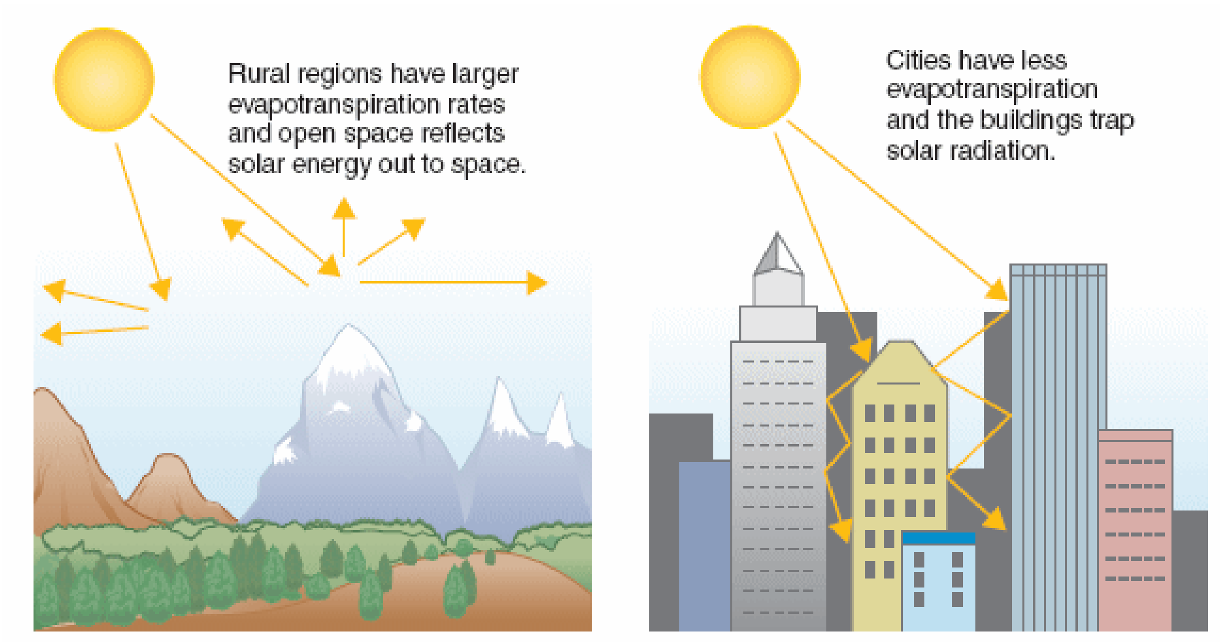

Figure 2: Visualization of the urban heat island effect (Adhikari, 2018)

The Netherlands created the Delta Plan on Spatial Adaptation (DPSA) to reduce the impacts of extreme climate events such as heat waves (Deltacommissaris, 2017). This delta plan has agreed on the fact that the Netherlands should be water-robust and climate proof by the time of 2050. The DPSA consists of four components: waterlogging, heat stress, drought and urban flooding. By 2019 every municipality has to carry out at least one climate stress test to visualize the vulnerability and bottlenecks with regards to extreme climate events.

The component heat stress has been underexposed with regards to other climate stress tests in terms of information, standards and labels. This is mainly due to the low level of urgency awareness of this component (Deltacommissaris, 2017). Therefore there is a great misunderstanding on the currently used heat stress maps as heat maps have different standards and use different methods to visualize the heat stress in the Netherlands. The standards to build a heat stress map are not based on strictly defined metrics, which creates a high level of uncertainty.

This research will focus on the component heat stress and aims to develop the most efficient adaptive cooling strategy for the Merwede Canal Zone (MWCZ) in Utrecht. The MWCZ is a suitable case study area for this research as it placed within the inner city of Utrecht and therefore characterized as urban area. As such, this research contributes to the current risk dialogue on what value is acceptable to build an adaptive cooling strategy in the Delta Plan on Spatial Adaptation.

1.2 Problem description

The UHI effect enlarges the total heat captured within urban areas as the heat, especially during heat waves can be captured in cities between the buildings which leads to less cooling of the living area on street (Kleerekoper, 2016). This effect accelerates the negative consequences of heat waves on human health as people tend to sleep less and are not be able to recover in the heat (Kleerekoper, 2016). Moreover, heat waves can become a serious problem concerning human health as heat waves are strongly related to the number of deaths (Garssen et al., 2005). The mortality is normally below average in summer and well above average in winter. But during the heat wave of 2003 was reversed (Fig. 3). During the 2003 Dutch heat wave mortality varied in parallel with temperature and peaks during the warmest days (Fig. 3). This shows that extreme temperature events can have substantial impacts on society.

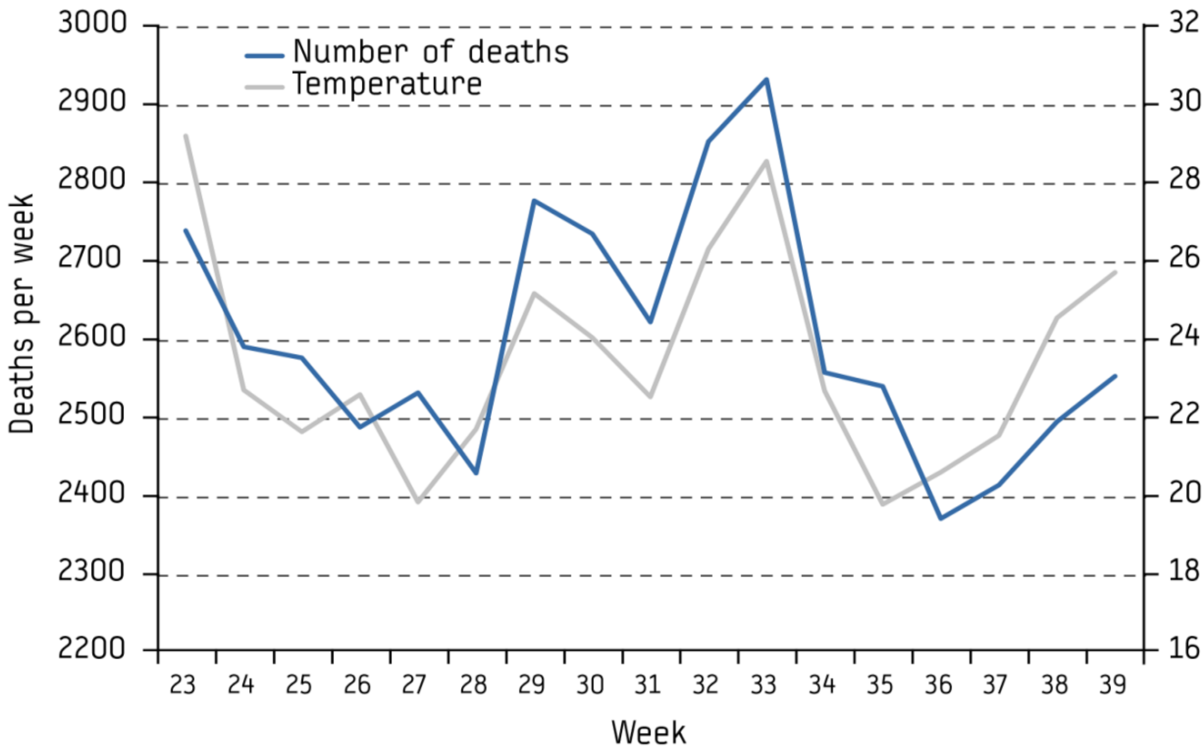

Figure 3: Mortality and average maximum temperature per week in the Netherlands from June to September 2003 (Garssen et al., 2005)

1.3 Research gap

In general, there is not a lot of research done to calculate the heat stress in urban areas or to create adaptive strategy plans in the Netherlands. The study of Kleerekoper (2016) aims to design an urban adaptation strategy for specific Dutch neighbourhoods in terms of outdoor thermal comfort and water management (Kleerekoper, 2016). The main finding of this research is that it proposes adaptive measures for the seven most common neighbourhood typologies. Hereby, urban areas can benefit from improvements in thermal comfort and energy systems (Kleerekoper, 2016). The study of Kleerekoper (2016) is relatively complete but it is not related to the effect of specific measures on the urban heat island effect.

The research done by Royal HaskoningDHV (RHDHV) for the Merwede Canal Zone is to some extent limited (Dolman & Groen, 2018). RHDHV researched the amount of heat stress in this area and created a map to visualize the heat stress for the current situation/optimized situation (Dolman & Groen, 2018). However the research gap within the project of RHDHV is that there are no multiple adaptive cooling strategies to see which measure is most effective to reduce heat stress (Dolman & Groen, 2018). This research contributes to the research gap as it will identify which adaptive measures are the most effective to reduce heat stress for this study area. Moreover this research is not only based on the daily mean urban heat stress but also amplifies the maximum values of the urban heat island effect.

1.4 Aim of this research and research questions

The main objective of this research is to quantify the amount of heat stress and to devise adaptive cooling strategies to efficiently decrease the amount of heat stress in the Merwede Canal Zone of Utrecht.

In order to reach this objective the following research questions and sub questions need to be answered:

The over-arching research question is:

> What is the most efficient adaptive cooling strategy to reduce heat stress in the Merwede Canal Zone (MWCZ) of Utrecht?

In order to answer the research question the following sub-questions are defined:

- What adaptive cooling strategy is most effective to reduce heat stress?
- What makes an adaptive cooling strategy efficient?
    - What are the costs and benefits for the different adaptive cooling strategies?

2. The theory of heat stress and definition of the study area

2.1 The Merwede Canal Zone

The Merwede Canal Zone (MWCZ) is part of the city Utrecht in the Netherlands. It is located southwest of the inner city of Utrecht (Fig. 4). The Merwede Canal Zone is divided into three parts: subarea 4, 5 and 6. The spatial scope of this research is limited to the subarea 5, which is denoted as ''the Merwede'' in Figure 4. The Merwede Canal Zone has a total area of 65 hectares, where 24 hectares are part of subarea 5 (Broekman et al., 2017). Utrecht has become one of the four biggest cities in the Netherlands due to extensive population growth. The population of Utrecht is expected to keep on growing from 340.000 inhabitants up to 410.000 inhabitants in 2030 (Gemeente Utrecht, 2017). It is important that Utrecht develops an efficient spatial strategy in order to facilitate the population growth of the city. The Merwede Canal Zone functions as an attractive spot to live/work and stay as it is close to the inner city of Utrecht (Fig. 4). Therefore the municipality of Utrecht commissioned an environmental assessment report (MER) in order to keep the attractiveness of the Merwede Canal Zone and to urbanize the city of Utrecht in in a sustainable way (Gemeente Utrecht, 2017). This makes the Merwede Canal Zone an interesting research area to assess the amount of heat stress for the current situation and to create adaptive cooling strategies to reduce the heat stress to acceptable levels. This heat stress assessment can be used as a solid basis to create an efficient and sustainable spatial adaptation strategy.

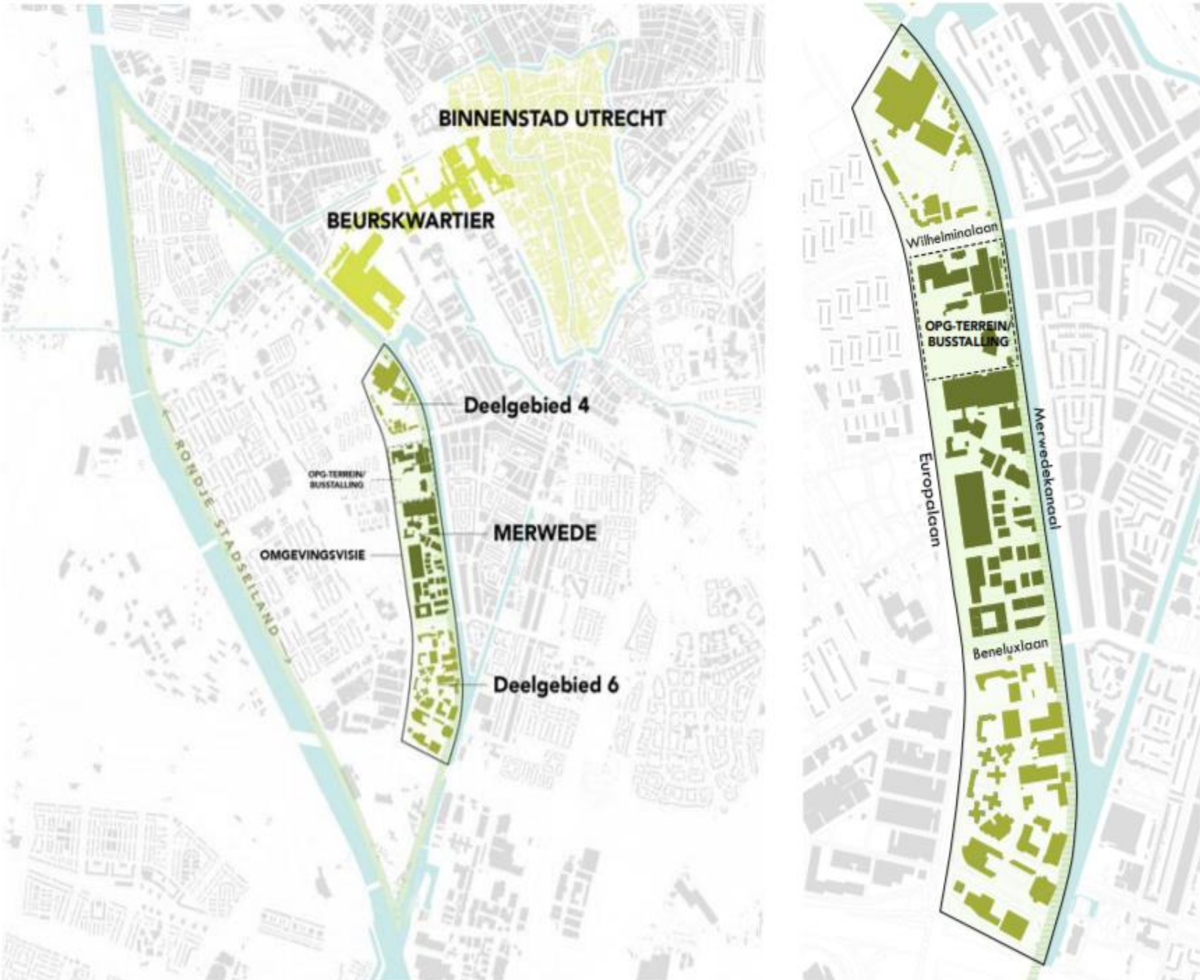

Figure 4: Location of subarea 5 (Merwede) in the Merwede Canal Zone (Broekman et al., 2017)

2.2 Heat stress in urban areas

2.2.1 The Urban Heat Island effect

There is no formal standard to express heat stress in urban areas. The discomfort of heat stress perceived by humans in urban areas is being caused by the urban heat island (UHI) effect. This research uses the UHI as an indicator for heat stress. The urban heat island effect is a relationship between the temperatures in urban areas compared to the temperatures on surrounding rural areas. The imbalance between the temperatures of rural/urban areas is caused by urban characteristics (Fig. 5). The relationship of the urban heat island effect is visualized in figure 5 and expressed by the following formula:

$$R_n + AH = R^{\downarrow}(1 - \alpha) + L^{\downarrow} - L^{\uparrow} + AH = H + LE + G$$

Equation 1: Surface Energy balance equation of the urban heat island effect (Ohmura & Raschke 2005)

Where:

R_n = Net radiation (W/m^{-2})
$R^{\downarrow}$ = Incoming shortwave radiation (W/m^{-2})
α = Surface albedo (-)
$L^{\downarrow}$ = Down welling long-wave radiation (W/m^{-2})
$L^{\uparrow}$ = Outgoing longwave radiation (W/m^{-2})
AH = Anthropogenic heat flux (W/m^{-2})
H = Sensible heat flux (W/m^{-2})
LE = Latent heat flux (W/m^{-2})
G = Thermal storage (W/m^{-2})

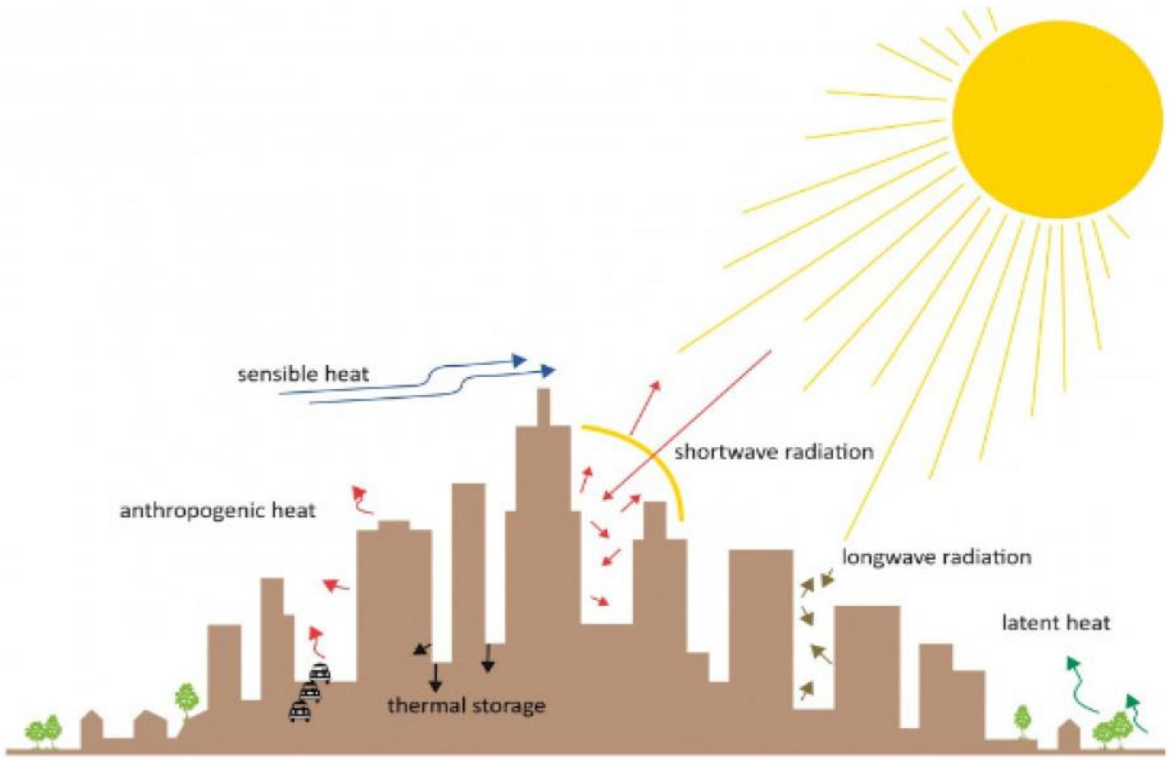

Figure 5: Visualization of the urban heat island effect with its radiative forcing terms (EPA, 2008)

The energy balance is different in urban areas than in rural areas due to multiple factors. Firstly the additional anthropogenic heat flux (AH) is higher in urban areas than in rural area due to more human activity in urban areas (Feng et al., 2012). The incoming shortwave net radiation ($R^{\downarrow}$) per area is the same for the urban area compared to the surrounding rural area. However the net radiation (R_n) may be different due to differences in albedo and outgoing longwave radiation (Fig. 5). This is mainly caused due to the adsorption and storage of heat (G) in buildings is larger which causes increasing heat release during the night and after a heat wave (Suomi, 2014). Moreover the limited evaporation (LE) forces the release of the net heat input (R_n + AH) to be in the form of longwave radiation ($L^{\uparrow}$) and sensible heat (H), which causes an increase in near-surface temperature in urban areas (Wong & Yu, 2005). As last, limited aeration between buildings increases the atmospheric resistance and consequently the surface temperature needed to achieve the required level of sensible heating (H) (Rajagopalan et al., 2014). These multiple factors combined cause that the temperature is significantly higher in urban areas than the temperature in rural areas, which is called the urban heat island (Fig. 6).

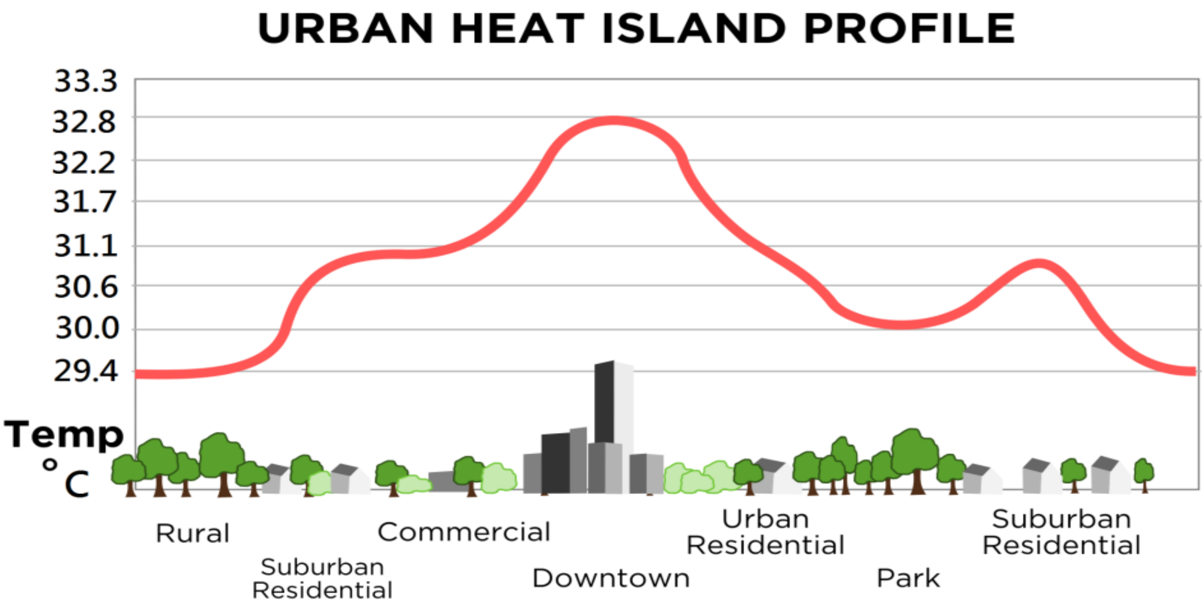

Figure 6: The urban heat island temperature profile (EPA, 2008)

The UHI effect combined with the occurrence of a heat wave can cause extreme temperatures within urban areas. There are three different types of UHI where can be focussed on (Rovers et al., 2014):

- The surface urban heat island, which is the difference in surface temperature between urban area and the surrounding rural area (Rovers et al., 2014).
- The atmospheric urban heat island, which is the difference in air temperature between urban area and the surrounding rural area (Rovers et al., 2014). This UHI effect can be categorized into two forms where:
  - The urban boundary layer UHI, where the urban heat island is based on the atmospheric boundary layer (ABL) above the city. The intensity is determined by its geographical position and the morphology of the city (Rovers et al., 2014).
  - The urban canopy layer UHI, which implies the urban heat island on the living level of the people. Within this layer the presence of buildings and trees have direct effect on the living level of the people on street (Rovers et al., 2014).

This research will focus on the urban canopy Layer UHI because this is the important factor for the quality of life as people live on street and houses (Rovers et al., 2014). The urban heat island effect has been caused by multiple components such as solar irradiation absorption, the lack of green measures, barriers in cities which block the wind, transport, heating and cooling systems and industrial activities (Kleerekoper, 2016). However the act of magnitude of these components to the urban heat island effect is different and is mainly due to two components: the lack of green measures and the adsorption of solar irradiation (Kleerekoper, 2016).

2.2.2 Temperature as an indicator of the urban heat island effect

The main parameter has to be quantified to tackle the problem of heat stress caused by the UHI effect. The main parameter is surface temperature and can be influenced by different sources. There are two main sources of heat within the UHI effect:

- Acute heat, which is the direct heat perceived by humans as apparent air temperature. This source of heat is mainly important during the day as the air temperature reaches its optimum at daytime (Dolman & Groen, 2018).
- Massive heat, which is the heat absorbed by buildings/paved area. This source of heat is mainly important during the night time as the surface air temperature drops and therefore the absorbed heat will be emitted by building/paved area (Dolman & Groen, 2018).

The two main sources of heat contribute differently to the urban heat island effect at different times of the day. Therefore it is important to address the 24-hour cycle of the UHI effect in order to better understand this phenomenon. The urban heat island effect starts building in the morning, where it slowly increases the temperature due to the net incoming solar radiation of the sun. The solar irradiation and temperature reaches its maximum at the afternoon, however this does not have a significant effect on the urban heat island as the temperature in rural areas reaches the same temperature as in urban areas.

The most important increase of the urban heat island effect kicks in during the late afternoon (~5-6pm) and holds throughout the night-time (Azevedo et al., 2016). This is due to the fact that temperature in rural areas cools down faster than the temperature in urban areas (Azevedo et al., 2016). This is mainly due to high heat capacity and high thermal conductivity of building materials/water bodies in urban areas (Van Hove, 2011). Urban areas have a higher thermal conductivity which absorbs more incoming solar radiation and emits longwave radiation (sensible heat) during the night (Suomi, 2014). This increased urban heat island effect holds the whole night until the early morning when the Urban Cool Island (UCI) kicks in. The UCI causes that temperature in urban areas during the morning is significant lower than temperature in rural areas (Theeuwes et al., 2015). This phenomenon is mainly due to the Atmospheric-Boundary Layer dynamics (ABL) (Theeuwes et al., 2015). The ABL is defined as the turbulent layer of the atmosphere closest to the Earth's surface (Stull, 1988). At night time the rural ABL cools and can be relatively shallow (±100m). While on the other hand the urban ABL is substantially deeper (±400m), because it remains supplied with emittance of heat which is stored in buildings during the day (Theeuwes et al., 2015). The difference in ABL causes a higher early morning heating rate over the countryside than over urban areas (Theeuwes et al., 2015). This results in higher temperatures during the early morning for rural areas than in urban areas which is called the UCI effect.

2.2.3 How to define heat stress with the UHI effect

The heat stress in urban areas caused by the urban heat island effect can have multiple impacts on society (Fig. 7). In total there are 24 consequences which are divided into 5 different themes: human health, network, water, liveability and outdoor space (Kluck et al., 2017). The scope of this research is limited to the pathway mortality within the theme of human health as this research will use this theme to make a risk label and set a standard on what is acceptable and what is risky in terms of heat stress (Fig. 7).

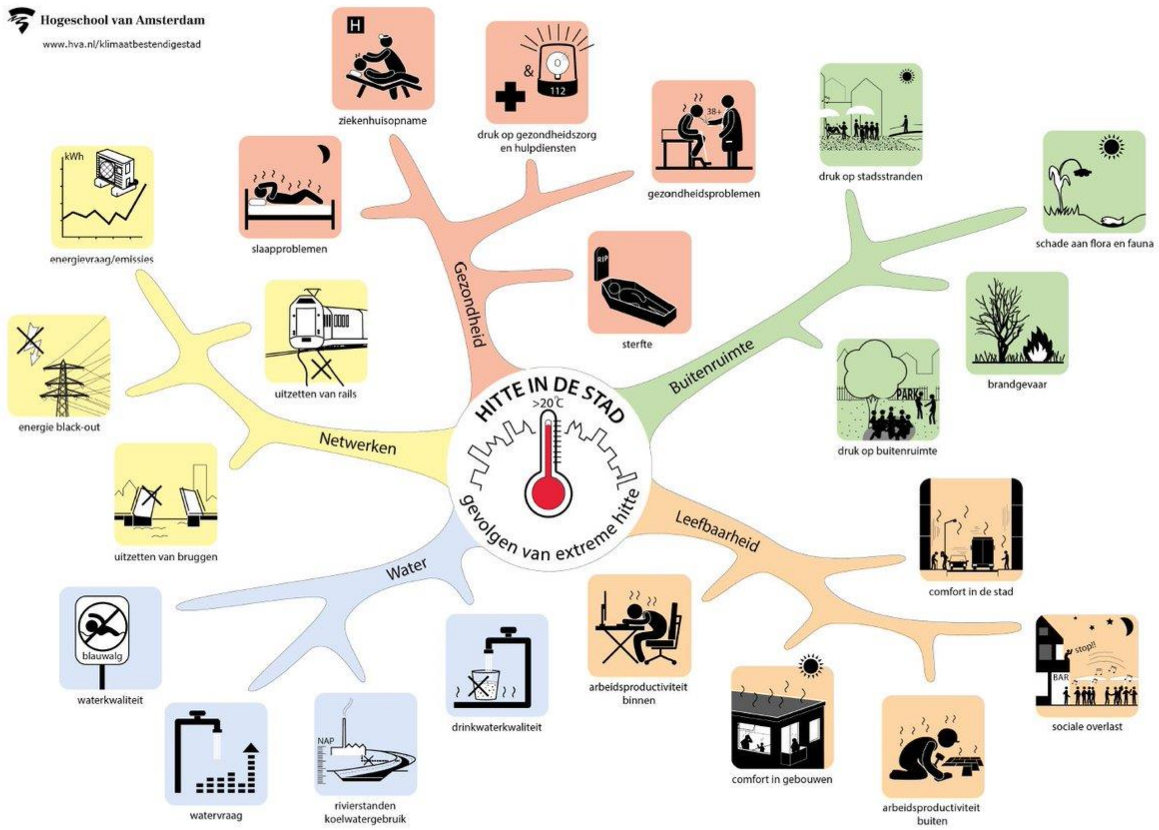

Figure 7: Mind map of the consequences of heat stress in urban areas (Kluck et al., 2017)

As shown in the introduction multiple standards are used to assess the risk of the urban heat island effect and currently there is no strict value on what is acceptable or risky. Within this research we use two different standards of the urban heat island effect to analyse heat stress:

- Daily mean heat stress (UHI_{24h}), which represents the average urban heat island effect of one day (24 hours).
- Massive heat stress (UHI_{max}), which represents the maximum value of the urban heat island effect with a 1-hour interval over a period of 24 hours (1 day).

2.2.4 Measures to reduce the urban heat island effect

The amount of heat stress in urban areas can be reduced by the use of adaptive cooling strategies. These strategies use three different types of measures to cool urban areas:

- By direct cooling through evaporation (''green'' measures)
- Reducing adsorption of radiation (albedo)
- Reducing the accumulation of heat (ventilation)
- Creating more shadow (blocking)

Reduction of heat stress by direct cooling indicates that green measures are introduced in the area. The implementation of green measures will cool the city in two ways. Firstly by blocking the incoming shortwave radiation from the sun that otherwise would have been absorbed by building/paved area (Wong & Yu, 2005). Secondly, urban trees cool the environment through evaporation and transpiration (evapotranspiration) (Akbari et al., 2001).

Another measure of direct cooling is to implement water bodies as water bodies can cool by evaporation; they absorb the heat which functions as a heat buffer. However not every water body has a cooling effect as it can contribute to the emittance of massive heat during night times (Kleerekoper, 2016). Therefore the construction of water bodies has to be done prudently. Water applications in general are more effective when they have a large surface, or when the water is flowing or dispersed (Kleerekoper, 2016). This is mainly to avoid extensive heating of the top layer of the water body. The effect of cooling by water evaporation depends on the airflow that replaces the cooled air through the city (Kleerekoper, 2016). Therefore implementing water bodies is not a simplistic measure to cool the UHI effect as it is depends on its scale, state and rate of flow (Kleerekoper, 2016). Thus, when implemented improperly water bodies can even contribute to the UHI at night (Steeneveld et al., 2011).

The next reduction of heat can be performed by changing the colour of the buildings. The colour of a building influences the albedo (%), because albedo is formulated as the measure of the diffuse reflection of solar radiation out of the total solar radiation received by an astronomical body (Taha et al., 1988). Short-wave radiation is absorbed in low albedo materials, while high albedo materials reflect the short wave radiation increasing the building albedo from 9 to 70% can reduce the annual cooling demand with 19% (Kleerekoper, 2016). The reduction of heat by ventilation can be done using more permeable materials. Permeable materials allow cooling by evaporation while hard materials accumulate heat (Kleerekoper, 2016). Therefore it is recommended to use light-coloured permeable materials if applicable.

The reduction of heat stress by blocking the incoming sunlight (creating shadow) can be done in multiple ways. As shown before it can be partly achieved by implementing trees which do not only cool by evapotranspiration but also creates shadow to its area (Kleerekoper, 2016). However the most important parameter in blocking the incoming radiation is the urban geometry (Kleerekoper, 2016). The urban geometry influences the incidence of incoming radiation on materials that can store heat and creates shadow between buildings/street surfaces.

The different measures taken to reduce the heat stress will not only decrease heat stress, but also influence the risk of flooding. As implementing green measures increases the infiltration rate of the area and therefore decreases the surface runoff in this area. Moreover, large water bodies can function as a buffer during extreme precipitation events where water can be stored ''safely'' instead of runoff from streets (Kleerekoper, 2016). The urban geometry plays an important part in distributing the large amount of water during an extreme precipitation event, where the geometry and altitude influences the runoff of the water on streets (Kleerekoper, 2016). Therefore in order to create a more adaptive climate strategy these impacts should be taken into consideration when implementing adaptive measures to reduce heat stress.

2.3 Hypothesis

The hypothesis of this research is that direct cooling through evaporation will have the largest effect on the reduction of the urban heat island effect. However, the implementation of green measures is expected to be very costly. Therefore I hypothesize that the most efficient strategy in terms of effect and costs will be a combined system with cooling through high reflectance materials (albedo %), ventilation and green infrastructure.

3. Methodology to calculate heat stress and its costs/benefits

3.1 The approach

The approach of this Master thesis research can be split up into two main parts. The first part is the spatial analysis with UCAM (Urban Climate Assessment & Management) which serves as input to the second part, the social cost-benefit analysis (Fig. 8). The UCAM-method has been developed by Witteveen & Bos, Wageningen University & Research (WUR) and KNMI (Groen et al., 2014).

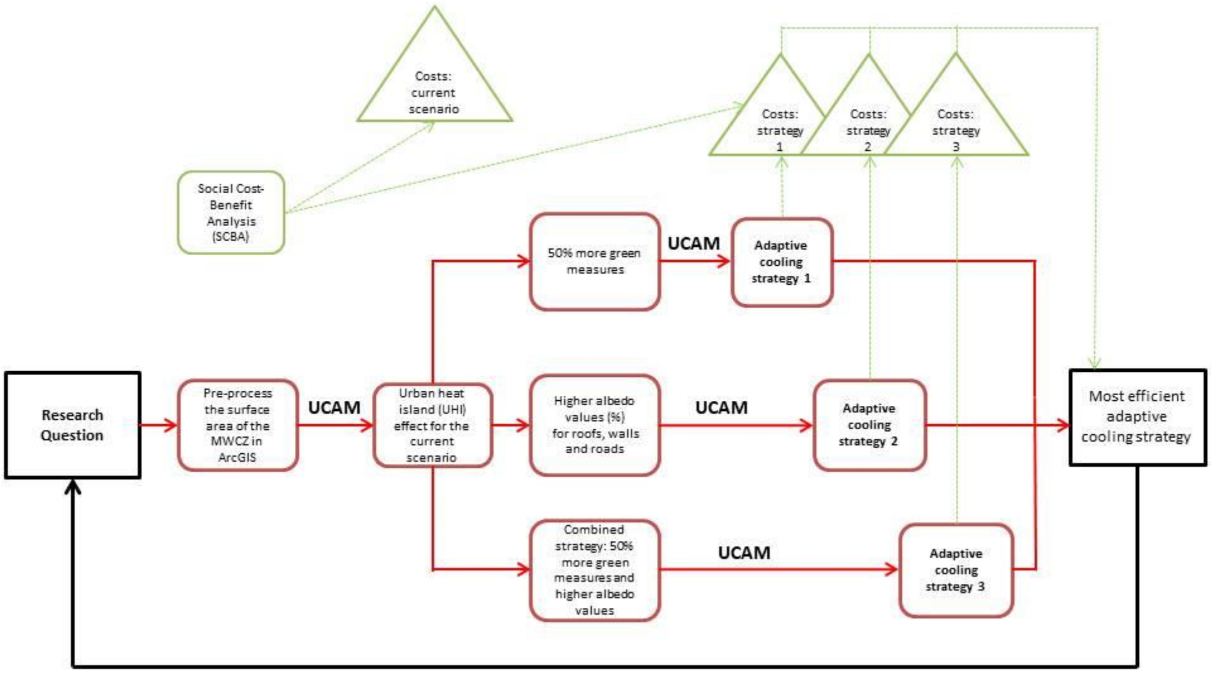

Figure 8: Flow chart of the approach which shows the three adaptive cooling strategies with its connection to the social cost-benefit analysis and the research question

Figure 8 shows that the social cost-benefit analysis is based on the output data of the spatial analysis with UCAM. The social cost-benefit analysis strengthens the results of UCAM by adding a financial dimension to the results. However, the spatial analysis with the UCAM-method is the most prominent analysis and the acts as the red thread within the approach (Groen et al., 2014). The UCAM-method has been chosen for this research because the model can provide a reliable estimate of the temperature in urban areas at limited calculation costs. Moreover the surface area can be adjusted in such a way that multiples adaptive cooling strategies can be implemented on a spatial scale to simulate recommended scenarios. The approach is to create four scenarios, which consist of three adaptive cooling strategies and a current situation. The adaptive cooling strategies will be based on the current situation as a reference situation (Fig. 8). In the end stage of this project the three strategies will be linked to costs and benefits to determine the most efficient adaptive cooling strategy to reduce heat stress.

3.2 Data collection

Two different types of data were collected in this Master thesis project: The data for UCAM and the data for the social cost-benefit analysis. The data for the UCAM-method consists of the surface area of the MWCZ, an Excel dataset with the calculations for the urban heat island effect and a raw data set of hourly temperature data. The raw data set of hourly temperature data came from the Weather Research and Forecasting model (WRF-model) study of the WUR. The Excel dataset to calculate the UHI effect is provided by Ronald Groen (RHDHV). All additional data used as input to create the different cooling strategies (e.g. albedo values of materials) were obtained from in-depth literature research.

The data for the cost-benefit analysis were partly obtained by doing a literature study on costs of adaptive measures and is structured in SCBA RAS (Social Cost-Benefit Analysis Rotterdam Climate Adaptation Strategy) Excel sheet for the MWCZ (Rebel et al., 2012). This Excel sheet was provided by Nanco Dolman, which contains the costs and benefits for several adaptive measures. Moreover this Excel sheet has been transformed in a sheet which can link the costs and benefits to the different types of surface area within the MWCZ. This Excel sheet was used to calculate the costs and benefits per hectare on the basis of the usage of certain heat stress measures per parcel in relation to the reference situation (e.g. % green).

3.3 The UCAM-method

The UCAM-method uses a raster grid of 100x100m (10.000 m^2) to cover the study area and divide the study area into smaller segments (Groen et al., 2014). In order to quantify the influence of urban characteristics on the UHI effect, the UCAM-method uses the classification system called Local Climate Zone (LCZ) (Stewart & Oke, 2012). With the use of advanced modelling software, the extra heat (UHI) can be calculated for the different LCZ's on the basis of different district types. The calculations done with UCAM are based on five different typical Dutch districts. The five district types are created on the basis of Dutch literature and cover practically all districts in the Netherlands (Fig. 9). The UCAM-method will assign a LCZ to each grid cell in order to get an idea of the urban characteristics of each grid cell (Groen et al., 2014).

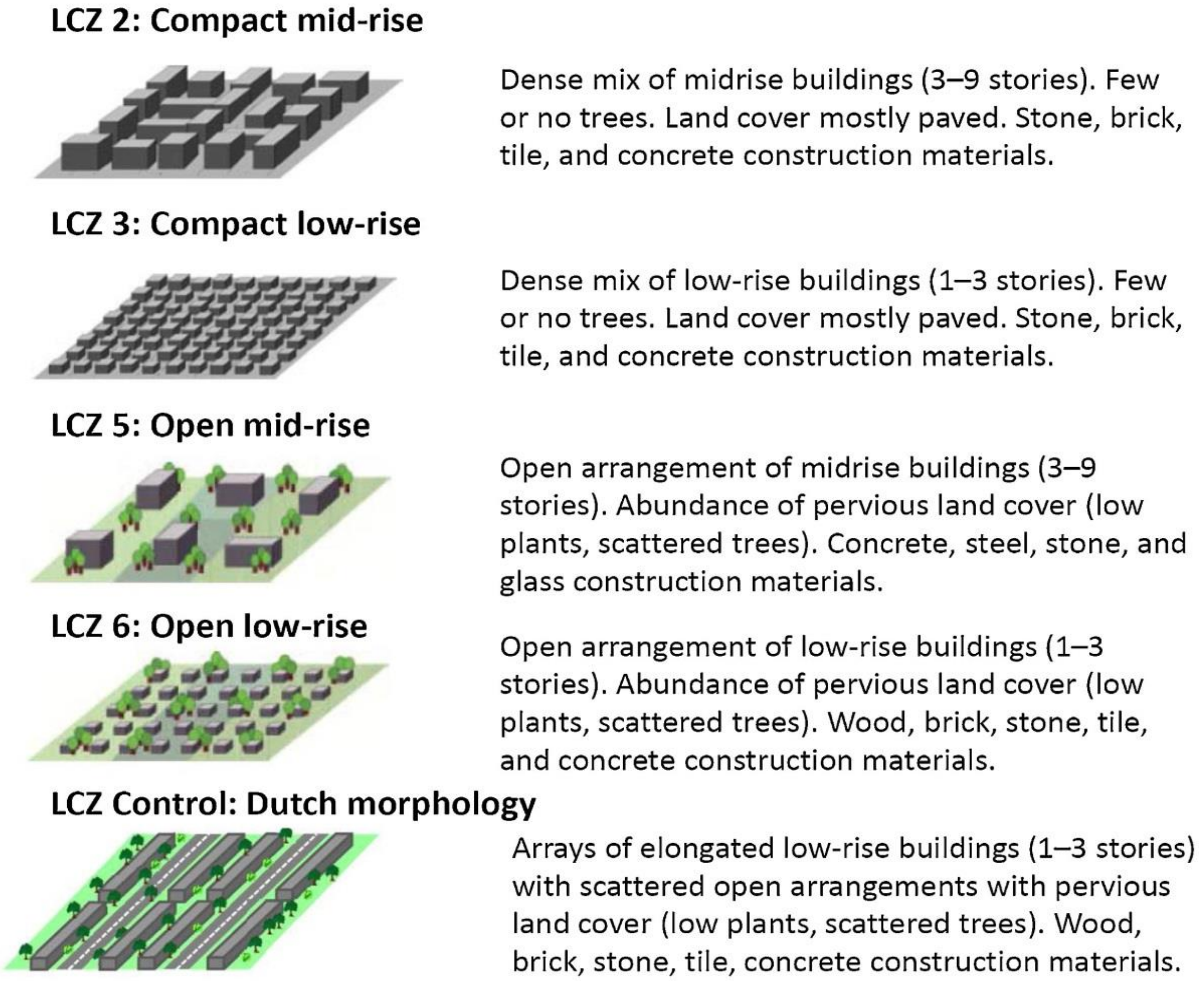

Figure 9: The five different LCZ types with it urban characteristics (Steeneveld et al., 2018)

The calculations and results of UCAM are based on an advanced model called Weather Research & Forecast (WRF). The Wageningen University and Research (WUR) performed simulations with the WRF-model to research the temperature profile during a specific Dutch heat wave (Steeneveld et al., 2012). Within the WRF-model five different district types (LCZ's) were modelled with the same weather conditions as the Dutch heatwave of July 2006 (19/07/2006). The simulations were done for varying building types and parameter values in order to validate the WRF-model and to quantify the urban heat island effect during a Dutch heat wave. The WRF-model provides a reliable estimate of hourly temperature data in urban areas during a heat wave. Moreover it can distinguish the different effects on rural or urban areas, which results in an absolute value of urban heat island per grid cell (Groen et al., 2014). The model simulations encompassed five heat wave days in total, where the first three days are a ''starting phase'' and the last 2 days were used for further analysis. For each simulation the value for the urban heat island effect was determined as the calculated temperature increase in the city relative to the temperature increase of the rural area. In total more than 1000 different model configurations were analysed to specify the heat sensitivity (Groen et al., 2014). The urban heat island sensitivities estimated from the WRF-model simulations are the basis of the heat assessment performed by UCAM to quantify the urban heat island effect for a specific area. Hereby the UCAM-model can simulate the temperature during a Dutch heat wave over the given area to get a 24-hour time-lapse with an interval of 1-hour and thereby be able to quantify a value for UHI_{24h} and UHI_{max}.

3.3.1 Adaptive cooling strategies

This research uses three adaptive cooling strategies in order to reduce the heat stress and is structured as follows:

- Adaptive cooling strategy 1 introduces a strategy which consists of increasing the percentage of green area (% green) by introducing more grassland, where all other values will be the same as the reference situation (current scenario). However green measures cannot be introduced everywhere as buildings, roads etc. have societal functions. Therefore we implement the green measures in the processed area with currently no function which is defined as ''Percentage other''. This area comprises of paved area which has no societal function and can be changed to a more green area without losing a societal function. Within this strategy 50% of the ''percentage other'' will be transferred into green area. The value of 50% is based on aerial photo interpretation.

- Adaptive cooling strategy 2 consists of a strategy where other materials and colours are used to reduce the percentage albedo of roofs, walls and roads, while all other values will remain the same as the reference situation. All the information of the available materials and colours with their corresponding albedo values has been addressed in literature and can be implemented within UCAM (Annex A). This strategy uses the highest albedo values for roof albedo (0.85), road albedo (0.50) and wall albedo (0.60) (Annex A). These values are implemented in every grid cell in order to decrease the urban heat island effect (Annex A).

- Adaptive cooling strategy 3 is a combined scenario of scenario 1 and 2 where both green measures and other materials are used to reduce the heat stress in the Merwede Canal Zone. Within this strategy the ''Percentage other'' is transferred into 50% more grassland area and the albedo values are: 0.85 for roof albedo, 0.50 for road albedo and 0.60 for wall albedo (Annex A).

The scope of research is limited to implement only green and albedo measures, because the lack of green measures and the adsorption of solar irradiation are the most prominent causes of the urban heat island effect (Kleerekoper, 2016). The implementation of water bodies has been excluded because the construction of water bodies is complicated and has to be done prudently to have positive impact on UHI effect. The implementations of large water bodies respond slowly to heating during the day, but also cool slowly due to its high thermal conductivity (Van Hove, 2011). Therefore large water bodies can support the UHI at night and reinforce the effect (Steeneveld et al., 2011). Current studies focus on how to successfully implement water bodies to cool urban areas; however this is out of the scope of this research due to its complexity.

3.3.2 Heat stress risk label for UHI_{24h}

As shows in Figure 7, heat stress can be linked to several consequences for human society. This research links the daily mean heat stress (UHI_{24h}) to mortality within the theme of human health (Fig. 7). In addition to the heat effects, the increase in temperature due to the urban heat island effect also support high atmospheric pollutant concentrations, in particular nitrogen oxides and ozone (Steeneveld et al., 2018). This research uses the excess risk (% mortality) of ozone as a threshold to estimate the risk of daily mean heat stress (UHI_{24h}).

The risk label for UHI_{24h} has been created in order to assess the urgency of a present value of UHI_{24h}. In order to provide the risk of UHI_{24h} a heat-index is determined. This heat-index is corresponds to a value between 0 and 1, where 0 indicates the lowest level of risk and 1 indicates the maximum risk. This factor is normalized over the maximum daily value of UHI_{24h} on the basis of the current simulated heat wave from WRF-model simulations, which is a maximum value of 3.3°C (Steeneveld et al., 2018). The risk labels are determined on the basis of amount of ozone in the air (in μg/m^3) in its relation to mortality. The European target value for ozone is 120μg/m^3, where the information threshold is 180μg/m^3 and the alarm threshold is 240μg/m^3 (Steeneveld et al., 2018). The amount of ozone for 120μg/m^3 is measured over an interval of 8 hours while the 180/240 μg/m^3 are measured over an interval of 1 hour (Gryparis et al., 2004). The difference of 60μg/m^3 between each threshold corresponds to an excess risk of approximately 1.9% as it is 0.31% for 1-hour ozone and 0.33% for 8-hour ozone per 10μg/m^3 (Gryparis et al., 2004). All the standard values are scheduled within table 1.

UHI risk over 24h (%/°C)	**Ozon 8h** (%/10ug)	**Ozon 1h** (%/10ug)	**Maximum daily value of UHI over 24h** (°C)
2,1	0,31	0,33	3,3

Table 1: Standard values to calculate the risk label for UHI_{24h} effect (Gryparis et al., 2004; see also Steeneveld et al., 2018)

To quantify the excess risk due to the urban heat island effect, we assume that mortality increases with 2.1% per °C (Steeneveld et al., 2018). To assess the excess risk of the UHI_{24h}, the risk due to the urban heat island effect (2.1% per °C) is determined corresponding to the excess risk of each threshold of ozone (approximately 1.9% per threshold). With these threshold values an excess level of risk can be determined with a corresponding value for UHI_{24h} (Table 2).

Category (-)	**Ozone** (μg/m^3)	**Method** (hours)	**Excess risk** (% mortality)	**Equivalent UHI_{24h}** (°C)
I	0	-	-	**0**
II	120	8h	((120-60)*0,31)/10 = 1,86	1,86/2.1 = **0,89**
III	180	1h	((180-60)*0,33)/10 = 3,96	3,96/2.1 = **1,89**
IV	240	1h	((240-60)*0,33)/10 = 5,94	5.94/2.1 = **2,83**

Table 2: Calculation of the equivalent UHI_{24h} (Steeneveld et al., 2018)

The value of equivalent UHI_{24h} (Table 2) leads to the following risk classification of UHI_{24h} (Table 3). The risk label can be used to make the value of the daily mean heat stress (UHI_{24h}) more tangible. The classification of risk for UHI_{24h} neglects the peak values of the urban heat island effect as it is the average value over 24 hours. Thus, this classification does not amplify the amount of massive heat which is absorbed by buildings and paved area during the day and emitted during night-time. In order to express this value we take the maximum value of each hour in the 24-hour cycles and create maps to show the peaks (maxima) of the urban heat island effect. However the UCAM-method works with raw hourly WRF data, therefore a trend analysis has been executed to validate the data per hour to get a realistic view of UHI_{max}. Both the daily average and the maxima values of heat stress maps are used to interpret how adaptive measures counteract the amount of heating during night-time (peaks) and during the day (average).

$UHI_{24h} < 0{,}89$ °C = Comfortable
UHI_{24h} 0,89 - 1,89 °C = Acceptable
UHI_{24h} 1,89 - 2,83 °C = Risky
$UHI_{24h} > 2{,}83$ °C = High risk

Table 3: Risk label for daily mean heat stress (UHI_{24h}) (Steeneveld et al., 2018)

3.4 The social cost-benefit analysis

The SCBA RAS calculation model is used to determine the costs and benefits for each adaptive cooling strategy (Rebel et al., 2012). This Excel sheet is able to define the costs and benefits for five different themes: Heat stress, flood risk, desiccation, water safety and accessibility. Within this Excel sheet we only use the theme heat stress and we select the measures which are used within each adaptive cooling strategy. The measures used are: implementation of public green parks (Merwede Park), more green area within the street (inner areas), adjusting material/colour use of streets and adjusting colour/structure of roofs. The costs and benefits of these measures are linked to the amount of hectares used within UCAM to determine the total amount of costs and benefits for this area.

The total amount of costs is determined by two variables: the investment costs and the maintenance costs. The total amount of benefits for heat stress is determined on the basis of multiple variables which are: residual value of investment, air quality, the value of housing and the effect on human health. Hereby the residual value is the calculated value which remains if the lifespan of a measure exceeds the timeframe of the SCBA (50 years). The total benefits with regards to air quality have been calculated by the avoided costs per kilogram for CO_2, particular matter (PM10) and NO_x. The value of housing has been accounted as an one-off increase per property. The effect of human health is a broad term and consists of three parameters: mortality, hospitalization and labour productivity (Rebel et al., 2012).

The SCBA RAS calculation model cannot predict the future; therefore two basic environment variables are used in the model: a climate scenario and a socio-economic scenario for the evolution of population and prosperity. The climate scenario used within this calculation model has been created by the Royal Dutch Meteorological Institute (KNMI). The KNMI created four climate scenarios for the Netherlands labelled as G_l, G_h, W_l and W_h (Klein Tank et al., 2014) (Table 4). Similar to the Dutch delta program the two most extreme scenarios (G_l and W_h) are used within the SCBA calculation to include climate change up to 2050 (Table 4) (Rebel et al., 2012).

Scenario code	Scenario	Toelichting
G_l	Moderate low	1°C global temperature increase up to 2050 relative to 1990 + no change in air flow patterns in West Europe.
G_h	Moderate high	1°C global temperature increase up to 2050 relative to 1990 + changing air flow patterns in West Europe (Winters become more soft and wet due to west wind and summer become drier due to more east wind)
W_l	Extreme low	2°C global temperature increase up to 2050 relative to 1990 + no change in air flow patterns in West Europe.
W_h	Extreme high	2°C global temperature increase up to 2050 relative to 1990 + changing air flow patterns in West Europe (Winters become more soft and wet due to west wind and summer become drier due to more east wind)

Table 4: Explanation of the four climate scenarios in the Netherlands up to 2050 (Klein Tank et al., 2014)

The economic scenario is based on a study of the Dutch Prosperity and Living Environment (WLO) (Janssen et al., 2006). They created four long term scenarios (GE, SE, TM and RC) for the socio-economic development in the Netherlands up to 2040 (Table 5). Hereby just as the climate scenario the two most extreme scenarios (GE and RC) are used within the SCBA RAS calculation model. These socio-economic scenarios are implemented within the calculations by adding input parameters, which consists of small price increases per year (Rebel et al., 2012). The population increase has not been implemented as input parameter within the SCBA RAS calculation sheet (Rebel et al., 2012). With two extreme climate scenarios and two socio-economic scenarios a total four delta scenarios can be used within the SCBA RAS calculation model.

Code	**Name**	**Population in 2040** *(million)*	**GDP/person 2040** *(2001=100)*
GE	Global Economy	19,7	221
SE	Strong Europe	18,9	156
TM	Transatlantic Market	17,1	195
RC	Regional Communities	15,8	133

Table 5: Explanation of the four socio-economic scenarios for the Netherlands in 2040 (Janssen et al., 2006)

Additional to the climate scenarios and the socio-economic scenario the SCBA also uses a discount rate to convert all future costs/benefits to their current or present value (Rebel et al., 2012). The discount rate has been used within the calculations because then all costs and benefits can be compared with each other on equal basis regardless of the time. The net present value can be calculated by using the following formula:

$$\mathrm{NPV} = \sum_{t=0}^{T} \frac{\mathrm{B}_t}{(1 + r^t)}$$

Equation 2: Formula for the net present value in relation to discount rate and time (Rebel et al., 2012)

Where:

NPV = net present value (€)
T = time frame over which investments are evaluated (e.g. depreciation time) (years)
t = time (years)
B_t = net benefits (€)
r = discount rate (-)

The Dutch Ministry of Finance determines the value of discount rate in the Netherlands. The imposed discount rate by the Ministry of Finance and which is used in the SCBA calculation model is 5.5% (Rebel et al., 2012). Moreover the SCBA calculation model uses a time frame of 50 years. However if the lifespan of a measure expires within 50 years then the measure is reinvested. On the other hand, if a lifespan is bigger than 50 years then a residual value has been determined on the end of the time frame. Hereby the total value of costs and benefits can be calculated over a time frame of 50 years for each adaptive cooling strategy.

4. Results

4.1 24-hour temperature and urban heat island cycles

The temperature cycle during the day shows how the temperature migrates throughout the day for the current situation, each adaptive cooling strategy and for the rural situation (Fig. 10). The consistent factor of each line is that the temperature increases the most during the day and cools during the night (Fig. 10).

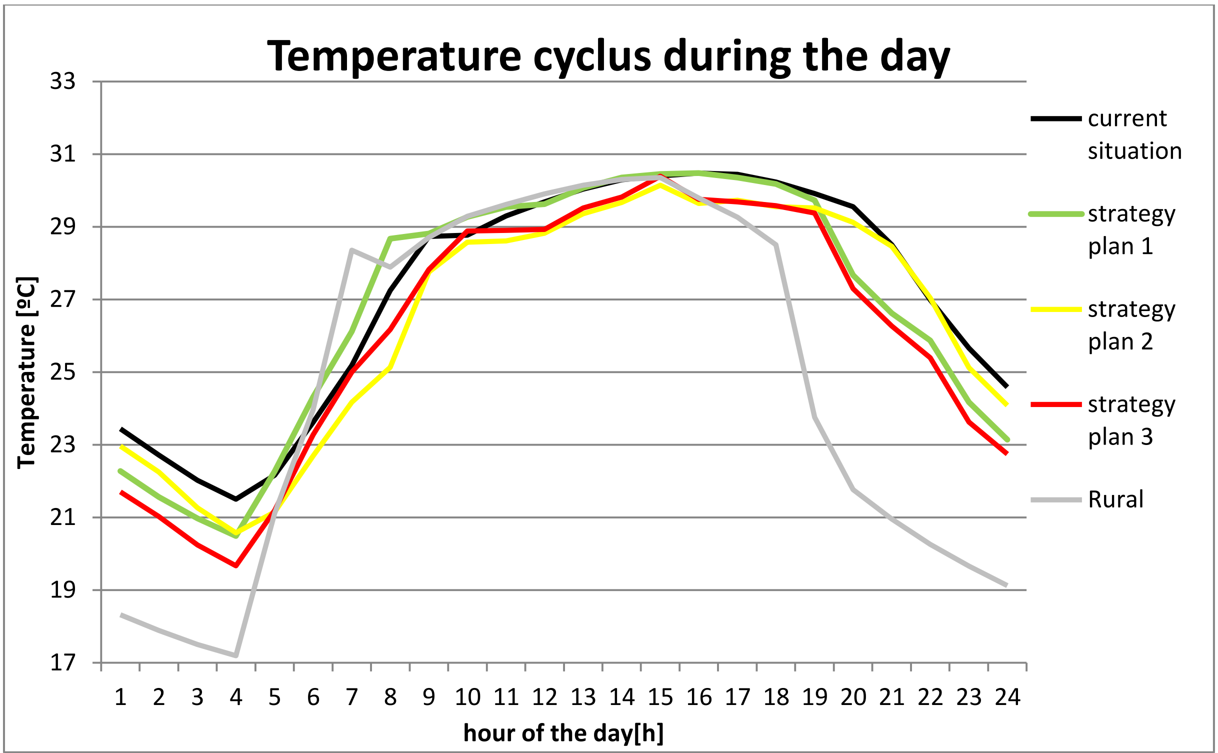

Figure 10: 24-hour temperature profile for each adaptive cooling strategy and rural situation

There are some differences in temperature within the different strategies/rural with regards to the current situation (Fig. 10). During the afternoon the decrease rate in temperature of the rural (grey) line is faster than for all urban area scenarios, resulting in the UHI effect (Fig. 11). This is mainly due to the fact that rural areas cool down faster than urban areas due to the emittance of sensible heat of urban areas at night-time (Rizwan et al., 2008). Figure 11 shows that the UHI effect is most prominent during night time (Fig. 11). Moreover the UHI profile is characterized by the Urban cooling Island (UCI) in the morning (~5-7 am) (Fig. 11). This effect is mainly due to the fact that the rural atmospheric boundary layer (ABL) is more shallow than the urban ABL, which results in a higher early morning heating rate over the rural area than over urban areas (Theeuwes et al., 2015).

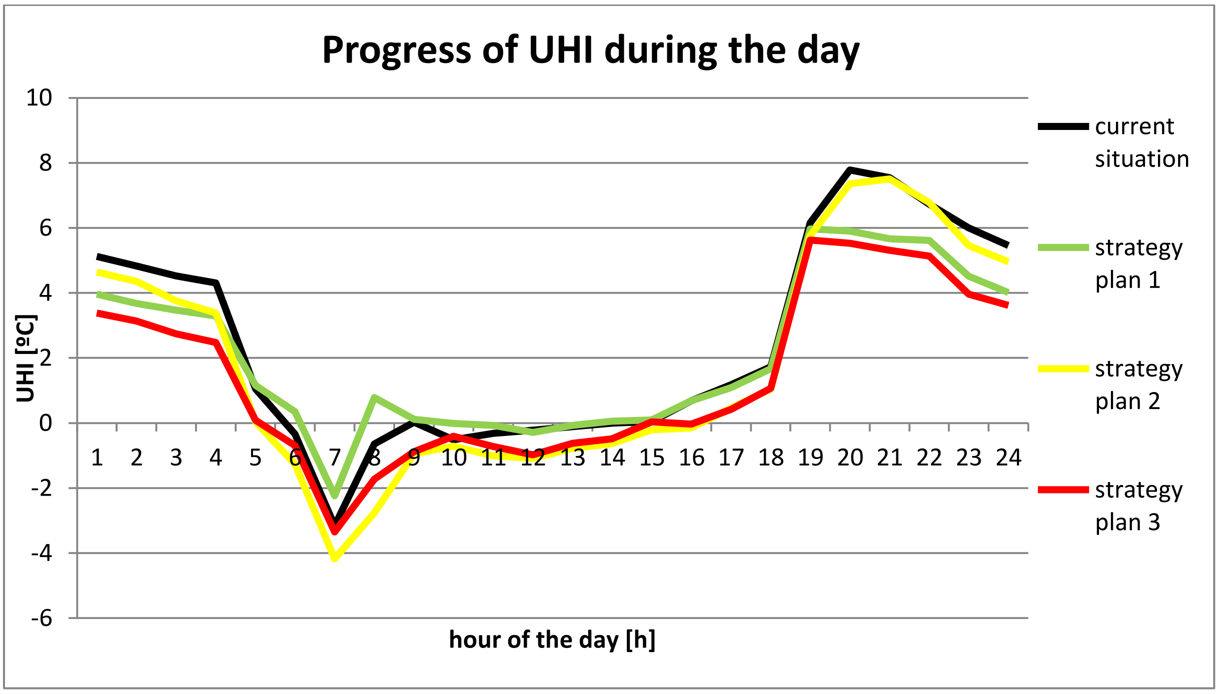

Figure 11: 24-hour UHI profile for each adaptive cooling strategy relative to the rural situation

There are also some minor changes within the proposed strategies relative to the current situation. The (green) line of strategy 1 shows that the temperature drops faster and earlier compared to the current situation during the afternoon (Fig. 10). This effect results in a lower temperature throughout the night compared to the current situation. However during daytime the green line shows more or less the same pattern as the current situation. Therefore it shows that the implementation of green measures mainly impact the night-time temperature and therefore night-time UHI effect. Moreover strategy 1 shows a lower peak during the UCI, which means that the ABL becomes more shallow by the implementation of green measures.

The (yellow) line representing adaptive cooling strategy 2 shows the adverse pattern in contribution to adaptive cooling strategy 1. Here the (yellow) line shows a larger decrease in temperature during the day than during the night (Fig. 11). Strategy 2 consists of the implementation of materials with a higher albedo values (higher level of reflectance) compared to the current situation. A higher level of reflectance (albedo) indicates that incoming solar radiation is reflected more than the materials do in the current situation. Therefore less heat can be absorbed during the day, which will be released in a smaller time radius at night. While in the current situation this takes longer for the used materials as here the thermal conductivity and heat storage is higher. However the situation changes when it starts to cool down (~17h), here the UHI effect of the adaptive cooling strategy 2 equals the UHI of the current situation. Thereby can be concluded that albedo mainly impacts the day-time albedo and has a small effect during night time. The contribution of strategy 2 to the UCI is significant as it increases the peak at the UHI which implies that the ABL becomes thicker.

The (red) line of strategy 3 does not show an additional effect as it is a combined scenario of strategy 1 and 2. The temperature decrease of strategy 1 and 2 just adds up results in the profile of strategy 3. This results in a low impact on UHI during the day and a high decrease of UHI during the night-time.

4.2 Adaptive cooling strategies

4.2.1 Current situation

Nowadays, almost every spot within the study area is risky with regards to the daily mean heat stress (UHI_{24h}) risk of the Merwede Canal Zone (Fig. 12). Moreover the northern part of the study area shows a high risk to heat stress (Fig. 12). The green spot just outside the western border of the research area is a comfortable spot when it comes to heat stress; this is due to the occurrence of a park (Park Transwijk). The UHI_{24h} map and the coherent risk map of the current situation (Fig. 12) will be used as reference situation for the different adaptive cooling strategies.

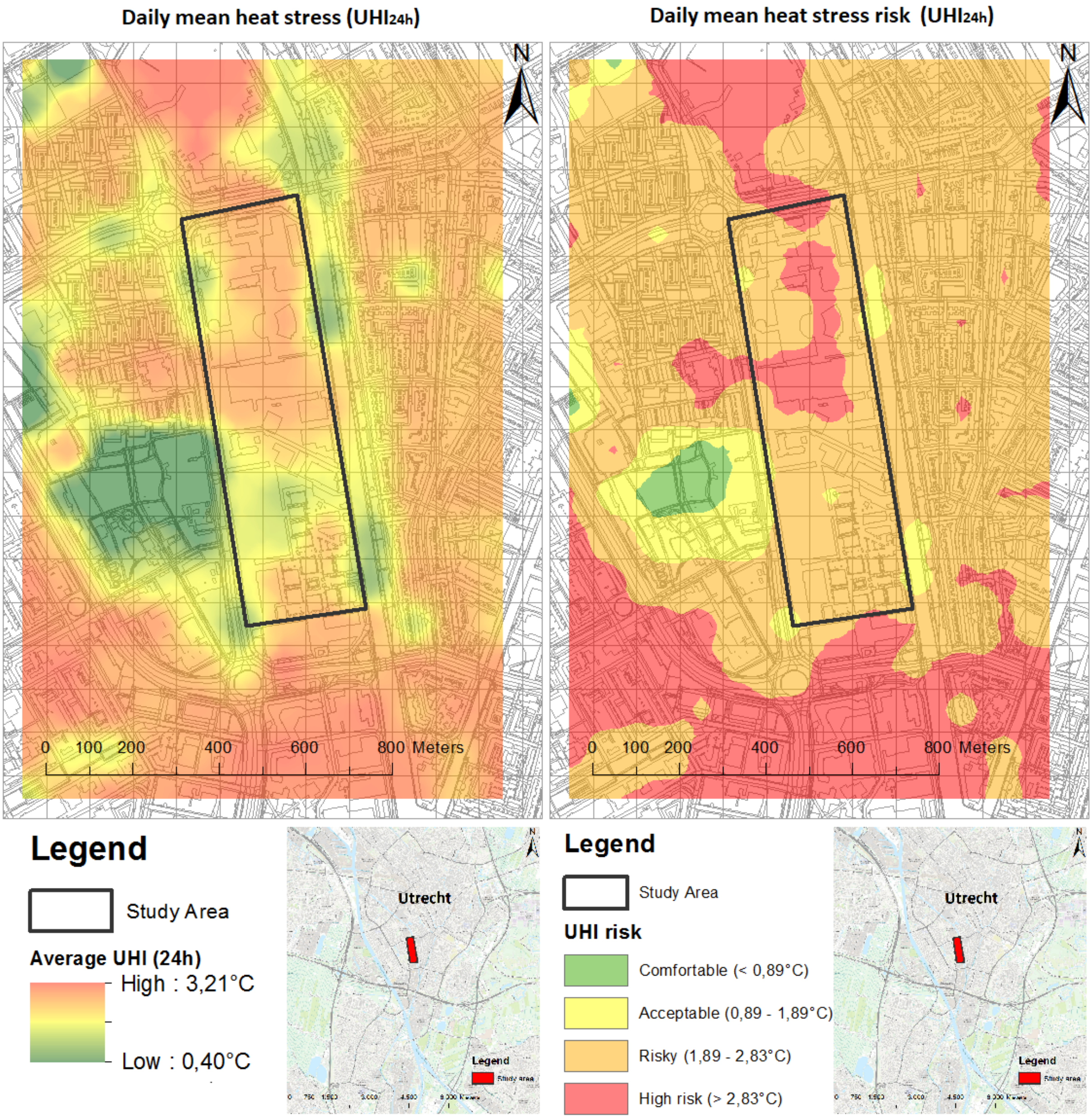

Figure 12: Daily mean heat stress maps of the current situation in the study area consisting of UHI_{24h} and the risk label

4.2.2 Adaptive cooling strategy 1 (green measures)

Adaptive cooling strategy 1 consists of implementing 50% more green instead of unused paved area (''percentage other''), which results in a net increase of 18% more green area in the study area (Fig. 13). Hereby the total percentage of green area within the study area has been increased from 18% to 36%. Figure 13 shows that there is a linear relationship between the percentages of green area and UHI_{24h} (ΔT) reduction. The increase of green area (36%) leads to an UHI_{24h} reduction of 0.45°C (Fig. 13). However this reduction is a mean reduction over the whole study area which disregards the spatial variability.

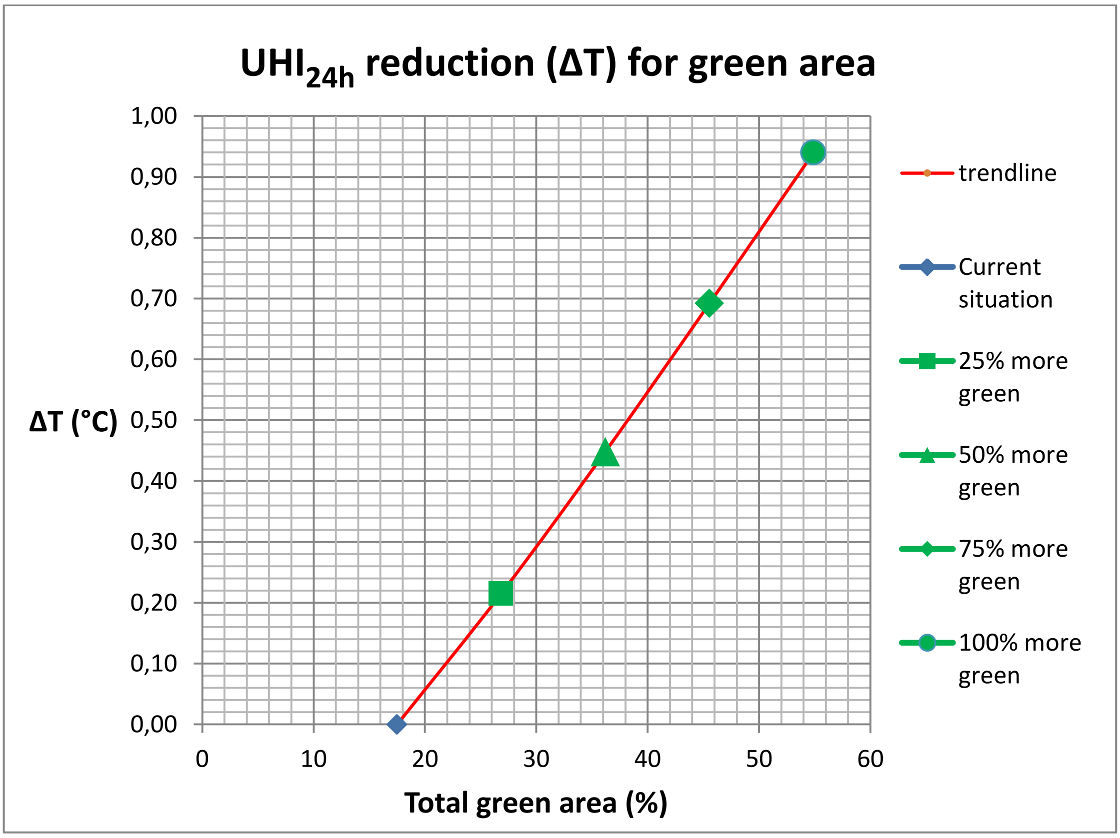

Figure 13: Graph of the relationship between more green area (%) and UHI_{24h} reduction for adaptive cooling strategy 1

The spatial output of adaptive cooling strategy 1 shows that implementing green measures has significant effect on the UHI_{24h} (Fig. 14). The amount of increase in green area (%) per grid cell is dependent of the amount of unused paved area. Where a higher value of ''percentage other'' results in more implementation of green area (%). Apart from the current situation (reference) there are no high risks present within adaptive cooling strategy 1 (Fig. 14). Moreover in the southern part of the research area some risky values are converted into acceptable values in terms of UHI_{24h} risk (Fig. 14).

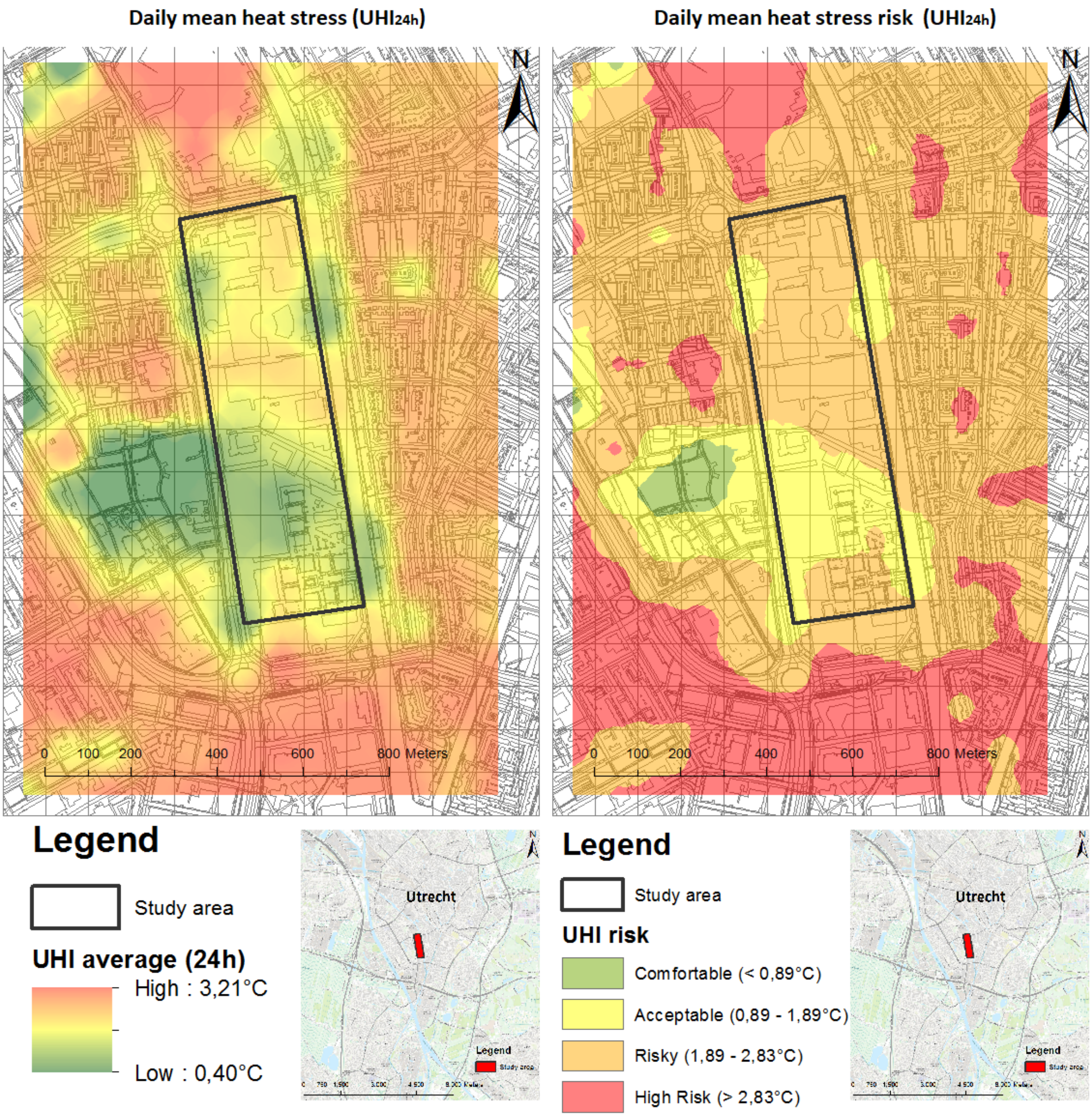

Figure 14: Daily mean heat stress maps of UHI_{24h} and the risk label for adaptive cooling strategy 1

4.2.3 Adaptive cooling strategy 2 (albedo)

In adaptive cooling strategy 2 the main focus is to lower the albedo value of roofs, roads and walls within the study area. The albedo values of different materials were obtained from literature research (Annex A). Figure 15 shows the relationship between the different albedo types and the UHI_{24h} reduction (Fig. 15). The figure shows that the most profit in terms of ΔT reduction can be achieved by changing the roof albedo (Fig. 15). Where, road and wall albedo can reduce the daily mean heat stress(UHI_{24h}) with respecitvely 0.22°C and 0,19°C at its maximum (Fig. 15). The roof albedo can decrease the daily mean heat stress with 0,67°C. Therefore this type of albedo measure can be determined as the main parameter within this strategy. Adaptive cooling strategy 2 consists of the implementation of the most extreme albedo types which is 0.85 for roof albedo, 0.50 for road albedo and 0.60 for wall albedo. The relationship between mean daily heat stress reduction (ΔT) and albedo (%) can be considered linear for both the roof, road and wall albedo (Fig. 15).

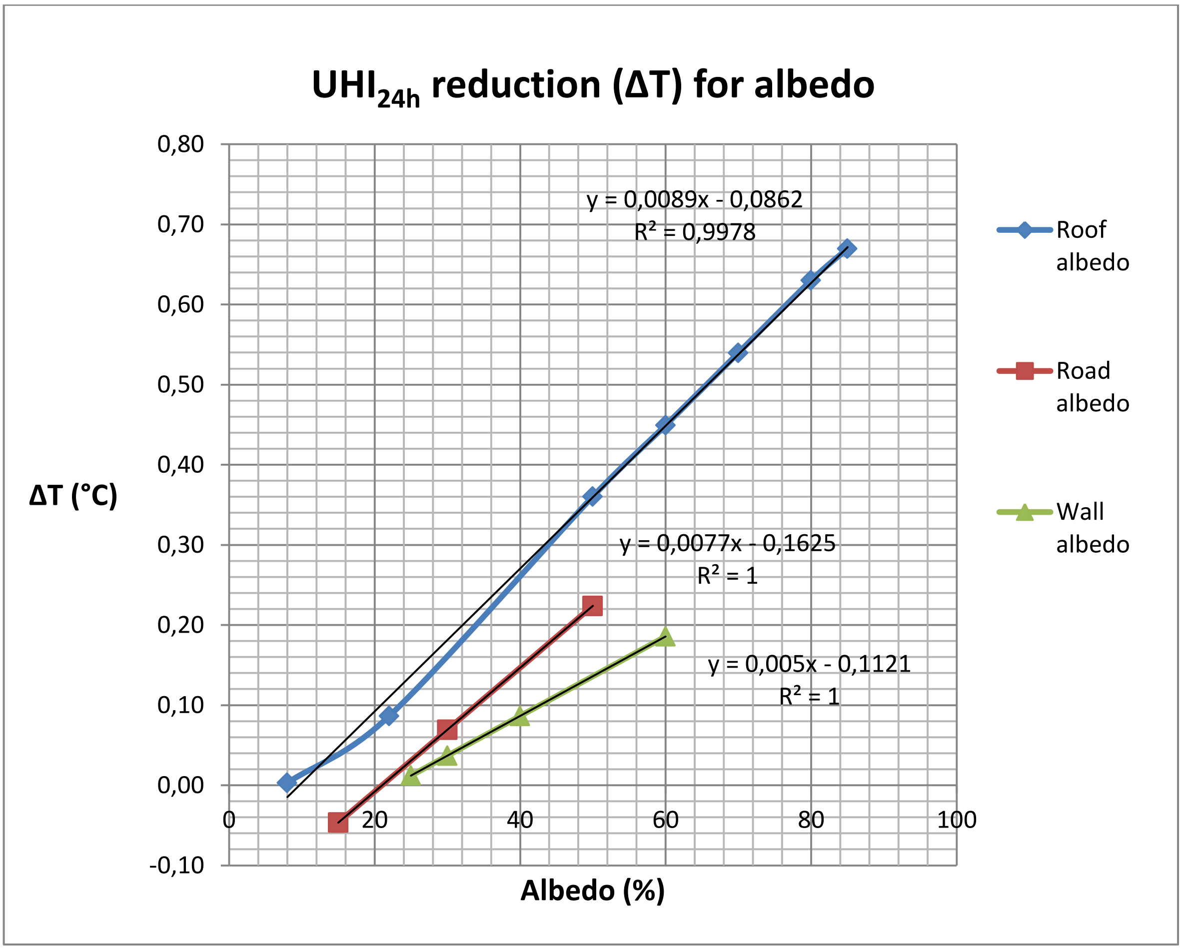

Figure 15: Graph of the relationship between different albedo types and UHI_{24h} reduction for adaptive cooling strategy 2

Figure 16 shows that the spatial effect of adaptive cooling strategy 2 on the UHI_{24h} is dependent on the type of surface area. Large buildings or roads cover a large surface which implies that the albedo can have a larger effect on the UHI_{24h}. Moreover, this figure shows show that the implementation of the most extreme albedo types has a significant result on reducing the UHI_{24h} (Fig. 16). The study area as a whole has become acceptable with no risky or high risk values. Where, the southwestern corner in the study area has become a comfortable area in terms of daily mean heat stress (UHI_{24h}).

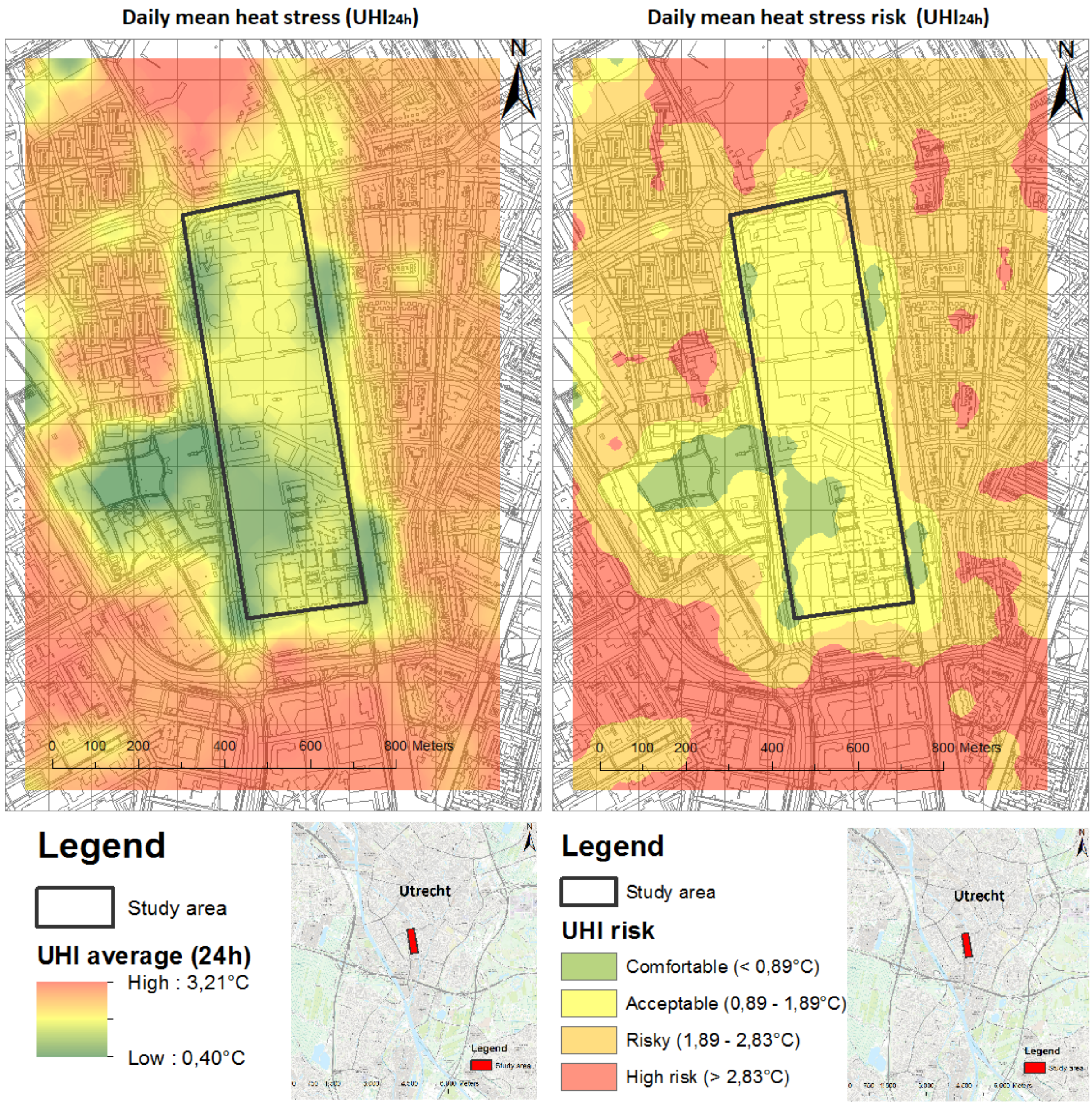

Figure 16: Daily mean heat stress maps of the UHI_{24h} and the risk label for adaptive cooling strategy 2

4.2.4 Adaptive cooling strategy 3 (combined scenario)

Adaptive cooling strategy 3 consists of a combination between adaptive cooling strategy 1 (more green area) and 2 (higher albedo values). Hereby we can assess if combining different measures has an extra beneficial effect on reducing the UHI_{24h}. Figure 17 shows that the spatial output of the daily mean heat stress (UHI_{24h}) for strategy 3 (Fig. 17) is comparable to the output of strategy 2 (Fig. 16). The difference within strategy 3 is that the comfortable spot in the southwestern corner has extended.

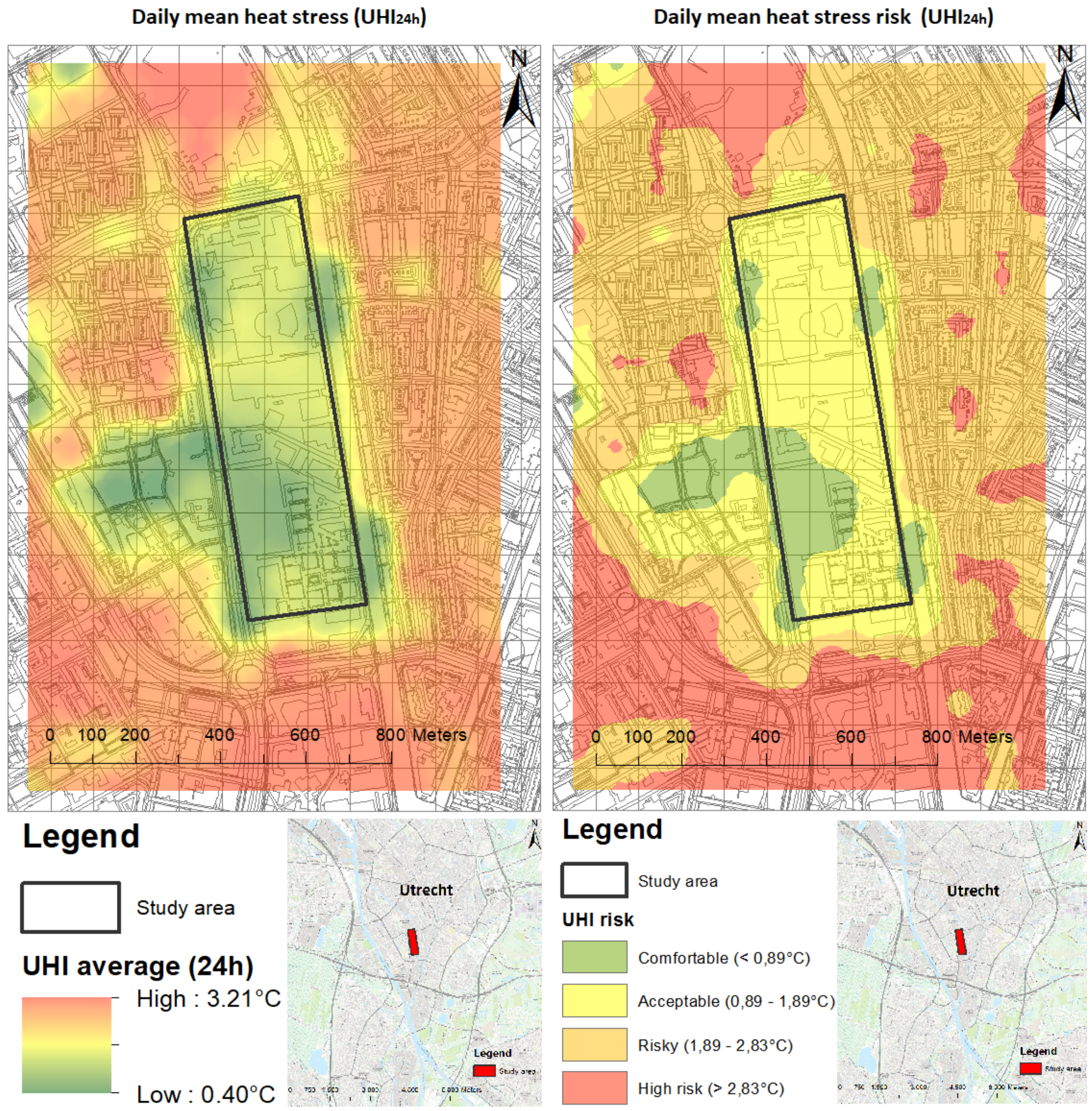

Figure 17: Daily mean heat stress maps of the UHI_{24h} and the risk label for adaptive cooling strategy 3

4.3 The urban heat island effect for each strategy

4.3.1 Daily mean heat stress (UHI_{24h})

Figure 18 shows the daily mean heat stress (UHI_{24h}) for every strategy. The interesting result of this figure is that strategy 2 (albedo) decreases the UHI_{24h} more than strategy 1. Strategy 2 leads to a decrease of 1.01°C, while strategy 1 leads to a decrease of 0.44°C (Fig. 18). However, the effect of strategy 1 could be much stronger if it is possible to implement 100% more green area instead of paved area. This scenario can lead to a decrease of 0.94°C with a total net value of 55% green area within the study area (Fig. 13). Strategy 3 shows the lowest UHI_{24h}, which expected as it is a combined scenario of strategy 1 and 2 (Fig. 18). However the total UHI_{24h} reduction in strategy 3 (ΔT=1.28°C) is lower than the combined UHI_{24h} reduction of strategy 1 and 2 (ΔT=1.45°C).

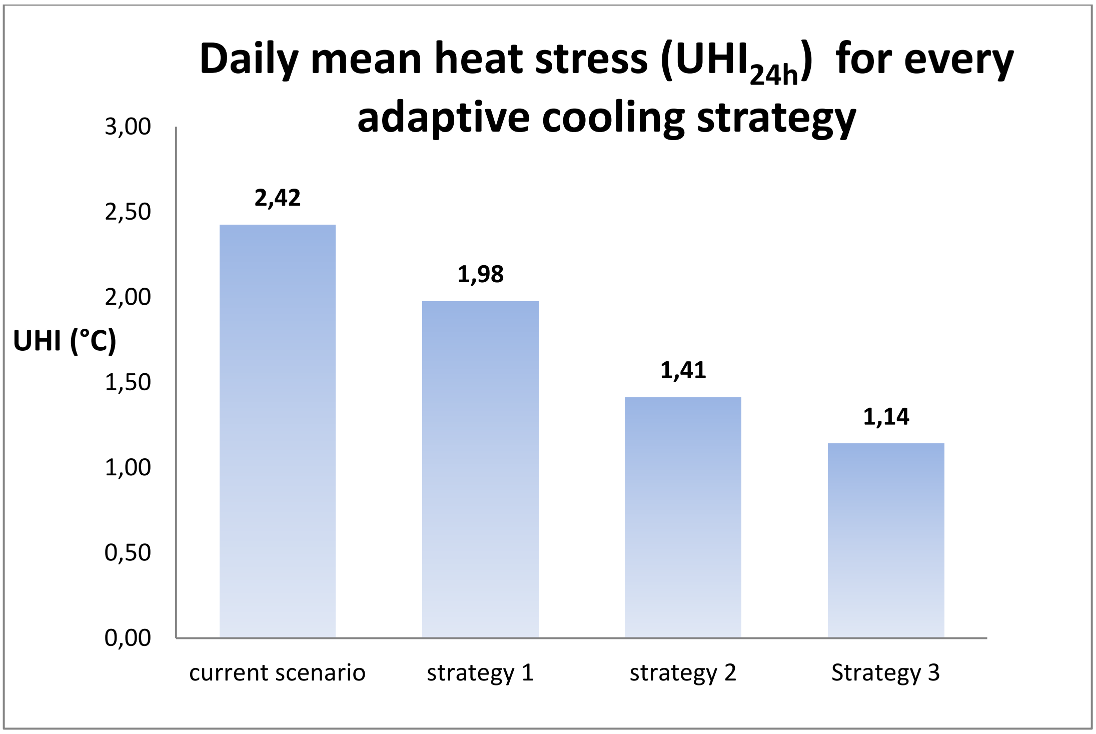

Figure 18: Bar diagram of daily mean heat stress (UHI_{24h}) for each adaptive cooling strategy

4.3.2 Massive heat stress (UHI_{max})

The UHI_{max} has been calculated to exhibit the extreme maxima of the urban heat island effect. Hereby the maximum value has been determined for each hour during 24 hours. The daily UHI_{max} shows a different pattern compared to the UHI_{24h}, where the more southwestern part of the study area shows high peaks of UHI_{max} up to almost 8.55 degrees Celsius in the current situation (Fig. 19). Figure 19 shows the effects of the different adaptive cooling strategies compared with the current situation. It can be seen that the implementation of green measures in strategy 1 lowers the peaks of the UHI_{max} in the north of the study area and creates a big green spot in the south of the study area (Fig. 19). The average UHI_{max} within the study area decreases from 7.35°C to 6.21°C (ΔT = 1.24°C). However if 100% more green area would have been implemented the UHI_{max} would have decreased significantly to 4.76 (ΔT = 2.59°C). In general this strategy causes an overall decrease in UHI_{max} which is mainly caused by the effect that green measures mainly impact at night-time.

Strategy 2 only lowers the UHI_{max} at specific locations within the research area (e.g. Southwest/east corners) (Fig. 19). This is mainly due to the fact that the southwest corner of the study area does not contain a lot of paved area (''percentage other''). Instead there are a lot of large buildings which insures that the change in albedo has a big impact on the UHI_{max} in this area. The average value within the study area has been decreased from 7.35°C to 5.93°C (ΔT = 1.42°C).

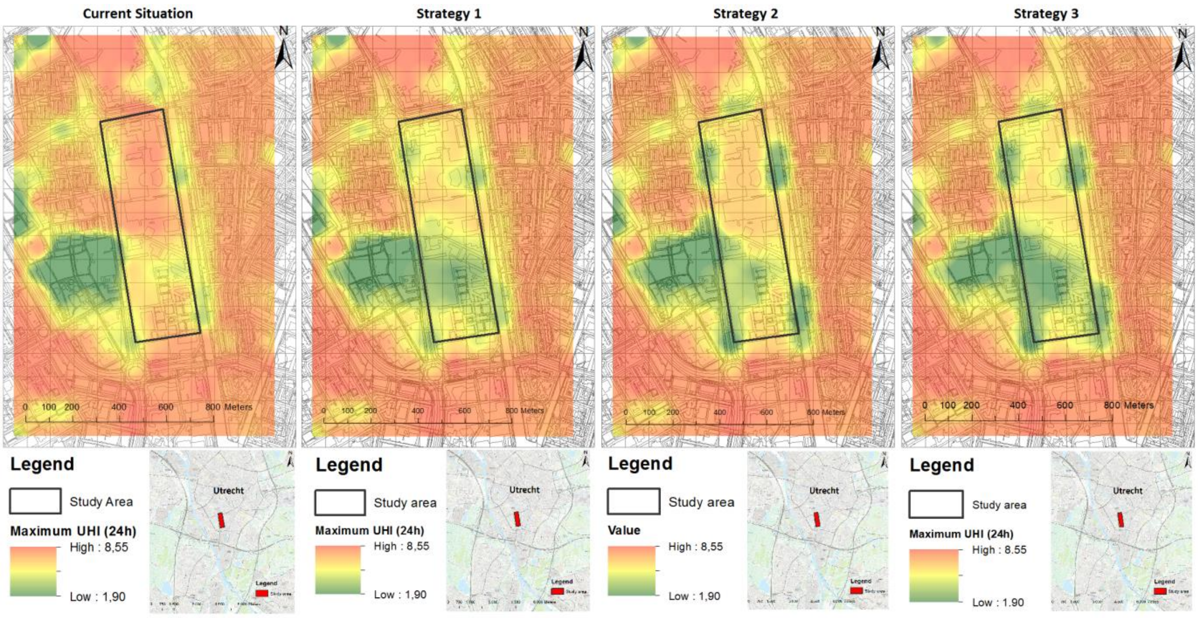

Figure 19: UHI_{max} for the current situation, adaptive cooling strategy 1, 2 and 3

Strategy 3 shows that the combined effect on UHI_{max} is smaller than the sum of the individual effects, which means that the two measures partly compensate each other (Table 6). The UHI_{max} has been decreased to 5.00°C from 7.35°C (ΔT = 2.35°C) in strategy 3, while combining the UHI_{max} reduction of strategy 1 and 2 is equal to 2.66°C. This implies that there is no additive effect on reducing the UHI_{max} for strategy 3 compared to strategy 1 and 2.

	Average ΔT reduction (UHI_{max}) (°C)
Current situation	-
Strategy 1	*1.24*
Strategy 2	*1.42*
Strategy 1+2	***2.66***
Strategy 3	***2.35***

Table 6: Average ΔT Reduction (UHI_{max}) of the different adaptive cooling strategies compared to the current situation

4.4 Social cost-benefit analysis

The costs and benefits are based on the input values of different materials and hectares of the research area. Hereby the total benefits are defined as: the residual value of investment, air quality, the value of housing and the effect on human health. The total costs are formulated as the total investment costs and the total maintenance costs over a lifespan of 50 years.

Adaptive cooling strategy 1 consists of the implementation of green areas in two ways: green parks and inner green areas. Hereby the total areas of these green areas have been increased with 50% with regards to the reference situation. The total costs of this investment are €225.271, while the total benefits with regards to heat stress are € 7.182.059 (Fig. 20). Adaptive cooling strategy 2 consists of the implementation of three different materials to lower the albedo of the corresponding, roof, wall and road albedo. The materials used within this strategy are: white Eco seal roofs (cool roofs), light-coloured limestone walls and yellow bricks for roads (Annex A). Hereby the total investment costs are € 2.415.708 and the benefits are € 7.764.289 (Fig. 20). Strategy 3 adds up the values of the total investments and benefits. Hereby the total investment costs are: € 2.640.979 and the total benefits are € 15.073.062 (Fig. 20).

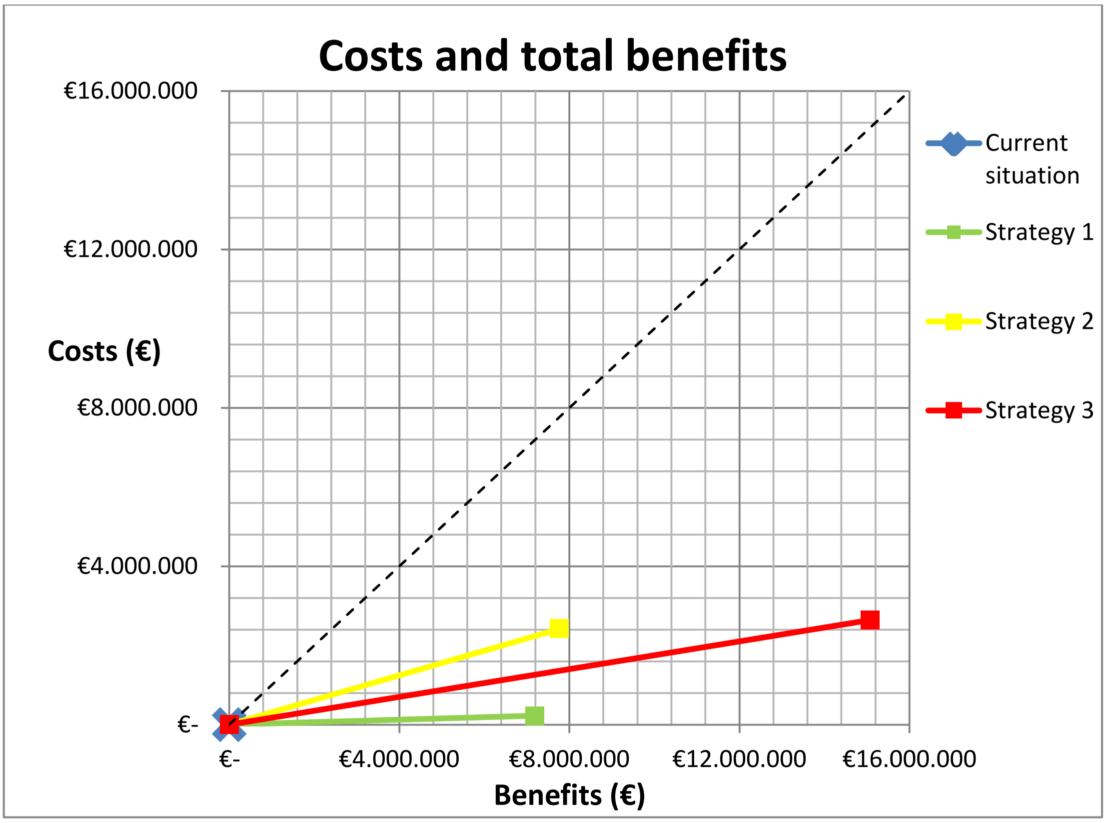

Figure 20: The costs and total benefits in net present value for each adaptive cooling strategy

The social cost-benefit analysis is a multi-faced analysis and therefore the costs and benefits are distinguished into four parts: benefit-cost ratio (BCR), net benefits, UHI_{24h} reduction costs and UHI_{max} reduction costs (Table 7). Hereby the BCR shows the efficiency in terms of total benefits per total costs. The net benefits show the efficiency in terms of maximizing the total net benefits. Where, the UHI_{24h}/UHI_{max} reduction costs show the efficiency in terms of the costs per reduction of one degree Celsius (€/°C) (Table 7).

Total benefits				
	Benefit-cost ratio (-)	Net benefits (€)	UHI_{24h} reduction costs (€/°C)	UHI_{max} reduction costs (€/°C)
Adaptive cooling strategy 1	**32**	6.956.788	**502.382**	**198.312**
Adaptive cooling strategy 2	3	5.348.582	2.388.051	1.705.509
Adaptive cooling strategy 3	6	**12.432.084**	2.056.862	1.116.910

Table 7: The total benefits related to its costs consisting of four parts: benefit-cost ratio, net benefits, UHI_{24h} reduction costs and UHI_{max} reduction costs

Table 7 shows that adaptive cooling strategy 1 is the most efficient in terms of benefit-cost ratio (BCR) as it has the highest ratio. Moreover, this strategy is most efficient as it has the lowest amount of the costs for reducing the UHI_{24h} and UHI_{max} per degree Celsius (Table 7). Adaptive cooling strategy 3 is more efficient in terms of total net benefits as it maximizes the total net benefits for this scenario (Table 7).

Within the social cost-benefit analysis all kind of benefits are taken into account (Fig. 20). In order to get a realistic view on the direct benefits a sensitivity analysis is performed to distinguish direct benefits from total benefits. The direct effects are formulated as the direct benefits for inhabitant, this implies in this case: the residual value of investment and the value of housing. The indirect benefits occur on the basis of the direct effects, but have an effect on other markets (e.g. healthcare or environment). These effects are in this case formulated as air quality and human health, and do not only have an effect on the inhabitants within the research area.

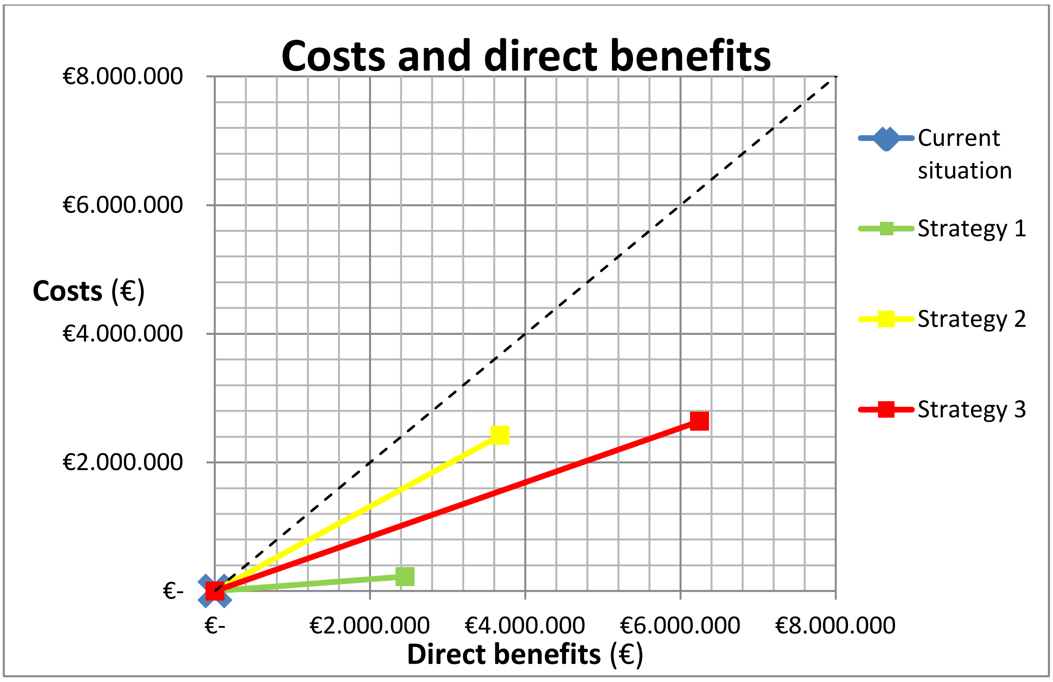

Figure 21: Costs and direct benefits in net present value for each of the three adaptive cooling strategies

Figure 21 shows the direct effects of the different adaptive cooling strategies in relation to its costs. It shows that the direct benefits to inhabitants still exceed the costs of the different adaptive cooling plans (Fig. 21). The direct benefits of adaptive cooling strategy 1 are € 2.447.880, the direct benefits of adaptive cooling strategy 2 are € 3.673.826 and the direct benefits of adaptive cooling strategy 3 are € 6.248.420 (Fig. 21).

Table 8 shows the direct benefit-cost ratio of the direct benefits and the net direct benefits. The total costs of each adaptive cooling remains the same and therefore the UHI_{24h}/UHI_{max} reduction costs are the same as in Table 7. Adaptive cooling strategy 1 is most efficient in terms of the direct benefit-cost ratio with a ratio of 11 (Table 8). While adaptive cooling strategy 3 is most efficient in terms of net direct benefits (Table 8). The direct benefits (Table 8) do not show any differences with regards to the total benefits (Table 7) in terms of the efficiency of the different adaptive cooling strategies.

Direct benefits		
	Direct benefit-cost ratio (-)	Net direct benefits (€)
Adaptive cooling strategy 1	**11**	2.222.609
Adaptive cooling strategy 2	2	1.258.119
Adaptive cooling strategy 3	2	**3.607.441**

Table 8: The direct benefits related to its costs consisting of two parts: benefit-cost ratio and net benefits

5. Discussion

5.1 The position of the UCAM-method in the world of heat stress

Nowadays, there is a misunderstanding with the currently available heat stress maps. The tendency of currently used heat stress maps are based on relationships between surface characteristics without the use of actual temperature records. The current risk dialogue on what value is acceptable for heat stress causes a big shift in understanding the actual heat stress in urban areas. Hereby new techniques are introduced on the basis of air temperature measurements and satellite imaging. More and more advanced heat stress models show up to predict the heat stress for future scenarios. However there is still no formal value or standard for heat stress and how to express the urban heat island effect, which results in many different heat stress assessments. Therefore the UCAM-method is compared to other heat stress assessment techniques or models in the Netherlands (Annex D) to check the reliability of the results. Hereby we address all the positive/negative characteristics and its application (Annex D). However not every positive and negative point could be addressed as many heat stress assessment methods lack open source documentation. Hereby we define three different types of heat stress assessments (Annex D):

1. Applied values for heat stress, where values for heat stress are assigned to specific area types on the basis of relationships between the surface characteristics (e.g. green, water, paved etc.)
2. Air temperature/satellite imaging, where heat stress maps are created on the basis of air temperature measurements and satellite imaging to visualize the heat stress for current situations.
3. Advanced heat stress models, where an advanced model is created on the basis of previous heat waves to predict the amount heat stress for current situations and future scenarios.

Air temperature and satellite imaging

The most commonly used technique to assess the amount of heat stress is on the basis of air temperature measurements and satellite imaging to measure temperature for the current situation. This technique is suitable to spatially visualize the temperature differences in the area to find the bottlenecks in terms of temperature. However the downside of using this technique is that no adjustments can be made to see how the urban heat island changes when implementing different measures. Moreover this technique has not been coupled to the rural temperature to calculate the actual UHI effect, but just shows the daily temperature profile.

Advanced heat stress models

The advanced heat stress models are mostly in its early phase where the models form a basis for future development of heat stress models. The Dutch Delta Plan on Spatial Adaptation proposed a standard for heat stress, where heat stress is defined as the frequency of a warm night (De Nijs et al., 2019). Hereby a warm night has been defined as more than 20 degrees Celsius ($T>20°C$). However this method only indicates the massive heat during night-time and uses the parameter temperature as an indicator for heat stress, instead of the difference between rural and urban temperature (UHI). Therefore this standard seems to lack some important information with regards to the UHI effect. The UCAM method has the ability to assess the daily mean heat stress (UHI_{24h}) and the massive heat stress (UHI_{max}) during night time.

Reliability of the UCAM-method

The most important factor of heat stress is determined by the extent of paved area (Hoeven & Wandl, 2018). Therefore implementations should focus on the contribution of heat stress by paved area. This is feasible within UCAM by reducing the percentage of paved area or by reducing the amount of heat stress emitted by paved area. The UCAM model focusses on increasing the albedo (%) to reduce the emittance of heat produced by paved area. Moreover the implementation of green measures reduces the total paved area (%) as this is the adjustable area to implement green measures. The UCAM method has the ability to both assess the UHI_{24h} and the UHI_{max} which is a more reliably way in representing the urban heat island effect than the proposed method of the DPSA. Therefore the UCAM method can be considered as a reliable quantitative tool to visualize the current heat stress and to model the heat stress for different adaptive cooling strategies. Although the UCAM modelling is be able to interpret the temperature data it should be noted that several simplifications have been applied and that it is still model simulation which represents a simplification of the reality.

5.2 Limitations and recommendations

Although the results of UCAM are promising and it is a quantitative way to express the urban heat island effect over a study area. There are some limitations with the use of this model.

Sky-view factor

The first limitation is that the model does not include the 3D sky-view factor (SVF). The sky-view factor is a dimensionless value between 0 and 1 which describes the openness of an urban surface (Bottyán & Unger, 2003). UCAM does include a 2-dimensional density factor of buildings but the built-up ratio does not completely describe the characteristics of an urban surface, because the vertical dimensions of buildings are not represented. The vertical dimension has been taken into account within the classification of different LCZ's, but this an approximation. In the cities the narrow streets and high buildings create deep canyons and this vertical geometry plays an important role in development of UHI (Bottyán & Unger, 2003). Hereby a DEM (Digital Elevation Model) tool has to be included to express the heights of urban areas and to calculate the Sky-view factor.

Classification of green area

The most important limitation of UCAM is within the classification of green area. UCAM does not quantify the difference between green measures, which implies that it has not the ability to distinguish different kind of green measures. Within the UCAM model the total green area is defined as a percentage of grassland which has a sufficient amount of soil moisture to evaporate. However a sufficient amount of soil moisture is not always present during a heat wave and only applicable if the grassland is irrigated. Moreover, different kind of green have a different impact on the UHI effect as the implementation of urban trees have a bigger impact on the UHI effect than low vegetation (EPA, 2008). Urban trees can both intercept the incoming solar irradiation causing buildings or paved area not to warm up (Akbari et al., 2001). Moreover urban trees cool the air temperature by evapotranspiration and also absorb CO_2 for their photosynthesis, which cools the environment (Akbari et al., 2001). While the evapotranspiration rate of low vegetation (e.g. grass) is much lower than urban trees (Stan et al., 2014). Moreover low vegetation does not create shadow by blocking the incoming solar irradiation. The UCAM assessment is not able to distinguish the variety of green measures which do impact the UHI effect differently.

Implementation of green area

The third limitation to this model is ability to implement green walls/roofs on buildings to decrease the UHI effect. The results of UCAM shows that roof albedo can have a major impact on the UHI effect (Fig. 15). However it is not possible to integrate green roofs within UCAM, this could only be done changing the roof albedo respectively to that of green roofs. Green roofs do have a beneficial effect in terms of evaporative heat transfer, which constantly acts as a heat sink and absorb radiative energy resulting in lower surface an air temperatures (Alexandri & Jones, 2008). One side-note to this implication is that green roofs have a different impact on the UHI at different heights (Oke, 1988). This beneficial effect coupled to a height relation has not been taken into account in the UCAM model and therefore green roofs cannot be implemented.

Wind factor

Another limitation in the UCAM model is the wind factor. The wind flow is highly dependent of the local urban geometry (Ricciardelli & Polimeno, 2006). Wind speed can decrease the intensity of the heat island in urban areas where the cooling effect of the wind helps to mitigate the adverse effects of heat island on the micro climate and human thermal comfort (Rajagopalan et al., 2014). However this relationship between wind and UHI has not been included within the UCAM model.

Blue measures

The next limitation of this model is the implementation of water (blue) measures. The model is able to define the percentage of blue area within the research area, but this is not an adjustable parameter. The actual cooling effect of water bodies is a complex process as it is dependent of its scale, state and rate of flow (Kleerekoper, 2016). This has not been implemented within UCAM and therefore cannot be used as an adjustable parameter to cool the UHI effect.

Resolution

The last limitation with regards to UCAM is that it uses a 100x100m grid cell size to indicate the surface area. The grid cell size of 10.000m^2 neglects the local effects of the UHI effect and thereby cannot calculate the local impact of measures. The adaptive measures have to be performed on a large scale in order to see its effect.

Limitations SCBA RAS

The limitation of the SCBA RAS is that several benefits are not included due to the lack of data or information (Rebel et al., 2012). This causes that the actual benefits in relations to its costs are still not complete and that the results only show the costs/benefits of the currently used parameters. Moreover the implementation of green measures is very specifically defined as in parks or inner green area, while UCAM only provides grassland as a green measure. This results in a small mismatch between the actual costs-benefits of the SCBA and the UHI modelling in UCAM.

Another limitation of the SCBA RAS is that the direct benefits are heavily influenced by the value of housing. This parameter only takes into account the actual value increase of housing while implementing a certain measure, but not the fact that less area becomes available to build houses. For example, while implementing more green area within the study area the value of houses increases, but less area can be used to build houses. This ''lost'' area has not been valued within the SCBA.

Recommendations UCAM

- The implementation of a DEM tool (in Dutch: AHN) to express the heights of urban areas. This tool can be used to calculate the Sky-view factor, which can also contribute to a wind flow tool. However it should be noted that these relations are very complex as it has to be executed on a 3-dimensional scale.
- Be able to distinguish different kinds of vegetation and its impact on the UHI effect. Thereby, the ability to implement vegetation on roofs (green roofs) with the effect on the UHI effect in relationship to its height.
- Improving the resolution of the UCAM model (100x100m) to a 10x10m grid in order to analyse the more local impacts of measures on the UHI effect.

Recommendations SCBA RAS

- Adding more parameters for the actual benefits by assessing more information such as: biodiversity, recreational value for inhabitants, energy use in building, CO_2 reduction.
- Be able to add the value of ''lost'' area per adaptive measure and indicate them as extra costs.

5.3 Interpretation of the results

Green area as an adaptive cooling strategy

The largest decrease in temperature can be gained during night-time as the urban heat island effect is significantly higher at night than during day-time (Fig. 11). The results show that the implementation of green measures (strategy 1) has a major impact on the UHI during night-time, while the implementation of other materials with higher albedo values (strategy 2) mainly impact the day-time UHI effect (Fig. 11). This effect is mainly due to the fact that green measures lower the emittance of sensible heat during the night as less heat gets captured in materials (Rizwan et al., 2008). Therefore the extent of green area has a high potential to reduce the UHI_{max} at night-time (Fig. 11).

The actual effect of implementing green measures (strategy 1) could theoretically be much stronger if it is possible to implement 100% more green area instead of paved area (Fig. 13). Practically, the implementation of 100% green is not feasible as some paved area has a societal function (e.g. a street for walking or a parking spot for cars). Hereby the limitation of implementing green walls/roofs has to be resolved in order to introduce more green area in terms of green roofs/walls.

Albedo as an adaptive cooling strategy

The implementation of higher albedo values in strategy 2 (Fig. 16) has a larger effect on the reduction of the UHI_{24h} than the implementation of green measures in strategy 1 (Fig. 14). The change in material to higher albedo values causes a higher level of reflectance for the incoming solar irradiation. This causes that less heat is absorbed during the day and therefore lower the urban heat island effect during the day. Strategy 2 shows that the research area has become acceptable in terms of daily mean heat stress (UHI_{24h}), while adaptive cooling strategy 1 shows some risky spots within the research area (Fig. 16). This is mainly due to the fact that the implementation of higher albedo materials lowers the UHI over a longer time scale during the day (Fig. 11), while adaptive cooling strategy 1 mainly lowers the urban heat island during the night in a shorter time period. The implementation of higher albedo values only lowers the UHI_{max} in spots with a high building density because more solar irradiation can be reflected, while adaptive cooling strategy 1 decreases the UHI_{max} over the whole research area (Fig. 19).

Although the fact that adaptive cooling strategy 2 has the largest impact at the UHI_{24h}. There is a downside in implementing these optimum albedo values. We have seen that this implementation mainly acts during the day because of the high level of reflectance for incoming solar irradiation (Fig. 11). This strategy uses the optimum albedo values for materials, however this might cause glare problems caused by the highly reflecting surfaces (Taha et al., 1992). These glare problems can be perceived as discomfort to humans and therefore materials with lower albedo values could be a more nuanced solution (Taha et al., 1992). However, this implies that the actual effect on reducing the UHI_{24h} and UHI_{max} becomes less than the proposed scenario (Fig. 15).

The effect of a combined scenario

Adaptive cooling strategy 3 shows that combining the different strategies has no extra beneficial effects on decreasing the urban heat island effect. Hereby, the effect of adaptive cooling strategy 3 on daily mean heat stress (UHI_{24h}) is smaller than the sum of the individual effect of strategy 1 and 2. This results in an overall acceptable/comfortable situation considering daily mean heat stress, where the two measures partly compensate each other. The effect of adaptive cooling strategy 3 on the UHI_{max} is also lower than adding the individual ΔT reduction of UHI_{max} for strategy 1 and 2 (Table 6). Therefore it can be concluded that combining different adaptive measures has no extra beneficial effect in reducing both the UHI_{24h} and UHI_{max} effect.

The most efficient adaptive cooling strategy

The social cost-benefits analysis showed that there are no ''bad'' solutions as every strategy is profitable with higher benefits over its total costs (Fig. 20). The implementation of green measures (strategy 1) has the lowest amount of benefits-cost ratio (BCR) for both the total benefits as the direct benefits (Table 7 & 8). Moreover, adaptive cooling strategy 1 showed that it requires the lowest amount of costs for reducing the UHI_{24h}/UHI_{max} per degree Celsius. The implementation of green measures does not only decrease the urban heat island effect but also has a positive impact on the urban water balance. Introducing more green area causes a higher level of water retention, which implies that that drainage into watercourses is more protracted and the peaks in flow associated with flood events are avoided (Lennon et al., 2014). While on the other hand increasing albedo values do not impact the drainage rate during flood events.

The implementation of higher albedo values (strategy 2) has a higher BCR and has some downsides in terms of producing glare. This could be reduced by the implementing lower albedo materials however this will significantly reduce its impact on the UHI_{24h} and UHI_{max} effect (Fig. 15). This will also increase the costs for reducing the UHI_{24h}/UHI_{max} per degree Celsius for this scenario and therefore is not the most efficient scenario.

Strategy 3 shows that it is most efficient in terms of total net benefits and direct net benefits. However the BCR and the costs for reducing the UHI_{24h}/UHI_{max} per degree Celsius are larger than adaptive cooling strategy 1. Despites the fact that green measures have a lower impact on decreasing the UHI_{24h} the implementation of green area can be considered as more climate-robust solution acting on different levels with the lowest costs for reducing the UHI_{24h}/UHI_{max} per degree Celsius. Therefore the implementation of green area is the most efficient way to reduce heat stress in urban areas.

5.4 Implications of this research

This research focussed on the most efficient way to reduce heat stress in urban areas. Nowadays the acceptable total amount of heat stress perceived by humans is not defined. The amount of heat stress can be downgraded into two different sources of heat: massive heating at night and acute heat during the daytime. This research uses a risk label on the basis of UHI_{24h} in its relation to human health to assess daily mean heat stress. On the other hand massive heat has been addressed by the calculation of hourly UHI_{max} values over the day. Hereby, the calculation of massive heat in terms of hourly UHI_{max} on a spatial scale is a new method.

Since there is no unformal way in how to express the urban heat island effect and neither for the risks of the urban heat island effect, heat stress assessments use different standards and definitions to define heat stress (Annex D). Hereby, the current risk dialogue on what value of UHI is defined as risky or acceptable can be considered as a continuous process (Fig. 22).

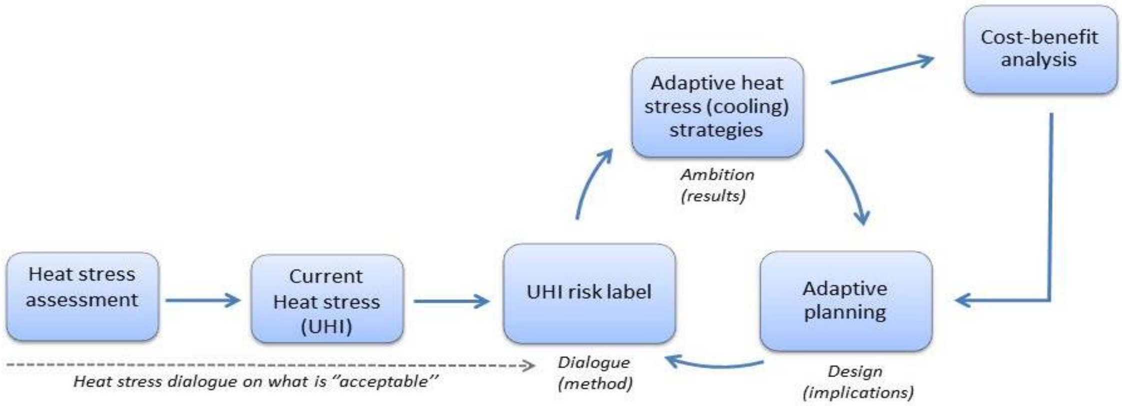

Figure 22: The correlation between the heat stress assessment and the social cost-benefit analysis to the current risk dialogue

According to the Delta Plan on Spatial Adaptation (DPSA) the method to express heat stress is the amount of tropical nights (minimal temperature of 20°C) per year (De Nijs et al., 2019). However this method only addresses the massive heat stress and does not include the rural temperature to calculate the urban heat island effect. This research contributes to the current risk dialogue by the use of a different approach based on UHI_{24h} and UHI_{max} (Fig. 22). This method can be used as a new standard method to calculate heat stress in urban areas; however than the typical Dutch heat wave (19/07/2006) should become a standard for future heat stress assessments. Therefore the scientific implication of this research proposes a new standard to define heat stress and express the urban heat island effect in terms of UHI_{24h} and UHI_{max} (Fig. 22).

This research can be used as a more practical implication as it shows that the implementation of green measures is the most efficient way to reduce the UHI_{24h} and the UHI_{max}. Hereby, the implementation of green measures has the highest benefit-cost ratio and requires the lowest amount of costs to reduce the UHI_{24h}/UHI_{max} per degree Celsius. With a common standard value for heat stress this research can be used to efficiently reduce the urban heat island effect by adaptive planning for other regions apart from the MWCZ (Fig. 22).

6. Conclusion

This research focussed on finding the most efficient adaptive cooling strategy to reduce heat stress in the Merwede Canal Zone of Utrecht. Hereby the quantitative UCAM-method was performed to spatially visualize the impacts of different adaptive cooling strategies on the UHI effect.

Nowadays the definition of heat stress in terms of a commonly use standard has not been established, therefore multiple heat stress assessments show up with different standards and labels of risk. This research contributes to the current risk dialogue on what value is acceptable for heat stress by using a different approach based UHI_{24h}, UHI_{max} and efficiency. Hereby a social cost-benefit analysis has been executed to draw a conclusion about the most efficient adaptive cooling strategy.

The results of the UCAM showed that changing albedo values of materials more like change the daily mean heat stress (UHI_{24h}) during the day. While on the other hand the implementation of green measures impact the massive heat stress (UHI_{max}) during night-time. The social cost-benefit analysis showed that the most efficient way to reduce heat stress is by the implementation of green measures. This is due to the highest benefit-cost ratio and the lowest amount of costs for reducing the UHI_{24h}/UHI_{max} per degree Celsius. Despite of the hypothesis which stated that a combined system would be the most efficient way to reduce heat stress. However a combined system of albedo and green measures does provide the highest amount of total net benefits and direct net benefits, but result in high costs for reducing the UHI_{24h}/UHI_{max} per degree Celsius. The implementation of green measures can be considered as the most climate-robust solution which impacts on multiple levels and mainly impacts the UHI_{max} during night-time at relative low costs.

The scientific implication of this research is that a new standard to define heat stress and express the urban heat island effect in terms of UHI_{24h} and UHI_{max} has been proposed. Thereby it can be used to define a common standard value to express heat stress in urban areas. The more practical implication of this research is that the implementation of green measures is the most efficient way to reduce heat stress in urban areas.

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8. Acknowledgements

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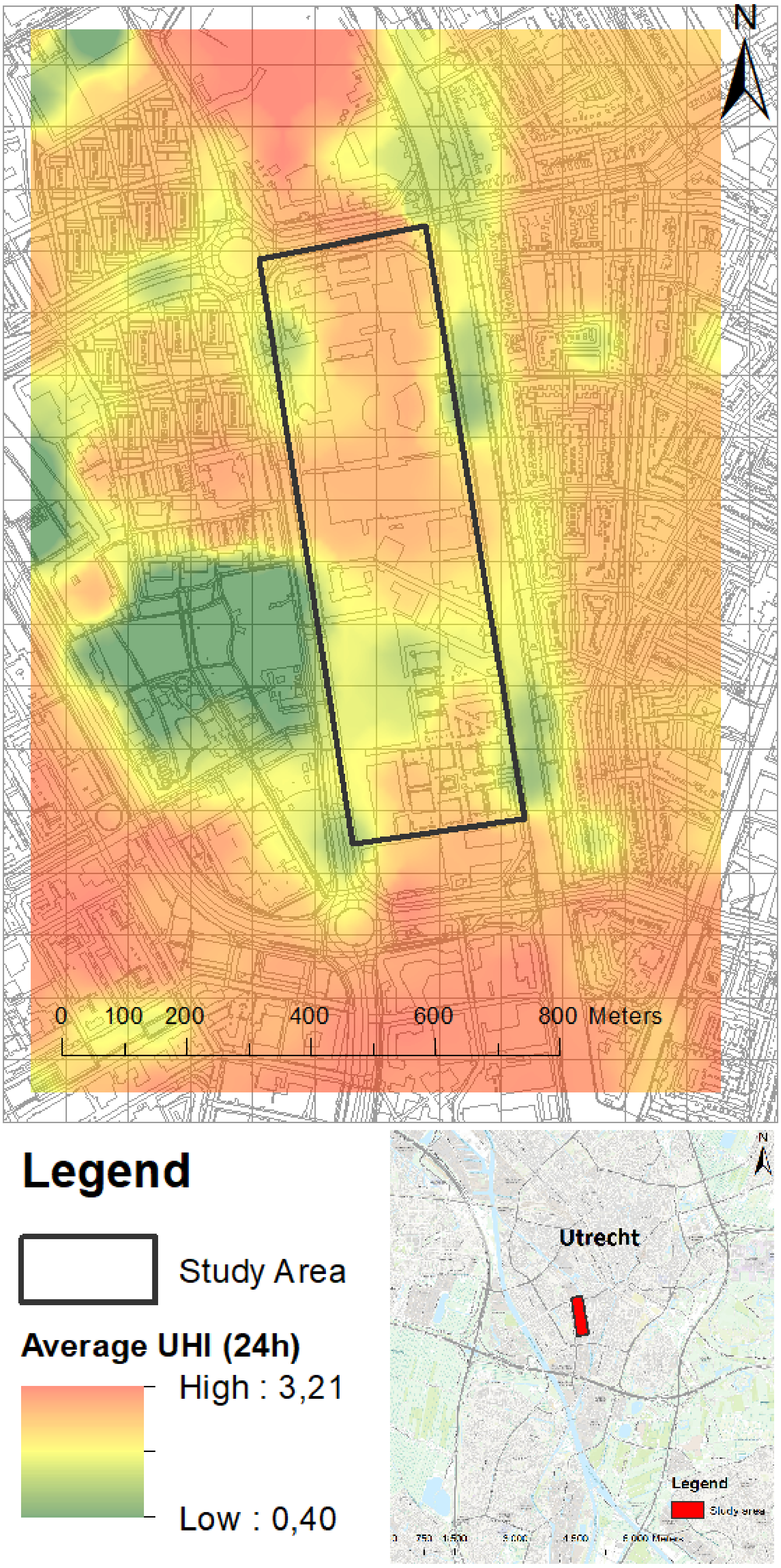
Annex A: Albedo values of roofs, walls and roads.

Choice	Roof albedo (%)	Description	Source	Status
1	8	Tar and gravel	Van Hove et al., 2011. Exploring the urban heat island intensity of Dutch cities	current situation
2	22	Roof tiles	Van Hove et al., 2011. Exploring the urban heat island intensity of Dutch cities	current situation
3	50	Roof with light coloured coating	Klok, 2010. Hittebeperkende klimaatmaatregelen voor Rotterdam onderzocht met Envi-met microschaal klimaatsimulaties.	-
4	60	Light coloured roof (limestone)	Klok, 2010. Hittebeperkende klimaatmaatregelen voor Rotterdam onderzocht met Envi-met microschaal klimaatsimulaties.	-
5	70	White concrete tiles	EPA, 2008, Reducing Urban Heat Islands: Compendium of Strategies. Heat Island Reduction Activities,	-
6	80	Built-up Roof Smooth surface with white roof coating	EPA, 2008. Reducing Urban Heat Islands: Compendium of Strategies. Heat Island Reduction Activities,	-
7	85	White Ecoseal (cool roof)	Kleerekoper et al, 2012. Thermisch comfort in de stad.	Strategy 2&3
Choice	**Road albedo (%)**	**Description**	**Source**	**Status**
1	15	Weathered asphalt	Van Hove et al., 2011. Exploring the urban heat island intensity of Dutch cities	current situation
2	30	Concrete stones	Van Hove et al., 2011. Exploring the urban heat island intensity of Dutch cities	current situation
3	30	Red bricks (rode klinkers)	Klok, 2010. Hittebeperkende klimaatmaatregelen voor Rotterdam onderzocht met Envi-met microschaal klimaatsimulaties.	-
4	50	Yellow bricks (gele klinkers)	Klok, 2010. Hittebeperkende klimaatmaatregelen voor Rotterdam onderzocht met Envi-met microschaal klimaatsimulaties.	Strategy 2&3

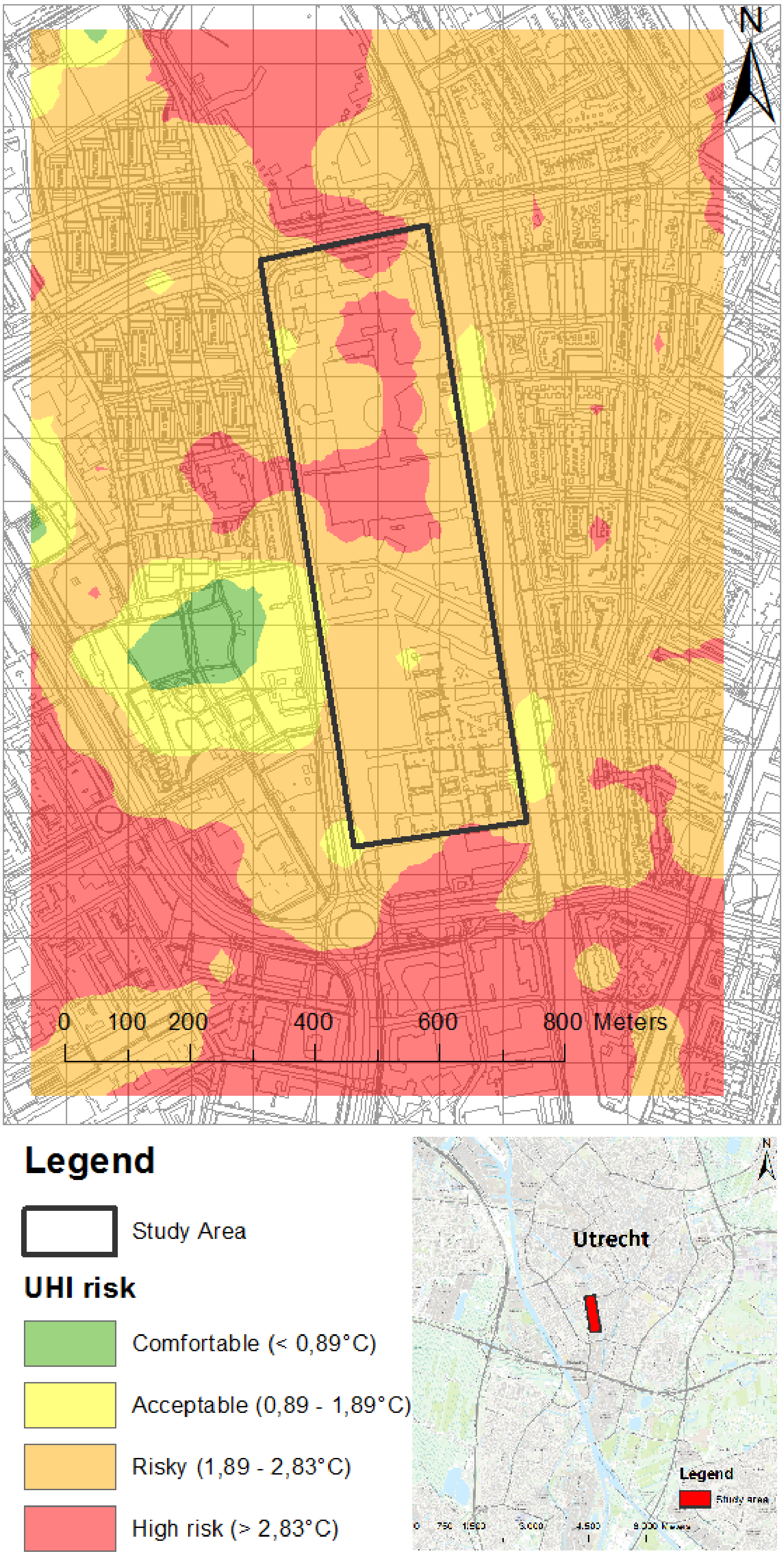
Choice	Wall albedo (%)	Description	Source	Status
1	25	Brown brick	Van Hove et al., 2011. Exploring the urban heat island intensity of Dutch cities	current situation
2	30	Red brick	Van Hove et al., 2011. Exploring the urban heat island intensity of Dutch cities	current situation
3	40	White/licht-coloured bricks	Kleerekoper et al, 2012. Thermisch comfort in de stad	-
4	60	Light-coloured walls of limestone	Klok, 2010. Hittebeperkende klimaatmaatregelen voor Rotterdam onderzocht met Envi-met microschaal klimaatsimulaties.	Strategy 2&3

Annex B: Heat stress maps

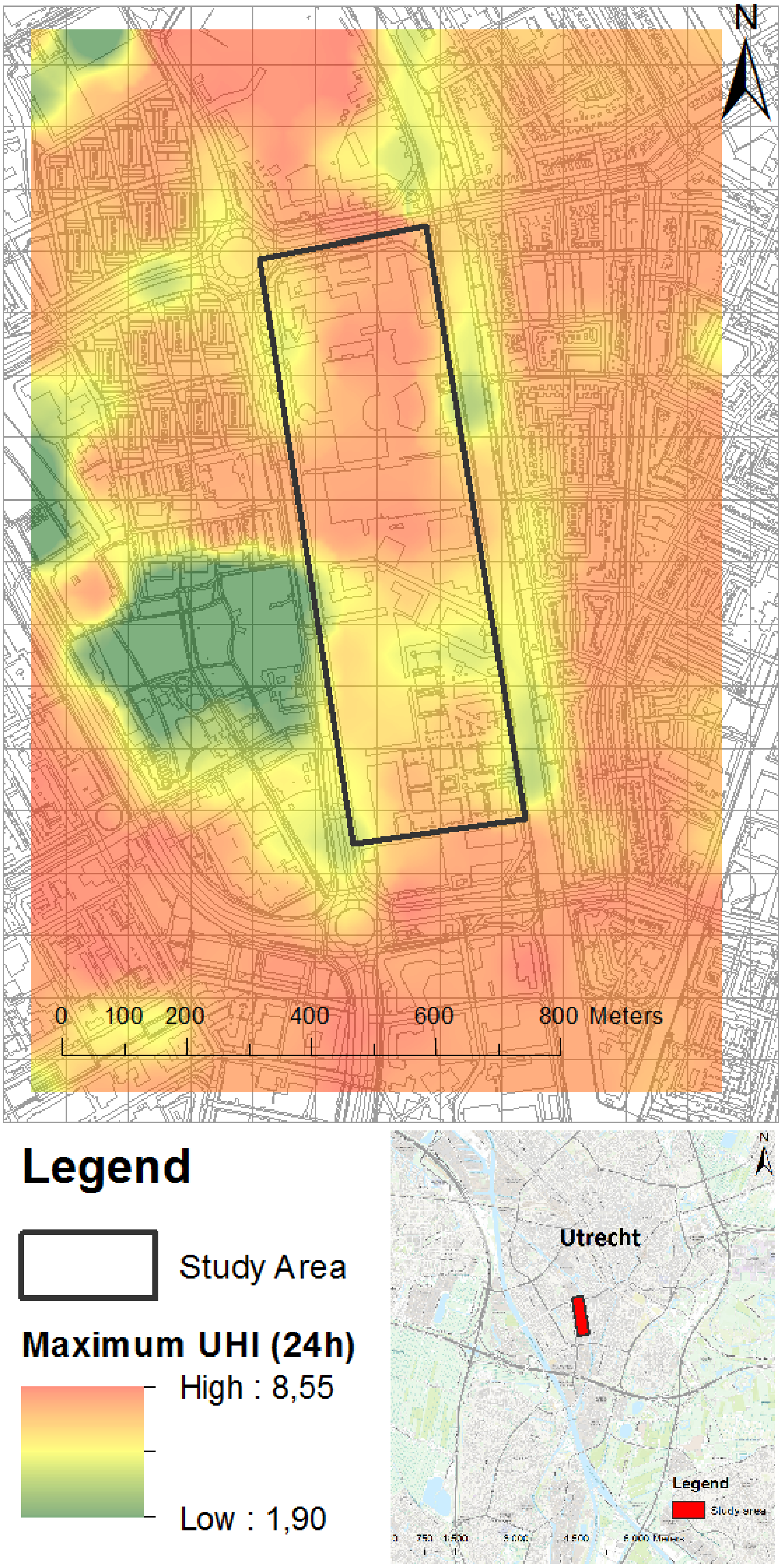
Current scenario: Daily mean heat stress map (UHI$_{24h}$)



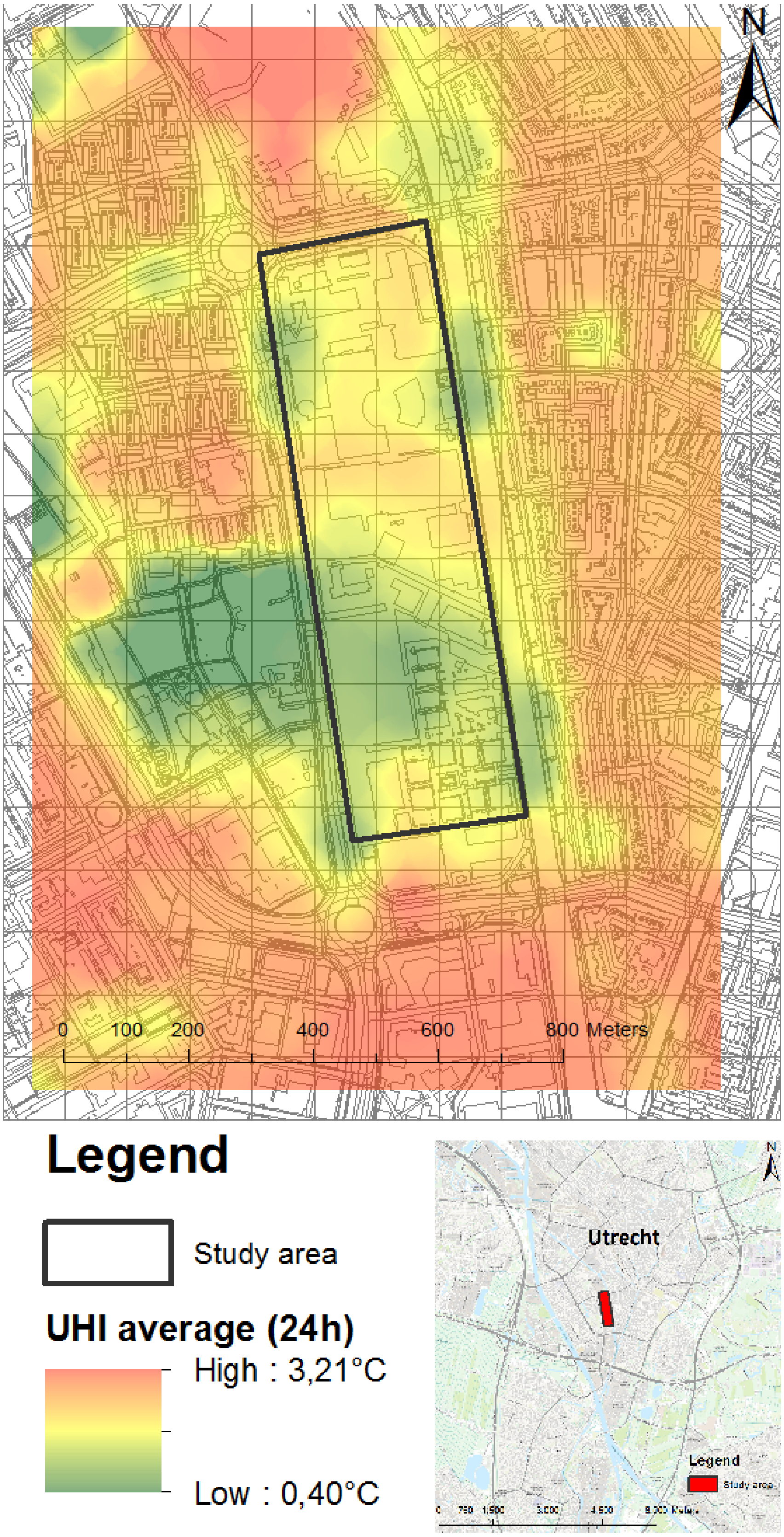
Current scenario: Daily mean heat stress risk map (UHI_{24h})



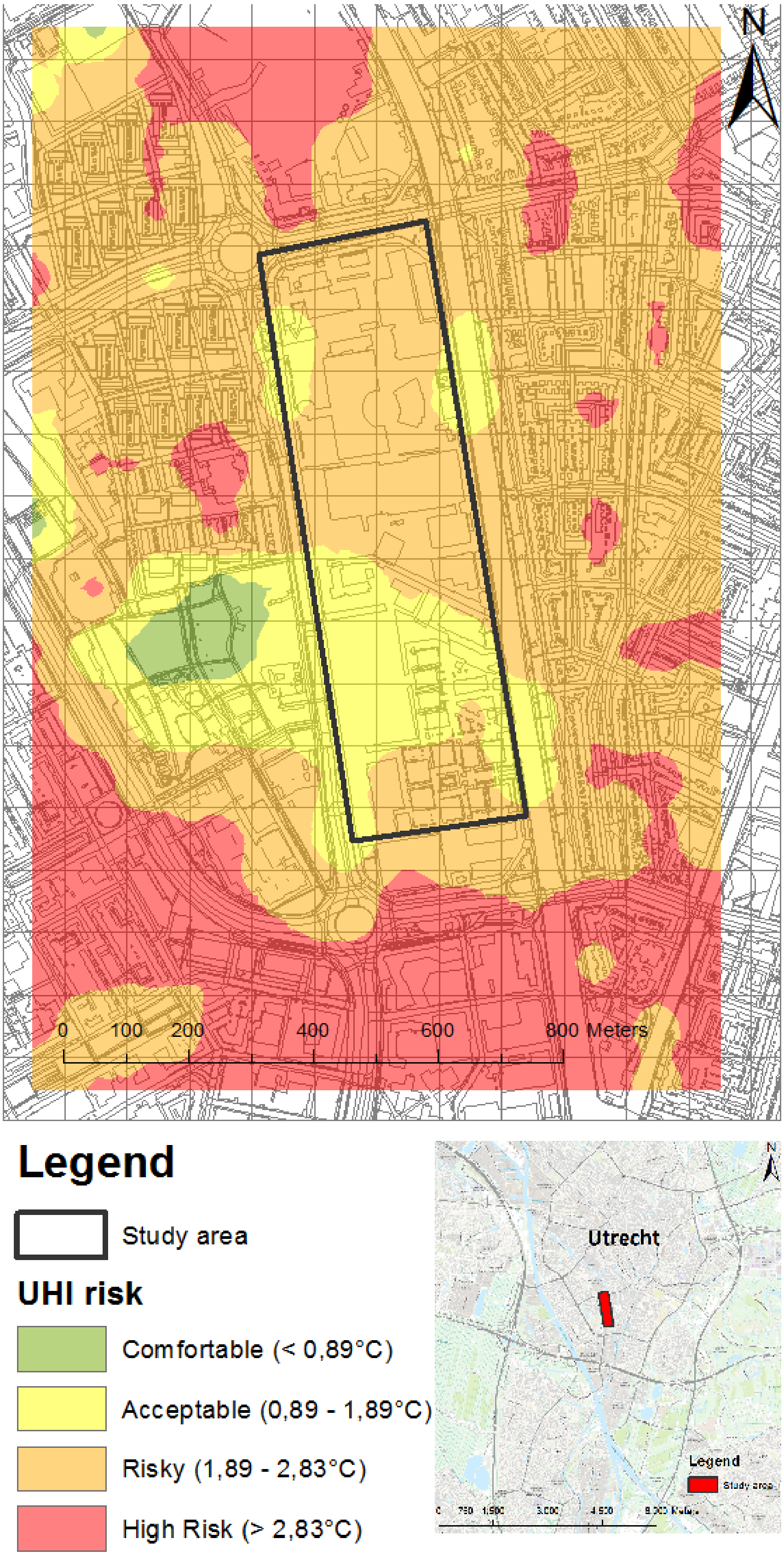
Current scenario: Massive heat stress (UHI_{max})



Strategy 1: Daily mean heat stress map (UHI_{24h})



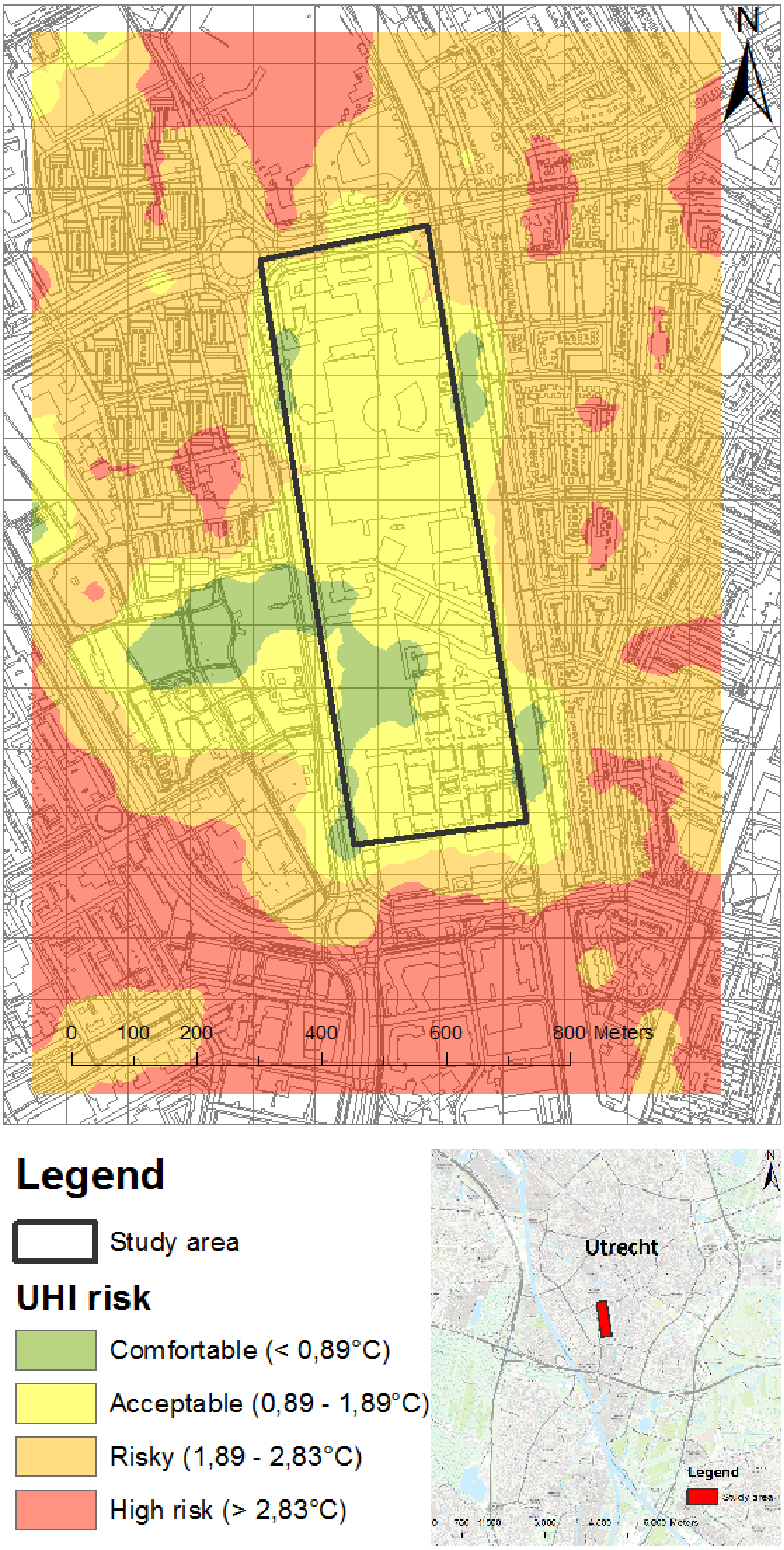
Strategy 1: Daily mean heat stress risk map (UHI_{24h})



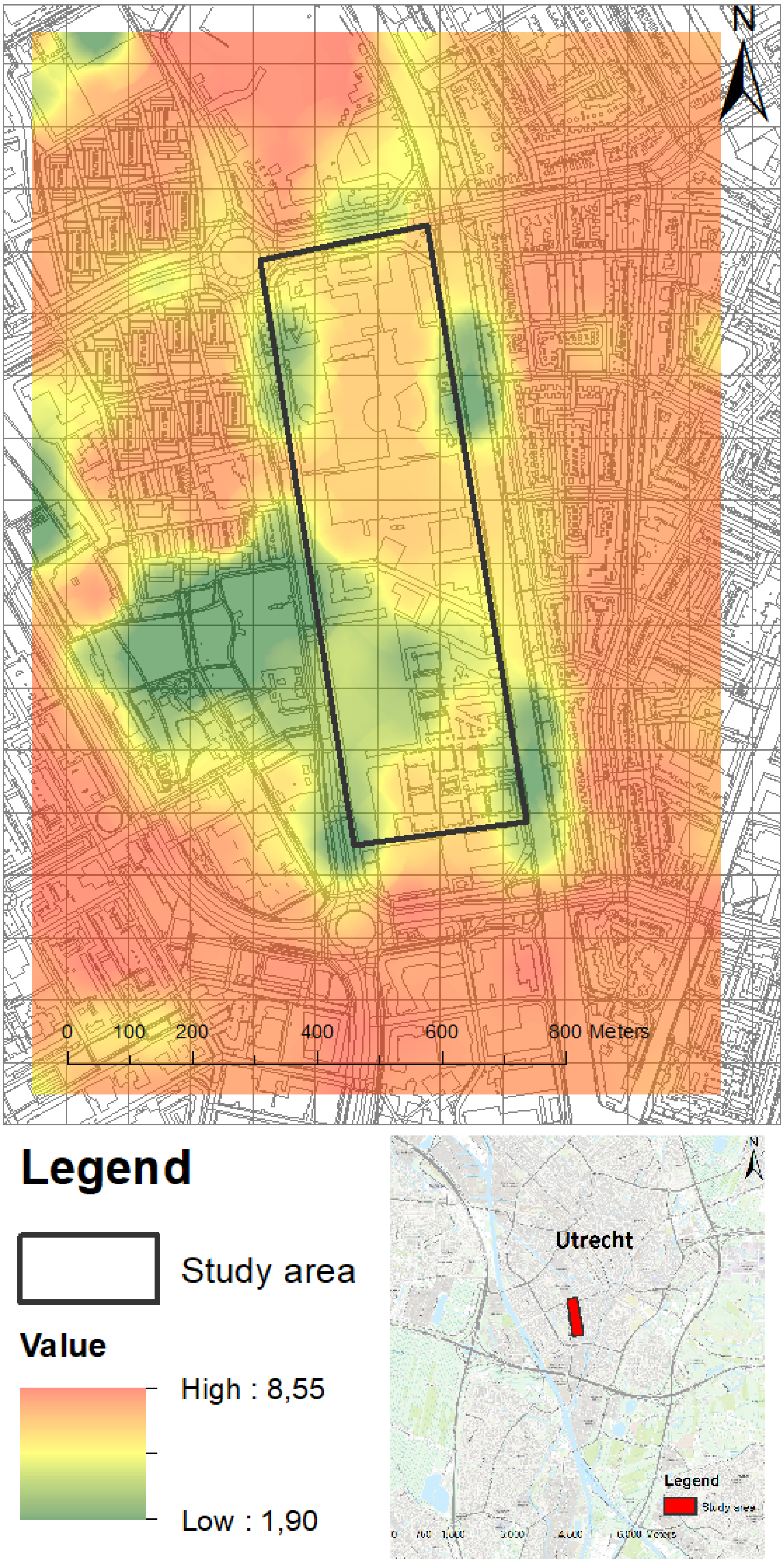
Strategy 1: Massive heat stress (UHI_{max})

Strategy 2: Daily mean heat stress map (UHI_{24h})

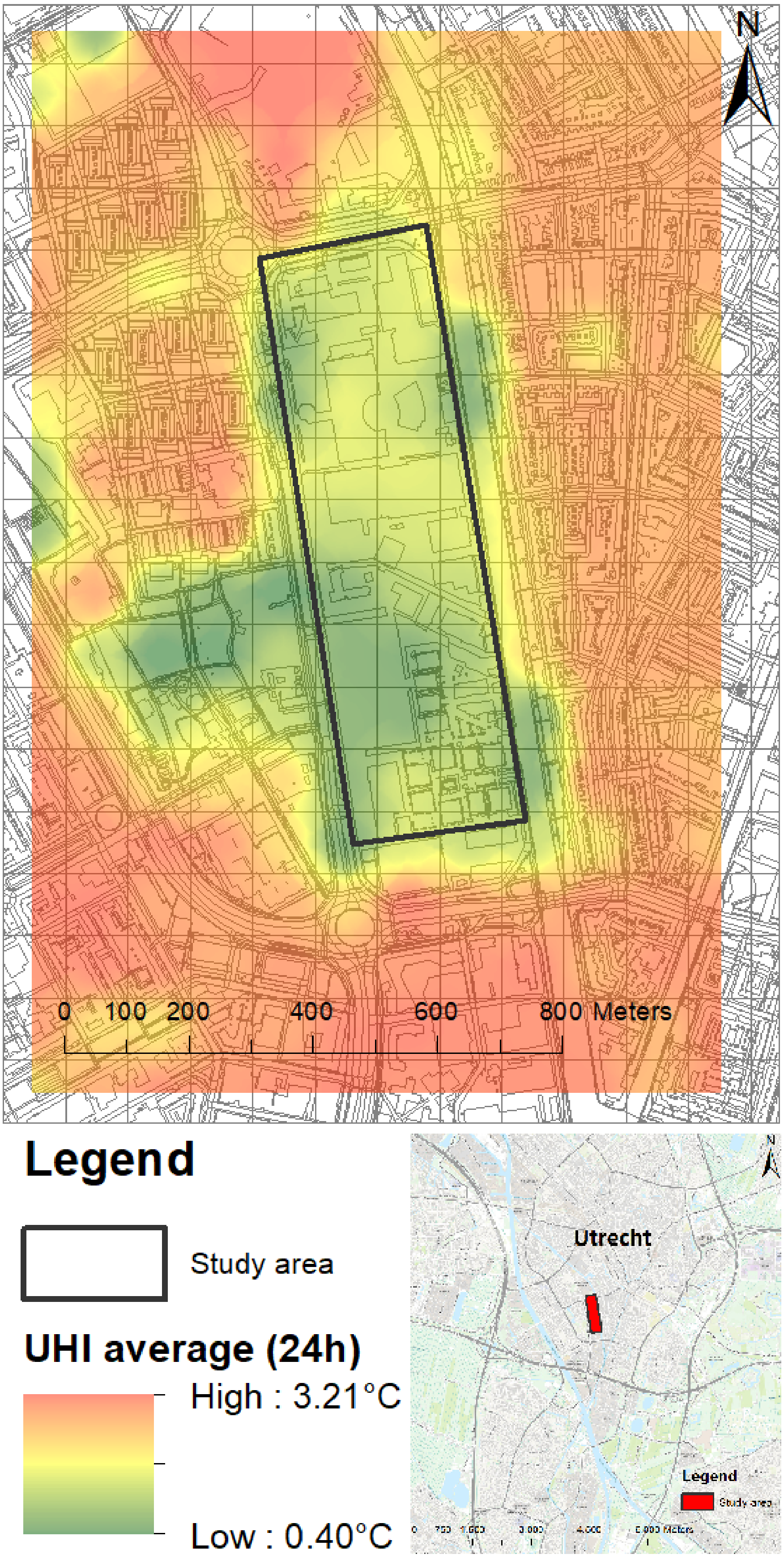
Strategy 2: Daily mean heat stress risk map (UHI_{24h})



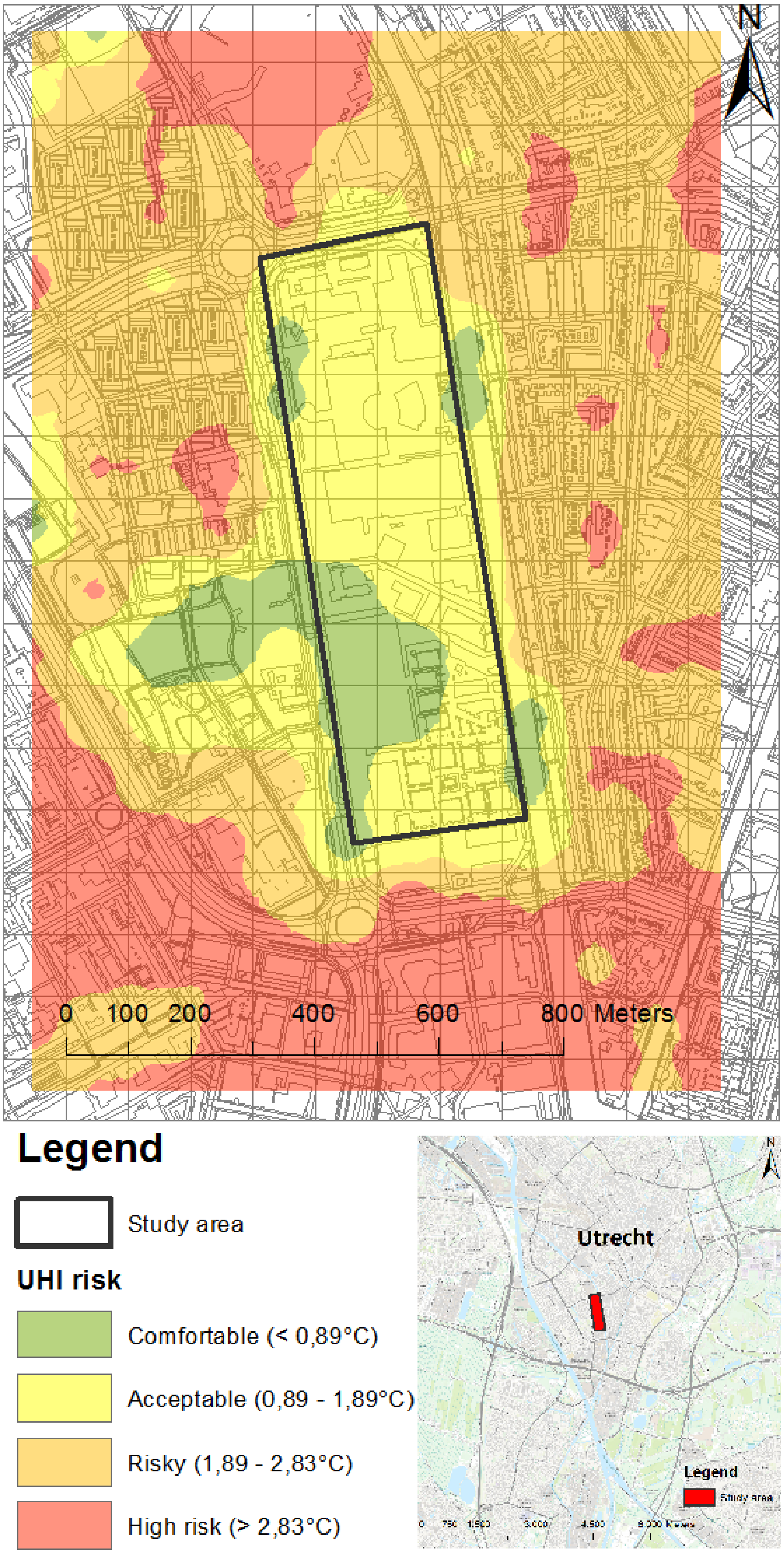
Strategy 2: Massive heat stress (UHI_{max})



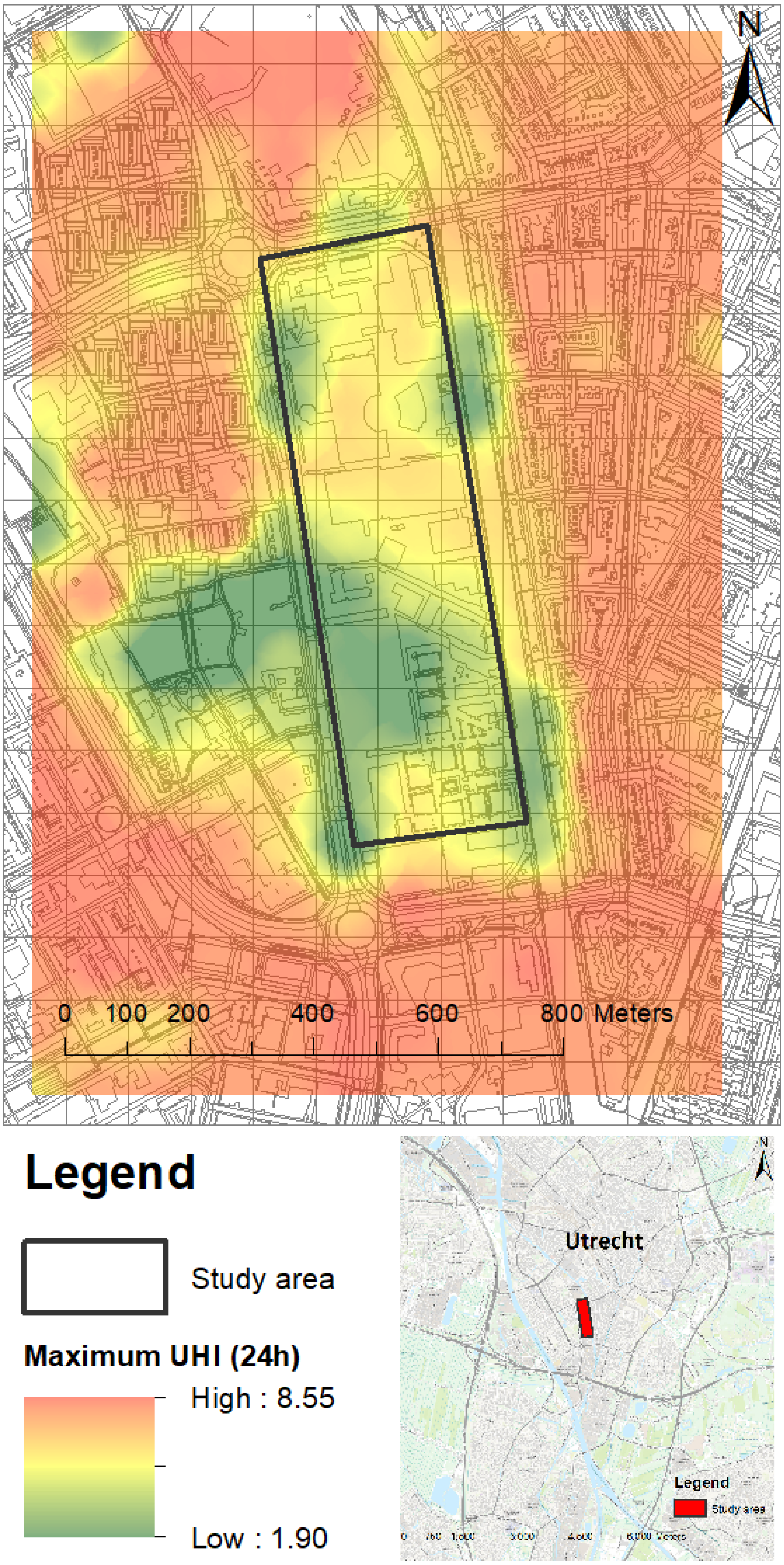
Strategy 3: Daily mean heat stress map (UHI_{24h})



Strategy 3: Daily mean heat stress risk map (UHI_{24h})



Strategy 3: Massive heat stress (UHI_{max})



Annex C: Social cost-benefit analysis

Costs

Heat stress measures	Current situation			Strategy 1			Strategy 2			Strategy 3		
Adjust the behavior of people (GGD)	DNA			DNA			DNA			DNA		
Orientation of buildings	DNA			DNA			DNA			DNA		
Cooling through ATES systems	DNA			DNA			DNA			DNA		
Public green - parks (Merwedepark)	DNA	hectare	-	14,48	hectare	89.523,38	DNA	hectare	-	14,48	hectare	€ 89.523,38
Spraying of roofs, facades and streets	DNA		-	DNA		-	DNA			DNA		
Green area within the street - inner areas	-	hectare	-	6,25	hectare	135.747,81	-	hectare	€ -	6,25	hectare	€ 135.747,81
Adjusting material and color use of streets	-		-	-		-	5,02	hectare	211.291,47	5,02	hectare	211.291,47
Isolation of buildings	DNA		-	DNA		-	DNA			DNA		
Adjust color and structure of roofs, including vegetation (green roofs)	-	hectare	-	-	hectare	-	10,59	hectare	€ 2.204.416,03	10,59	hectare	€ 2.204.416,03
Airconditioning	DNA		-	DNA		-	DNA			DNA		
Investment costs MWKZ - discounted over 50 years			**€ -**			**€ 225.271,20**			**€ 2.415.707,50**			**€ 2.640.978,70**

Benefits

Heat stress measures	Current situation			Strategy 1			Strategy 2			Strategy 3		
Adjust the behavior of people (GGD)	DNA			DNA			DNA			DNA		
Orientation of buildings	DNA			DNA			DNA			DNA		
Cooling through ATES systems	DNA			DNA			DNA			DNA		
Public green - parks (Merwedepark)	DNA	hectare	-	14,48	hectare	5.230.304,66	DNA	hectare	€ -	14,48	hectare	€ 5.357.018,64
Spraying of roofs, facades and streets	DNA		-	DNA		-	DNA			DNA		
Green area within the street - inner areas	-	hectare	-	6,25	hectare	1.951.754,46	-	hectare	€ -	6,25	hectare	€ 1.951.754,46
Adjusting material and color use of streets	-		-	-		-	5,02	hectare	1.606.523,00	5,02	hectare	1.606.523,00
Isolation of buildings	DNA		-	DNA		-	DNA			DNA		
Adjust color and structure of roofs, including vegetation (green roofs)	-	hectare	-	-	hectare	-	10,59	hectare	€ 6.157.766,13	10,59	hectare	€ 6.157.766,13
Airconditioning	DNA		-	DNA		-	DNA			DNA		
Benefits MWKZ - discounted over 50 years			**€ -**			**€ 7.182.059,12**			**€ 7.764.289,13**			**€ 15.073.062,23**

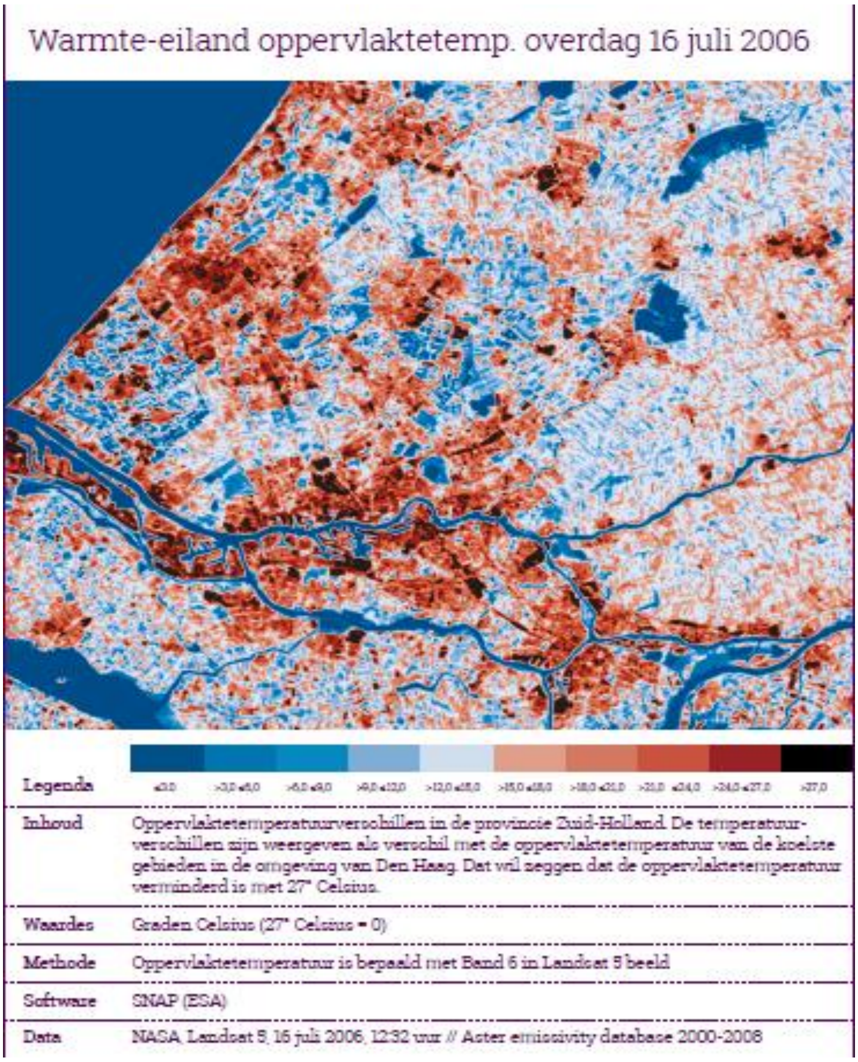
Direct benefits

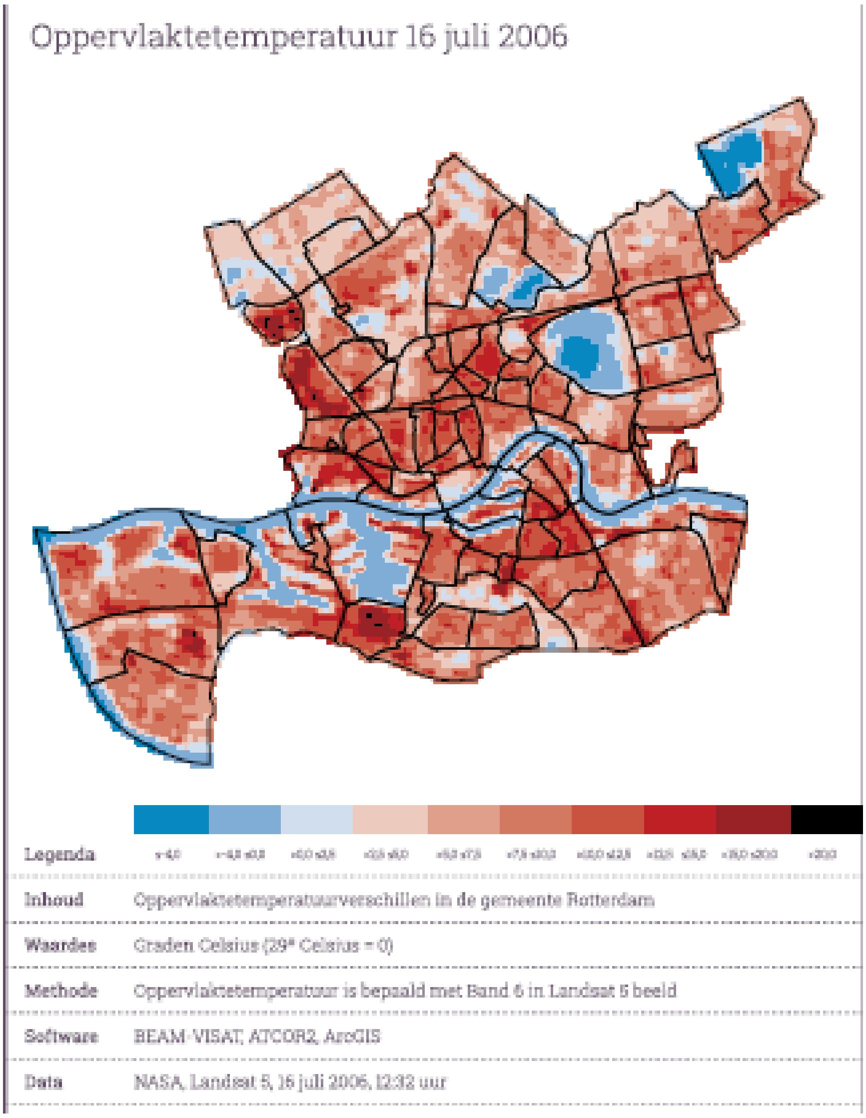
Heat stress measures	Current situation			Strategy 1			Strategy 2			Strategy 3		
Adjust the behavior of people (GGD)	DNA			DNA			DNA			DNA		
Orientation of buildings	DNA			DNA			DNA			DNA		
Cooling through ATES systems	DNA			DNA			DNA			DNA		
Public green - parks (Merwedepark)	DNA	hectare	-	14,48	hectare	1.634.255,77	DNA	hectare	€ -	14,48	hectare	€ 1.760.969,75
Spraying of roofs, facades and streets	DNA		-	DNA		-	DNA			DNA		
Green area within the street - inner areas	-	hectare	-	6,25	hectare	813.624,18	-	hectare	€ -	6,25	hectare	€ 813.624,18
Adjusting material and color use of streets	-		-	-		-	5,02	hectare	1.489.099,65	5,02	hectare	1.489.099,65
Isolation of buildings	DNA		-	DNA		-	DNA			DNA		
Adjust color and structure of roofs, including vegetation (green roofs)	-	hectare	-	-	hectare	-	10,59	hectare	€ 2.184.726,45	10,59	hectare	€ 2.184.726,45
Airconditioning	DNA		-	DNA		-	DNA			DNA		
Direct benefits MWKZ - discounted over 50 years			**€ -**			**€ 2.447.879,95**			**€ 3.673.826,11**			**€ 6.248.420,04**

Annex D: Table of different heat stress assessments

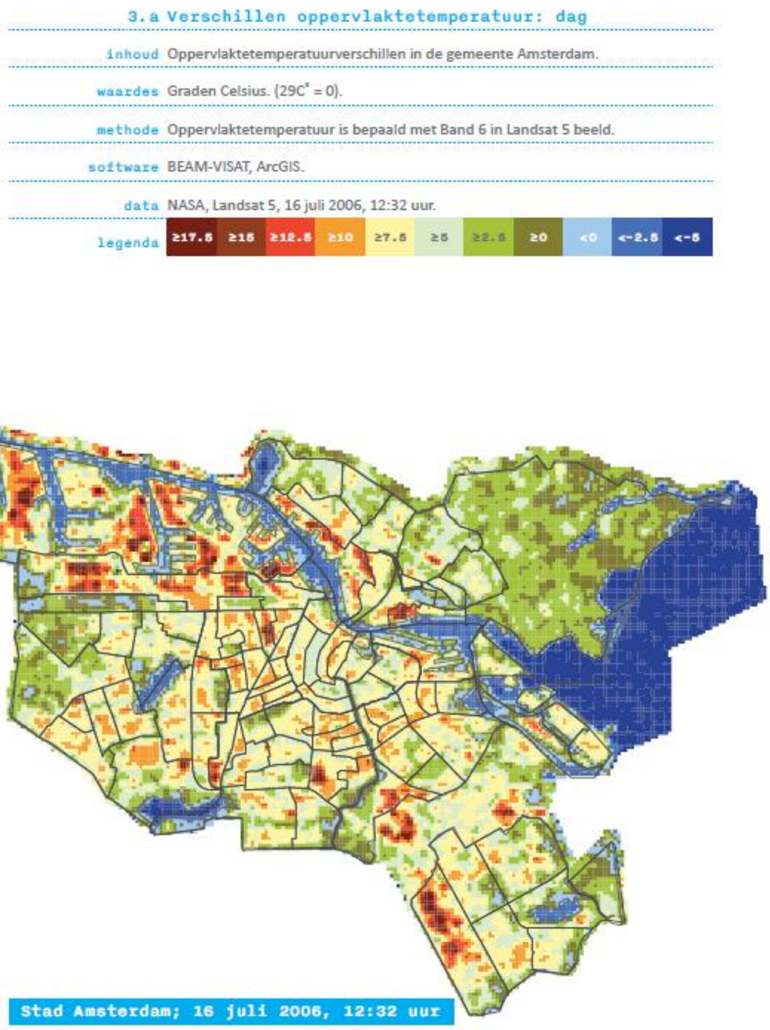
Type of heat stress model	Name of the model	Positive characteristics (+)	Negative characteristics (-)	Application
Applied values for heat stress	**Klimaatatlas** https://www.klimaatatlas.net/	+ Gains insight in an early stage for the problem heat stress	- Simplistic relations - No absolute values in legend - lacks documentation of the used method.	To visualize the heat stress over the Netherlands for every municipality in an early stage.
				

Air temperature measurements and satellite imaging	**HaagseHitte** (Hoeven & Wandl, 2018)	**+** Correlation of the UHI effect with the surface energy balance **+** correlation heat stress and mortality of elder people (75+)	- No adaptive measures can be implemented to create plans. Only recommendations can be given based on the current scenario. - Only applicable on the surface area of The Hague	An advisable tool for adaptive cooling strategies in the Hague

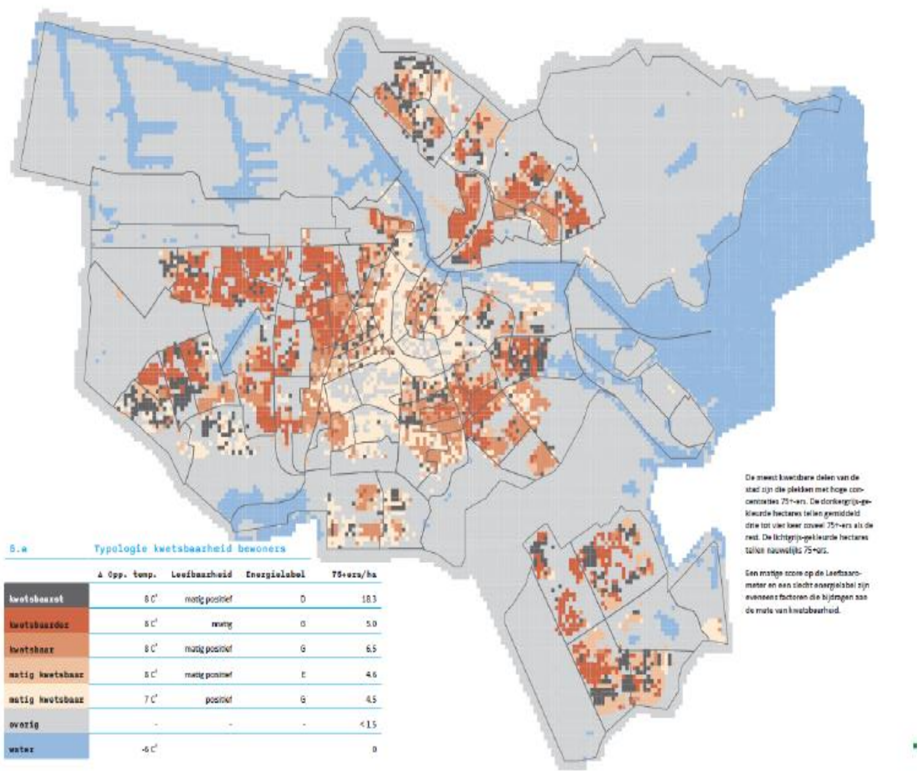


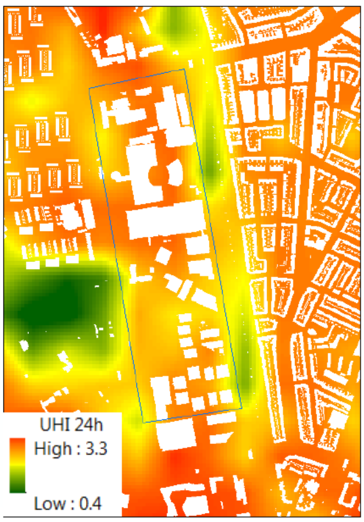
Air temperature measurements and satellite imaging	**Hotterdam** (Hoeven & Wandl, 2015)	**+** based on surface temperature measurements/ satellite imaging **+** Correlation heat stress and mortality of elder people (75+)	**-** No adaptive measures can be implemented to create plans. Just recommendation s can be given based on the current scenario. **-** UHI is not specified, only the surface temperature in the city	Create heat stress maps of Rotterdam city and shows the correlation between heats stress and health risk in order to raise attention for human health effects during a heat wave.
	 			

Air temperature measurements and satellite imaging	**Amsterwarm** (Hoeven & Wandl, 2013)	+ The influence of shadow by buildings is taken into account + A 3D-model is implemented to calculate the sky view factor to take into account the ratio between surface area and buildings + UHI maps distinguish the daily UHI and the UHI at night time	-Tests are processed on the basis of albedo and sky-view factor, however shadow and sky-view factor are dependent of each other. - Surface area indicated as traffic surface have a cooling effect because the surface area is topped by the foliage of trees.	Creates heat stress maps of Amsterdam to visualize the current heat stress and the vulnerability of its citizens in order to do recommendations to reduce the heat stress in parts of Amsterdam.

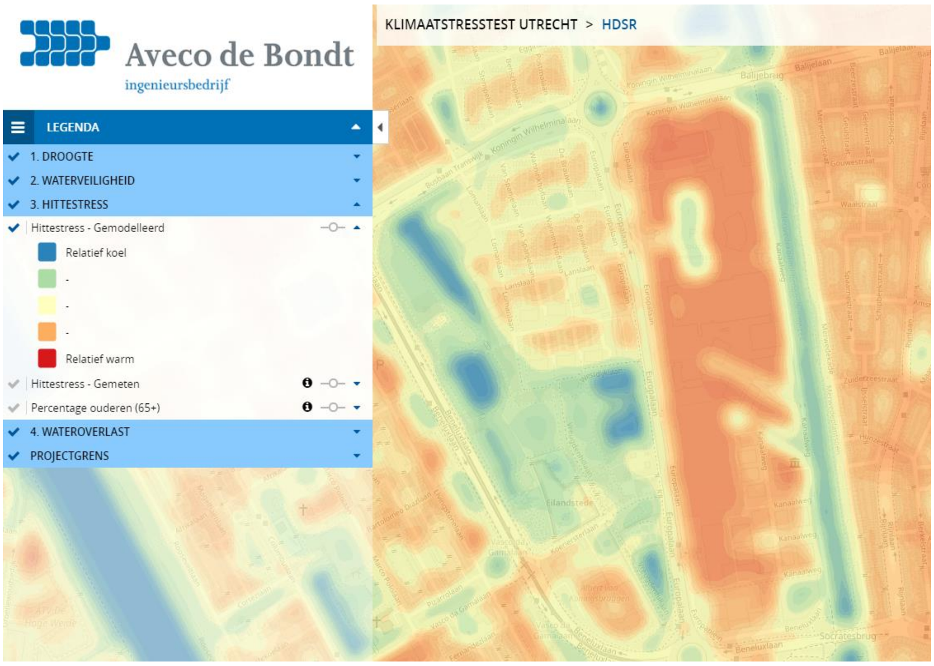


Air temperature measurements and satellite imaging	**Climate proof cities (CPC) TNO** (Rovers et al., 2014)	**+** The vulnerability map includes multiple factors such as energy label and employees per hectare. **+** Vulnerability expressed in three components: exposure, sensitivity and adaptability	**-** Vulnerability of heat stress on the basis of surface temperature **-** No UHI calculations and thus no comparison of urban temperature with rural temperature **-** The labelling method is not clear as it is too relative (no absolute numbers)	Research is carried out in broad context of urban development to see the impact of the Urban Heat island and to think of measures to decrease this effect.



Advanced heat stress Models	**UCAM (Urban Climate Assessment & Management)** (Groen et al., 2014)	+ Can broadly be used for every surface area + Easy to adjust values and implement adaptive cooling strategies + The simulation of heat stress is based on an existing heat wave and is validated on the basis of weather measurements. + The ability to make a time-lapse of 24 hour (per 1-hour) of heat stress to see the difference in massive and acute heat stress + takes into account local district characteristics such as density of buildings etc.	- No relation with social effects (such as mortality of elder people 75+) - Only includes district characteristics, albedo and % green as adjustable parameters. - Cannot distinguish between variety of green measures (e.g. trees and grass count the same). - Pre-processing the surface area is time consuming - Green roofs are not taken into account and cannot be implemented in the future simulations.	Heat stress model to simulate the UHI_{24h} and UHI_{max} for different surface areas.
				

Advanced heat stress Models	**Klimaateffectatlas** http://www.klimaateffectatlas.nl/nl/	**+** available for all parts of the Netherlands + open-source viewer which cover the Netherlands **+** includes information of massive heat in night time	**-** resolution is too small for adaptation plans (as this requires smaller resolution) **-** only available for the year of 2050 and current status - lacks open source documentation of the tool viewer.	This tool has been created to give a first impression for the future threats of flooding, heat stress, and droughts in specific areas across the Netherlands.

Advanced heat stress Models	**AvecodeBondt heat stress model** https://avecodebondt.geoapps.nl/klimaatstresstest_utrecht#dcedecf9-7665-e811-9406-00155d0ad53c	+ The ability to compare modelled data with measured values + Uses a small raster data grid which results in a good resolution	- Modelled data more extreme than the measured values - No absolute values in the legend - Lacks open source documentation to explain the data	Very detailed heat stress model to simulate the UHI for Utrecht.
				

<table>
<tr>
<td rowspan="2">Advanced heat stress Models</td>
<td>Atlas Natuurlijk Kapitaal

https://www.atlasnatuurlijkkapitaal.nl/kaarten</td>
<td>+ uses absolute values as in UHI (°C) in the legend

+ can show the UHI effect for the Netherlands

+uses a small resolution which enables to zoom in on local UHI</td>
<td>- UHI effect is based on mean air temperature differences between rural and urban on yearly basis

- Not able to simulate the UHI effect during heat waves

- Not able to show the UHI effect during the night-time.</td>
<td>Shows the urban heat island effect for the Netherlands and can be used for urban designers andclimate adaptation policy advisers to see where measures could be taken.</td>
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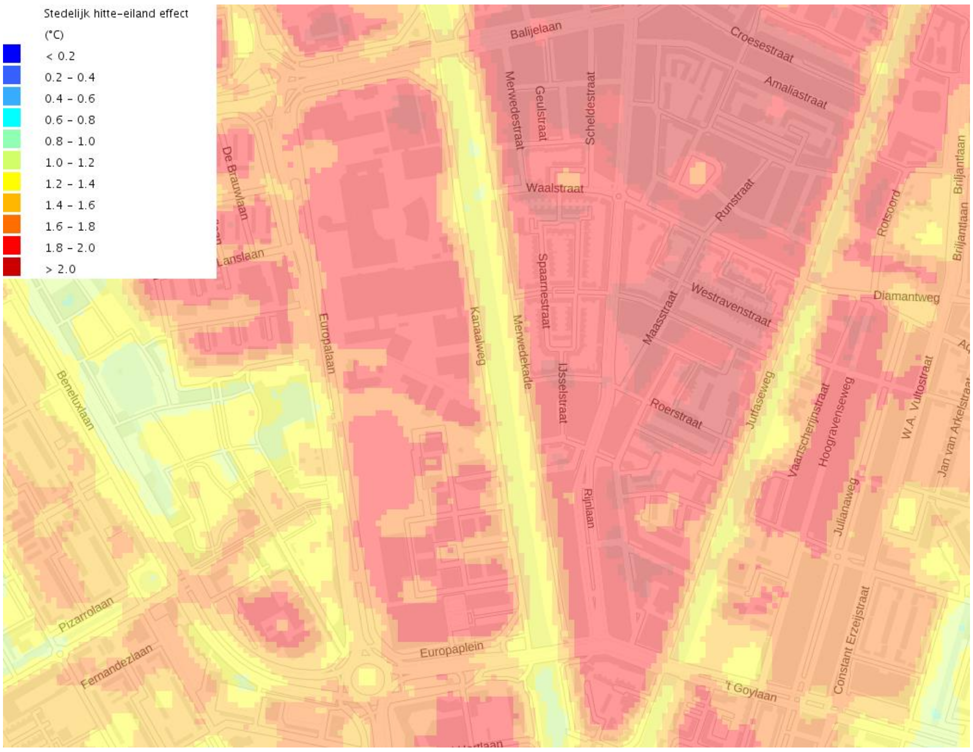
<td colspan="4">
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