Risk Management for Heat Stress and Pluvial Flooding in the Centrumgebied of Utrecht Science Park

Internship Research Project

Gebiedsontwikkeling

Vastgoed en Campus

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February, 2022

Abstract

The Gebiedsontwikkeling (GBO) team at Utrecht University are re-developing the centrumgebied of Utrecht Science Park with the ambition to provide a safe environment for users in the face of climate change. Climate change will most likely lead to an intensification of natural hazard severity and frequency, thereby enhancing the likelihood of disaster – the loss of life, injury, or destroyed and damaged assets. Therefore, understanding and mapping the risks presented by a changing climate is prudent.

Risk mapping is the evaluation of (natural) hazards and the exposure and vulnerability of a location and population to that hazard. Risk mapping was undertaken evaluating two hazards; heat stress and pluvial flooding across two severity scenarios. Exposure and vulnerability of the centrumgebied and its elements (i.e. population, buildings, land-use) was calculated using a multi-criteria analysis of key impact elements and their characteristics. Population vulnerability was evaluated for three scenarios, demonstrating to decision makers that this component dynamic, not static.

Merging the heat stress and flooding risk maps commonalities where maximal risk occur were identified, namely along transport infrastructure, vegetation and large areas of impermeable street surfaces. These locations of elevated risk provide GBO decision makers with a list of priority areas to focus redevelopment strategies and to plan suitable adaption and resilience measures into their designs.

To evaluate which adaption measures are most effective and suitable for the Centrumgebied, the Climate Resilience City toolbox / Klimaatbestendige Stad Toolbox (KBS) was used. This toolbox is an open source online software used to evaluate climate adaptation measures - both technical and nature based - to heat stress, drought and flooding. Using this tool, it was possible to map various scenarios onto the centrumgebied, both independently and with GBO stakeholders.

Measures were evaluated using a cost benefit analysis of relevant metrics relating to heat stress and flooding, revealing that adding trees to the city scape was the most effective measure against both hazards. Thereafter, the best nature based solutions were adding bioswales and rainwater detention ponds. The best technical solutions were green roofs with drainage delay, hollow roads and permeable pavements. Social Solutions, although unable to be mapped on the KBS toolbox, can have wide-spread impacts on how natural hazards are manifest into risk. Ensuring the local population is willing, informed and engaged with climate adaptation strategies is essential to ensure their efficacy. Living Labs have been identified as a methodology that involves diverse stakeholders in any given adaptation project. In this sense, Living Labs can tie together nature-based, technical and social solutions in an integrated form. Further, there is a need to test the effectiveness of each proposed measure and any possible co-benefits that may arise. The Living Lab methodology could do so with stakeholder co-creation, meanwhile addressing user values, behaviours and practices.

Follow up research evaluating how the proposed 2050 land-use design will impact the form of flooding and heat stress would provide valuable insight into how risk will manifest in the future vision. Testing measures from the KBS toolbox on this land-use design will provide a valuable comparison to this study. Finally, researching un-intended consequences and strategies to diversify the risk portfolio of GBO is necessary to ensure the campus is resilient to the impacts of future climate change.

Key words: Risk mapping, natural hazards, heat stress, flooding, climate adaption and resilience, nature based solutions, technical solutions, social solutions.

Contents

Acronyms

BV – Building Vulnerability

GBO – Gebiedsontwikkeling / Area Development

GIS – Graphic Information Systems

HU – Hogeschool Utrecht

IPCC – Intergovernmental Panel on Climate Change

KBS – Klimaatbestendige Stad Toolbox / Climate Resilient City Toolbox

MCA – Multi-criteria Analysis

NbS – Nature Based Solutions

PET – Physiological Equivalent Temperature

PV – population vulnerability

PV_DH – Population Vulnerability – Day, High Season

PV_DL – Population Vulnerability – Day, Low Season

PV_N - Population Vulnerability – Night

SEV – Socio-economic Exposure and building Vulnerability

UHI – Urban Heat Island

USP – Utrecht Science Park

UU – Utrecht University

UULabs - Utrecht University Living Labs for Sustainable Development

V&C - Vastgoed en Campus / Real Estate and Campus

1. Introduction

Climate change will intensify land degradation processes. This decline in land function is a result of inter-connected phenomenon known as “natural hazards”, which, magnified by climate change, manifest as “increases in rainfall intensity, flooding, drought frequency and severity, heat stress, dry spells, wind, sea-level rise and wave action, and permafrost thaw” (IPCC 2019, p.10). Human activities have unequivocally changed our climate and rapid and widespread action is necessary to manage the consequences. The aforementioned natural hazards are ones that we have faced collectively throughout history, but it is the frequency and intensity of these hazards which is now the key uncertainty. Although we (society) have directly contributed to climate change, we can still act to limit the negative consequences, as for all the aforementioned hazards, their “outcomes… [can be] modulated by land management” (IPCC 2019, p.10).

Each of these natural hazards can be expected to manifest in different ways depending on geographical location and associated land-use practices. The Netherlands is vulnerable to many of these hazards being a low-lying country situated on a delta, with its capital and many major cities located on the coast, while also depending heavily on agriculture – being the second biggest exporter of food in the world (Jukema, 2019). A platform built through a partnership between the European Commission and the European Environment Agency, evaluated the adaptation priorities of the Netherlands to be “warmer, wetter, dryer and rising sea level” (Climate-ADAPT, 2020). Specifically relating to heat stress, intense precipitation events, drought, and sea level rise. Heat stress and flooding (pluvial) are the focus of this report.

The Gebiedsontwikkeling (GBO) team at Vastgoed en Campus (V&C) are currently working toward the re-development of the centrumgebied of Utrecht Science Park (USP), situated on the eastern border of the municipality of Utrecht in the Netherlands. GBO are drawing up a vision and plans for 2050, with the ambition to make the centrumgebied a true public space where “the facilities and the built environment offer opportunities for the exchange of ideas and for new forms of cooperation” (Stedenbouwkundige Visie, 2020). Within this vision, there are plans to broaden the internationalisation of the campus, with “buildings for education, research and patient care will stand next to the catering industry, a hotel, conference facilities and a theatre. In addition, there is room for housing and entrepreneurship” (Stedenbouwkundige Visie, 2020).

In this context of future development coinciding with rapid warming and altering of climate norms, there is a unique opportunity to ensure climate resilience and adaptative practices are integrated into the plans for the re-development of the campus. To ensure the operations and lived experience of those working, studying, visiting and living at USP can continue to do so without their livelihood, homes and lives being threatened by natural hazards.

To do this, a literature review explores what the physical manifestations of the climate crises entails and how this impacts natural hazards. Next, a distinction will be made between hazard and risk, and how the risk equation can be used as a tool to identify the vulnerability and exposure of society to these natural hazards. Mapping the exposure, vulnerability and hazard potential as risk will provide a visual tool to identify key areas of risk, and their causation. Identifying locations to test strategies that either mitigate, adapt or allow the centrumgebied to become more resilient to natural hazards. Evaluating strategies that can be used to address climate risk, from technical, social and nature based solutions is key to understanding the various opportunities available to the USP, and which strategy is most suitable. It is hoped the results from this report will advise the V&C GBO team on how best to approach this period of instability presented by climate change and to ensure that the people, education, research, medical practices and operations of USP can continue long into the future.

Aim:

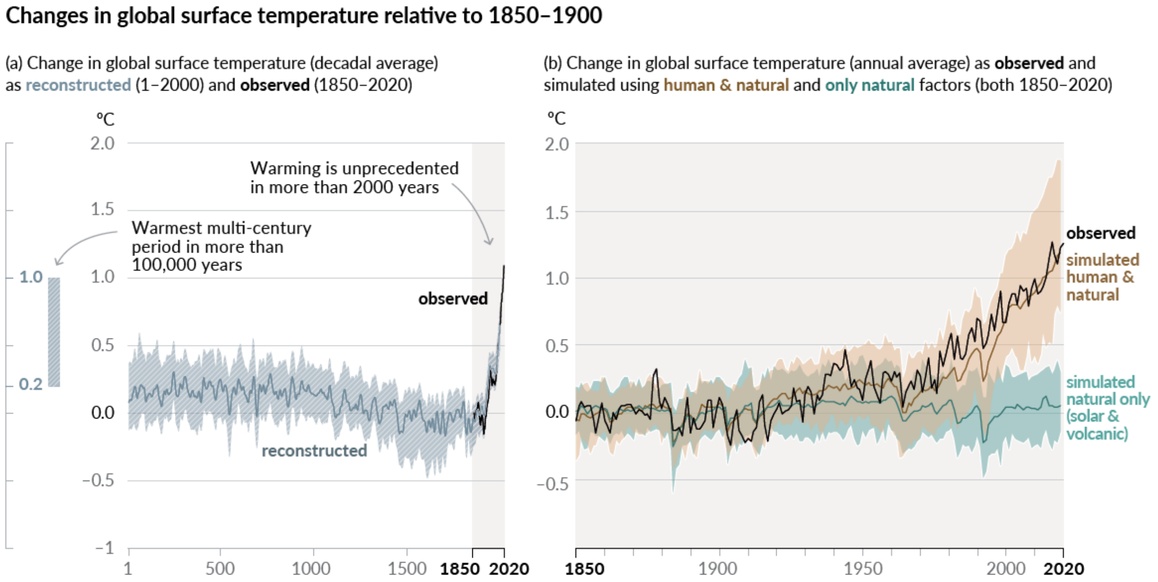
The aim of this research project is to analyse the risk faced in the centrumgebied from heat stress and flooding in the face of a changing climate. Combining socio-economic, building and population vulnerability and exposure with hazard maps, a detailed risk map will be developed. Based on this risk map, a series of strategies will be mapped and evaluated as to how the GBO team can incorporate technical, nature and social based solutions to either mitigate, adapt or become more resilient to these hazards.

2. Background

I. Climate Crises

In the face of the climate crises and the slow uptake of measures decided in the Paris Agreement by governments, alongside the inability to make serious commitments in COP26, means that increasingly it falls to individuals, organizations and enterprises to prepare for the impacts and consequences of a rapidly warming world.

In short, since the pre-industrial period (1850 CE) human activities have “unequivocally” led to the warming of the Earth’s atmosphere, ocean and land (IPCC 2021) (Figure 1). Our activities have set the planet on a trajectory of continued warming which impacts the relative stability of the climate that we’ve experienced for the last 10,000 years which gave rise to agriculture and the development of civilisation (Gowdy, 2020). This warming will destabilise these climate norms leading to increasing variability and unprecedented events (IPCC 2021). Warming impacts the cryosphere, meteorological conditions, sea-level rise and habitable zones within various biospheres. Not only is the emission of greenhouse gases and the associated warming causing havoc on climate norms, but our actions are also leading catastrophic biodiversity and pollinator loss, soil erosion and desertification, water and air pollution and natural resource depletion (IPCC, 2019).


Changes in global surface temperature relative to 1850–1900

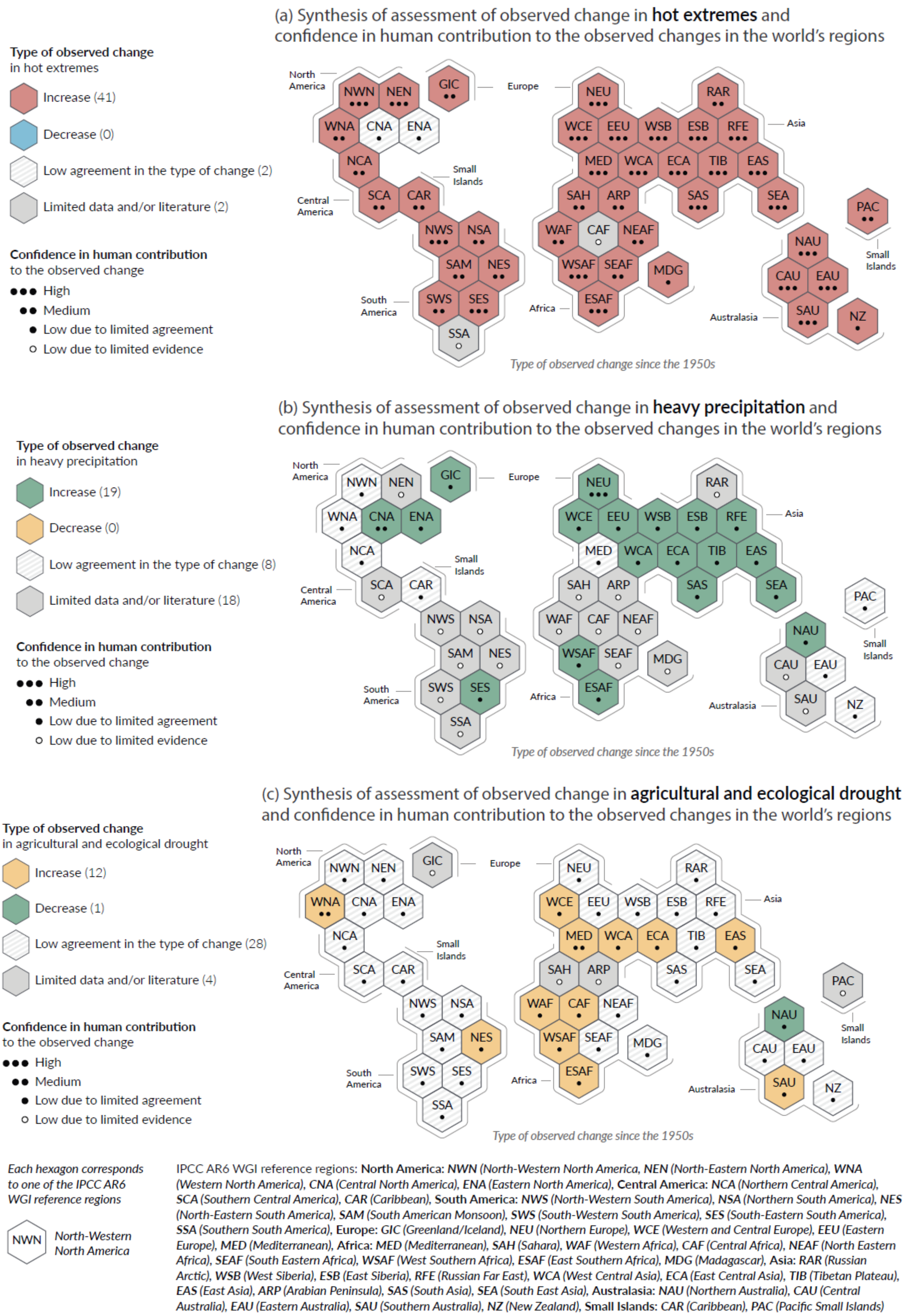
(a) Change in global surface temperature (decadal average) as reconstructed (1–2000) and **observed** (1850–2020)

(b) Change in global surface temperature (annual average) as **observed** and simulated using human & natural and only natural factors (both 1850–2020)

Figure 1: Global surface temperature variation. Changes relative to 1850-1900. Figure adapted from IPCC, 2021.

Human activities have increased the chance of compound extreme events, which are the “combination of multiple drivers and/or hazards that contribute to societal or environmental risk” (IPCC, 2019, p.9). With climate change, processes of land degradation, i.e. undesirable change or disturbance to land, are exacerbated. Land degradation can take place as a result of human activity and are modulated by land-management practices, but natural phenomena such as increases in rainfall intensity and flooding, the frequency and severity of drought, heat stress and sea-level rise, to name a few, can all lead to the break-down and destruction of the biophysical environment (IPCC, 2019).

Hereafter follows an exploration of climate related hazards that all contribute to land-degradation, and how these are expected to evolve as a consequence of climate change and projected warming.



(a) Synthesis of assessment of observed change in **hot extremes** and confidence in human contribution to the observed changes in the world's regions

(b) Synthesis of assessment of observed change in **heavy precipitation** and confidence in human contribution to the observed changes in the world's regions

(c) Synthesis of assessment of observed change in **agricultural and ecological drought** and confidence in human contribution to the observed changes in the world's regions

IPCC AR6 WGI reference regions: **North America:** *NWN (North-Western North America, NEN (North-Eastern North America), WNA (Western North America), CNA (Central North America), ENA (Eastern North America),* **Central America:** *NCA (Northern Central America), SCA (Southern Central America), CAR (Caribbean),* **South America:** *NWS (North-Western South America), NSA (Northern South America), NES (North-Eastern South America), SAM (South American Monsoon), SWS (South-Western South America), SES (South-Eastern South America), SSA (Southern South America),* **Europe:** *GIC (Greenland/Iceland), NEU (Northern Europe), WCE (Western and Central Europe), EEU (Eastern Europe), MED (Mediterranean),* **Africa:** *MED (Mediterranean), SAH (Sahara), WAF (Western Africa), CAF (Central Africa), NEAF (North Eastern Africa), SEAF (South Eastern Africa), WSAF (West Southern Africa), ESAF (East Southern Africa), MDG (Madagascar),* **Asia:** *RAR (Russian Arctic), WSB (West Siberia), ESB (East Siberia), RFE (Russian Far East), WCA (West Central Asia), ECA (East Central Asia), TIB (Tibetan Plateau), EAS (East Asia), ARP (Arabian Peninsula), SAS (South Asia), SEA (South East Asia),* **Australasia:** *NAU (Northern Australia), CAU (Central Australia), EAU (Eastern Australia), SAU (Southern Australia), NZ (New Zealand),* **Small Islands:** *CAR (Caribbean), PAC (Pacific Small Islands)*

Figure2: Global synthesis of observed changes in a) hot extremes, b) heavy precipitation and c) agricultural and ecological drought. Widespread increases across all three factors is noted, demonstrating that climate change is already impacting every inhabited region in the world. Figure adapted from IPCC, 2021.

II. Explanation of Hazards: Why they occur more with climate change:

Extreme events:

A warming climate increases the incident of extreme events. In the past, events of a certain size, intensity and duration were infrequent, and dependant on the coalescing of various meteorological factors such as patterns of natural climate variability for instance El Nino and La Nina (IPCC 2021). However, with increased warming, these previously extreme events will become the normal, as "every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (very likely), and heavy precipitation (high confidence), as well as agricultural and ecological droughts in some regions (high confidence)." (IPCC 2021, p. 15) (Figure 2). A warmer climate will intensity both very wet and very dry weather as well as climatic events and seasons, which has clear consequences for flooding and drought (IPCC, 2021). For example, higher temperatures provide more energy to the hydrological system, so events such as hurricanes will become stronger, and more intense. Further, blocking anti-cyclones can persist and generate heat waves and droughts that can last for durations much longer than anything we've experienced in the past. Even with 1.5°C of global warming, "there will be an increasing occurrence of some extreme events unprecedented in the observational record" (IPCC 2021, p. 15) (Figure 3).

Studying Figure 3, it is possible to see how changes is in shifted mean, increased variability and changed symmetry can all impact the extremes felt by climate change. The integral under the curve changes at the 95th quartile much faster than the mean (Willows & Connell, 2003). This results in more rapid changes in extremes than the mean. It is most likely that a combination of these three graphs is what takes place, which in any case, results in a change in extremes.

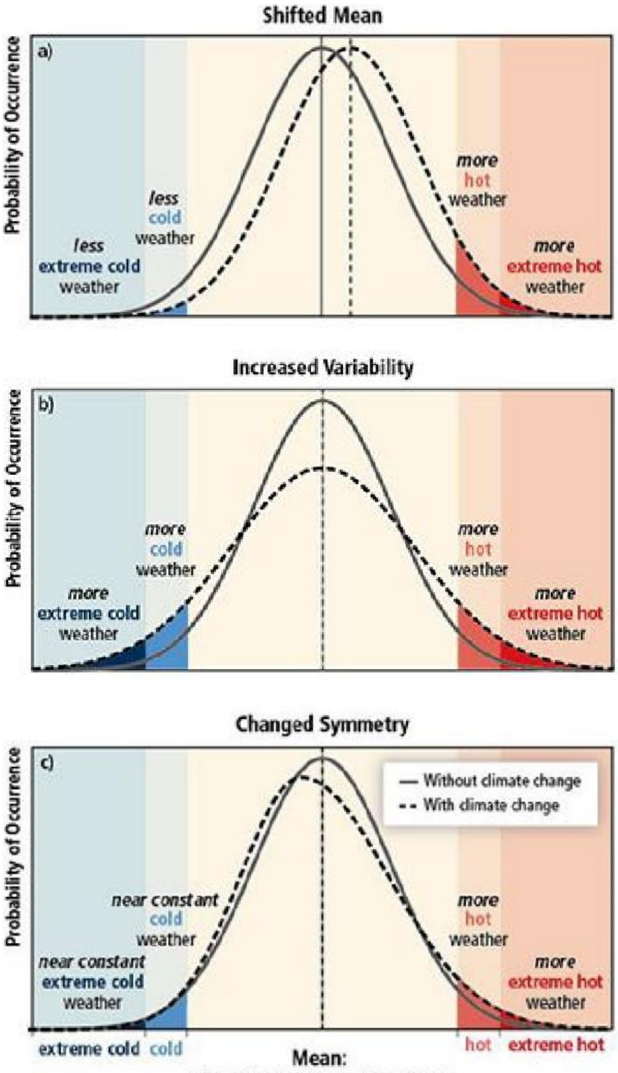


Figure 3: How changes in a) shifted mean, b) increased variability and c) changed symmetry impacts weather and temperature extremes. Figure adapted from IPCC 2012.

Heat Stress:

Heat waves and Drought

Heat stress is a physical manifestation of a blocking high pressure system. These high pressure systems, also known anticyclones, can become “stuck” over an area for a few days up to several weeks, leading to what is commonly referred to as a “heat wave”. These blocking anticyclones are formed as a consequence of soil moisture and sea-surface temperature (Vautard et al., 2007). Warm sea-surface temperatures are the trigger for the formation of anti-cyclones and their characteristic warm and dry air. These systems with their dry air promote increased transpiration in plants and vegetation and rapidly dry out the soils which can lead to wide-spread droughts (Vautard et al., 2007). This increase in sensible heat-flux from dried out soils can help maintain this anticyclone, increasing the period in which it’s stationary and “blocking”, thereby extending the period of the heatwave (Yuya & Hiroyuki, 2011). Researchers have found that the “memory” of soils has a direct impact on the degree to which extreme heat events occur, with heat-waves in central US tend to be preceded by periods of drought (Chang and Wallance, 1987), and summer time European heatwaves are a consequence of winter-time rainfall deficits (Vautard et al., 2007).

With projected warming of the oceans to continue, and human induced climate change leading to increased ecological and agricultural droughts as a consequence of increased land evapotranspiration, it seems increasingly likely that heatwaves are to become more frequent and intense in the years to come (IPCC, 2021).

Night-time temperatures x Urban Heat Island

High night-time temperatures have a direct link with excess mortality (Matthies and Menee, 2009). This is because peoples core-temperatures that have risen during the day are un-able to cool down in the night, and people may not realise that their core temperatures are rising while they are asleep where-as they could take action were they awake.

Heat waves are compounded by a phenomenon known as the “Urban Heat Island” effect. The Urban Heat Island (UHI) can add between 1°C - 6°C to ambient air temperatures, absorbing this heat during the day-time, and radiating it out at night; significantly raising night-time temperatures (Matthies and Menee, 2009). More than 50% of the world’s population currently live in cities, and this densification of space is leading to natural systems becoming artificial ones, with poorly ventilated concrete “canyons” with black asphalt roads raising thermal storage capacities and “point-sourced” heating via vehicles and air-conditioning that further amplify temperatures (Luber and McGeehin, 2008).

Therefore, not only is human activity exacerbating the natural phenomena that cause these impacts, but so too is the very environment in which a majority of the human population currently reside. The built-environment is amplifying these hazards to cause compound events that pose a serious risk to human health and well-being.

Flooding

Rainfall intensity

With additional warming, the frequency and intensity of heavy precipitation events is “very likely” to increase, with an estimate of 7% increase in intensity of extreme daily precipitation for each 1°C of global warming (IPCC, 2021) (Figure 4). With more intense and frequent heavy rainfall, the associated pluvial flooding events are also projected to become more intense and frequent among many regions, including the Pacific Islands and much of North America and Europe (Figure 2) (IPCC, 2021).

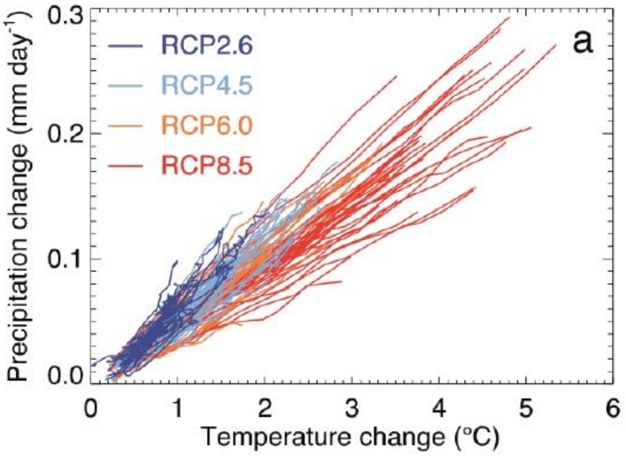


Figure (4): Relationship between temperature change and precipitation change for various 'representative concentration pathways' (RCP) scenarios. Figure adapted from IPCC 2013

Generally speaking, warmer temperatures accelerate the hydrological cycle, with warmer temperatures increasing the rate of evaporation over the oceans. Based on the Clausius-Clapeyron relation, warmer air temperatures can hold more water – at a relationship of 7% more water per 1 degree Kelvin, implying warmer temperatures will therefore lead to more rainfall. However, recently modelling from the Royal Netherlands Meteorological Institute (KMNI) found that this relationship can be up to 14% per degree of warming in many parts of Europe (Lenderink & Meijgaard, 2008). Their results imply that changes in short-duration precipitation extremes are scaling faster than expected compared to the classically accepted Clausius-Claperyon relation, and the extremes may be twice as high - leading to significant impacts in terms of local flooding, water damage and erosion (Lenderink & Meijgaard, 2008).

Increased rainfall also has other implications for the hydrological cycle – increased runoff into rivers increases stream flow and the erosive power of rivers. This increased water load can lead to overflow of river banks and flooding of historical flood plains. However, the modern challenge of over-population and our previous technological fixes have led us to collectively forget the need for floodplain and wetland preservation, and infrastructure such as housing, business and transport have all been allowed to be built on flood plains (Halliday, 2020). With extreme events predicted to become more frequent and intense, it can be expected that fluvial flooding will increasingly overwhelm infrastructure that was previously safe from flooding.

Further, as with the UHI enhancing the impact of heat stress and heat waves, our urbanised environment with high degrees of impermeable surfaces, the concentration of water in sewers, and the destruction of natural buffer systems (i.e. wetlands and forests) all leads to the increased likelihood of intense rainfall to manifest into floods.

Sea level rise

Warming of our climate system has resulted in multiple factors leading to sea-level rise. Thermal expansion is responsible for 50% of the sea level rise between 1971-2018, with glacial ice loss accounting for 22%, followed by ice-sheets with 20%, and land-water storage variability contributing 8% (IPCC, 2021).

Again, with this relative sea level rise, extreme events that only occurred once per 100 years in the recent past are now projected to occur at the very least once per year at more than 50% of all tide gauge locations by 2100 (IPCC, 2021). This sea level rise will contribute to increases in severity and frequency of coast flooding, especially to low-lying areas such as the Netherlands and Bangladesh, and to coastal erosion along a majority of sandy coasts (IPCC, 2021).

Storms

Warming atmospheric temperatures have a threefold impact on storms. Warmer sea surface temperatures increases the amount of water that is evaporated. Warmer atmospheric temperatures allow for more water vapour to be held in the atmosphere, and finally warming will ensure that greater swathes of oceans reach the minimum temperature of 26.5°C necessary for tropical cyclones (hurricane/ typhoon) formation.

According to future projections by Knuston et al., (2010), the intensity of tropical storms are predicted to increase by 2-11% by 2100. There is low confidence in the long-term regarding the frequency of these storms (IPCC, 2021), with Knuston et al., (2010) predicting a reduction in frequency of 6-34%, balanced by a substantial increase in the frequency of the most intense cyclones when modelled at a higher resolution. Challenges with computer modelling of these complex systems limits our ability for clear predictions, but based on current understanding we can expect tropical cyclones to become more intense in the next 80 years.

Impacts to Cities

Around 55% of the world's population currently live in cities, and this is predicted to increase to 70% by 2050 (World Bank, 2020). The very nature of cities, with large percentages of concrete and tarmac surfaces, limited green space, and many sources of heat and carbon emissions result in an intensification of warming (IPCC, 2021). Rising urbanisation in combination with more frequent heat waves will lead to the increase in severity of these extremes within urban contexts (IPCC, 2021).

Urbanization also compounds mean and heavy rainfall precipitation, both over and downwind of cities, especially regarding the run-off intensity due to high percentages of impermeable surfaces and rapid water flow through sewers (IPCC 2021). In coastal cities, the combination of extreme rainfall and river overflow events are combined with the prospect of extreme sea level events such as sea level rise and storm surge, highly increasing the probability of flooding (IPCC, 2021).

III. Hazards and Risk

Natural hazards are the physical manifestation of various atmospheric, land-surface and oceanographic processes, and have been cited as fundamental processes in the restructuring and shaping of our natural environments (Cook et al., 2018). It is only when human beings and their associated systems (agriculture, infrastructure and possessions) are exposed to these natural hazards does the concept of risk enter the equation.

As surmised by Cutter (1996); "Risk has two domains: it includes the potential sources of risk (industrial, flooding, transportation) and the contextual nature of the risk itself (high consequence, low consequence)." (p.536). Cutter developed a schematic where various factors of society and geography interact, intersect, and feedback to map the inter-relations of hazard and risk (Figure 5).

Hazard potential is the balance between risks and mitigation, with mitigation being strategies that actively reduce or prevent the hazard (UNEP, n.d.). Risks can be modified by mitigation, either reducing the hazard potential through good mitigation practices, or amplifying risk through poor or no mitigation practices (Cutter, 1996) (Figure 5).

Hazard potential is modified through its relationship with the "social fabric of society", i.e. societies ability to respond, the understanding of risk, socio/economic indicators, and its relationship with "geographic context", i.e. the location, situation and proximity to the hazard (Cutter, 1996). These two "filters" determine the overall social vulnerability and the biophysical vulnerability respectively, which together form the "place vulnerability" (Cutter, 1996). This is a closed loop, so place vulnerability is fed back into risk and mitigation, which can either positively or negatively impact both the risk and mitigation of a hazard (Figure 5).

The reason for increasing research in how to minimise risk is a function of the costs associated with our civilisation. Aforementioned hazards are becoming more extreme and intense, and it is the risk of civilisational assets (housing, infrastructure, logistics, farming), the loss of life (human, non-human) and destruction to environment and associated ecosystem services (water, food, recreation, climate regulation) which makes these growing hazards such a risk.

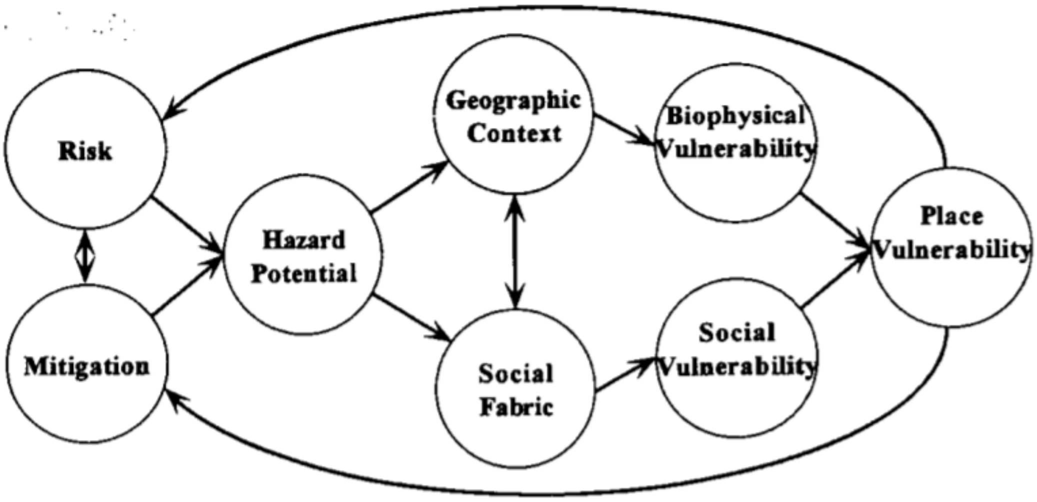


Figure 5: The Inter-relations of hazard and risk. This flow map shows how risk, hazard, and socio- economic and geographical factors inter-relate with risk. So too how mitigation feeds into this loop and how all these factors are related in the formation of risk. Figure Adapted from Cutter (1996).

Let's go through this framework using heat waves as an example.

Starting with the hazard potential. At a base level, heat waves threaten human lives. This risk is in the form of not being able to keep the body's core temperature at the normal level (35.6-37.5 °C), which manifest in heat cramps, heat stroke and even death. These risks can be mitigated through practices such as air-conditioning, increased fluid intake and staying out of the full sun, especially at the hottest times of the day.

The geographic context is place based. The Netherlands, along with the rest of Europe, is expected to experience increasingly intense and extensive heat waves in the summer months (IPCC, 2021). Europe has already experienced such heat waves in the past, such as in June and July 2019 when two distinct heatwaves set all-time high temperature records, with a new Dutch record breaking temperature of 40.7°C being recorded in North Brabant. Further, the Dutch are the most densely populated country in the EU, and one of the most densely populated countries in the world, with over 92% of the population living in cities (O'Neill, 2021). Thus the geographic context and the biophysical characteristics of the Netherlands can be said to be vulnerable to the hazard of heat waves.

The social fabric, and social vulnerability is the lens through which the biophysical vulnerability to a hazard is experienced by society. The degree to which a population can suffer harm when exposed to a hazard is directly related to socio-economic and demographic characteristics (Dong et al., 2015). Unfortunately, the way that society has organised itself is an unequal one, and the impacts of hazards such as heat-waves are also felt unequally. Extreme heat disproportionally affects the old, the very young, the disabled, the poor and the marginalised – with ethnic minority groups being especially vulnerable during heatwaves. This was exemplified during the 2006 Los Angeles heat wave where African Americans had a mortality nearly double that of the city's average (Hansen et al., 2013).

The combination of biophysical vulnerability and social vulnerability results in place vulnerability. This can be mapped to a high resolution by combing social and biophysical data. In a study conducted by Wolf and McGregor (2013), it was found that those who were most vulnerable to heat stress in London were those who also lived in areas that were likely to experience the greatest temperatures during extreme heat events.

This then completes the loop, and exemplifies how place vulnerability can feedback into risk and mitigation. Factors such as high-density housing, welfare dependency, poor health, isolation and the elderly can all exacerbate the risk presented by heat-waves (Wolf and McGregor, 2013). These exacerbating factors are directly related to socio-economic and demographic characteristics prevalent in our society. Wealthier members of society tend to live in larger houses with gardens containing trees and greater distances between buildings to allow for air-flow. They can afford air-conditioning and tend to work white collar jobs that don't require them to be outside in the heat. This is also reflected in the relative wealth of the country, as not only are human lives at risk, but so too is non-human life (nature + agriculture), public utility infrastructure such as water and electricity supply, as well as public transport such as rail – which can all have compound effects on risk should they fail (Kovats and Hajat, 2008).

It is through this complex web of socio-economic, demographic and geographical factors that risk is modulated. Short term mitigation strategies such as air-conditioning can actually compound long-term impacts through increased energy consumption and fossil fuel emissions, while increasing reliance on energy infrastructure that itself is vulnerable to these hazards (Kovats and Hajat, 2008). It is by mapping these relationships that more effective mitigation strategies can be developed, with long-term urban planning implement strategies such as passive cooling and external shading, the development of transport and energy policies where the most economically and socially vulnerable are not at a disproportional risk of mortality to these natural events.

A method to construct risk maps that encapsulate the socio-economic, demographic and geophysical aspects of hazards in the risk equation. Risk is the result of a multi-criteria analysis of hazard, exposure and vulnerability (Figure 6). Using this equation, it is possible to develop a risk map that will identify areas that are most susceptible to a hazard.

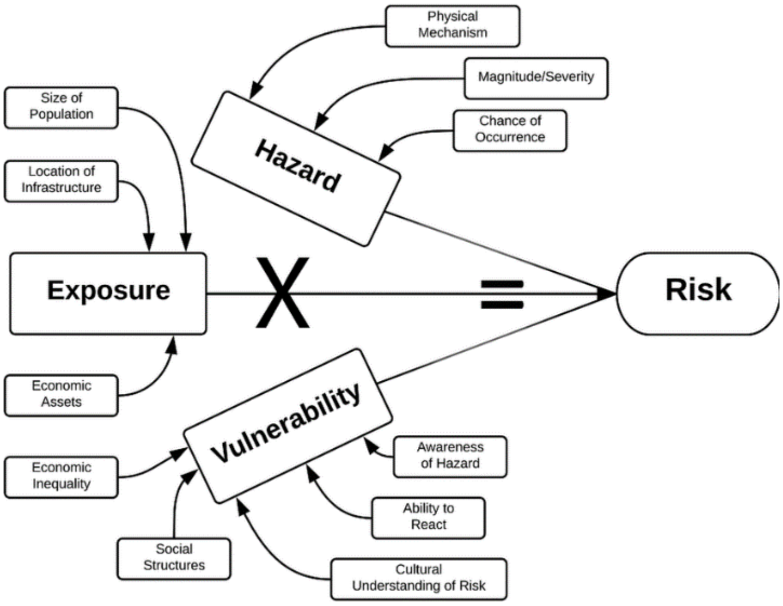


Figure 6: The risk equation. Risk is calculated as a function of hazard x exposure x vulnerability. Each of these three factors are a reflection of a series of characteristics that represents the natural, physical and social fabric of society.

IV. Climate Adaptation, resilience and mitigation

With humans congregating increasingly in urban centres various strategies are being developed to minimise the potential hazard faced by society in the face of climate change. These strategies of negating the potential impact, minimising the damage and dealing with the aftermath can be summarised as climate mitigation, adaptation and resilience.

Climate Mitigation

This refers to strategies that actively **reduce or prevent** the hazard, or the original causes of the hazard – i.e., the emissions of greenhouse gases (UN Environment Programme, n.d.)

Climate Adaption

This involves taking measures to **prepare for** and **adjust to** the current impacts of climate change, as well as the impacts predicted for the future (European Commission, 2021)

Climate Resilience

This is the ability to “**anticipate, prepare for and respond to**” the impacts of natural hazards, their trends and perturbations in relation to climate change (Centre for Climate and Energy Solutions, n.d.).

Using these three definitions, it is possible to distinguish between the end-goal of various strategies and the short and long-term goals each strategy attempts to address. The specific strategies will be addressed in a following chapter.

3. Strategies to Address Climate Risks

It has been argued that climate change was a major driver of past societal collapse (Diamond, 2005; Weiss & Bradley, 2001) with factors such as "loss of soil fertility, erosion from reliance on annual plants, soil salinization, water mismanagement, and the inability to withstand prolonged droughts" identified as key factors in collapse, along with inequality ("the hereditary control of economic surplus") as well as "overexploitation of the natural world" (Gowdy, 2019, Scheidel, 2018; Scott 2017).

Despite this, civilisation has endured and spread. With the rise of industrialisation and the technological era people are increasingly abandoning rural life for an urban one, leading to increasing urbanisation and the materialisation of mega cities. With this urbanisation and densification of infrastructure containing housing, businesses, schools, medical centres and transport; the threat to these elements from natural hazards becomes increasingly costly and logistically challenging.

To combat this, a range of technical solutions, also known as grey-infrastructure, has been developed and refined.

I. Technical Solutions:

These types of solutions refer to human developed and engineered "traditional" approaches to risk management. These solutions are typically well-studied and new innovations are constantly emerging and reviewed for their efficacy (Lin et al., 2021). For water management, these are exemplified by pipes and hard surfaces (Kepetas & Fenner, 2020). For heat-waves, air-conditioning is a prime example, but new innovations such as systems-based heating and cooling through the use of cooling towers or centralised generation and distribution can reduce energy consumption and limit sensible heat (Lin et al., 2021).

As with many other sectors, big data and "internet-of-things" tools are increasingly being incorporated into management portfolios to help inform decision makers in real-time about resource needs and flows in cities (Lin et al., 2021). These systems are becoming increasingly common under "smart-cities" frameworks, and systems such as on-demand watering can help to "save, recycle and upcycle water before or during droughts and floods" (Lin et al., 2021 p.480). Using technologies such as these, it is possible to mitigate short-term hazards such as droughts and floods, and even adapt more effectively to climate risks through effective management.

However, these types of technological interventions require resources that are often out of reach for many cities. For successful mitigation these technological solutions must be properly constructed and maintained, which tends to require social and governmental intervention (i.e. funding) that can present barriers for implementation (Lin et al., 2021).

There are various simple technological solutions, such as building materials and paint that increase the albedo (i.e. reflectiveness) of urban surfaces. High albedo surfaces, which rather than absorbing solar radiation during the day and release this energy as heat during the night, reflect this sunlight back into space and thereby reduce the heat load of buildings during summer months (Francis and Jensen, 2017). Replacing asphalt with surfaces that are lighter in colour and allow water to infiltrate into the subsurface – i.e. "permeable pavements", are also a highly effective low-tech solutions to address urban heat (evaporative cooling effects) and stormwater runoff (Li et al., 2013).

However, a key challenge presented by the climate crises is that all the technologies we've developed so far are based on the extremes we've experienced during the relatively stable period of the Holocene. Now that we've entered a new geological epoch known as the "Anthropocene", these maximum extremes, these 1 in 100 year events that we have built our sea-walls and levees to, will increasingly become defunct. This is because extreme events are going to become more severe and more frequent.

Relying on technology that was adequate in the past will not be sufficient to deal with the hazards of the future. Therefore, many in the literature advise diversifying your portfolio regarding risk, and this involves integrating not only technological solutions, but also social and nature based solutions into one comprehensive strategy that is place-and-situation based. Through this integration urban centres can become more adaptative and resilient to natural hazards, as well as helping mitigate these hazards in the first place.

II. Social Solutions

Social solutions relate to social values, behaviours and practices (Sheppard 2011). The social perspective and attitudes of a population can change in various ways, either in the direction of tolerance toward and willingness to implement previously unacceptable measures – as demonstrated by the implementation of an evening curfew for the first time since the second world war in the Netherlands. Through government-led initiatives and laws, people's behaviour and attitudes can be dramatically altered. The same can also be said about grass-root initiatives, such as the Fridays for Futures protest that began with one schoolgirl protesting and turned into a global movement. On the other hand, previously accepted measures can be weaponised and a population can become intolerant to what was previously acceptable – as demonstrated by the anti-vax movement plaguing the effectiveness of many governmental vaccine roll-out programs.

The behaviour, practices, beliefs and values of the public can have wide-spread impacts in how natural hazards are manifest into risk. Successful campaigns, from top-down governmental programmes to bottom-up neighbourhood-scale grassroots initiatives can "lower perceived barriers around sustainable climate solutions and motivate action through engagement, learning and hands-on involvement" (Lin et al., 2021). This can vary from the scale of promoting home-grown food and up-take of allotments, to addressing the 'Not In My Backyard' (NIMBY) challenges to do with solar panels and wind-turbines necessary to ensure the green energy transition to mitigate against further greenhouse gas emissions and further global heating.

Further, many social challenges are facing up to the inequalities that climate crises reveals. As in the heat wave example, those most vulnerable to the risk are predominantly the 'have-nots' in society. Inequality breeds vulnerability. Social actions that can reduce inequality and limit the impact on vulnerable groups is vital. These vulnerable groups, who tend to have less access to cooler private or public green spaces, technology (i.e. air conditioning), and perhaps most importantly: information about how to respond during a crises or how to become more adaptive and resilient to the hazards that will affect them the most (Lin et al., 2021).

III. Nature based solutions

In short, Nature based solutions are a series of strategies in which we utilise and enhance nature to help manage societal challenges (Seddon et al., 2020, Cohen-Shacham et al. 2016). Nature based solutions is an 'umbrella term' for other established approaches, i.e. ecosystem-based adaptation, eco-disaster risk reduction, ecosystem services, natural climate solutions and green and blue infrastructure (Seddon et al., 2020, Nature, 2017, Griscom et al. 2017).

All of these approaches are "grounded in the knowledge that healthy natural and managed ecosystems produce a diverse range of services on which human wellbeing depends, from storing carbon, controlling floods and stabilizing shorelines and slopes to provide clean air and water, food, fuel, medicines and genetic resources" (Seddon et al., 2020 p.2, Millennium Ecosystem Assessment, 2005).

For example, the use of vegetation and blue-green infrastructure can provide a wealth of eco-system services. Eco-system services are defined as any positive benefit that nature, wildlife and various ecosystems (i.e. forests, rivers, wetlands, oceans) provide to human beings. These can be divided into four key categories: provisioning, regulating, cultural and supporting (Figure 7). Within each of these four categories key benefits from the processes of the natural world are highlighted – from raw materials, to climate regulation, soil building and recreation. For example, using tree cover within cities is typically used to cool transportation corridors by providing shading, but scale this up to the regional scale, and the process of transpiration and the associated evaporative cooling can influence mesoclimatic patterns (Lin et al, 2021, Scott et al., 2016, Kabisch et al., 2016). In cities susceptible to flooding, the use of bioswales along streets or constructed wetlands that help to manage both vertical and horizontal hydrological flows are becoming more widespread (Lin et al., 2021, Pauleit et al., 2019).

There are three key ways in which Nature Based Solutions (NbS) differ, which alters the benefits that they can provide.

Firstly, NbS encompass a range interventions, from the protection and restoration of natural ecosystems toward a more hybrid approach through 'grey-green' managed systems (Sutton-Grier et al. 2018). This range of interventions has accordingly a range of impacts on the environment. Protecting natural forests, grasslands and wetlands results in greater carbon storage than their managed counterparts, due to greater age, soil depth and diversity (Watson et al. 2018), yet managed systems still reap benefits. These managed or hybrid systems, such as green roofs or city parks can provide both social and physical benefits, from mental and physical wellbeing to urban cooling and storm-water management (Keeler et al. 2019).

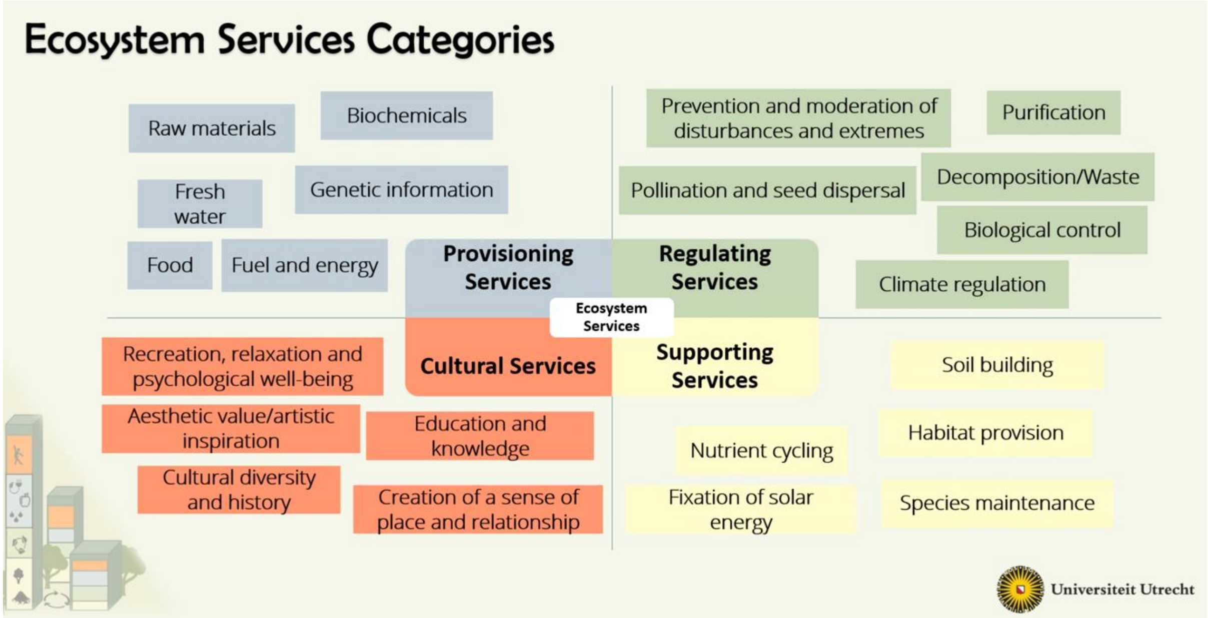


Figure 7: Ecosystem Service Framework. Figure adapt from Katharina Hecht (PhD UU – Buildings as Organisms

Secondly, the mode in which NbS themselves are applied can impact their own resilience – i.e. their ability to survive and recover from perturbations while maintaining their ecosystem services (Seddon et al., 2020). For example, applying NbS toward the protection and restoration of natural systems – such as old growth forests or diverse native species – will promote the ecosystem services that these systems provide via climate adaptation and mitigation (i.e. carbon storage in old growth forests, or flood protection provided by mangroves) which in itself will help the NbS strategies become more resilient. It does this while providing cultural ecosystem services such as inspiration (i.e. bio-mimicry) and education about natural systems (Seddon et al., 2020). On the other hand, apply NbS that do not account for ecological principles, such as local biodiversity, and implementation strategies such as non-native monocultures result in increased vulnerability to environmental change in the long-term, and may even introduce a host of unintended consequences and trade-offs in which ecosystem services are provided (Seddon et al., 2020).

Thirdly, NbS can vary in the degree to which they are designed and implemented by local communities (Reid et al., 2018). One aspect of NbS – that is Ecosystem Based Adaptation – emphasises "participatory community-based climate adaptation", wherein a series of strategies, from conservation, restoration and sustainable management make up a broader adaptation strategy that specifically accounts for social, economic and cultural benefits for the local community to which it will be applied (Secretariat of the Convention on Biological Diversity, 2009).

NbS are unique in this regard. By utilising NbS to tackle issues such as heat stress or flooding, such as creating bioswales, there tend to be a range of other ecosystem services that are addressed simultaneously. For example, bioswales increase biodiversity (i.e. supporting services) via habitat creation, which then promotes regulating services through pollinators. Additionally, cultural services are addressed through aesthetics and green benefits to psychological well-being. This aspect of NbS is especially valuable in terms of risk. As stated by the IPCC "The main challenge for local adaptation to climate extremes is to apply a balanced portfolio of approaches, as a one-size-fits-all strategy may prove limiting for some places and stakeholders" (IPCC 2012, p.582, Silva and Costa, 2018). In other words, massive singular investments in one isolated strategy/ infrastructure project is not recommended, especially in the face of climate change, as if this strategy fails the risks will be great. Alternatively, should your investments be diversified, should one strategy fail, the risks are spread and dissipated amongst other initiatives (Silva and Costa, 2018). This is where NbS is highly valuable, as it can tackle a range of challenges (from heat and flooding mitigation and adaption, biodiversity loss, well-being, and eco-system restoration), allowing for greater diversity in the issues you're tackling, and removing the reliance and tendency toward isolation, where we try to solve one problem with one solution. This leads onto the final strategy to address climate risks – Integrated solutions.

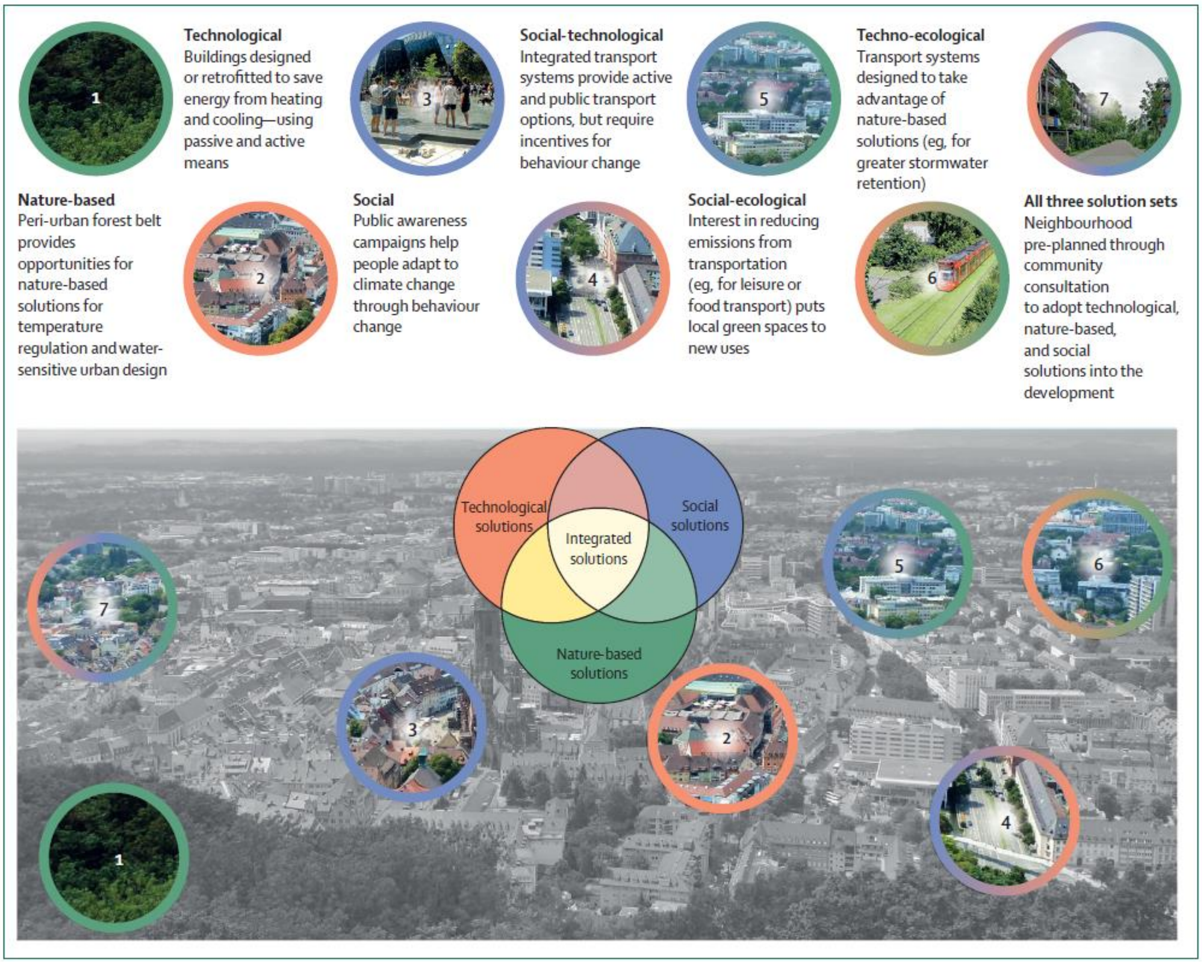
IV. Integrated solutions.

In theory, integrated solutions are simple: take technical infrastructure projects, social projects along with NbS, and combine them. However, reality is much messier.

While NbS already go a long way toward integrated solutions, with their potential to provide "climate mitigation solutions *and* simultaneously providing climate resilient and adaption planning, especially in urban areas" (Frantzeskaki et al., 2019), they are not the all-encompassing solution to climate change. The reason why is that individual solutions are unable to deal with the scale, complexity and inter-connectedness of climate change – especially in cities and urban environments (Lin et al., 2021). As summarised by Lin et al., (2021, p.480), "The different qualities of the individual solution types, when integrated, can provide the necessary components to enable structural or systemic transformation, while ensuring that the focus is not too narrow with specific or one-dimensional outcomes" (Figure 8).

For example, traditional grey infrastructure addressing flood protection, such as pumping stations and dykes can be enhanced through NbS. Practices such as restoring wetlands, beach nourishment and waterfront re-naturing can all aid grey infrastructure in preventing flooding, but also provide benefits in terms of biodiversity conservation and recreation (Aerts et al., 2014).

An example that requires more social integration is addressing urban transportation. NbS such as previously mentioned tree shading can provide cooler transport alternatives such as walking and cycling, combined with permeable pavements to help replenish the groundwater. Promoting more people to take the bike or walk will also take a step toward climate mitigation by reducing fossil fuel emissions in cities, and help minimise point-source heat emissions to reduce the UHI (Lin et al., 2021). However, the behaviour of citizens must change to embrace these types of transport, and this requires economic and psychological tools (i.e. incentives and disincentives) to shift away from vehicular transport to active transport (Fontaras et al., 2017, Byerly et al., 2018,). It is through these integrated solutions that the myriad of factors that contribute to climate change can be addressed. Continuing down the traditional path of one solution for one problem will only lead to greater vulnerability in the future, and to infrastructure "lock-in" that will prevent future adaptation to highly variable and evolving climate hazards.



Nature-based
Peri-urban forest belt provides opportunities for nature-based solutions for temperature regulation and water-sensitive urban design

Technological
Buildings designed or retrofitted to save energy from heating and cooling—using passive and active means

Social
Public awareness campaigns help people adapt to climate change through behaviour change

Social-technological
Integrated transport systems provide active and public transport options, but require incentives for behaviour change

Social-ecological
Interest in reducing emissions from transportation (eg, for leisure or food transport) puts local green spaces to new uses

Techno-ecological
Transport systems designed to take advantage of nature-based solutions (eg, for greater stormwater retention)

All three solution sets
Neighbourhood pre-planned through community consultation to adopt technological, nature-based, and social solutions into the development

Figure 8: How technical, social and nature-based solutions can overlap to form integrated solutions. Examples 1-7 show how different circumstances across urban environments might result in various combinations of solutions to form integrated solutions. Each solution is place-based and reflects the needs of that specific location and community. Figure adapted from Lin et al,. 2021.

4. Study Area

I. Broader Context – Hazards at regional Scale

The Netherlands is a low-lying country situated on a delta, and has been battling against the north sea for two thousand years to maintain and reclaim their land. The Netherlands is vulnerable to the impacts of climate change both in the short and long term.

Near term impacts resulting from a warming world are manifesting in heatwaves, droughts and wildfires which impact ecosystems, as well as the health and mortality of all (living) things. Further, rising temperatures will lead to instability in the climate regime and result in increased extremes, not only in temperature, but also rainfall (IPCC, 2021). Intense rainstorms over short periods will lead to flooding, destroying lives, infrastructure and ecosystems, as clearly demonstrated by the recent extreme precipitation in Limburg between the 13-15th July 2021. On the other hand, extended periods of drought will impact those most vulnerable in society, as well as the continued deterioration of ecosystems.

Longer term impacts involve the continued destabilization of climate norms, soil subsidence, changing river discharges along with accelerated rise in sea level (Delta Programme, 2021). Sea-level rise not only threatens coastal infrastructure, such as the nation capital of Amsterdam, but also issues in river discharge impacting broader swathes of the country. This can lead to environmental challenges such as saline intrusion which impacts agricultural activities, coastal erosion and drinking water quality (Climate-adapt, 2020).

Climate Adapt (2020), a partnership between the European Commission and the European Environmental Agency, have evaluated, in order of most urgent risks, the adaption priorities of the Netherlands:

I. Warmer
    i. Changing temperatures
    ii. Heatwaves
    iii. Wildfires
    iv. Soil degradation and erosion
    v. Spread of Invasive species
II. Wetter
    i. Changing precipitation patterns
    ii. Precipitation and/or hydrological variability
    iii. Floods
    iv. Soil degradation and erosion
III. Drier
    i. Water scarcity
    ii. Drought
    iii. Soil degradation
IV. Rising sea-level
    i. Floods
    ii. Saline intrusion
    iii. Coastal erosion

II. Utrecht Science Park

Utrecht Science Park (USP) is located on the Eastern edge of the Municipality of Utrecht. The science park is the largest in the Netherlands and encompasses 322 hectares comprising of 130 businesses, a hospital, 3000 student accommodations, and bus and tram infrastructure allowing daily visits of 27000 staff members and 51000 students (Utrecht Science Park Foundation, n.d.). The USP functions as a mini-city at a neighbourhood scale, providing facilities for education, research, healthcare, businesses and start-ups, infrastructure, housing, catering, sport and culture.

The USP has the vision and means to contribute to the creation of a sustainable society. As outlined in the 'Strategic Plan 2016-2020':

"Utrecht University focuses on sustainability in the performance of its core duties and in the way it runs its business. Under the strategic theme of Sustainability, Utrecht University boasts a unique combination of expertise in both social and natural sciences, which makes it ideally placed to contribute to the transition to a sustainable society. The university is keen to contribute to this through its teaching and research, but also strives to be a source of inspiration in the way it runs its business."

This ambition has spawned a series of documents outlining how Utrecht University (UU) aim's to ensure sustainability is integrated within its operational strategy. All these plans coincide with national strategies such as the "Delta Programme 2022" and regional documents such as Gemeente Utrecht's "Omgevingsvisie", which all address the impacts faced by the Netherlands in relation to climate change, and the plans to develop to become "Climate Proof" (National Delta Programme, 2022). Internal documents such as the 'Biodiversity Strategy (2021)', 'Vision Document Sustainable Buildings Utrecht, (2019)', and contracted documents such as 'Stedenbouwkunde visie Utrecht Science Park Centrum en Oost" by Barcode architects in 2020, all detail UU's - the majority owners of USP– strategy to address these challenges.

The university explicitly recognises the challenges faced by climate change and acknowledges that many of the planetary boundaries, as outlined by Rockstrom and Steffen (2009), "have been exceeded: temperature rises, biodiversity loss and nitrogen are already at dangerous levels." (UU Website n.d.). As a consequence Utrecht University created a 'Declaration of Planetary Commitment'.

In line with this vision, UU's 'Real Estate and Campus'(V&C) department has generated a series of ambitions for the centrumgebied of the USP. "The UU has and assumes the social responsibility to accelerate the transition to a sustainable society; and it has every reason to use its resources as effectively as possible. The redevelopment of the USP centre area of the USP is an opportunity to fulfil this social responsibility. However, the transition to a sustainable society is complex." (Stedenbouwkunde Visie, 2020. My own translation).

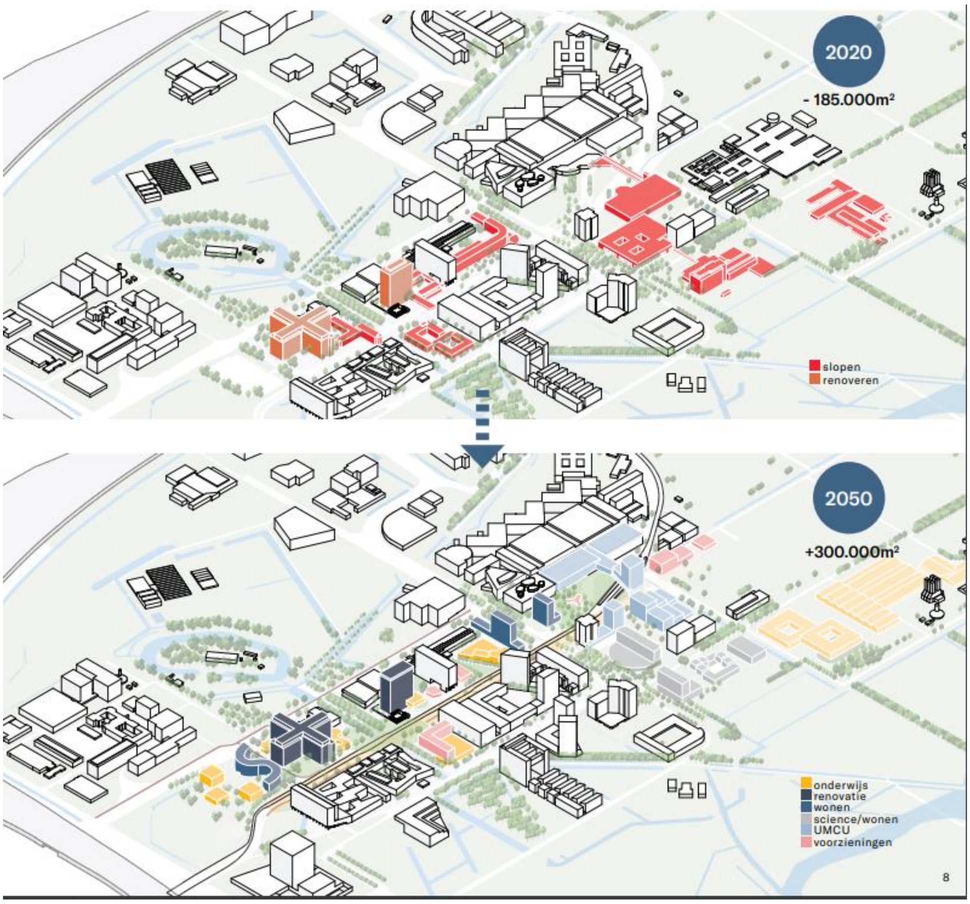


Figure 9: 2020: 2050 vision of the Centrumgebied. Figure adapted from Stedenbouwkunde Visie, 2020.

V&C aim to utilise the campus and its surroundings to address the complex physical and social challenges that the climate crises presents. It outlines this ambition firstly in the pursuit of the generation of a commons: “The outdoor space, the facilities and the built environment offer opportunities for the exchange of ideas and for new forms of cooperation”, in the pursuit of creating a true “public space” where “The events, the experiences, activities and people's memories determine the quality of the campus.” (Figure 9) (Stedenbouwkunde Visie, 2020. My own translation).

This creation of a public space is not isolated, and in line with the Biodiversity Delta Plan this public space will be an “Urban environment that connects to the surrounding nature… to link up the current green fragments and use them as green zones and water buffers” (Stedenbouwkundige Visie, 2020. My own translation). It is this interaction of society and nature where the university envisions its role as an “Agent of Change”. Through the methodology framework of ‘Living Labs’, UU is committed to utilising its three pillars; research, education and business operations toward sustainability. “The aim is to transform the University into a Living Lab where researchers, students and managers work together to find solutions for a sustainable campus and, by extension, society.” (UU Website n.d.).

Utrecht Science Park faces many of the same hazards as the Netherlands as a whole, only its sphere of influence and hazard impact occurs at the neighbourhood scale. By recognising the threat of the climate crises and outlining a series of strategies to address these challenges via the biodiversity plan, sustainable building and operational strategies and activating its occupants through Living labs, the UU is on track to achieve its climate goals. It is through this lens that the hazards and risks of the USP will be evaluated and how the UU can mobilise it’s considerable resource and expertise to implement, test and execute the adaptation and mitigation strategies necessary to achieve climate resilience.

5. Methods

I. Developing a risk map.

Developing a risk map of the USP involves combining three factors – hazard, vulnerability and exposure. Each of these three factors has a series of sub-components that can be quantified in a multi-criteria analysis to provide a total risk value, which can be mapped using Graphic Information System (GIS) software – ArcMap Pro - to inform spatial risk.

Multi-criteria analysis (MCA) is a methodology that can be used to identify a location or most likely phenomenon based on multiple layers of information (Eastman, 1999). MCA is beneficial as it utilises multiple lines of approach, or methodologies, and in that way makes up for shortcomings in any single methodology (Hester and Velasquez, 2013). Using MCA, it is possible to analyse a series of variables, in this case physical hazards from natural phenomenon, and social and economic vulnerability and exposure, and rank them. By ranking hazard, vulnerability and exposure components, a range of criteria can be incorporated into the risk equation, however, a key challenge of MCA is the determination of weight for each criteria (Hanai, 2018). Following the method developed by the Italian Ministry for the Environment and Territory, along with the Asian Disaster Preparedness Centre (Dall'Osso et al., 2006), their MCA analysis has been adapted to evaluate the risk to heat stress and flooding at the USP. The results are a GIS map visualising risk in a classified numerical scale, with each classification representing the amalgamation of conditions set during the MCA analysis.

i. Hazard Maps

For hazards, heat stress and flooding maps were adapted from the municipality of Utrecht's regional climate stress test. In 2018, the municipality published the results from a partnership with the Stichtse Rijnlanden Water Board, the Utrecht Security Region and thirteen neighbouring municipalities, with two studies commissioned for Utrecht itself, where the consultancy Tauw mapped scenarios for heat stress and Arcadis the consequences for extreme precipitation.

Tauw – Heat Stress Map

The heat stress maps developed by Tauw uses a model that calculates the influence of various urban land-use types (i.e. concrete vs. grass) on outdoor temperature at a local scale. The model applies a series of inferences into its calculation of 'gevoeltemperarture' (perceived temperature), which indicates how warm a person would feel in a given situation, such as in the full sun or in a shaded area, versus air temperature which indicates how warm it is outside. Applying the inferences that trees provide a cooling effect via evaporation (transpiration) and shading, with water also providing cooling effects on the air parcels directly above the surface. Assuming air parcel mixing, this cooling effect extends beyond the discrete boundaries of trees and water bodies. Various other structures with corresponding heating or cooling properties were incorporated into the model. For example: buildings (high and low rise; with a heating effect); green elements with a cooling effect and concrete surfaces (heating). The assumption was made that these isolated effects could be summed, and mapped to a resolution of 1.5m. Their model presents spatial temperature differences at the end (15:00) of a hot summers day with no wind – as is common during Dutch heat-waves (Van de Ven et al., 2016). The model presents a qualitative temperature scale with zones much cooler to much warmer (+/- 5 degrees) than the surrounding countryside. One heat stress model is based on the current climate (2015), while the 2050 model results is based on a general increase of 2.1 °C compared to the current climate (Van de Ven et al., 2016).

Arcadis – Pluvial Flooding

The Municipality of Utrecht commissioned Arcadis to develop a climate stress test related to flooding for the Spatial Adaption Delta Plan (2018). Arcadis utilised the 'Data Quality Audit tool', which contains a hydraulic model of the urban water system, and analyses how the city of Utrecht processes water after a heavy rain shower. Arcadis utilised another tool to validate the data from the urban water system model. This validation is done by comparing actual measured values to the results from the model.

The model highlights areas sensitive to flooding during extreme precipitation events based on the urban fabric and elevation. Evaluating two different rainfall events, the model can predict the potential effects of heavier rainfall events in the future (Regional Adaption Plan, 2019). The model incorporates local scale variability based on AHN2 Digital elevation model of the Netherlands. The creators note that the model does not include smaller elements such as fences, which can reduce the reliability of surface flows behind houses as compared to streets. Water infiltrates in green areas, such as gardens and meadows, and is discharged via sewers. It is the capacity of sewers which determines the outflow of water – should sewers become full during heavy rainfall, water will remain on the street and drain to areas of lower elevation. The models generated by Arcadis are based on rainstorm events of 1 in a 100 year and a 1 in 1000 year event.

ii. Vulnerability and Exposure

Calculating the vulnerability and exposure is dependent and related to various social-economic parameters as summarised by Cutter (1996) and previously explored in their visual model of risk (Figure…). For this study, following the methodology developed by Italian Ministry for the Environment and Territory, along with the Asian Disaster Preparedness Centre (Dall'Osso et al., 2006), the identified components that can be evaluated to quantify vulnerability and exposure are:

- Built environment
- Population
- Socio-economic aspects

A series of impact elements have been made for each of these components. In this sense, the impact elements are those characteristics of the components considered that could mostly be affected by floods or heat stress.

For the components chosen to represent vulnerability and exposure, the impact elements are:

Built Environment

- **building material "m"** (susceptibility to water damage and heat absorption)
- **description of ground floor "g"** (susceptibility to water damage and assets at risk)
- **number of stories/ size "s"** (taller buildings have more spatial area for solar absorption = more energy radiation (especially at night). Greater population at risk larger the building.)
- **design "d"** (cladding type, glass vs. concrete, colours (reflectivity), green roofs, solar shading)
- **foundations "f"** – (basements that can be flooded, susceptibility to water damage).

Vulnerability level is given by:

$$\mathbf{V(a, A) = Si\ (wi \cdot ei)} \qquad \text{for } i = 1, n \qquad \mathbf{(1)}$$

Where:

- **V (a, A)** = vulnerability level of the element a (e.g. a given building), belonging to the vulnerability parameter A (e.g. the built environment).
- **wi** = weighting coefficient
- **ei** = vectorial value estimated for the impact element
- **n**= total number of impact elements related to the parameter A

Impact Element	Impact element value (Flooding)				
	=1	=2	=3	=4	=5
Building Material (m)	Reinforced concrete		Mixture		Wood
Ground Floor (g)	Open plan without moveable objects		Open plan with moveable objects		No open plan
Design (d)	Raised ground floor + surrounding vegetation		Vegetation surrounding		Below ground level usage
Foundations (f)	Deep-pile foundations		Mean foundations		surface spread foundations

Table 1: Table depicting the relative weights for each impact element to be used in the multi-criteria analysis for building vulnerability for flooding. These criteria were weighted during a field survey of the buildings in the centrumgebied.

Impact Element	Impact element value (Heat Stress)				
	=1	=2	=3	=4	=5
Building Material (m)	White surfaces/ reflective		Bricks or wood + concrete		Black surfaces/ glass
Heating/ cooling	Solar shading/ cooling towers		Air conditioning		none
No. stories/ size (s)	1 story		3 stories		7+
Design (d)	Green Roofs + vegetation surrounding and solar shading				South facing orientation, limited shading, high window density

Table 2: Table depicting the relative weights for each impact element to be used in the multi-criteria analysis for building vulnerability for heat stress. These criteria were weighted during a field survey of the buildings in the centrumgebied.

Once values have been identified for each of the impact elements (Table 1 and 2), they must be “weighted” using a weighting criteria. The weighting criteria helps identify the type of damage each parameter would be subject to (Table 3 and 4) (Dall’Osso et al., 2006). For example, regarding built environment for the flooding hazard, the weighting criteria will be evaluated by a pairwise comparison between structure damage and damage given to flooding. The introduction of a fictitious factor is needed for calculation reasons. Each of the impact elements will be evaluated among themselves with respect to a single weighting criterion, which will give a ranking for each impact element with respect to a given weighting criterion (Dall’Osso et al., 2006). The result will be a total weighting of each impact element for a set of criteria, which is the calculated product between the “criterion weight and the relative weight of the impact element considered (Dall’Osso et al., 2006 p.14).

Relative weight for Built Environment

Built environment	**Flooding**	M	G	D	F	FF	Total	Relative weighting = total/9
Building material	M	-	0	1	1	1	3	0.33
Ground floor	G	1	-	1	1	1	4	0.44
Design	D	0	0	-	0	1	1	0.11
Foundations	F	0	0	0	-	1	1	0.11
Fictious factor	FF	0	0	0	0	-	0	

Table 3**:** Multi-criteria analysis assigning weights to each of the impact element values to provide the relative weighting used to calculate building vulnerability in relation to pluvial flooding.

Based on the multi-criteria analysis and resulting relative weights equation 2 was formulated to calculate vulnerability to pluvial flooding for the build environment.

V(a, built environment (Flooding)) = 0.33 M + 0.44 G + 0.11 D + 0.11 G **(2)**

Built environment	**Heat Stress**	SM	AC	HD	S	FF	Total	Relative weighting = total/11
Surface and materials	SM	-	0	1	0	1	2	0.18
Heating/ cooling	AC	1	-	1	0	1	3	0.27
Design	HD	1	1	-	0	1	3	0.27
stories	S	1	1	0	-	1	3	0.27
Fictious factor	FF	0	0	0	0	-	0	

Table 4: Multi-criteria analysis assigning weights to each of the impact element values to provide the relative weighting used to calculate building vulnerability in relation to heat stress.

Based on the multi-criteria analysis and resulting relative weights equation 3 was formulated to calculate vulnerability to heat stress for the build environment.

V(a, built environment (Heat Stress)) = 0.18 SM + 0.27 AC + 0.27 HD + 0.27 S **(3)**

Population Vulnerability

Population vulnerability is dependent on four key characteristics. These characteristics were once again evaluated using a multi-criteria analysis and relative weighting table based on online data (Table 5). It was therefore possible to develop an equation that evaluated the population vulnerability of USP. The characteristics are:

- Density (total number of people)
- Number of vulnerable (i.e. children, senior citizens, disabled)
- Gender (no. women)
- Mean income (per age group).

However, population vulnerability is not simply dependent on the statistics of these four characteristics, as these characteristics are dynamic and change with time. Therefore, to properly evaluate population vulnerability, equation 4, developed by Dall'Osso et al., 2006 was utilised.

$$\text{PV (Population Vulnerability)} = S_{DN}\, S_H\, [PV_H] + S_{DN}\, S_L\, [PV_L] \qquad \textbf{(4)}$$

S_{DN} – depends on when the hazard occurs: Day or Night. The population at USP differs drastically between visitors during the working day, and residents at night. This impact element data must refer to a reference unit, which we have been calculating previously at the resolution of the building scale. However, population data could only be found at the centrumgebied scale, therefore we calculated the mean Building Vulnerability (BV) inside the reference unit scale – i.e. the resolution of the centrumgebied. The mean values for BV were calculated from V(a, built environment) for the two hazard scenarios, heat stress and flooding (equations 2 and 3).

$S_{DN} = BV/5$ - if hazard occurs at night (everyone inside buildings, reduced population)

$S_{DN} = (1/2 + BV/10)$ - if the hazard occurs during the day (population mixed between indoors and outdoors, as well as a heightened population).

S_H = High season – taking into account variability throughout the year: i.e. during term dates

$S_H = 1$ - If hazard takes place during "working hours".

$S_H = 0$ - If hazard takes place when the university is closed.

S_L = Low season – should the hazard take place when the university is closed (i.e. holidays)

$S_L = 1$ - If hazard takes place when the university is closed

$S_L = 0$ - If hazard takes place during "working hours".

PV_H (population vulnerability in high season)

$$= [w_1\,(\text{density})_H + w_2\,(\text{gender})_H + w_3\,(\text{vulnerable})_H + w_4\,(\text{mean income})_H] \qquad \textbf{(5)}$$

PV_L (population vulnerability in low season)

$$= [w_1\,(\text{density})_L + w_2\,(\text{gender})_L + w_3\,(\text{vulnerable})_L + w_4\,(\text{mean income})_L] \qquad \textbf{(6)}$$

Population vulnerability will be also be calculated using a MCA, in the same process as the built environment. This involves choosing a weighting criteria, which as previously, are identifying the type of damage the parameter is subject to.

Population Data for the whole USP:

The challenge here is reference units. As population risk and vulnerability will be calculated with this reference unit. The smallest unit is at a building scale, but data availability and the scale of the data means the reference may have to encompass the whole centrumgebied. Applying these values relevant to the whole USP to centrumgebied resulted in applying a estimate ratio to the data. The centrumgebied encompasses 45% of total USP buildings, and therefore it is estimated to encompass 45% of USP population. The population data results are summarised in Table 5.

	Residents (H_L)	Visiting (H_H)			
Population Data for whole USP:		Students	Staff	Total (staff + students)	Source
Density (total number of people)	3100	51000	27000	78000	Dutch Central Bureau of Statistics (CBS, 2022) Stichting Utrecht Science Park (2022)
Number of Vulnerable (children, senior, disabled)	20			9360	Dutch Central Bureau of Statistics (CBS, 2022) De Rijksoverheid (n.d.)
Gender (no. of women)	1675			40560	City of Utrecht Archive (2009)
Mean Income (per age category)	5448 euro/year	5448 euro/year	30000 euro/year	mean = 13946 euro/year	Statistica Research Department (2021)

Table 5: Results of online research into USP population vulnerability. This data was used in the impact element evaluation to calculate population vulnerability at the scale of the centrumgebied. These values were sourced for the whole of Utrecht Science Park (i.e. scale of reference data), and thereafter adjusted to the relative proportion that could be expected to occupy the centrumgebied. The centrumgebied contains 45% of total USP buildings, therefore population data was adjusted to match this weighting.

Impact Element	Impact element value (Population)				
	=1	**=2**	**=3**	**=4**	**=5**
Density (D)	>1000 people per sq km		10,000 people per sq km		50,000+ per square km
Vulnerable (V)	<10% of population vulnerable		Medium vulnerable population (20%)		High population of Vulnerable (> 50%)
Gender (G)	< 20%		50%		> 80%
Mean Income (I)	Above Mean (50k+)	Mean Income (30,000 euros/ year)	15,000		Mean income (<10,000)

Table 6: Table depicting the relative weights for each impact element to be used in the multi-criteria analysis for population vulnerability. These criteria were weighted using online available data and statistics for the city of Utrecht and the USP.

Population Vulnerability		D	V	G	I	FF	Total	Relative weighting
Density	D	-	1	1	1	1	4	0.36
Vulnerable	V	1	-	0	0	1	2	0.18
Gender	G	0	0	-	1	1	2	0.18
Mean Income	I	0	1	1	-	1	3	0.27
Fictious factor	FF	0	0	0	0	-	0	

Table 7**:** Multi-criteria analysis assigning weights to each of the impact element values to provide the relative weighting used to calculate Population Vulnerability.

Relative weight Population

Based on the gathered population data (Table 5), it’s impact element value (Table 6) a relative weighting of each population vulnerability characteristic was conducted (Table 7). The result is equation 7 where each impact element receives a relative weighting and it is possible to calculate Population Vulnerability High/Low , to be input into equation 4.

$$PV_{H/L} = [0.36(\text{density}) + 0.18\ (\text{gender}) + 0.18\ (\text{vulnerable}) + 0.27\ (\text{mean income})] \quad \textbf{(7)}$$

Socio-Economic Exposure and Building Vulnerability

Natural hazards can affect assets through direct damages, but also the production of goods and the running of services (i.e. indirect losses). As a result, natural hazards can have both direct and indirect impacts on the economics of place. However, when conducting spatial risk mapping it is only possible to map direct damages, as indirect losses are not always linked to a particular location, and therefore indirect damages must be understood from a qualitative perspective. Therefore, when mapping the socio-economic consequences of hazard it will only be possible to quantify the “use” of buildings or sets of infrastructure.

$$\text{Socio-Economic Exposure} = (e_1 \times V(a, \text{Built Environment}))/5 \quad \textbf{(8)}$$

Where e_1 is the value given to the “building use” of each impact element, taken at scale of buildings. Suggested values for the socio-economic exposure of buildings was taken from Dall’Osso, et al., 2006 (Table 8).

Socio-economic Exposure of buildings/ Land-use	
Building Use/ Land-use	e_1
Public Health	5
Education	3
Drinking Water and Sanitation	4
Transports	3
Energy	4
Industry and Commercial	2
Agricultural and Livestock	3
Tourism	4
Authorities	5
Religious/ Historical	2
Living House	1
Vegetation	3

Table 8: Building/ Land-use values used to calculate the Socio-economic exposure in the centrumgebied using equation (8). All values were taken from Dall’Osso, et al., 2006.

iii. Risk mapping

Risk Level

The numeric values of risk can be calculated as the product between hazard level, vulnerability (Population, Building) and exposure (socio-economic). Each of these components has a value range between 1 and 5, and the risk level of each element is therefore given by:

$$\boldsymbol{R = \frac{Hazard\ x\ Vulnerability\ (population\ ,\ \ building)\ x\ Exposure(socio-economic)}{5}} \qquad \textbf{(9)}$$

Values for hazard, population and vulnerability were generated using the aforementioned equations (1-8) and were utilised to generate a series of layers with associated values held in attribute tables on ArcGIS PRO. These layers were then multiplied together using equation 9 to generate a final map with a spatial distribution of R. R is an integer value ranging from 1 to 5, where 5 is maximum risk level, and 1 minimum.

Equation 9 can be expanded to showcase the whole calculation as:

$$\boldsymbol{R = \frac{Hazard\ (scenario)\ x\ Population\ scenario\ \big(Eq\!:4(5\ or\ 6)\big)\ x\ Building\ Vulnerabiltiy\ (Eq\!:1(2or\ 3))\ x\ Socio-economic(Eq\!:8)}{5}}$$

R was calculated for each of the four hazard scenarios, for three population vulnerability scenarios (equation 4). The result is twelve risk maps (Table 9), outlining two severity scenarios for each hazard type (flooding/ heat stress), assessing risk in three vulnerability scenarios.

Population Vulnerability Scenario:	Hazard Scenario:			
	Flooding 1-100	Flooding: 1-1000	Heat Stress: Current	Heat Stress: 2050
Day time – High Season	Equation 5 used in Equation 4	Equation 5 used in Equation 4	Equation 5 used in Equation 4	Equation 5 used in Equation 4
Day Time – Low Season	Equation 6 used in Equation 4	Equation 6 used in Equation 4	Equation 6 used in Equation 4	Equation 6 used in Equation 4
Night Time – High and Low Season	Equation 5 used in Equation 4	Equation 5 used in Equation 4	Equation 5 used in Equation 4	Equation 5 used in Equation 4

Table 9: This table outlines the three Risk maps generated for each hazard scenario. For each type of hazard, two severity scenarios were used. Three population scenarios were also used to understand how the movement and actions of people effect risk. One scenario was used for Night-time, as the values for the impact element of both high and low season were the same. The result is twelve maps evaluating the relationship between hazard, population and socio-economic vulnerability as a single integer: R. R maps the spatial distribution of risk around the centrumgebied of USP.

Identifying key areas of risk

The result from the risk map will present the centrumgebied in a ranking, from 1-5, i.e. from least risk to maximum risk. This is the result of the relative weighting and intersection between all aforementioned factors, from hazards, vulnerability and exposure. This risk map, will provide project leaders within the university a tool to understand how risk is manifested in the centrumgebied, to identify which areas are at most risk, and assist them in creating a strategy and priority list for action to address areas in the redesign of the centrumgebied.

II. Mapping potential Solutions: Climate Resilient City Toolbox

Based on the results of the hazard map, a series of solutions will be mapped using the open software Adaptation Support Tool know as ‘Climate Resilient City Tool Box’ (Klimaatbestendige Stad Toolbox (KBS)). This open data tool was developed by Deltares in cooperation with Wageningen University, Atelier GroenBLAUW, TNO, Bosch Slabbers, Tauw and Hogeschool van Amsterdam. The Toolbox, in their own words:

“The Climate Resilient City Toolbox can be used to explore which adaptation measures can better protect a neighbourhood, site or street against flooding, drought and extreme heat. The tool is primarily designed for use in sessions with stakeholders and experts from different backgrounds. A joint answer is formulated to the question of how a site or area can be made more climate resilient. The toolbox offers a common knowledge base for the (risk) dialogue between all those involved in the area design.”

Users can select from 40 adaption measures, ranging from nature-based to grey infrastructure. The toolbox has been created specifically in the context of the Dutch climate, using measures that have been previously proven and verified, with relevant unit prices for construction, management and maintenance costs for each measure (Brolsma et al., 2021).

Evaluating Solutions – Climate Adapt Tool

What follows is a brief and simplified summary of the KBS tool, it’s model construction and parameters, and how and why this tool can be used to evaluate potential climate adaption solutions. More detailed information can be found in the supporting documentation list – found on this website.

Depending on local conditions (spatial location data) and user input information, the KBS tool generates a ranked list of strategies to promote a more climate resilience depending on the urban setting. The ranking of each measure is based on the effectiveness of each measure to address water quantity (reduction and runoff) and minimising heat stress in the selected region. The user can draw the measures onto a geo-reference background image (i.e. satellite photo or map), computing the area of the measure and thereby calculate the effects and costs of each measure relative to heat stress and flooding (Brolsma et al., 2021). The effectiveness of measures related to flooding is calculated on a multi-reservoir model (Figure 10), meteorological data and estimates of storage capacities. Impacts relating to heat stress are calculated on local cooling of said measure (literature) and the area of the drawn measure (Brolsma et al., 2021).

Model purpose

The Urbanwb model is a simplified, basic hydro(geo)logical model, developed to calculate the return period of run-off events in small urban areas where hydro-geological conditions are similar for the entire study area. This model is much more simplified than other hydraulic models (i.e. SOBEK and MIKE-urban), but the main advantage of Urbanwb is “that multiple different rainstorms with all kinds of actual antecedent weather conditions, resulting in all kinds of different initial conditions in all parts of the urban water system, are calculated. Other relevant advantages are that both model building and model calculations take much less time.” (Brolsma et al., 2021).

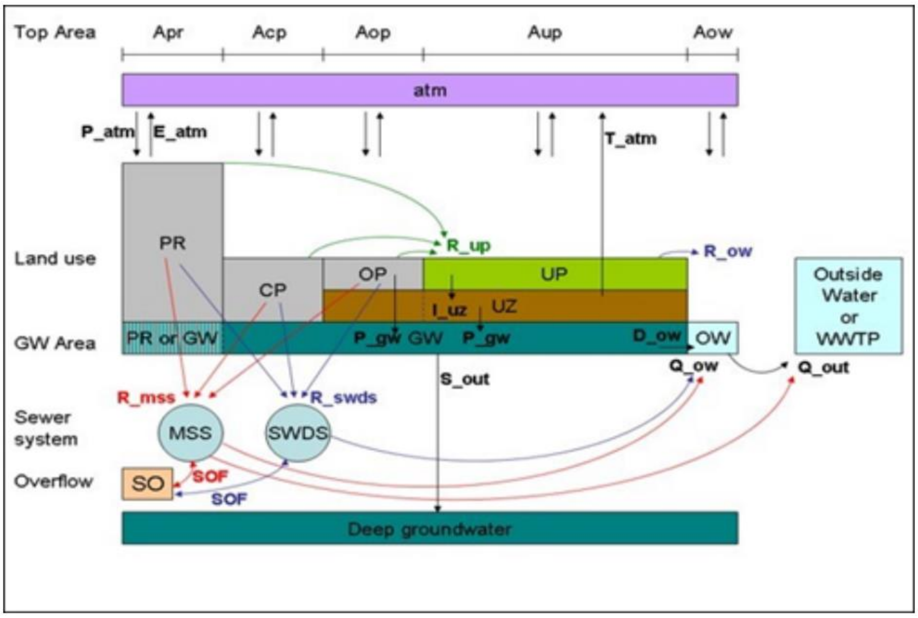


Figure 10: Schematic overview of Urbanwb model with its fundamental elements. Using this model, it is possible to quickly model the major hydrological dynamics in an urban system and generate an estimation of the water quantity distribution and water system behaviours under certain conditions based on the geographical location and user set parameters. Figure adapted from Brolsma et al., 2021.

General model description

The Urbanw model encapsulates “dominant dynamic hydrological processes of an urban water system”, and can therefore be described as a conceptual lumped model for water balance modelling in urban environments (Brolsma et al., 2021). The Urbanwb model (Figure 10) incorporates rainfall-runoff processes, surface water and sewer systems (mixed and stormwater drainage) and shallow groundwater (saturated and unsaturated zone), and three external boundaries to which water can be exchanged: atmosphere, deep groundwater and outside water/ waste water treatment plant (Brolsma et al., 2021). More information about components and general assumptions can be found here.

Urban Heat Stress

The KBS Tool provides information and evaluation of measures relating to Urban Heat Stress as a function of Physiological Equivalent Temperature (PET) values in °C. Brolsma et al., (2021) acknowledge there are many possible ways to indicate urban heat stress, but PET was chosen as one of the main indicators in the Netherlands, and thus has been used to align with country standards. The PET values work at a resolution of $2*2m^2$, and provides an indication of heat stress that people may be exposed to. Heat stress is evaluated by multiplying the PET values by the reduction factor that can expected by each measure intervention, providing the expected PET reduction in °C. This method was chosen as a way to evaluate how individual interventions can impact heat stress, accounting for the overlaying of earlier heat reducing measures (i.e. shadow of existing trees/ buildings and existing vegetation), without a doubling up of effects of the old and new interventions (Brolsma et al., 2021).

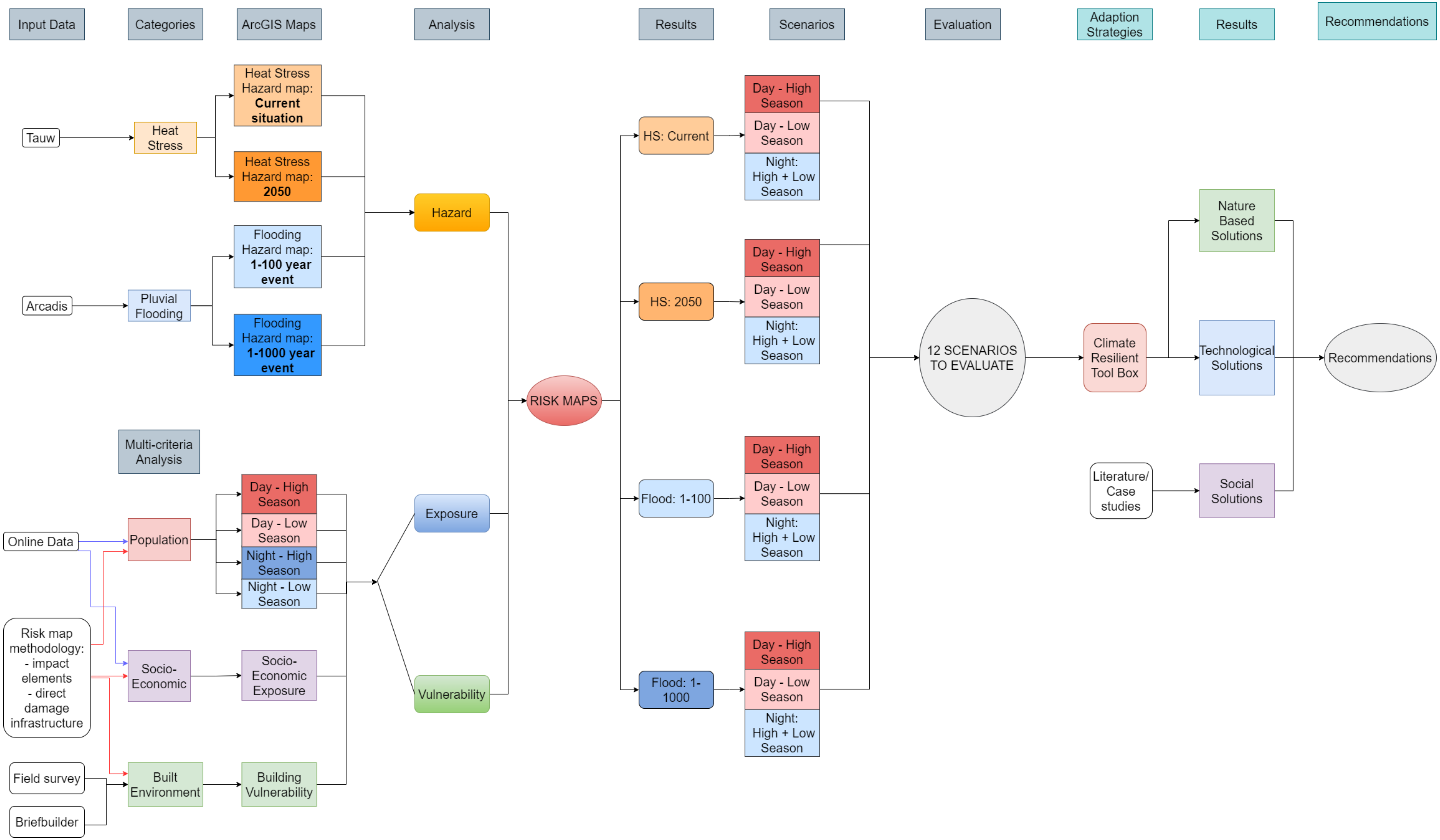


Figure 11 - A workflow summary of the Methodology.

6. Results

I. Mapping the Centrumgebied

In order to create a risk map of the Centrumgebied, it was first necessary to digitise the buildings, transport networks, vegetation, green roofs, and water present in the study area. In doing so, it was possible to calculate the relative area that each of these land-uses occupy in the centrumgebied (Figure 13).

The proposed re-development for the centrumgebied in 2050, as envisioned by Barcode Architects, was also digitised – again, the buildings, transport networks, vegetation, green roofs and water area. In doing so, it was possible to evaluate the proposed land-use changes, and how this would potentially impact flooding and heat stress scenarios in 2050 (Figure 13).

The result of contrasting land-use changes between the current land-use of the centrumgebied and the 2050 vision are shown in Figure 12. In 2050, the net area of buildings is set to increase (~2700m^2), and so too is the total area of green roofs – with a greater number of buildings having green roofs. Despite significant increase in green roof area (6300m^2), both the area of water and street level vegetation decreases. The most significant consequence of this is that the total area of impermeable street surface increases by 50,000m^2 or by 47% of current impermeable surface area. This significant increase in impermeable surface has detrimental consequences for both heat stress and flooding (larger area of brick/ concrete for heat absorption and night-time radiation, net reduction in permeable surfaces (vegetation and water bodies) that can remove or store excess water during storm events).

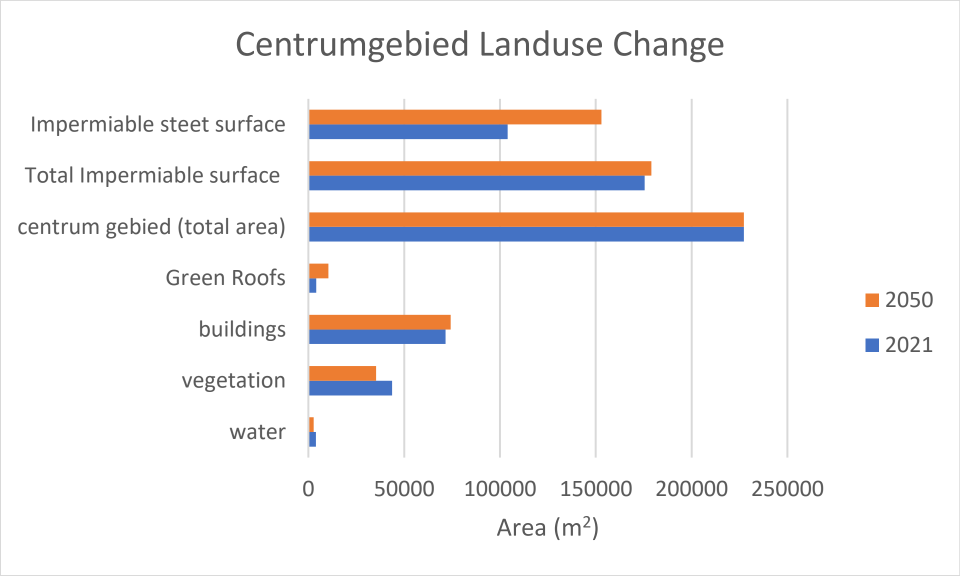
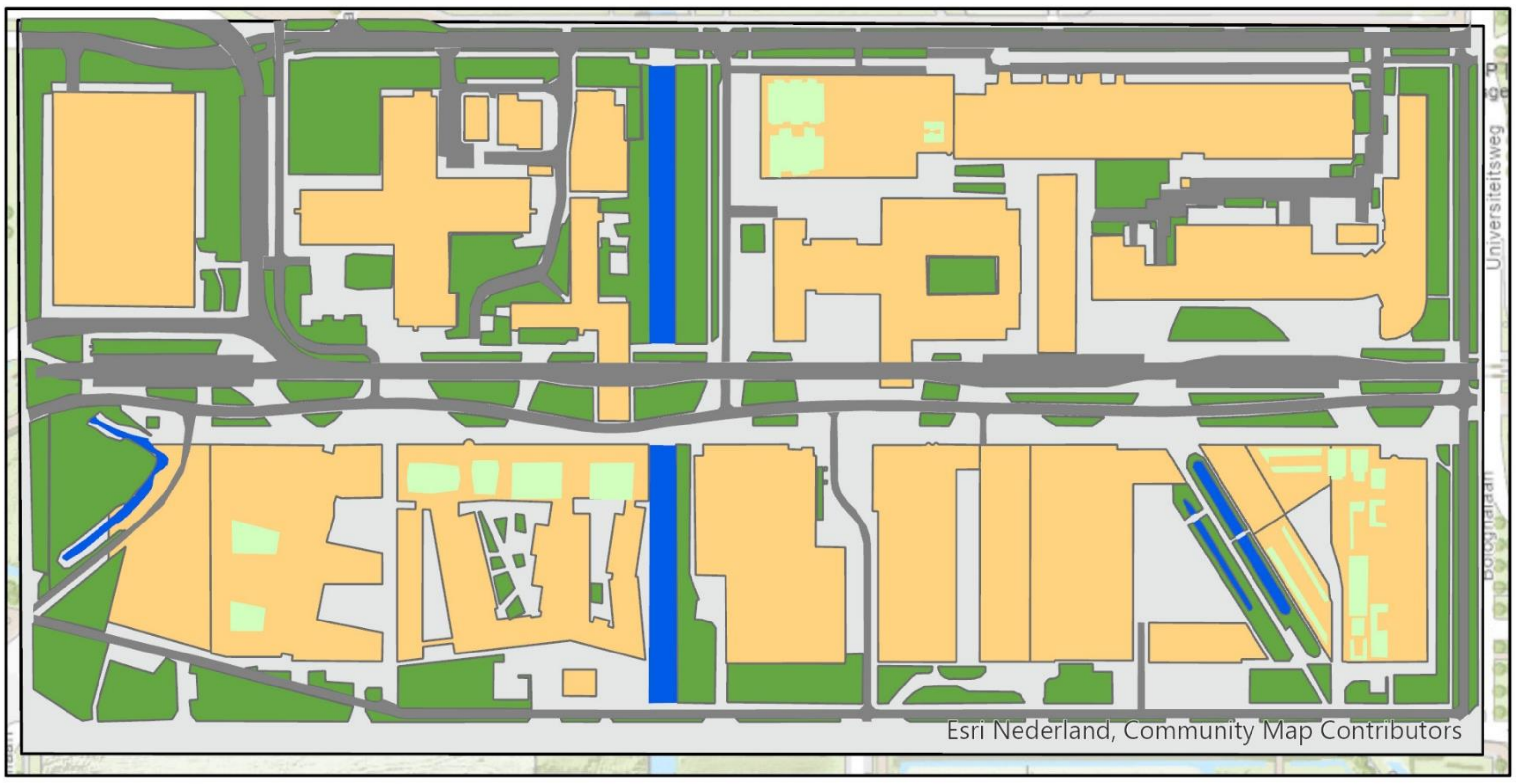


Figure 12: Graph contrasting the changes in land-use area between the current situation (2021), and the 2050 vision for the centrumgebied, as designed by Barcode Architects

Land use - Centrumgebied, USP



A: Land-use: 2022

⬛ infrastructure
🟩 greenroof
🟦 water
🟩 Vegetation
🟧 Buildings
⬜ Centrumgebied

N

0 25 50 100 Meters

Digitized Land-use map of the Centrumgebied, Utrecht Science Park as seen presently in 2022.

B: Land-use:2050

⬛ transport_2050
🟩 greenroofs_2050
🟦 water_2050
🟩 vegetation_2050
🟧 buildings_2050
⬜ Centrumgebied

N

0 25 50 100 Meters

Digitized Land-use map of the Centrumgebied, Utrecht Science park from the 2050 vision document, as created by Barcode Architects.

Location of the Centrumgebied in Utrecht Science Park (USP).

The USP's location (red), relative to the city of Utrecht

Figure 13: Land-use in the centrumgebied, and the location of the centrumgebied relative to USP and the City of Utrecht.
A: Represents the current situation
B: Represents the 2050 vision of the centrumgebied as designed by Barcode Architects.

The buildings, transport networks, vegetation, green roofs and water area were all manually digitised using the Graphic Information Software (GIS) product ArcGIS Pro.

II. Risk Mapping

The risk maps were developed by combining hazard maps, population vulnerability and Socio-economic vulnerability maps.

i. Hazard Maps:

The hazard maps were adapted from Utrecht Municipalities regional climate stress test. Two heat stress maps were developed by Tauw, one for the present situation (Figure 14), and one extrapolated for 2050 based on forecasted warming of 2.1°C (Figure 15). Arcadis provided two pluvial flooding hazard maps, one for a 1-100 year event (Figure 16), and the other for a 1-1000 year event (Figure 17).

Heat Stress

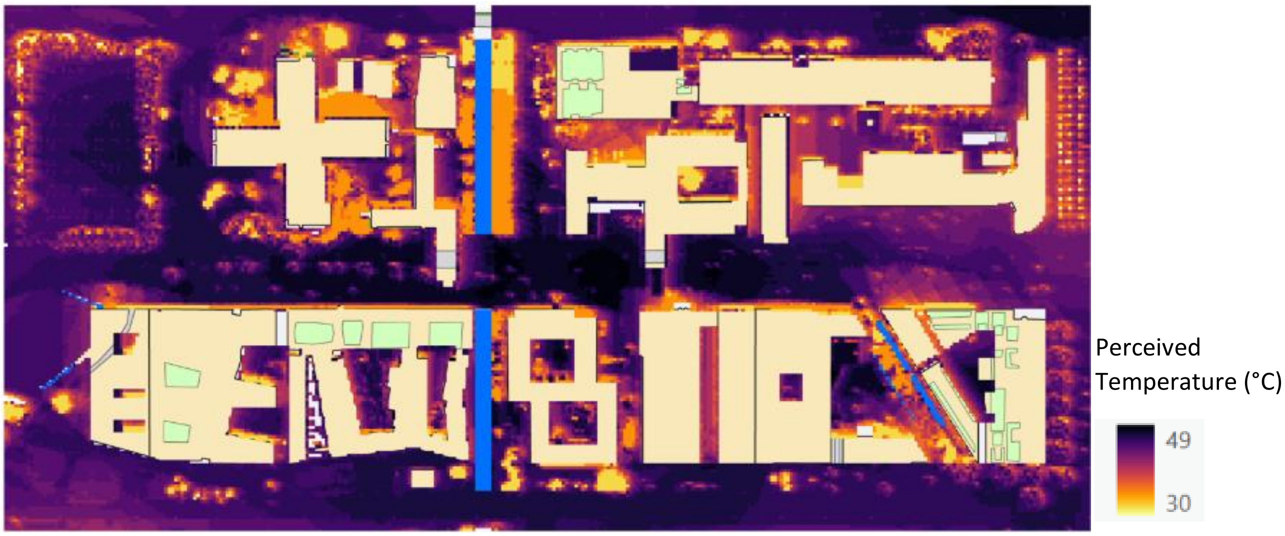


Figure 14: Heat Stress Hazard – current. The 'gevoeltemperarture' (perceived temperature), which indicates how warm a person would feel in a given situation. The model presents spatial temperature differences at the end (15:00) of a hot summers day with no wind – as is common during Dutch heat wave. This heat stress model is based on the current climate (2015). Map adapted from Tauw (2015)

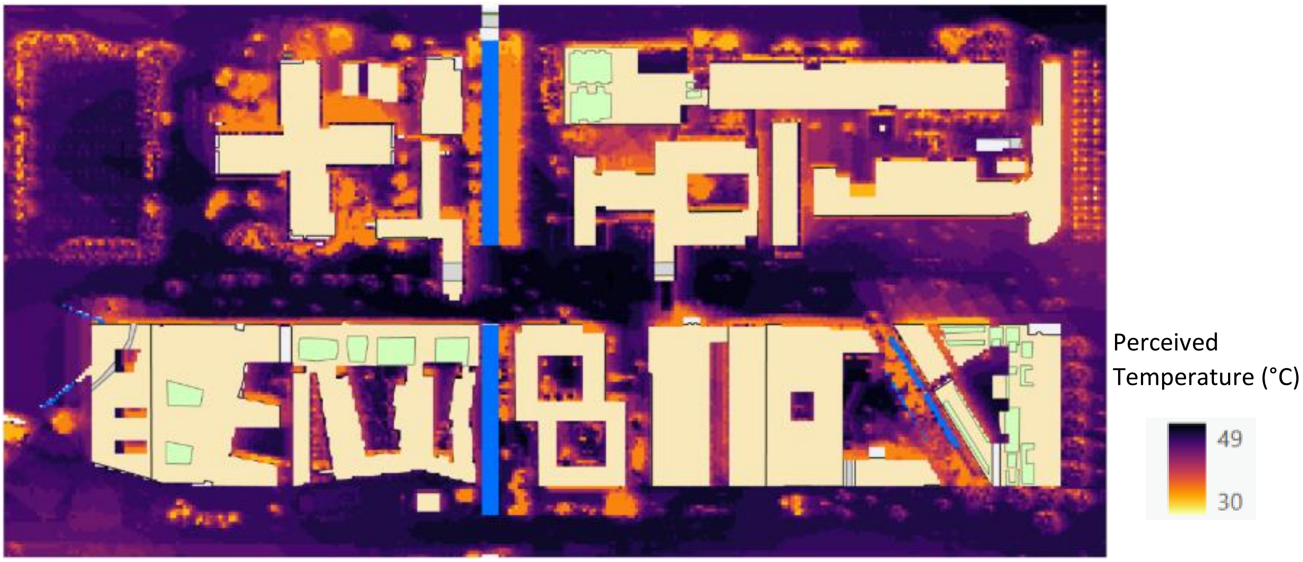


Figure 15: Heat Stress Hazard – 2050. The 'gevoeltemperarture' (perceived temperature) which indicates how warm a person would feel in a given situation. The model presents spatial temperature differences at the end (15:00) of a hot summers day with no wind – as is common during Dutch heat wave. The 2050 model results is based on a general increase of 2.1°C compared to the current climate. Map adapted from Tauw (2015).

The areas of the centrumgebied that received the largest heat stress are those that correspond with the highest amount of concrete, and minimal vegetation. This is apparent along the central line of the centrumgebied along which the tram, bus and cycle lanes run. This area is predominantly paved to allow for the ease of movement into the centrumgebied via tram, bus or bike, but also for movement between buildings on foot. Accessibility is a key area that the UU and V&C work toward, and consequently, paved surfaces are the best surface to accommodate the range of mobility of individuals (i.e. the disabled, those in wheelchairs, visually impaired). The key differences between the current situation and that in 2050 is the increase in maximum temperature (feel temperature) from 45°C to 49 °C.

Flooding

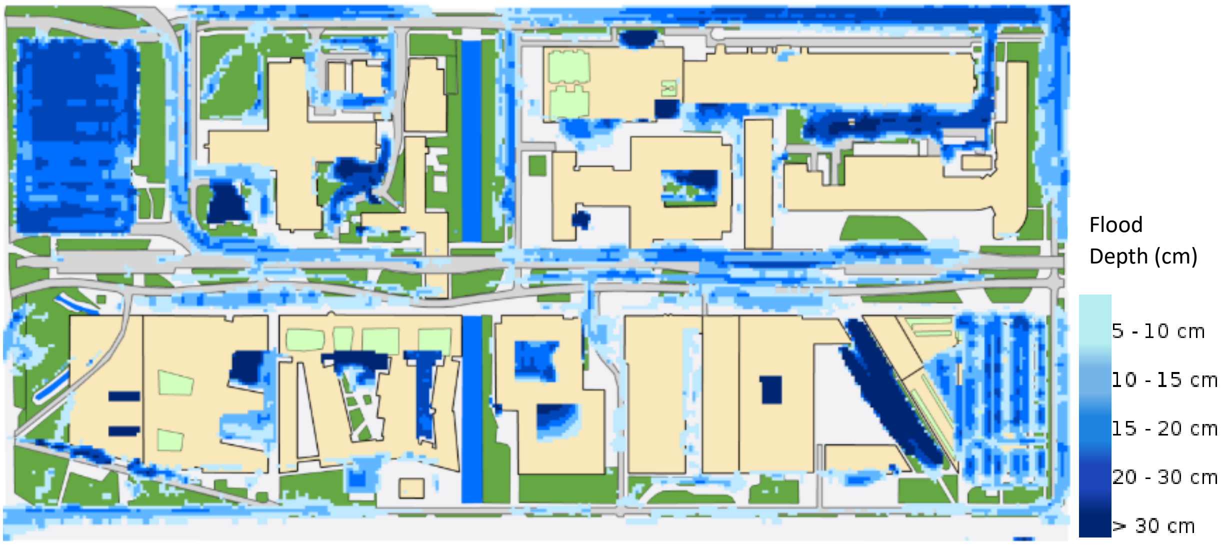


Figure 16: Flooding Hazard: 1-100 year event. The model highlights areas sensitive to flooding during extreme precipitation events based on the urban fabric and elevation. Water infiltrates in green areas, such as gardens and meadows, and is discharged via sewers. should sewers become full during heavy rainfall, water will remain on the street and drain to areas of lower elevation. Adapted from Arcadis (2018).

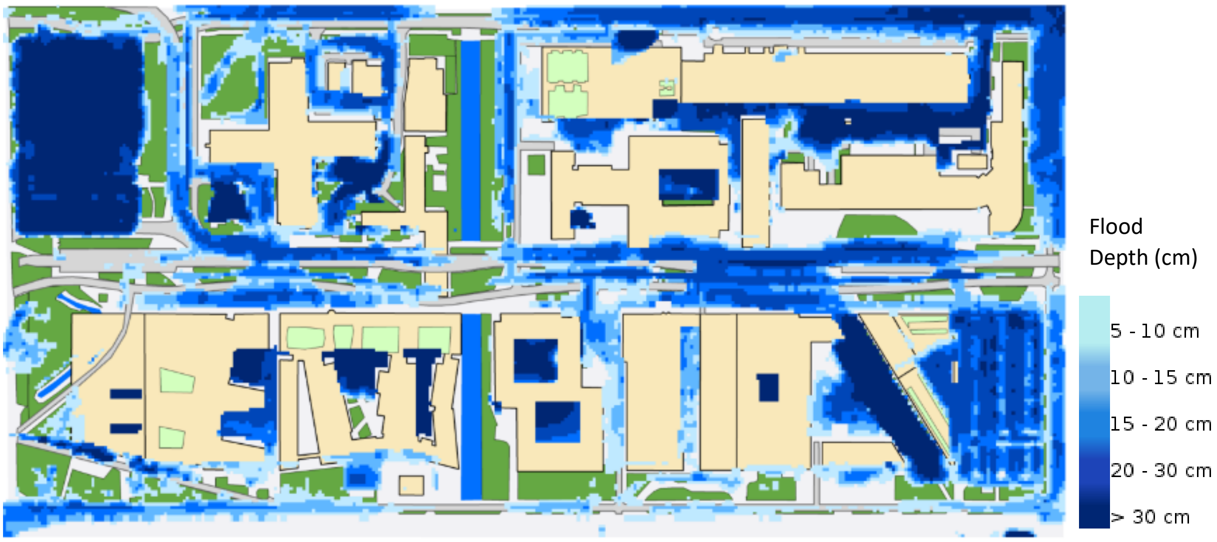


Figure 17: Flooding Hazard: 1-1000 year event. The model highlights areas sensitive to flooding during extreme precipitation events based on the urban fabric and elevation. Water infiltrates in green areas, such as gardens and meadows, and is discharged via sewers. Should sewers become full during heavy rainfall, water will remain on the street and drain to areas of lower elevation. Adapted from Arcadis (2018).

The areas flooded once again are concentrated around impermeable surfaces, primarily along cycle paths, tram and bus lanes, and large areas of concrete – such as the areas between the Bestuursgebouw and the Marinus Ruppertgebouw. The parking area (P6) on the Padualaan is also demonstrates how low-lying, highly impervious areas are highly susceptible to flooding. Another key area of flooding are the courtyards in the central area buildings. This can put the interiors of buildings themselves at risk of flooding, especially should their ground floors be lower than street level. This is certainly the case of the Library in Hogeschool Utrecht's (HU) Maatschappij en Recht building. A final area of flooding hazard in both scenarios is the small passage between the studentenhusivesting De Bisschoppen buildings and the HU Gezondeidszorg en Life Sciences & Chemistry building. This narrow area contains a small dyke and a trees lining the walkway. In both heat-stress hazard maps this area has a relatively low heats stress, but conversely has a high flooding potential. This could be as a result of this small body of water being disconnected from surrounding fluvial networks, with large amounts of water draining toward this dyke due to the high density of impermeable surfaces and buildings in the surroundings.

ii. Population Vulnerability

Population vulnerability was calculated for the centrumgebied using the metrics: Density, Number of Vulnerable, Gender and mean income (age). The data was only available for the science park as a whole, and fractionalised based on the fact that the centrumgebied accounts for 45% of all USP buildings (Table 5).

Population vulnerability is also a function of the time of day and time of year in which the hazard occurs (Table 10). As a result, different calculations were made for population vulnerability during the day, during the night, and during the high season (i.e. term time) and the low season (i.e. vacations/ weekends). For both heat stress and flooding, the highest population vulnerability is presented during the day, in the high season. This is where you have the maximum daily visitors to the centrumgebied, along with residents all moving around the campus, moving from building to building and utilising transport infrastructure. The lowest population vulnerability occurs during the night – both in the low and high seasons – as this is when the visiting population has left the campus, and residents are inside, with little footfall outdoors.

Centrumgebied	Population Vulnerability (1-5)	
	Heat Stress	Flooding
Day – High Season	4	3
Day – Low Season	3	2
Night – High Season	1	1
Night – Low Season	1	1

Table 10: Population vulnerability values (1-5) for the four different scenarios. Day vs. night – where the amount of people moving around is significantly reduced, and therefore so too is exposure to hazards (indoors vs. outdoors), and high season vs low season, which is the different in the total number of people in the study area: i.e. when the university is open and operating vs. weekends and vacations when the university is closed for traditional business operations.

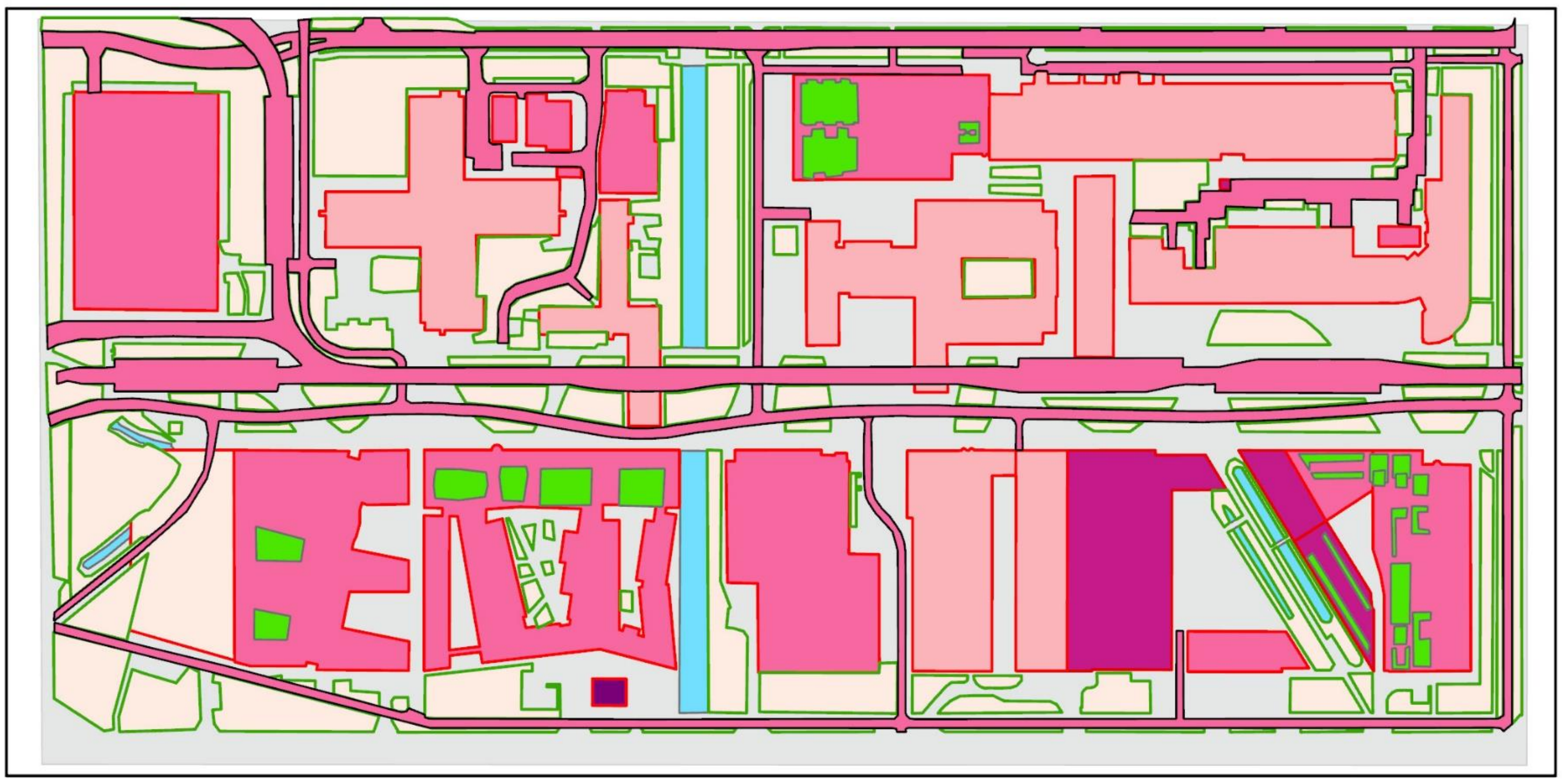
iii. Socio-economic Exposure and Building Vulnerability.

Socio-economic Exposure and building Vulnerability (SEV) values were given to various land-use elements in the digitised map of the centrumgebied (Figure 18). Values for transport, education, energy, living homes, vegetation and commercial infrastructure were assigned values based on the methodology developed by Dall'Osso et al., (2006). Further, built environment impact elements for heat stress and pluvial flooding were determined from a field survey conducted at the USP, and a multi-criteria analysis.

Vegetation has a socio-economic vulnerability of 1 and transport a value of 3. Based on the field survey evaluating characteristics of the buildings, multi-criteria analysis, and SEV values of various building types, there is a range of building vulnerability relating to heat-stress and flooding. Large, dark and south-facing buildings are especially vulnerable to heat-stress. Especially if they have a high density of windows, with no solar shading. A greater number of buildings are vulnerable to heat stress as compared to flooding. This can be attributed to numerous large (7+ floors) buildings, with a North-South orientation leading to a prolonged period of solar absorption by the longest axis of buildings as the sun travels east to west. Dark cladding and high window content enhance the impacts of solar radiation to users of buildings. Resulting in a greater dependence on air conditioning to regulate temperatures.

Buildings that are low-lying, have no open plan and surface spread foundations are more vulnerable to flooding impacts, both of the contents of the buildings, but also to structural damage. The majority of buildings have a vulnerability of 3 or lower in the centrumgebied, with the exception of HU Gezondheidszorg en Life Sciences & Chemistry building and the studentenhuisvesting De Bisschoppen buildings – the only two major buildings with a flooding vulnerability of value of 4.

Socio-Economic Exposure and Building Vulnerability



A: Vulnerability and Exposure to Pluvial Flooding (1-5)

infrastructure

SEV_t

🟥 3 (10)

Vegetation

SEV_V

☐ 1 (143)

Buildings

BV1_F_MAX

☐ 1 (1)

🟥 2 (8)

🟥 3 (13)

🟥 4 (4)

🟪 5 (1)

greenroofs

🟩 greenroofs (24)

water

🟦 water (7)

Centrumgebied

⬜ Centrumgebied (1)

Socio-economic exposure and building vulnerability (1-5) to Pluvial Flooding.

Land-use elements evaluated are transport infrastructure, vegetation and buildings.

Number of elements per category shown in brackets.

B: Vulnerability and Exposure to Heat Stress (1-5)

infrastructure

SEV_t

🟥 3 (10)

Vegetation

SEV_V

☐ 1 (143)

Buildings

BV1_HS_MAX

🟥 2 (1)

🟥 3 (16)

🟥 4 (10)

greenroofs

🟩 greenroofs (24)

water

🟦 water (7)

Centrumgebied

⬜ Centrumgebied (1)

Socio-economic exposure and building vulnerability (1-5) to Heat Stress.

Land-use elements evaluated are transport infrastructure, vegetation and buildings.

Number of elements per category shown in brackets.

Figure 18: Socio-economic exposure and building vulnerability of the various buildings and land-use types in the centrumgebied.
A – represents the vulnerability and exposure to pluvial flooding.
B – represents the vulnerability and exposure to heat stress.

Values for transport, education, energy, living homes, vegetation and commercial infrastructure were assigned values based on the methodology developed by Dall'Osso et al., (2006). Further, built environment impact elements for heat stress and pluvial flooding were determined from a field survey conducted at the USP, and a multi-criteria analysis.

III. Risk Maps

Combining hazard, population and building vulnerability and socio-economic exposure a risk map for the centrumgebied was calculated. The resulting maps depict the risk for heat stress and flooding (two severity scenarios each), with three population vulnerability scenarios: 1) day – high season, 2) Day – Low season and 3) Night – High and low season (same vulnerability score). The result is a total of twelve risk maps, presenting various levels of risk depending on the scenario.

Heat Stress

Heat Stress Risk Maps – Current Situation

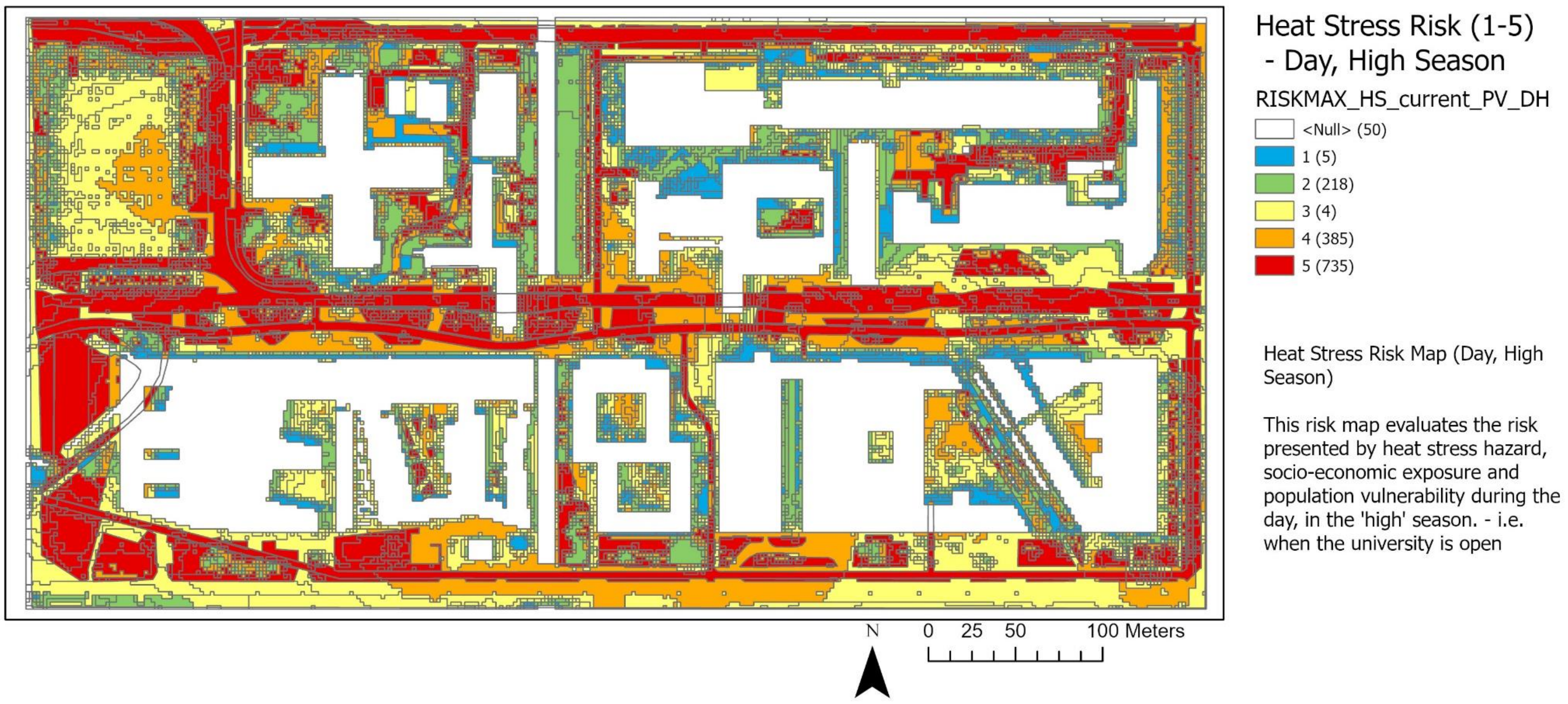
The heat stress (current) hazard map (Figure 14), was combined with the socio-economic exposure and building vulnerability (figure 18) and three population vulnerability scenarios (table 10), resulting in three different risk maps.

The first risk map in figure 18, is for the scenario: Day time, in the high season. In other words, during the working day while the university is open to teaching, research and all associated business operations, when the university is at its busiest, with the greatest number of people occupying and moving around the campus. This results in the greatest risk for heat stress. The maximal risk value of 5 is clustered around transport networks that encircle the buildings of the centrumgebied, with much of the impermeable paved surface that intersperses these transport networks achieving a risk value between 3 and 4. Vegetation also has a maximum risk value of 5, as plants are especially vulnerable to high levels of heat-stress. This is especially true in the raised grass beds along the central avenue of (Heidelberglaan) of the centrumgebied, as these vegetation plots are primary composed of grass, with few trees. It is possible to see that areas located close to water bodies and vegetated areas with high densities of trees (such as along the eastern border of the centrumgebied) that the risk values are significantly lower. All street and building names can be found in Appendix 1.

The second risk map in Figure 19 depicts risk scenario during the day, in the low season – i.e. during weekends or vacation when traditional university operations are halted, and the number of people visiting and occupying the campus is significantly reduced (Table 10). This reduced number of people occupying the campus has a clear impact on risk outside of the Heidelberglaan. Transport infrastructure where most people are like to be located, along with their dark and artificial surfaces once again results in a maximum risk value of 5. This is also the case in the paved courtyard area between the Bestuursgebouw and the Marinus Ruppertgebouw. Once again the grass planters also have a maximum risk level due to their vulnerability to heat stress. Areas proximal to water and high densities of trees, as well as areas proximal to buildings on the north-side (i.e. shadows) have a significantly reduced vulnerability to heat stress. Areas with a risk value of 1 can be proximal to areas with a risk value 5. This shows how spatially variable heat stress risk can be as a function of the natural and built environment.

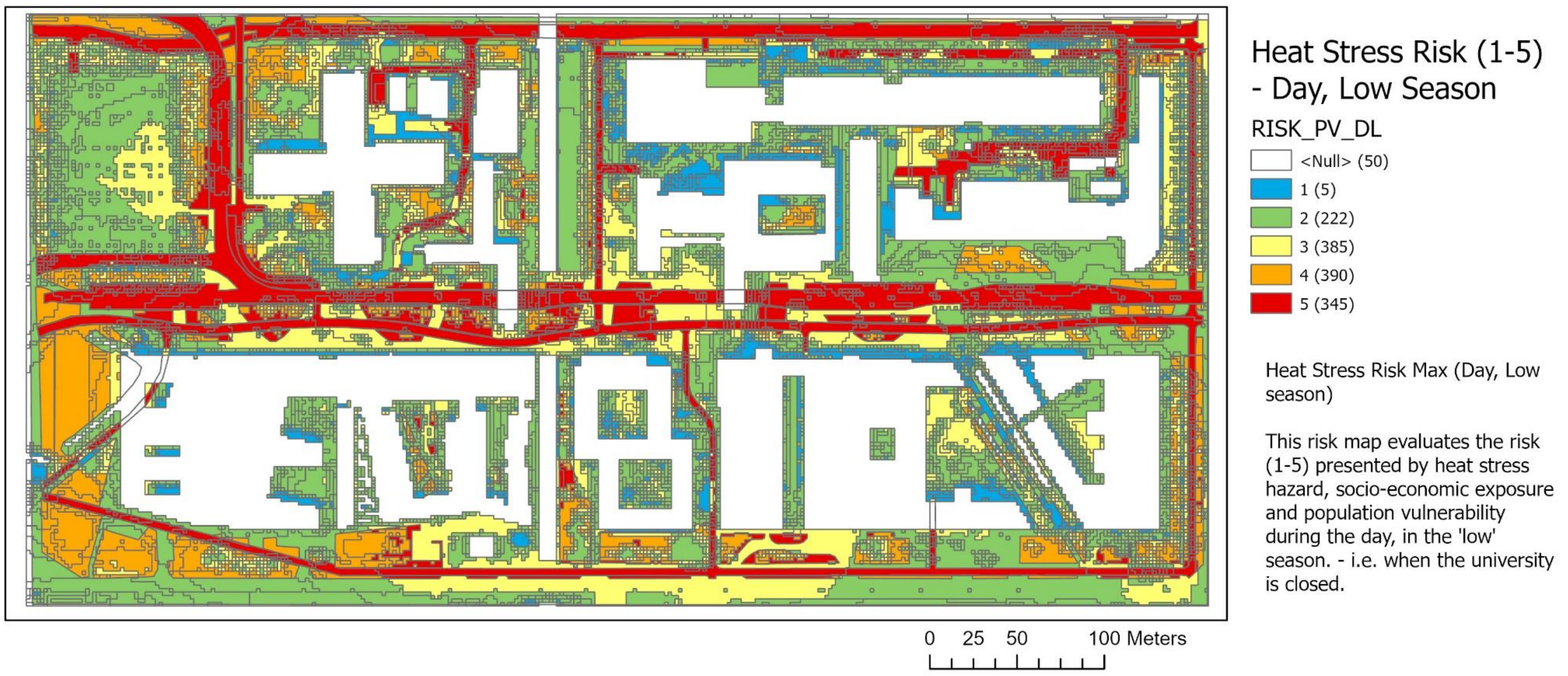
The third risk map from Figure 19 depicts the risk during the night, during both high and low seasons. The presence of upper risk values (4+) is significant reduced, and so too is the area that these risk values occupy (Figure 21) . This is because night time temperatures are significantly lower without the radiating effects of the sun. Although the UHI does result in raised night-time temperatures, the number of people moving around the campus is significantly reduced, and most people will be inside where climate regulation is possible. Once again, the central transport links along Heidelberglaan have the highest risk, which can be attributed to the high levels of paved and artificial surfaces that absorb solar radiation during the day and radiate them out at night.

Heat Stress Risk Maps - Present Day



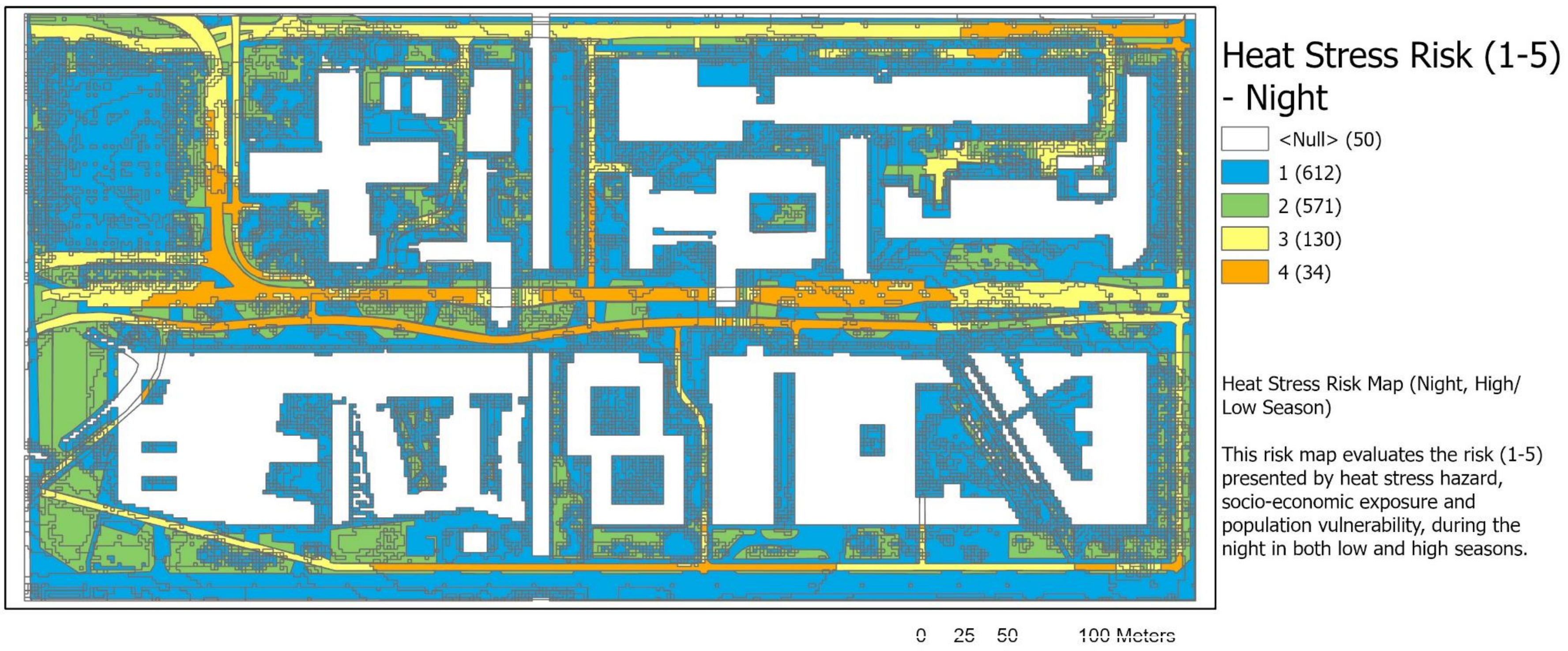
Heat Stress Risk Map (Day, High Season)

This risk map evaluates the risk presented by heat stress hazard, socio-economic exposure and population vulnerability during the day, in the 'high' season. - i.e. when the university is open



Heat Stress Risk Max (Day, Low season)

This risk map evaluates the risk (1-5) presented by heat stress hazard, socio-economic exposure and population vulnerability during the day, in the 'low' season. - i.e. when the university is closed.



Heat Stress Risk Map (Night, High/ Low Season)

This risk map evaluates the risk (1-5) presented by heat stress hazard, socio-economic exposure and population vulnerability, during the night in both low and high seasons.

Figure 19: Heat Stress Risk Maps – Current (2015) climate scenario.

This risk map is the amalgamation of the heat stress (current scenario) hazard map, the socio-economic exposure and building vulnerability maps for three population vulnerability scenarios, Day – high season, Day – Low season and Night. The result is three maps evaluating the risk for a dynamic population of the centrumgebied presented by a heat stress hazard modelled on the current climate scenario (2015).

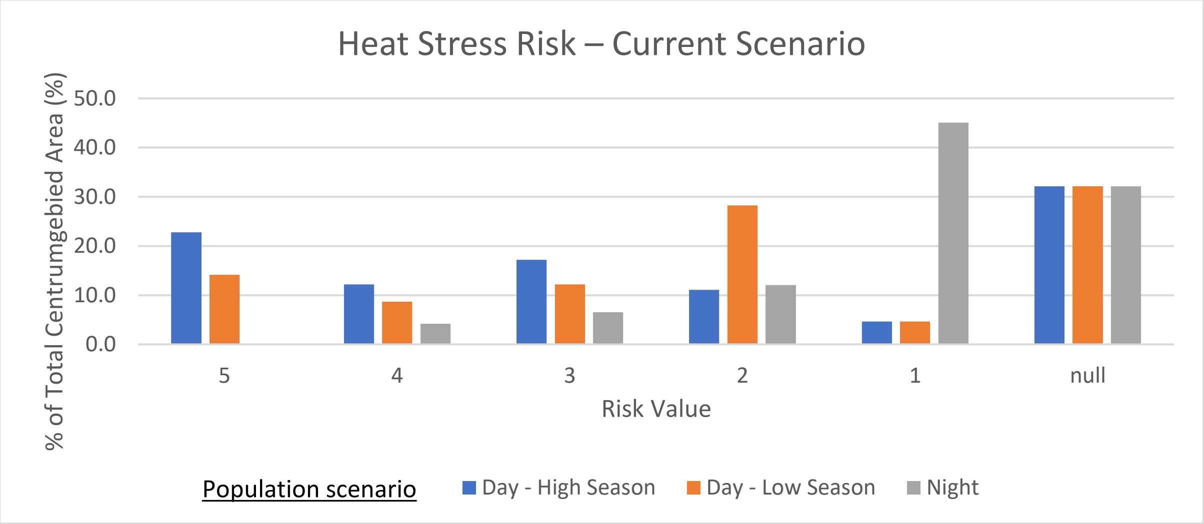


Figure 20: Risk value for Heat Stress (current) for each of the three population vulnerability scenarios, and the corresponding area (%) of centrumgebied that each risk value occupies.

Figure 20 depicts the total areas that each level of risk level occupies. In the population scenario Day – High Season, nearly 25% of centrumgebied area (building footprint area and zero hazard values comprise the null value). Compare this to night time, where 0% of the centrumgebied has a risk value of 5. As the scenarios shift to low season and night time, the total area of centrumgebied with risk values about 4 shifts downwards. The largest proportion of the centrumgebied has a risk value of 2 for the day time – low season scenario, and a value of 1 for night time scenarios. The relative composition that each risk value has relative to the total risk area (not including null values) is evaluated in Figure 21. Here the distribution of risk values and their proportion of total risk area is made clear.

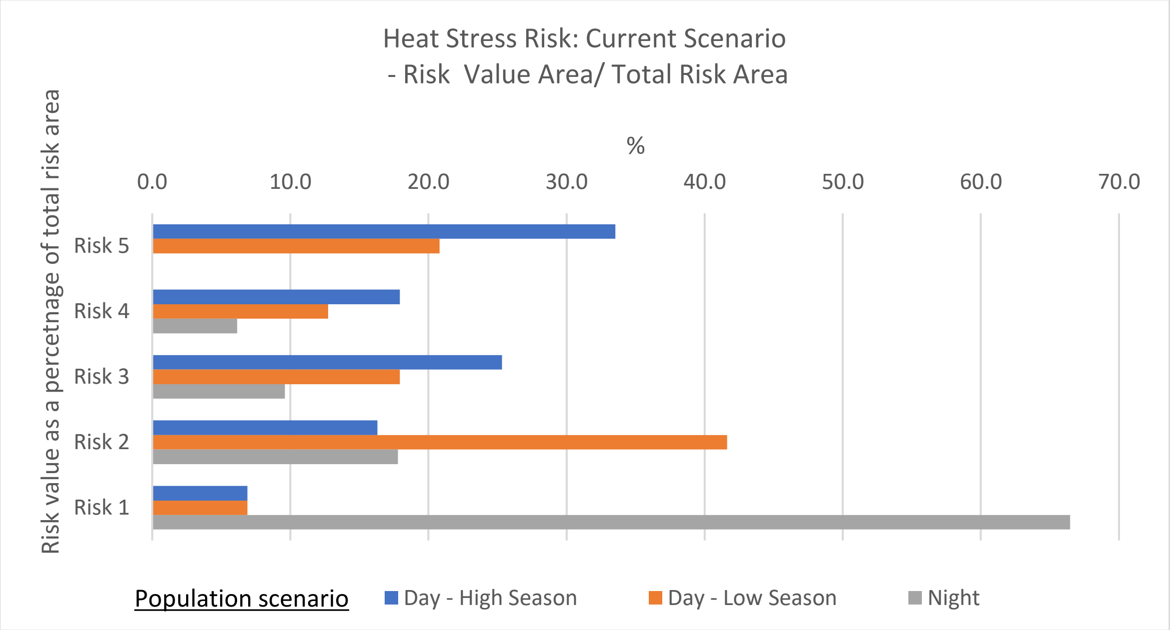


Figure 21: The percentage that each risk value category comprises of the total area of risk. Null values are removed from the calculation. For example, For the Population vulnerability scenario Day – High season, the risk value of 5 accounts for 34% of the total risk area for that scenario. Whereas a risk value of 2 accounts for 42% of the total risk area for the Population Vulnerability Day – Low season scenario.

Heat Stress Risk Maps – Projected for 2050

To generate the three risk maps for the 2050 heat stress scenario, the hazard map (Figure 15) was combined with socio-economic exposure and building vulnerability of the centrumgebied (Figure 18), and the three population vulnerability scenarios (table 10). The resulting three risk maps (Figure 22), showcase the projected values for heat-stress in 2050 for with the current land-use of the centrumgebied.

Common themes are once again clear – with all transport infrastructure and vegetation achieving the maximum risk value of 5 in the day - high season scenario. In this scenario all other impermeable surfaces have a risk value of 4, and the only areas with a risk value below four are those located proximal to the northern side of buildings where solar shading occurs, such as the paved area between the Willem C. van Unnikgebouw and the Educatorium, or proximal to numerous trees or water bodies, i.e. the tree lined avenue between the Martinus J. Langeveldgebouw and the Universiteitsbibliotheek.

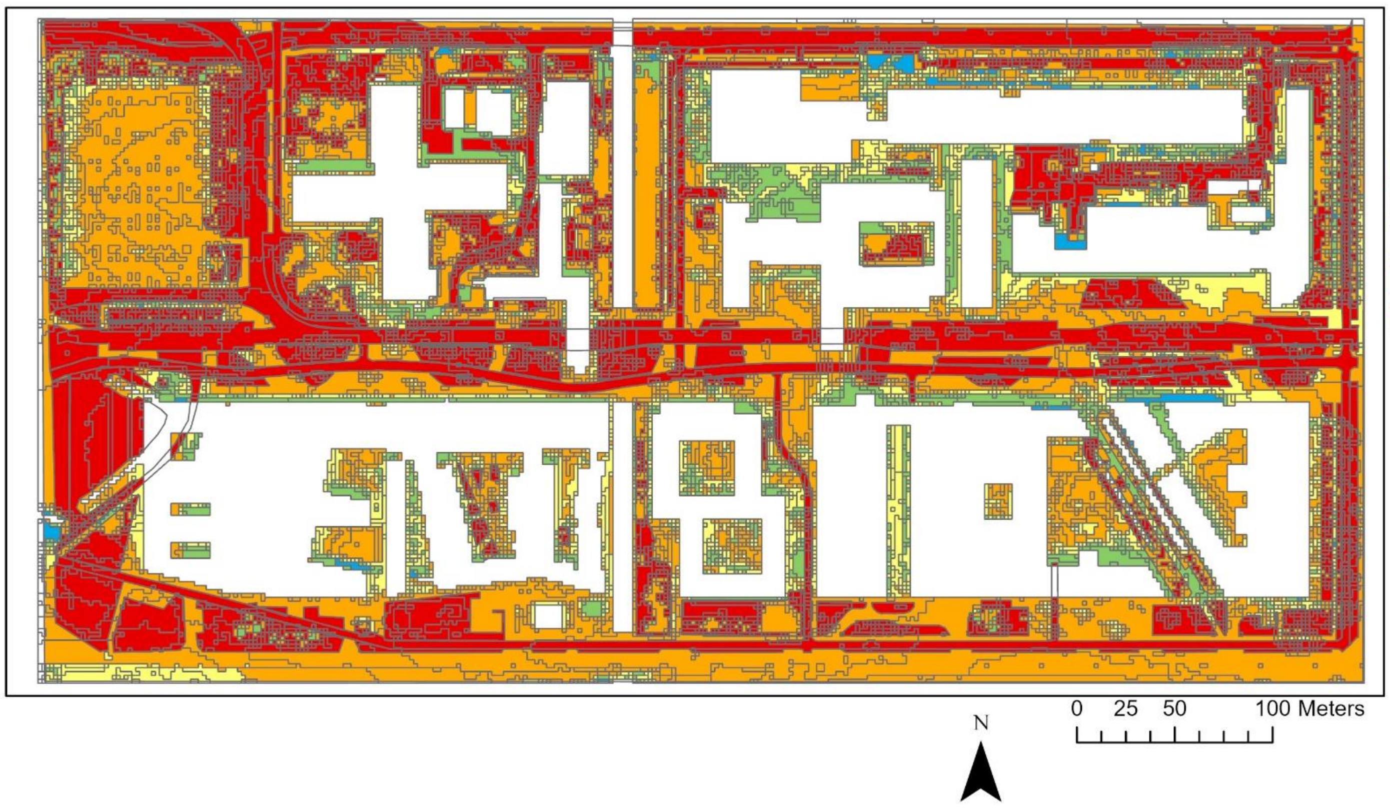
In the Day – Low season population vulnerability scenario, the transport networks where people congregate are still designated with a risk value of 5. Further, the grassy vegetation surrounding buildings and the raised planters along Heidelberlaan (central avenue) also have a maximum risk value of 5. However, the majority of walkways and impermeable surfaces risk values have dropped a level to a value of 3. This can be linked to the lower footfall expected across these areas due to a reduced population occupying the centrumgebied during the low season. Once again, a similar pattern emerges where areas proximal to the northern face of buildings have the lowest risk factor (solar shading), as well as areas located proximal to water and numerous trees (i.e. groups of trees, not a singular tree), as seen along the eastern border of the centrumgebied (alongside the Bestuursgebouw and the HU Economie, Management, Communicatie, ICT & Media building).

Finally, in the night time scenarios (High + low season), risk drops significantly. No area on the centrumgebied has a risk of 5, and the transport networks are the only locations with a risk value of 4. Vegetation and raised planters have their risk dramatically reduced (risk value = 2) and the paved surfaces have a risk value of 1. Only the paved area between the Marinus Ruppertgebouw and the Bestuursgebouw has an elevated raised risk value of 4 compared to other paved areas.

In Figure 22 it is possible to see what percentage areas each risk value composes based on the three population vulnerability scenarios. For the high season, Day scenario over 50% of the centrumgebied has a risk value above 4, (Figure 23). Risk values 1-3 only comprised 22% of the total risk area (Figure 24). The risk presented by heat stress in 2050 during the day while the university is open is very worrying. Action must be taken to address the potential harm to life, vegetation and infrastructure in the centrumgebied. Even when the university is not open (low season), the risk presented by heat stress during the day has over 20% of the centrumgebied with a risk of 5, and over 25% with a vulnerability of 3 (Figure 23). This implies that even by removing a significant proportion of the population from the centrumgebied, the risk present by heat-stress in 2050 is still significant to infrastructure, buildings and vegetation.

It was unfortunately not possible to map the impacts of heat-stress on the 2050 land-use map of the centrumgebied as envisioned by Barcode Architects (Figure 13b), as population data and building vulnerability (based on relevant impact elements (i.e. table 2)) do not exist. Further, the hazard map for heat-stress 2050 was also modelled on the current land-use, and there are gaps in the data where the current buildings are located. To understand the risk presented to the 2050 situation, a new hazard map would have to be modelled using the digitised land-use map created in this study (Figure 13b). This could be a central task in follow up research to better evaluate the 2050 vision for the centrumgebied.

Heat Stress Risk Maps - 2050



Heat Stress Risk - Day, High Season

⬜ <Null> (48)
🟦 1 (2)
🟩 2 (35)
🟨 3 (4)
🟧 4 (246)
🟥 5 (1069)

Heat Stress Risk Map (Day, High Season)

This risk map evaluates the risk (1-5) presented by heat stress hazard, socio-economic exposure and population vulnerability during the day, in the 'high' season. - i.e when the university is open.

Number of elements at risk in brackets.

Heat Stress Risk - Day, Low Season

⬜ <Null> (48)
🟦 1 (2)
🟩 2 (39)
🟨 3 (246)
🟧 4 (331)
🟥 5 (738)

Heat Stress Risk Map (Day, Low Season)

This risk map evaluates the risk (1-5) presented by heat stress hazard, socio-economic exposure and population vulnerability during the day, in the 'low' season. - i.e. when the university is closed.

Heat Stress Risk - Night

⬜ <Null> (48)
🟦 1 (287)
🟩 2 (828)
🟨 3 (90)
🟧 4 (144)
🟥 5 (7)

Heat Stress Risk Map (Night, High + Low Season)

This risk map evaluates the risk (1-5) presented by heat stress hazard, socio-economic exposure and population vulnerability during the night in both 'high' and 'low' seasons.

Figure 22: Heat Stress Risk Maps – 2050 climate scenario.

This risk map is the amalgamation of the heat stress (2050) hazard map, the socio-economic exposure and building vulnerability maps for three population vulnerability scenarios: Day – high season, Day – Low season and Night. The result is three maps evaluating the risk for a dynamic population of the centrumgebied presented by a heat stress hazard modelled on the 2050 climate scenario.

Finally, during the night, risk is significantly reduced. You can clearly see the shift in risk toward the lower risk values, with a risk value of 1 comprising 60% of the total risk area (Figure 24). However, the impacts of night time radiation from buildings and paved surfaces can still pose a serious risk, and lead to greater dependence on energy intensive air-conditioning, which as mentioned previously, will only positively feedback into planetary warming.

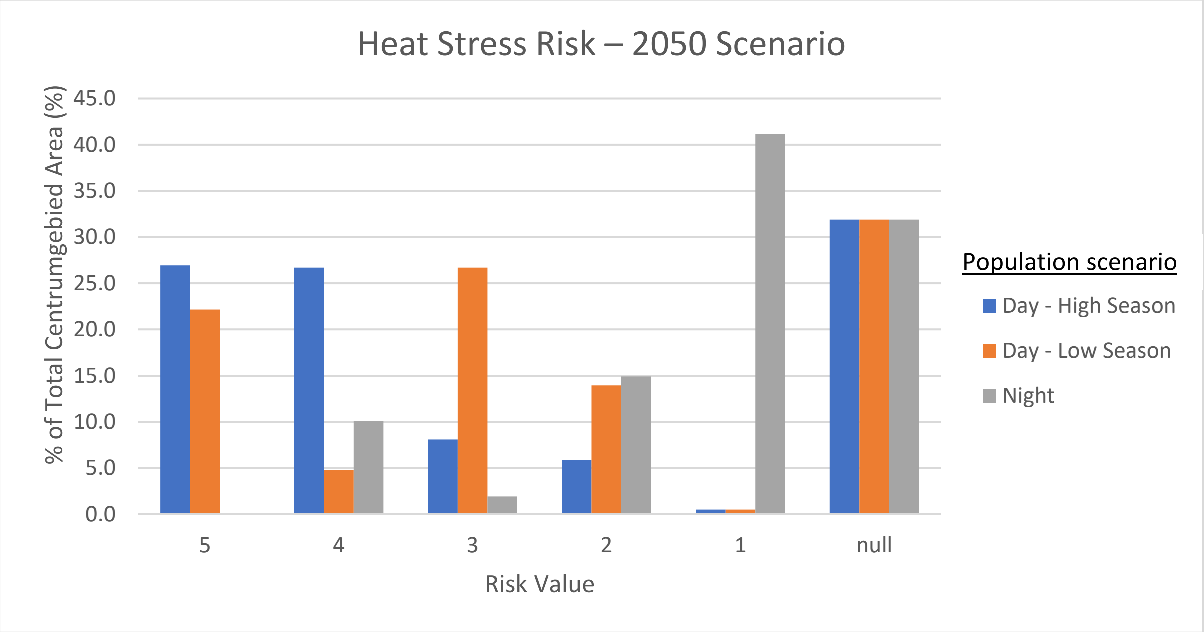


Figure 23: : Risk value for Heat Stress (projected for 2050) for each of the three population vulnerability scenarios, and the corresponding area of centrumgebied (%) that each risk value occupies.

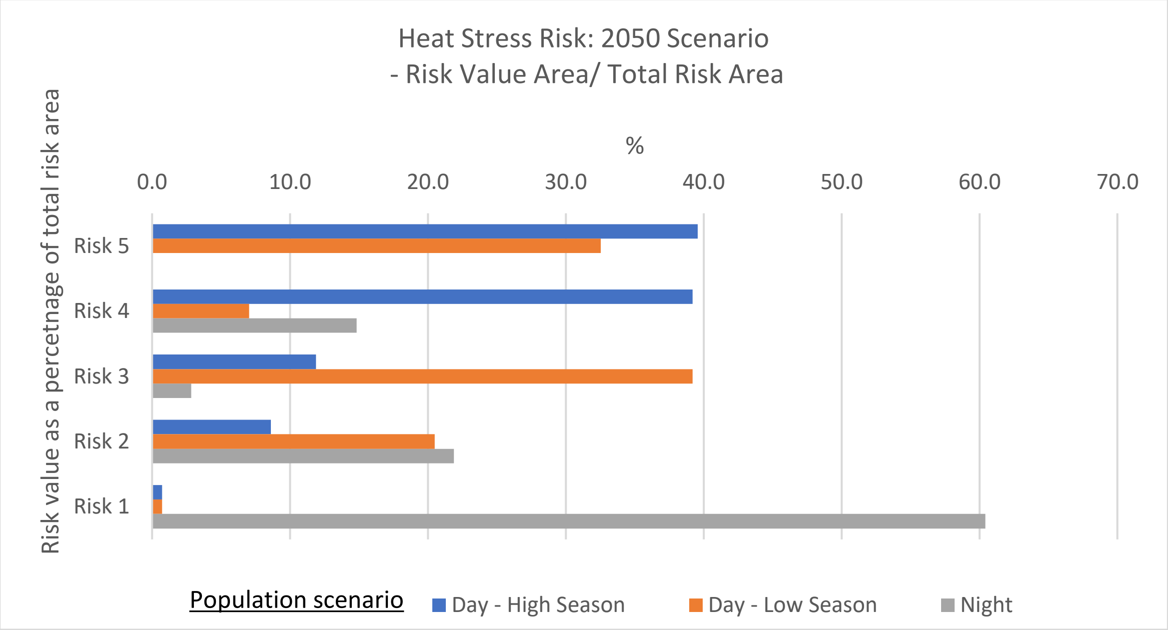


Figure 24: The percentage that each risk value category comprises of the total area of risk. For example, For the Population vulnerability scenario Day – High season, the risk value of 5 accounts for ~40% of the total risk area for that scenario. Whereas a risk value of 2 accounts for ~20% of the total risk area for the Population Vulnerability Day – Low season scenario.

Flooding

Flooding Risk - 1-100 year event.

To generate the three risk maps for the 1-100 year flood risk scenario, the flood hazard map for a 1-100 year event (Figure 16) was combined with the socio-economic exposure and building vulnerability (Figure 18) and three population vulnerability scenarios (Table 10). The resulting three risk maps (Figure 25), showcase the risk values for flooding in the current situation of the centrumgebied.

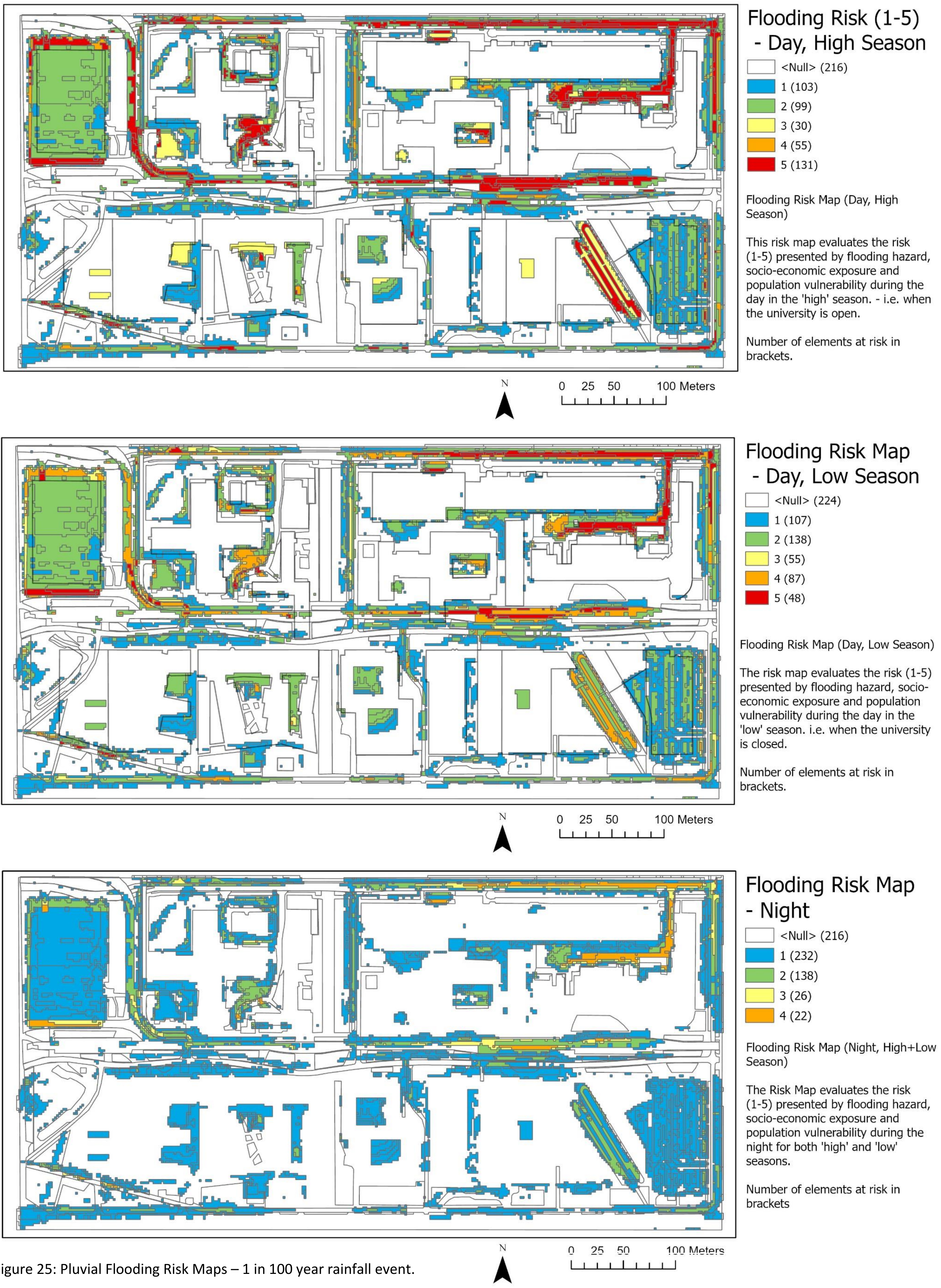
Flooding risk is predominantly clustered around transport infrastructure along the northern border of the centrumgebied (Leuvenlaan), the paved area between the Marinus Ruppertgebouw and the Bestuursgebouw (Leuveplein), and the bus and tram network that runs in along the Heidelberglaan along the centre of the centrumgebied. Another notable location of flooding is along the walkway between the HU Gezondeidszorg en Life Sciences & Chemistry building and the studentenhusivesting De Bisschoppen buildings. Other than small pockets located elsewhere, maximum flooding risk values (5) are all clustered along these areas. There are broader locations of minimal flooding risk (i.e. 1-2) located in various paved surfaces throughout the centrumgebied, but there is also a much larger null value (i.e. 0) for flooding than compared to heat stress. This is the result of the hazard map (Figure 16), which only depicts flooding in certain areas throughout the centrumgebied.

As the population vulnerability scenarios shift from the high season to the low season (day time), as with the heat stress risk maps, the overall level of risk decreases. The total surface area extent of level 5 risk is greatly reduced (Figure 26), but an elevated risk (values of 4-5) still exist in the aforementioned hotspots. The total flooded area remains the same, it is simply the area that elevated risk values occupy that decrease as a smaller population is exposed to the hazard (Figure 27).

In the final scenario, night time (high + low season), you can see that no locations in the centrumgebied have a risk level of 5, and only a very small portion of the previously high risk hotspots have a risk value of 4. The walkway between the HU Gezondeidszorg en Life Sciences & Chemistry building and the studentenhusivesting De Bisschoppen buildings now have a flood risk of only 1-2 - a threefold reduction in risk as compared to the day-time. Once again, a smaller population exposed to a hazard results in a significantly reduced risk.

Evaluating the proportions of the centrumgebied occupied by various flood risk values (Figure 26) we see that a much smaller percentage of the centrumgebied is exposed to flooding risk as compared to heat stress. Flooding risk is clustered in much smaller areas, and this results in a maximum risk value of 5 during the day in the high season occupying under 10% of the centrumgebied area. This is a consequence of the null values accounting for almost 70% of the centrumgebied area for flooding as compared to just over 30% for the heat stress scenarios. When evaluating the total area each risk value composes as a percentage of total risk area (i.e. not including null value areas), it is still clear that the lower values of risk (i.e. 1 to 2) predominate the total area of risk (Figure 27). This implies that the campus, other than certain hotspots, experiences a relatively low risk to disaster from a flooding event correlating to a 1-100 year storm event.

Flood Risk Maps - 1 in 100 year event



Flooding Risk Map (Day, High Season)

This risk map evaluates the risk (1-5) presented by flooding hazard, socio-economic exposure and population vulnerability during the day in the 'high' season. - i.e. when the university is open.

Number of elements at risk in brackets.

Flooding Risk Map (Day, Low Season)

The risk map evaluates the risk (1-5) presented by flooding hazard, socio-economic exposure and population vulnerability during the day in the 'low' season. i.e. when the university is closed.

Number of elements at risk in brackets.

Flooding Risk Map (Night, High+Low Season)

The Risk Map evaluates the risk (1-5) presented by flooding hazard, socio-economic exposure and population vulnerability during the night for both 'high' and 'low' seasons.

Number of elements at risk in brackets

Figure 25: Pluvial Flooding Risk Maps – 1 in 100 year rainfall event.

This risk map is the amalgamation of the flooding hazard map, the socio-economic exposure and building vulnerability maps for three population vulnerability scenarios: Day – high season, Day – Low season and Night. The result is three maps evaluating the risk for a dynamic population of the centrumgebied presented by a flooding hazard modelled on a 1-100 year rainfall event.

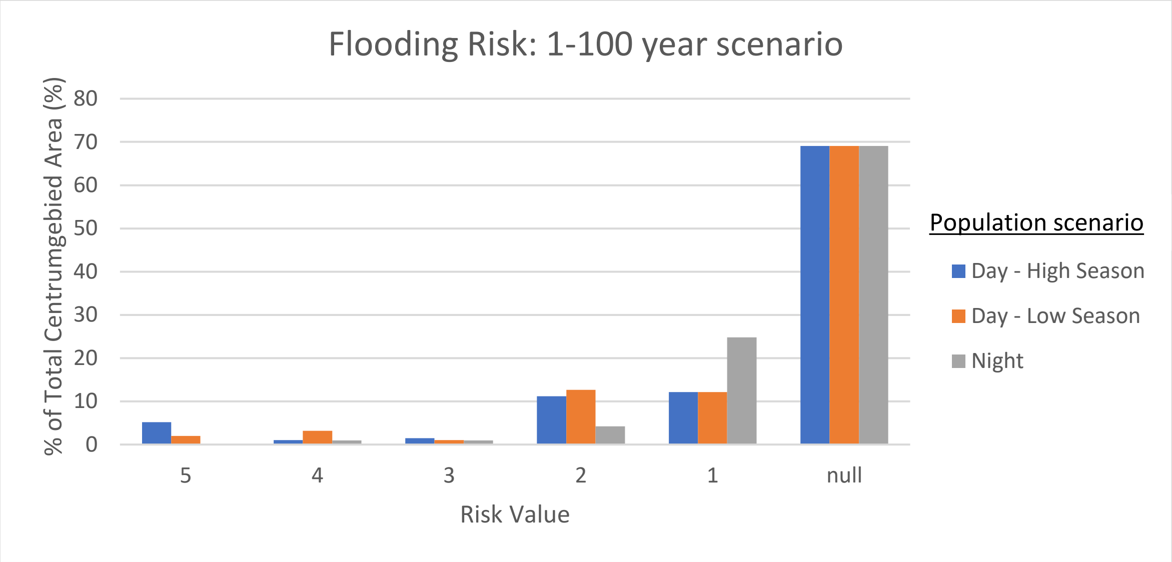


Figure 26: Risk value for Pluvial Flooding (1-100 year event) for each of the three population vulnerability scenarios, and the corresponding area of centrumgebied (%) that each risk value occupies.

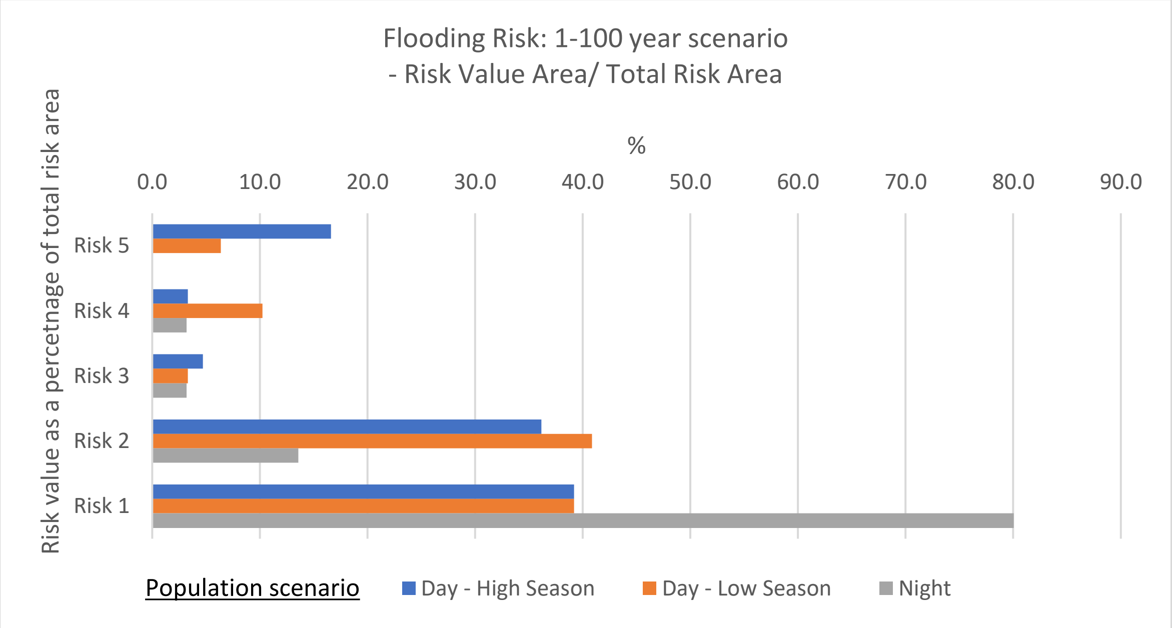


Figure 27: The percentage that each risk value category comprises of the total area of risk. For example, For the Population vulnerability scenario Day – High season, the risk value of 5 accounts for ~16% of the total risk area for that scenario. Whereas a risk value of 2 accounts for ~40% of the total risk area for the Population Vulnerability Day – Low season scenario.

Flooding Risk - 1-1000 year event.

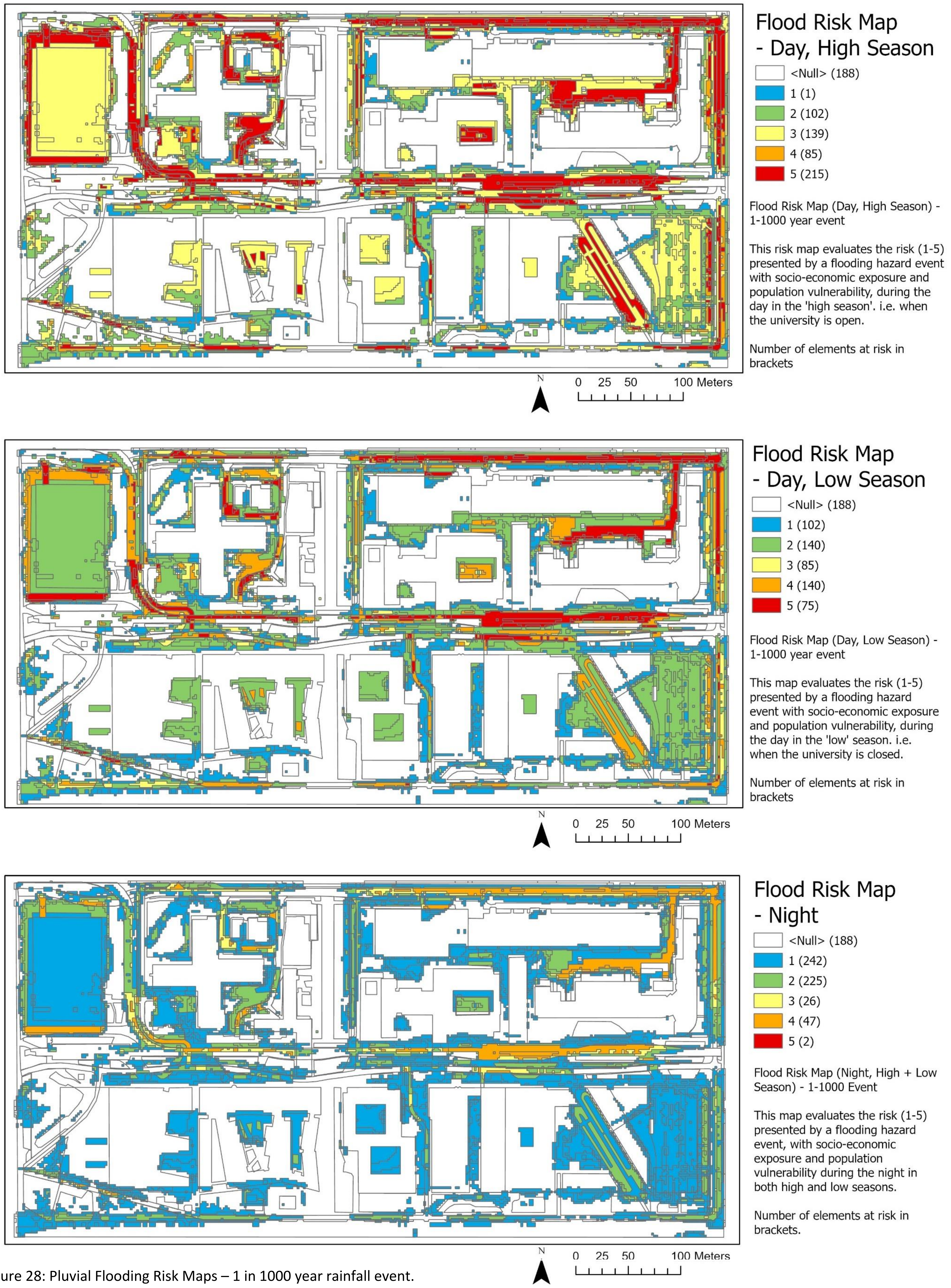
To generate the three risk maps for the 1-1000 year flood risk scenario,, the flooding hazard map for a 1-1000 year event Figure 17 was combined with the socio-economic exposure and building vulnerability (Figure 18) and three population vulnerability scenarios (Table 10). The resulting three risk maps (Figure 28), showcase the risk values for flooding as a result of a 1-1000 year event in the current land-use situation of the centrumgebied.

As with the 1-100 flood risk map (Figure 25), the areas of maximum risk are clustered around transport infrastructure; particularly along the bus and tram links in front of the Bestuursgebouw (Heidelberglaan), as well as the Padualaan road (bus lane) that goes in between the Hugo R. Kruytgebouw and the Parkeerterrein Padualaan (P6). Paved surfaces in-between buildings, such as the Bestuursgebouw and the Marinus Ruppertgebouw, the walk way between HU Gezondeidszorg en Life Sciences & Chemistry building and the studentenhusivesting De Bisschoppen buildings, as well as the paved roads that line the eastern edge of the Hugo R. Kruytgebouw and the Sjoerd Groenmangebouw also have maximum risk values, in both day time scenarios (High season + Low Season) (Figure 28). With the increased severity of the hazard, there is a net increase in the risk value across all three population vulnerability scenarios, which is reflected in Figure 29, where it is possible to see a shift in the total area flooded: the null value has reduced from 69% of centrumgebied area in the 1-100 year event (Figure 26), to 58% for the 1-1000 year risk map (Figure 29). Therefore, not only is there a greater net area of the centrumgebied at risk during the 1-1000 year flooding scenario, but so too is the severity of risk.

In the Population vulnerability: Day – High season scenario, 10% of the centrumgebied area has a maximum risk value of 5. This is a doubling of maximal risk area as compared to the 1-100 year risk map. It is clear that there has been a shift to the higher values of risk in the 1-1000 map, with Figure 30 showcasing the shift in net area represented by risk values higher than 3, as compared to the 1-100 scenario (Figure 27).

As we move from population vulnerability during the day from high to low season (i.e. open vs. closed university), a familiar pattern emerges. Once again areas of maximum risk are located in the aforementioned hotspots; but the severity of risk shifts down the value scale (Figure 30). This too is the scenario for night (high + low season). Maximum risk is located in the same hotspots, but the severity of the risk category is lowered due to a lower population left exposed and vulnerable to the hazard. Using this knowledge, key areas of flooding vulnerability can be identified to adaptive action, while understanding how population and building exposure and vulnerability can mediate the extent of risk, decision makers can develop a strategy about how to best adapt to, mitigate and become more resilient against flooding.

Flood Risk Maps - 1 in 1000 year event



Flood Risk Map (Day, High Season) - 1-1000 year event

This risk map evaluates the risk (1-5) presented by a flooding hazard event with socio-economic exposure and population vulnerability, during the day in the 'high season'. i.e. when the university is open.

Number of elements at risk in brackets

Flood Risk Map (Day, Low Season) - 1-1000 year event

This map evaluates the risk (1-5) presented by a flooding hazard event with socio-economic exposure and population vulnerability, during the day in the 'low' season. i.e. when the university is closed.

Number of elements at risk in brackets

Flood Risk Map (Night, High + Low Season) - 1-1000 Event

This map evaluates the risk (1-5) presented by a flooding hazard event, with socio-economic exposure and population vulnerability during the night in both high and low seasons.

Number of elements at risk in brackets.

Figure 28: Pluvial Flooding Risk Maps – 1 in 1000 year rainfall event.

This risk map is the amalgamation of the flooding hazard map, the socio-economic exposure and building vulnerability maps for three population vulnerability scenarios: Day – high season, Day – Low season and Night. The result is three maps evaluating the risk for a dynamic population of the centrumgebied presented by a flooding hazard modelled on a 1-1000 year rainfall event.

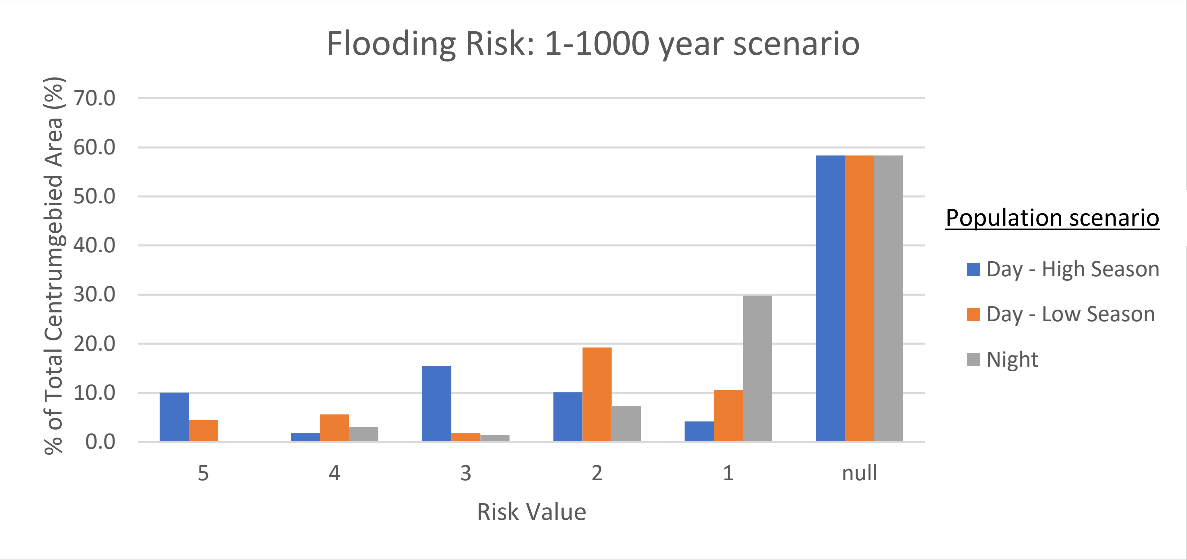


Figure 29: Risk value for Pluvial Flooding (1-1000 year event) for each of the three population vulnerability scenarios, and the corresponding area of centrumgebied (%) that each risk value occupies.

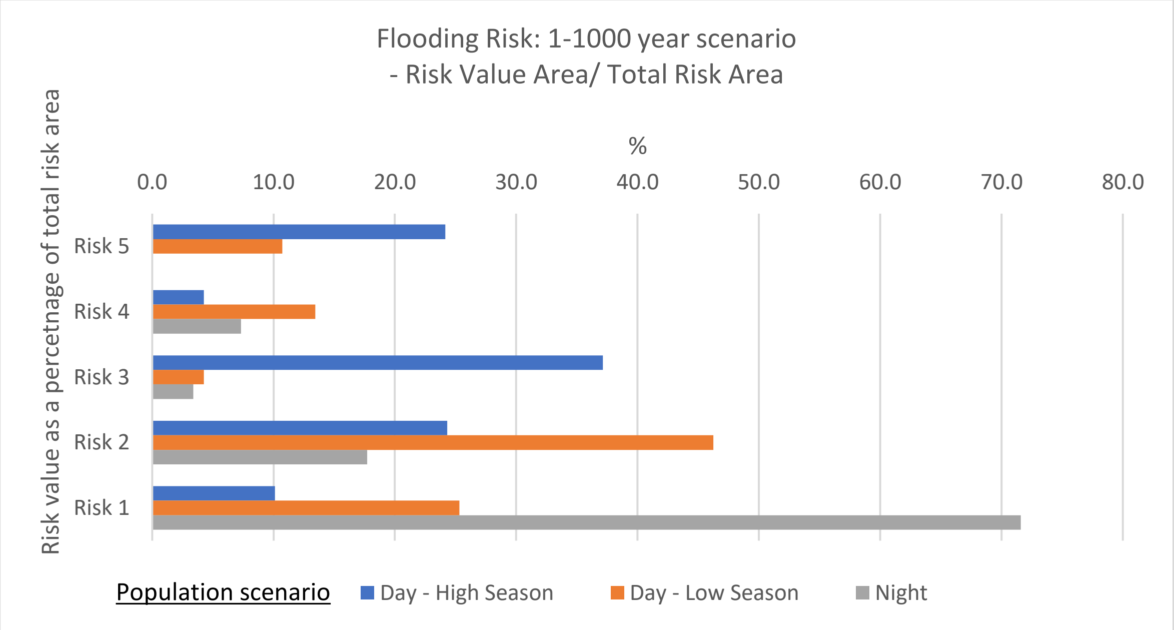


Figure 30: The percentage that each risk value category comprises of the total area of risk. For example, For the Population vulnerability scenario Day – High season, the risk value of 5 accounts for ~24% of the total risk area for that scenario. Whereas a risk value of 2 accounts for ~46% of the total risk area for the Population Vulnerability Day – Low season scenario.

IV. Risk Map Summary

Using these risk maps it is possible to identify recurring hotpots of risk throughout the centrumgebied. This provides decision makers with valuable data to focus redevelopment and climate adaption measures. However, not only are the locations of risk necessary for informed decisions, but so too is understanding how the multidimensional socio-economic-geophysical intersection of exposure and vulnerability interact with natural hazards and manifest into risk, and how risk evaluates the potential for disaster.

In university campuses with a transient and dynamic population, it is vitally important to account for population vulnerability to natural hazards. Further, with the planned redevelopment of the centrumgebied, understanding the factors that contribute to building vulnerability and exposure will allow for informed decisions about how best to plan, design and implement the refurbishment of existing, and construction of new buildings. Unfortunately, we have limited control over natural hazards and their severity, but making decision and design choices that can limit the exposure to these hazards, as well as the vulnerability of the USP population and buildings can go a long way to minimising risk. The impact of a variable population vulnerability on risk was demonstrated by using three population vulnerability scenarios.

Using these risk maps, it is therefore possible to evaluate the locations on campus that present maximum risk to disaster as a consequence of flooding and heat stress hazards, and thereby develop a strategy to address these locations of consistent risk. In Figure 31, heat stress and flooding maps have been overlaid to see which areas present the highest risk to both hazard types. The maps have been split into two scenarios: A) the low severity hazard scenario (current heat stress values, 1-100 year flood event), and B) a high severity hazard scenario (2050 heat stress, 1-1000 year flood event). In both maps, the highest population vulnerability was used: day time – high season. With these two maps, it is possible to identify that transport infrastructure, vegetation and pockets of paved surfaces between buildings present the greatest risk. Using these maps, it is possible to design, map and evaluate a series of strategies that aims to address risk and to minimise the potential for disaster. To do so, an online tool – the Climate Resilient City Toolbox – has been used to model a series of measures to address flooding and heat stress, and evaluate the impact, costs and therefore a cost-benefit analysis of different strategies.

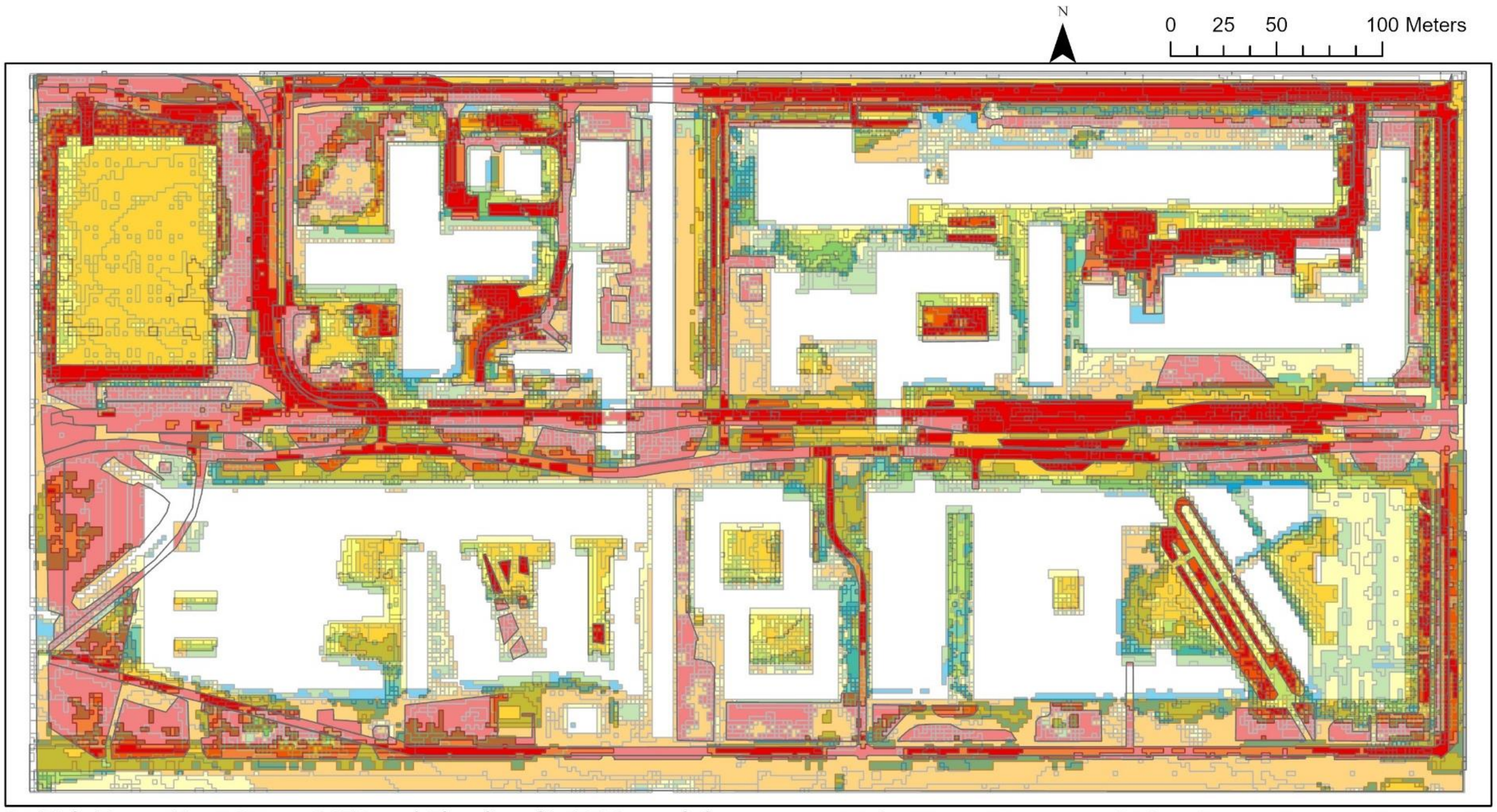
Merging Flooding and Heat Stress Risk Maps - A Risk Overview

A: Risk Maps: Heat Stress (current) and Flooding (1-100 year) for the Day - High Season scenario.

Merging the risk maps for heat stress and flooding we can identify hotspots of risk for both hazards. This generates areas of priority where decision makers must implement adaption measures.

Risk - Heat Stress and Flooding - Current Scenario

Heat Stress Risk Map - (Current)	Flooding Risk Map - (1-100 year)
⬜ <Null> (50)	⬜ <Null> (216)
🟦 1 (5)	🟦 1 (103)
🟩 2 (218)	🟩 2 (99)
🟨 3 (4)	🟨 3 (30)
🟧 4 (385)	🟧 4 (55)
🟥 5 (735)	🟥 5 (131)



B: Risk Maps: Heat Stress 2050 and Flooding (1-1000 year) for the Day - High Season scenario.

Merging the risk maps for heat stress and flooding we can identify hotspots of risk expected for both hazards with climate change. This generates areas of priority where decision makers must implement adaption measures.

Risk: Heat Stress and Flooding - Severe Scenario

Heat Stress Risk - 2050	Flooding Risk - 1-1000
⬜ <Null> (48)	⬜ <Null> (188)
🟦 1 (2)	🟦 1 (1)
🟩 2 (35)	🟩 2 (102)
🟨 3 (4)	🟨 3 (139)
🟧 4 (246)	🟧 4 (85)
🟥 5 (1069)	🟥 5 (215)

Figure 31: Merging Heat and Flooding Risk maps to generate a total hazard overview of the centrumgebied.

A: Merging the layers: Heat stress risk (current) and Flood Risk (1-100) to identify hotspots of risk for both heat stress and flooding in the low severity hazard scenario for a high population vulnerability scenario (Day – high season).

B: Merging the layers: Heat stress risk (2050) and Flood Risk (1-1000) to identify hotspots of risk for both heat stress and flooding in the high severity hazard scenario, for a high population vulnerability scenario (Day – high season).

Number of elements at risk in brackets.

7. Evaluation

I. Climate Resilient City Toolbox

Having identified the key areas of maximum risk to heat stress and pluvial flooding in a range of hazard, socio-economic and population vulnerability scenarios, it was then possible to test a series of adaptation measures and their suitability to minimising these risks. To do so, the Climate Resilient City (KBS) Toolbox was used to map, quantify and thereafter evaluate the impact of various measures – from traditional grey infrastructure to nature based.

Using Figures 31 as a guideline for key locations to implement measures to address the heightened risk in these “hotspots”, it was possible to spatially map a variety of techniques onto the centrumgebied and quantify their impact.

The resulting map (Figure 32) presents what a more climate adaptive centrumgebied could look like. All cycle networks have been fitted with permeable pavement systems that promote water infiltration, and so too have the high risk hotspots between buildings (i.e. the Leuveplein between the Bestuursgebouw and the Marinus Ruppertgebouw, and between the Hugo R. Kruytgebouw and the Sjoerd Groenmangebouw) been mapped with permeable pavements. The bus and tram lanes have been mapped with “hollow roads” that increases the amount of water able to be stored in these places, and slows the rate of water entering sewer systems while promoting evaporative cooling. The raised vegetation planting beds and other green strips have been expanded and trees have been added to these locations: providing solar shading, local cooling via evapotranspiration, and a net sink for surface water infiltration. To further test the potential of redeveloping the campus, all available roof space has been mapped with “green roofs with drainage delay” to slow the rate of water entering sewerage systems during storm events, and also to increase biodiversity and to reduce thermal absorption of solar radiation directly onto building roofs. Bio-swales have also been added to key areas of risk, such as along the eastern border of the Parkeerterrein Padualaan (P6), along the northern border of the Marinus Ruppertgebouw, and the eastern borders of the Bestuursgebouw and the HU Economie, Management, Communicatie, ICT & Media building. A water roof has also been added to the open-top Parkeergarage on Cambridgelaan (P8), as well as two scenarios on the Parkeerterrein Padualaan (P6): permeable paving and an underwater storage tank. Testing these two-scenarios we can calculate the cost-benefit analysis of two different types of grey-infrastructure projects.

Overall, using this tool it is possible to map various climate adaptation methods and create a rough understanding of the cost of construction and maintenance of these measures, as well as the relevant climate adaptive impacts they have. To evaluate the effectiveness of each measure, the cost per environmental benefit was calculated. In Figure 33 it is possible to see the benefit/cost analysis for four environmental indicators: storage capacity (m^3), groundwater recharge (mm/year), evapotranspiration (mm/year) and heat reduction (°C). These four factors address risk associated both to flooding and heat-stress.

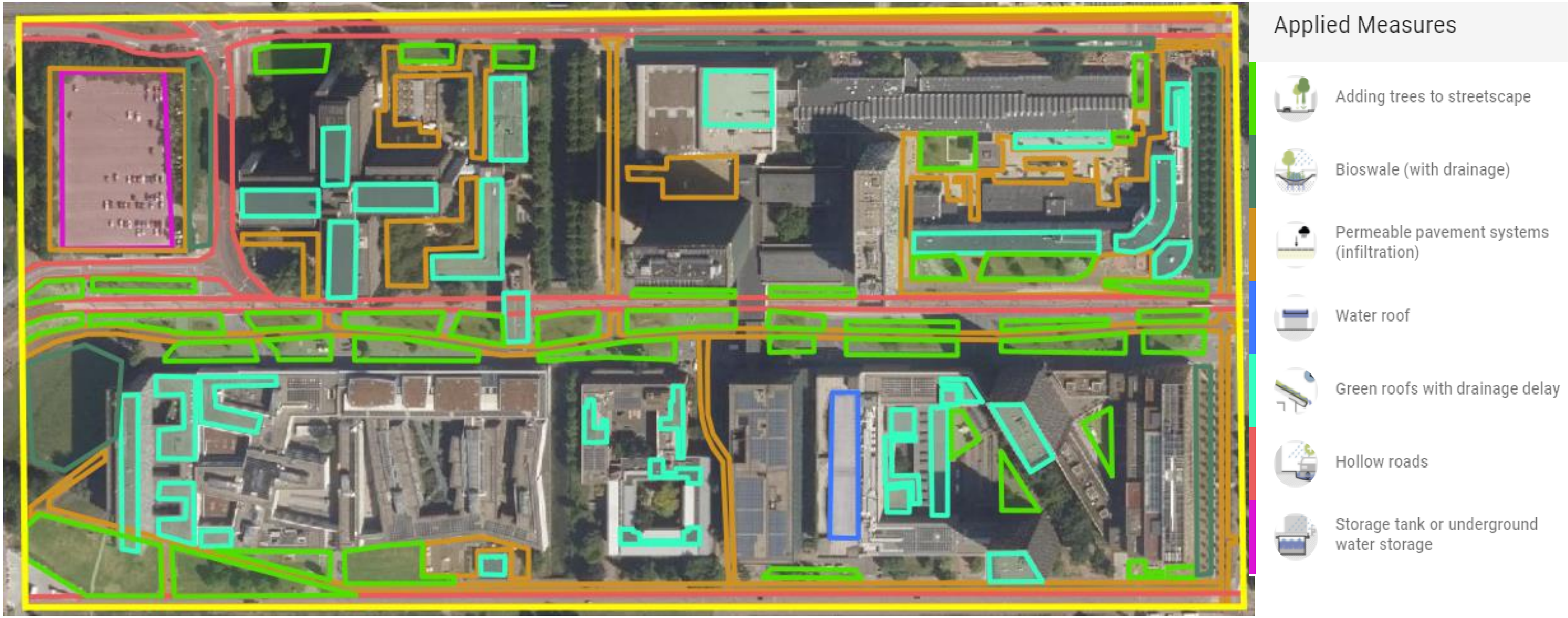


Figure 32: Climate adaption strategies that could be applied to the Centrumgebied to address both heat stress and pluvial flooding risk. This map was created based on the current land-use of the centrumgebied. Measures were applied to retain the function of each area, but alter it in such a way to be more climate adaptive based on the hazard type and risk level (Figures 31). For example, the grassy vegetation has all been replaced by trees. Walkways and cycle paths have been replaced by permeable pavement systems. Roads and tramways have been fitted with hollow roads.

Evaluating the benefits/ cost of the various measures; adding trees to the streetscape consistently has the best (other than storage capacity where it comes in second) environmental benefits per cost of construction. Bioswales are the most effective method when it comes to increasing water storage capacities, and also perform well relating to ground water recharge and heat reduction. These two nature based solutions also bring a host of co-benefits, such as promoting biodiversity and ecosystem services when implemented.

Hollow roads are third most effective in terms of storage capacity, and second most effective in terms of evapotranspiration. This technical solution is an effective measure regarding flood risk management while maintaining land-use of transport infrastructure. Green Roofs with drainage delay can be classified as an integrated solution, combining nature based solutions and co-benefits for heat stress and biodiversity along with technical solutions regarding pluvial flooding, with medium benefits across all four environmental indicators. Water roofs are also an integrated solution, but provide less effective benefits in all four indicators evaluated.

Interestingly, permeable pavements come in 5th place regarding storage capacity/ construction costs but scores zero on groundwater recharge. This is an unexpected result as should previously paved surfaces be transformed into permeable pavement, it would be logical that this provides a greater surface area into which water can now infiltrate into the sub-surface, rather than run-off into sewers to be transported else-where. This result merits further investigation. It also calls into question the validity of this tool, and that decision makers and local stakeholders should use this tool as a starting point in discussions for strategy implementation, and that each decision should be followed up with testing and further research.

Despite this, the KBS Toolbox provides a vital resource for envisioning future re-development of urban environments, and gives a quick and easy way for stakeholders and decision makers to evaluate different strategies, assess their suitability, effectiveness and cost for the given situation. This approach was employed with the wider GBO advisor team. During an online workshop, the KBS Toolbox was explained and participants had the opportunity to map their own measures onto the centrumgebied (Appendix 2). The range of designs that stakeholders employed demonstrates the flexibility of this tool when planning, discussing and designing the redevelopment of the centrumgebied. Analysing the cost/ benefit of each measure employed by the GBO team, once again adding trees to the cityscape, or creating an urban forest, was the most cost-effective strategy in all four metrics: storage capacity (m^3), groundwater recharge (mm/year), evapotranspiration (mm/year) and heat reduction (°C).

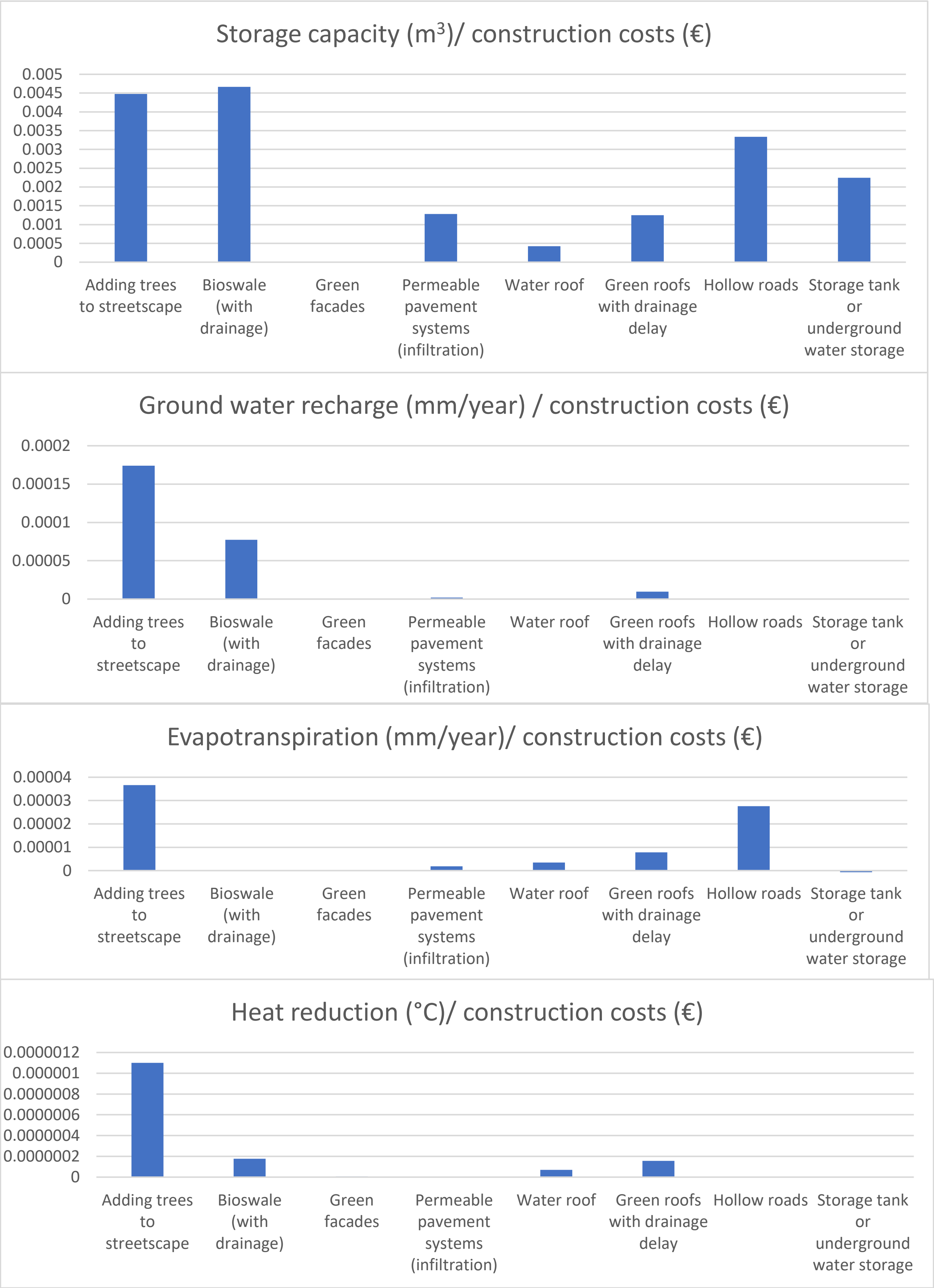


Figure 33: Climate adaption measure divided by cost of implementation. Evaluating benefit/cost of each adaption strategy. Based on the climate tool box scenarios as presented in Figure 32.

8. Discussion

Risk Mapping

The results from the risk maps provide a series of scenarios in which decision makers and key stakeholders from GBO and V&C can make more informed choices about how to plan for the redevelopment of the centrumgebied while accounting for current and future risks presented by heat stress and flooding.

When overlaying the two risk maps for flooding and heat stress for the two severity scenarios (figure 31), it is possible to find commonalities where maximal risk occur. This provides an integrated view of the risk presented for both heat stress and pluvial flooding. Through the categorised nature of the risk map (i.e. values 1-5), it is possible to establish a priority of areas to address. The first step should be addressing areas with the maximal risk value of 5. Transport infrastructure, vegetation and certain areas of paved surfaces present the greatest risk to disaster. As a result, the Heidelberglaan can be identified as the primary area of risk, followed by the Padualaan, and the Leuvenplein.

These areas have maximum risk due to the prevalence of transport networks (busses, trams and cycle paths) which concentrate people along designated pathways, comprised of impermeable and low albedo infrastructure that is technical and costly in nature. Therefore, transport networks have high exposure (economic assets), and vulnerability due to high population concentrations using these transport networks.

Paved (i.e. impermeable) surfaces account for 67% of the centrumgebied area (including transport networks), and so too account for elevated risked in certain areas (i.e. Leuvenplein). This risk is a function of low albedo surfaces absorbing and re-emitting solar energy, heightening temperatures and contributing to the UHI, and their impermeable nature preventing water infiltrating into the sub-surface, leading to surface water flooding and the overwhelming of sewer networks. This susceptibility to hazards is combined with a heightened exposure of a population as these are key throughfares of students and employees navigating between transport links, offices, education facilities, housing and catering, all leading to high risk.

Finally, vegetation is at high risk predominantly due to heat stress, as typically vegetation acts to reduce the impacts of flooding by acting as a sink, infiltrating the water into the subsurface. However, specifically along the Heidelberglaan, vegetated areas are raised ~1m off the ground in planting beds, thereby removing any potential benefits of vegetation to absorb, buffer and infiltrate excess water from the surrounding paved areas – a redundancy of this nature based solution to flooding and a key area to address in the re-development of the centrumgebied. Although vegetation and green areas can provide many benefits when it comes to flood control, it is itself very vulnerable to heat stress. Extended periods of extreme heat can lead to irreversible damage to plant development and result in senescence or death. With climate change and the rapid warming of surface temperatures, endemic species (native) have been unable to adapt and the climate norms in which they've evolved no longer exist. As a result, the vegetated areas throughout the centrumgebied, which are typically grassy areas with limited shading due to sparse tree cover, are highly exposed to solar radiation and high temperatures and therefore achieve the maximum risk value when modelled to a Dutch-heat wave scenario.

Using the risk mapping methodology, it was possible to evaluate socio-economic consequences of natural hazards. Risk mapping encapsulates the transient nature of population dynamics and how this variability can either compound or limit the risk presented by a hazard. Therefore three population vulnerability scenarios were employed: two day time scenarios, in the high season (i.e. opening hours of the university) and the low season (i.e. weekends, holidays). Two night-time scenarios were also evaluated (i.e. high and low season), but the differences in vulnerability between the two was negligible so only one scenario was used for night-time. Although this method is imperfect as the heat stress map was calculated at the end (1500) of a hot summers day with no wind, and therefore does not reflect actual night-time temperature levels (notwithstanding that the impacts of UHI effect radiating heat absorbed during the day at night can result in heightened night-time temperatures). Using these three scenarios does help to reinforce to decisionmakers that risk to natural hazards is modulated by the exposure and vulnerability of a population and not just the impacts of the hazard itself. Thus, three population vulnerability risk maps were created displaying its impact on risk, but also helping identify which areas, despite a variable population, still present an unacceptable level of risk and should therefore be a focus in the re-development of the centrumgebied.

Building vulnerability was also included in the risk analysis. Using field data, impact elements and the multi-criteria analysis of building's characteristics showcases how buildings throughout the centrumgebied have different vulnerabilities relating to flooding and heat stress. For-example, outlining that large buildings, with North-South orientation, dark cladding and no solar shading present a heightened vulnerability to heat-stress allows decisionmakers to address these characteristics in redevelopment plans. Impact elements for flooding can be utilised by decision makers in the same way. Unfortunately, building area was not included in the models used to calculate heat stress and flooding hazard maps. As a result, building areas were not included in the risk analysis as their hazard value was null. It is possible to overlay their vulnerability scores (1-5) to each hazard on the risk maps (Appendix 3), but calculating risk for these buildings was not possible. This presents a limitation, but it does present a methodology that can be used in follow-up research, should hazard maps be computed that includes the influence of buildings and their area.

This touches upon a limitation in evaluating the 2050 centrumgebied area as envisioned by Barcode Architects. With the hazard maps computed by Tauw and Arcadis being based on the land-use of the centrumgebied in 2015, it was not possible to evaluate how the proposed redevelopment of the centrumgebied would impact the distribution of hazards. It was also not possible to evaluate 2050 building vulnerability as data on the characteristics of these buildings is un-available. Follow-up research using the impact elements and multi-criteria analysis methodology of this study could evaluate buildings to see what construction materials and design elements will present the lowest vulnerability to heat stress and flooding. So too would modelling hazard maps based on various land-use scenarios of the centrumgebied in 2050 provide valuable insights into how land-use change and design can amplify or reduce natural hazard potential.

The risk maps developed in this study provide decision-makers in GBO and V&C with the understanding of how the impacts of natural hazards are modulated by exposure and vulnerability of buildings, infrastructure and a population, and how the intersection of these variables can result in heightened or lowered levels of risk. Using this knowledge and a series of risk maps detailing the current land-use scenarios of the centrumgebied, a more structured approach to managing hazards can be utilised and implemented in the redesigning of the centrumgebied to become more resilient and adaptive to the risk presented by climate change.

Evaluating Climate Adaption, Mitigation and Resilience strategies.

Identifying transport networks, vegetation and key paved areas of elevated risk, it was possible to focus on these high risk areas and test various adaptation, mitigation and resilience scenarios using the “Climate Resilience City Toolbox” (KBS).

A first assessment was conducted by the author, testing methods using the current form and function of the centrumgebied – i.e. not changing the location and function of land-use, just applying technical and nature based solutions to these locations (Figure 32). For example, the raised grassy vegetation beds were replaced by trees at ground level, providing localised cooling through evapotranspiration and shading, and acting as a sink for flooding as a point of infiltration. Transport networks were fitted with “hollow roads” that can store water during storm events, and act as a buffer to prevent sewer systems from being overwhelmed. Paved surfaces and cycle lanes were replaced by permeable pavement systems that allowed for the infiltration of water into the sub-surface, again reducing the pressure on sewer systems.

Based on this first assessment, it was possible to evaluate the benefit/cost of individual measures to help decisionmakers and investors see which measure could be the most effective while accounting for their costs. The results (Figure 34), imply that adding trees to the landscape is the most cost-effective measure in all factors (groundwater recharge (mm/year), evapotranspiration (mm/year), heat reduction (°C)), except storage capacity (m^3), in which bioswales is marginally a better investment.

Using such a methodology: mapping various adaption measures (i.e. adding trees, bioswales, green roofs, permeable pavements etc.) on the centrumgebied in areas of maximum risk and evaluating the cost/benefits of each measure, generates not only a ranking of measures based on the efficacy, but also about the location and form of the measures. Testing different iterations, arrangements, sizes and locations of measures generates a range of information that can be utilised for a first assessment of a project plan. Such a methodology was employed with the wider GBO team from V&C. During an online workshop, team members utilised the KBS Toolbox to draft various scenarios and employ different measures to the centrumgebied based on the risk maps developed in this study (Appendix 2).

The outcome from the stakeholder session were consistent with the results from this study. Adding trees to the city scape, or creating an urban forest, was the most cost-effective measure to address heat stress and flooding in the centrumgebied. Bioswales were also effective, when selected by the stakeholder, so too were rainwater detention ponds in relation to groundwater re-charge. The most effective technical solution that stakeholders chose were green roofs with drainage delay, followed by permeable pavement systems.

Utilising nature based solutions can lead to a host of green benefits and eco-system services that go beyond the primary goal of implementation, i.e. addressing heat stress or flooding hazard. The eco-system services framework outlines how nature based solutions can provide provisioning (i.e. food, water, materials), regulating (climate, purification), supporting (habitat, nutrients) and cultural (education, aesthetic, recreation) services. All these benefits should be accounted for, and lend a stronger impetus for using these measures over technological solutions. As previously mentioned, nature based solutions also tend to address a range of natural hazards (i.e. minimising impacts of both heat stress and flooding), and therefore help diversify risk management portfolios to spread risk across a range of measures rather than singular strategies.

These green benefits are accounted for in the KBS toolbox. It is worth noting however, the spatial scale at which these measures are calculated occur over 10x10 meters, so there can be issues with "doubling up" of green benefits if multiple measures are used in close proximity. Therefore it is best to evaluate green benefits with only one measure per time. These are the green benefits calculated in the toolbox:

- Reduced labour and healthcare costs due to vegetation (Remme et al. 2018)
- Particulate matter (PM10) reduction by vegetation (Remme et al. 2018)
- Influence of water and vegetation on residential property values (Remme et al. 2018)
- Physical activity increases due to vegetation (Paulin et al. 2019)
- Increased cycling for commuting purposes due to vegetation (Paulin et al., 2019)
- Carbon sequestration by vegetation (Remme et al. 2019)

It is also worth noting that there are further co-benefits that cannot be directly calculated, and are therefore not represented in the results of the KBS toolbox. These co-benefits include:

- Biodiversity: adding green and blue areas to a region can have positive impacts on plant and animal biodiversity. This in itself can have positive influence on other co-benefits such as pollination (Brolsma et al., 2021).
- Recreation: Green spaces can contribute to other forms of recreation than increases in physical activity, and healthcare benefits of commuting by bike as already quantified by the KBS toolbox. Outdoor working, meeting, meditating, eating and reading spaces can provide a wealth of personal, mental and physical wellbeing benefits to the users of these spaces.
- Social Cohesion: The creation of more green spaces can generate encounters between users of these spaces to promote social cohesion and liveability (Brolsma et al., 2021).
- Experience value: blue and green measures can increase the attractiveness of an area, bringing new and improved experience value to users and residents of these areas (Brolsma et al., 2021).
- Noise reduction: Greenery has a dampening effect on noise. This can minimise the noise disturbance of traffic and construction, providing a more liveable and stress free environment for residence and other users (Brolsma et al., 2021).
- Changing subsidence/ CO_2 emissions of peat: minimising groundwater depletion, or promoting the recharging of groundwater levels can reduce the subsidence of these areas, especially in peat lands, and reduce CO2 emissions from these peat soils (Brolsma et al., 2021).
- Pollination: Increasing the green area in urban environments can enhance the habitat of various pollinator species. Pollinators are vital for many crops and other plant life, so by reviving habitats to address the alarming decline in inspect species can positively contribute to a wide range of floral biodiversity (Brolsma et al., 2021).

However, as previously mentioned in the literature review, the implementation of these green (and grey) measures can also lead to unintended consequences. Therefore it is vital that proper research, modelling, testing and monitoring of any potential measure is conducted before wide-spread application. For example, indigenous trees are preferable to be planted to address issues of storage capacity, groundwater re-charge, evapotranspiration and heat reduction. By using indigenous species, this measure will promote local biodiversity, and help rejuvenate the campus to an ecological setting before the land was transformed into a science park. However, if we accept that the climate historic climate settings are changing, and that the Netherlands is experiencing increasingly warmer summers and wetter winters, indigenous trees may not be able to withstand these new environmental norms, leading to their death and the loss of any potential nature-based solutions to heat and flooding risk. Should decision makers instead opt for non-native species that are more heat resilient and water tolerate so that the climate adaptive benefits can be maintained and that these species can survive the coming hazards, it must be noted that the local and historical biodiversity of the area will be altered, with consequences to local flora and fauna that we may not understand or even realise until it’s too late.

Therefore, when making decisions about which adaptive measure to implement, it is vitally important to discuss with relevant experts, but also with the citizens and users of these spaces to understand what is acceptable and necessary in order address the risks presented by heat stress and flooding.

A method to research, evaluate and test such multi-dimensional and transdisciplinary challenges could be in the form of Living Labs.

Living Labs are a “physical or virtual space in which to solve societal challenges, especially for urban areas, by bringing together various stakeholders for collaboration and collective ideation” (Hossain et al., 2018). In this sense, living labs may be the key of incorporating social and integrated solutions into the portfolio of GBO and V&C to better manage the risk presented by climate change, and help diversify and broaden the portfolio away from solely technical and nature-based solutions.

Utrecht University Living Labs for Sustainable Development (UULabs), is a start-up organisation within the Programma Duurzaamheid (Sustainability Programme), that promotes and facilities the living lab methodology within Utrecht University. The goal is to turn the campus into a living lab, connecting operational staff (i.e. GBO), researchers, students and external partners to collaborate on projects addressing sustainability. In this vein, a series of living labs could be set up to test technical and nature based solutions on campus, and evaluate their suitability to address the climate challenges faced in the centrumgebied. This collaboration of stakeholders also helps foster social solutions relating to these challenges; promoting engagement, identifying behaviour, practices and beliefs of all key users of the centrumgebied and thereby impacting vulnerability characteristics such as awareness of hazards, ability to react and social structures which can collectively contribute to a lowering of population vulnerability and therefore risk. Further, this type of collaboration can provide further research into integrated solutions (i.e. combining nature based and technical solutions) and the necessary follow-up research to better understand the un-intended consequences of any measure.

9. Recommendations

Based on the developed risk maps of the centrumgebied, locations that present the highest level of risk (5) were identified:

- Transport infrastructure
    - 1st: Along the Heidelberglaan: bus, tram and cycle lanes
    - 2nd: Along the Padualaan: bus and cycle lanes
    - 3rd: Along the borders of the centrumgebied (Leuvenlaan, Bolognalaan, Cambridgelaan) (cars and cycle lanes)
- Vegetation
    - Heidelberglaan
- Paved surfaces:
    - Central avenue of the Heidelberglaan. Specifically in front of Casa Confetti and the Bestuursgebouw
    - Paved surfaces of the Leuvenplein between the Martinus Ruppertgebouw and the Bestuursgebouw
    - between the studentenhusivesting De Bisschoppen buildings and the HU Gezondeidszorg en Life Sciences & Chemistry building

Adaptation, Mitigation and Resilience Strategies were developed based on independent and stakeholder assessments utilising the KBS toolbox and cost-benefit analysis of measures. The recommendations for implementation in the aforementioned locations are:

Nature Based Solutions**:**
1. Adding trees to city scape/ urban forest
2. Bioswales
3. Rainwater detention pond

Technical solutions:
1. Green roofs with drainage delay (co-benefits)
2. Hollow roads
3. Permeable pavements
4. Water roofs (co-benefits)

Social Solutions:
1. Living Labs – UULabs
2. Values, behaviours and practices – Educating, engaging and informing
3. Community outreach – Community Engaged Learning

Ideally, any application of these measures that can include two or more of the above measures – i.e. an integrated solution – would provide “the best of all worlds”, thereby harnessing all the benefits that each of these different measures present, and covering their deficiencies. Images and more information about recommended nature based and technical solutions can be found in Appendix 4 and 5 respectively.

Caveats must be noted on three points: the diversity of the risk portfolio, co-benefits and un-intended consequences.

Diversifying risk portfolio

As previously mentioned, having a range of measures that can address both flooding risk and heat stress reduces the risk of catastrophe should one of these measures fail. Nature-based solutions lends itself well to a diverse risk portfolio, as many of measures address both heat stress and flooding, as well as providing numerous co-benefits. Alternatively, large technological infrastructure investment can address the consequences of a hazard very effectively, such as an underground water storage system, but should this system fail and your portfolio has no other measures that address flooding risk raises the potential for disaster.

Co-benefits

Co-benefits are additional benefits that a measure brings to the environment that aren't the primary goal of the measure. For example, bio-swales allow for water infiltration into the groundwater, and provide shading and evaporative cooling due to the presence of trees, thereby addressing both flood risk and heat-stress. Additionally, bioswales also promote biodiversity and a range of eco-system services. Compared with the technical solution of hollow roads, which addresses flooding, but brings no co-benefits.

Un-intended consequences

It must be noted that although nature based solutions help diversify your risk portfolio and bring a range of co-benefits, there may be unintended consequences by applying these measures. For example, using trees to address issues of address heat stress and flooding risk. Using indigenous species of trees will promote local biodiversity, and help rejuvenate the ecology of the campus. However, their ability to withstand projected climate change and thus their adaptive measures may limit their long-term effectiveness. Should decision makers instead opt for non-native species that are more heat resilient and water tolerant so that the climate adaptive benefits can be maintained, but the local and historical biodiversity of the area will be altered. As a result, long-term decision making is necessary, as well as evaluating any possible un-intended consequences when selecting measures.

Follow up research

Finally, to properly understanding the efficacy, suitability and potential un-intended consequences of the aforementioned measures, further research is required.

Creating new hazard maps using the proposed land-use of the centrumgebied in 2050 will allow for risk mapping based on that design, and allow decision makers to understand how significantly increasing the amount of impervious street surface (as discovered in Figure 12) will impact heat stress and flooding risk.

Using the 2050 land-use map as a base-layer to test new land-use measures in the KBS toolbox will provide a useful comparison to this study. Currently adding your own base-layers is in a BETA phase in the KBS toolbox. Connecting with the designers of the tool may speed up this process.

Finally, a form in which this research could take place that would also lead to additional benefits in terms of social solutions would be living labs. Using living labs as a methodology will allow for a transdisciplinary approach to solving these solutions. Bringing together stakeholders with diverse expertise and backgrounds will increase the likelihood that integrated solutions are implemented. As Living Labs the foster the co-creation of technical and nature based solutions to climate hazards with social aspects relating to exposure and vulnerability being addressed inherently through the process of diverse stakeholder engagement helps promote the integration of various solutions that is required to solve the complex challenges presented by climate change.

10. Conclusion

Climate change presents an alternating of climate norms, leading to an unprecedented frequency and severity of natural hazard events. These hazard events present new challenges to an peri-urban environments such as USP. The assets and populations residing here represent elements that are exposed and vulnerable to increasingly severe hazards, which manifests in elevated risk. This heightened risk of disaster demands action by decision makers and the GBO team to ensure the continued safety of the USP and it's elements in the future.

This study conducted risk mapping of the centrumgebied in USP with the aim of identifying key areas of risk relating to heat stress and pluvial flooding. Two severity scenarios of these hazards were evaluated, along with three population vulnerability scenarios to demonstrate how future climate change can impact risk, and how vulnerability of a population is not static, but dynamic. Using this information, key areas of risk were identified - primarily along transport infrastructure, vegetated and paved surfaces - and location priorities for GBO decision makers to begin designing the adaptive strategies for the re-development of the centrumgebied.

Using these risk maps it was possible to map, test and evaluate various adaptation measures to minimise the risk at these locations. To do so, the open source KBS toolbox was utilised. This toolbox was designed to explore adaption measures relating to flooding, drought and extreme heat with stakeholders from different backgrounds to determine suitable approaches. This methodology was employed in this study, conducting independent mapping of the centrumgebied, along with a workshop session with key stakeholders from GBO to map measures and evaluate their outcomes. Overall, nature based solutions, specifically the addition of trees to the cityscape, or the creation of an urban forest, provided the most cost-effective solution in terms of storage capacity (m^3), groundwater recharge (mm/year), evapotranspiration (mm/year) and heat reduction (°C).

Nature-based and technical solutions were evaluated using this toolbox. With the recommendation of adding trees, bioswales and rainwater detention ponds being the most effective nature based solutions. The best technical solutions were green roofs with drainage delay, hollow roads and permeable pavements. It was not possible to map social solutions, but based on developments already occurring on the campus with UULabs, it is recommended to continue with this approach as Living Labs bring together diverse stakeholders to co-create solutions, thereby addressing social solutions in terms of user values, behaviours and practices. In this sense, Living Labs can tie together nature-based, technical and social solutions in an integrated form. Allowing for the testing of the effectiveness of each proposed measure, any possible co-benefits that may arise, along with evaluating un-intended consequences.

Follow up research evaluating how the proposed 2050 land-use design will impact the form of flooding and heat stress would provide valuable insight into how risk will manifest in the future vision, along with testing measures from the KBS toolbox on this land-use design will provide a valuable comparison to this study. Finally, researching un-intended consequences and strategies to diversify the risk portfolio of GBO is necessary to ensure the campus is resilient to the impacts of future climate change.

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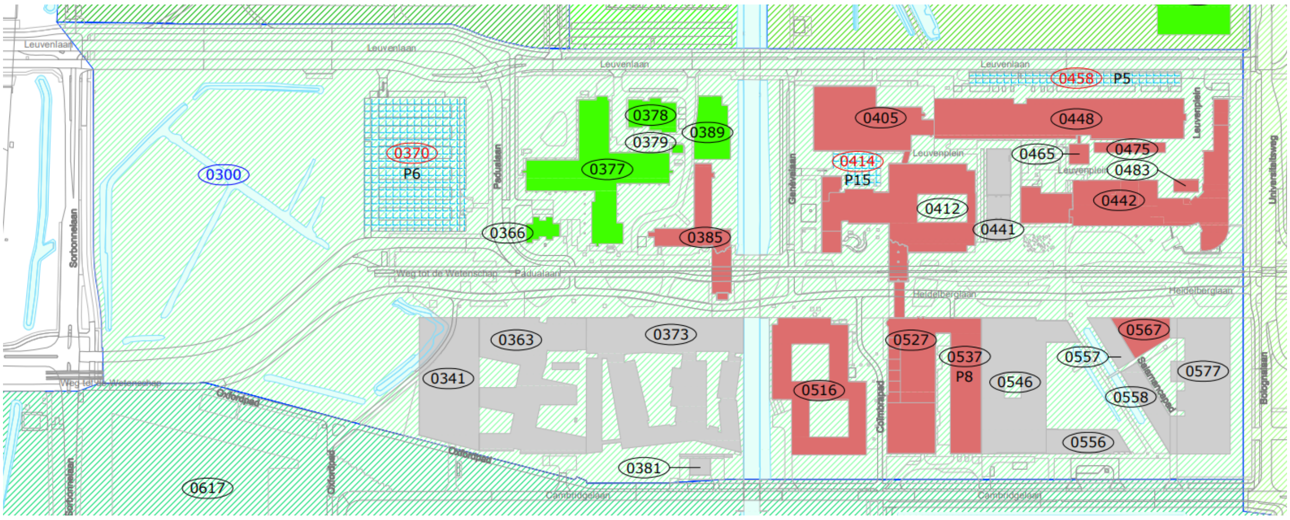
Appendix



0341 HU Educatie, Onderwijs & Opvoeding Padualaan 97
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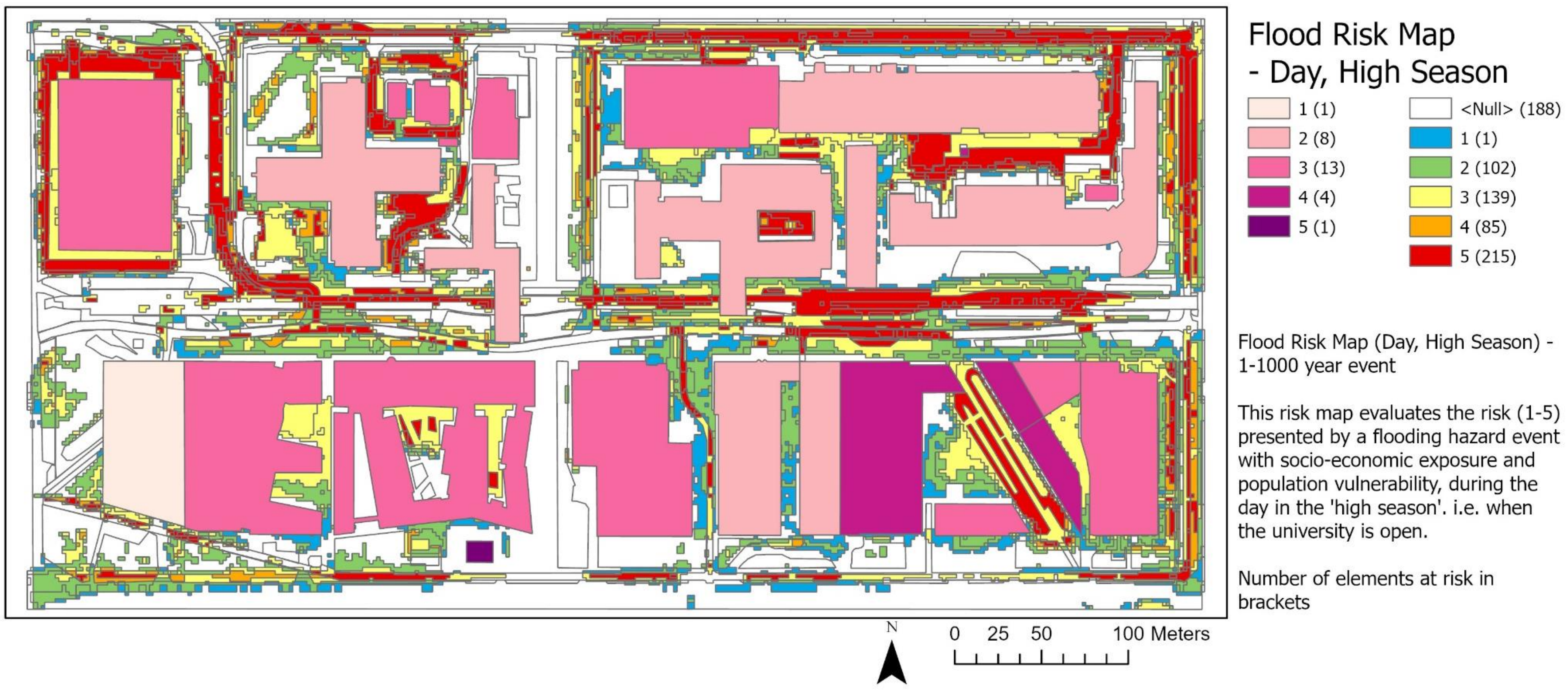
0366 Fietsenstalling Kruytgebouw Padualaan 8
0370 Parkeerterrein Padualaan (P6) Padualaan
0373 HU Maatschappij en Recht Padualaan 101
0377 Hugo R. Kruytgebouw Padualaan 8
0378 Centrale Dienstengebouw Padualaan 10
0379 Gassenopslag Padualaan 8
0385 Sjoerd Groenmangebouw Padualaan 14
0389 Nicolaas Bloembergengebouw Padualaan 12
0405 Educatorium Leuvenlaan 19
0412 Willem C. van Unnikgebouw Heidelberglaan 2
0414 Parkeerterrein Educatorium (P15) Genevelaan
0441 Casa Confetti Leuvenplein 10-322
0442 Bestuursgebouw Heidelberglaan 6-8
0448 Marinus Ruppertgebouw Leuvenlaan 21
0458 Parkeerterrein Leuvenlaan (P5) Leuvenlaan
0465 Sterrentoren Leuvenlaan 21
0475 Fietsenstalling Bestuursgebouw Leuvenplein
0483 ketelhuis Bestuursgebouw Leuvenplein 2
0516 Martinus J. Langeveldgebouw Heidelberglaan 1-1b
0527 Universiteitsbibliotheek De Uithof Heidelberglaan 3
0537 Parkeergarage Cambridgelaan (P8) Cambridgelaan 108
0546 HU Gezondheidszorg en Life sciences & Chemistry Heidelberglaan 7
0556 Studentenhuisvesting De Bisschoppen short-stay Cambridgelaan 112-310
0557 Studentenhuisvesting De Bisschoppen Salamancapad 1-387
0558 Studentenhuisvesting De Bisschoppen (2) Salamancapad 389-403
0567 De Bisschoppen laagbouw Heidelberglaan 11-13
0577 HU Economie, Management, Communicatie, ICT & Media Heidelberglaan 15

Appendix 1: Centrumgebied – Buildings and Street names. Figure taken from the Brief builder tool used by V&C.

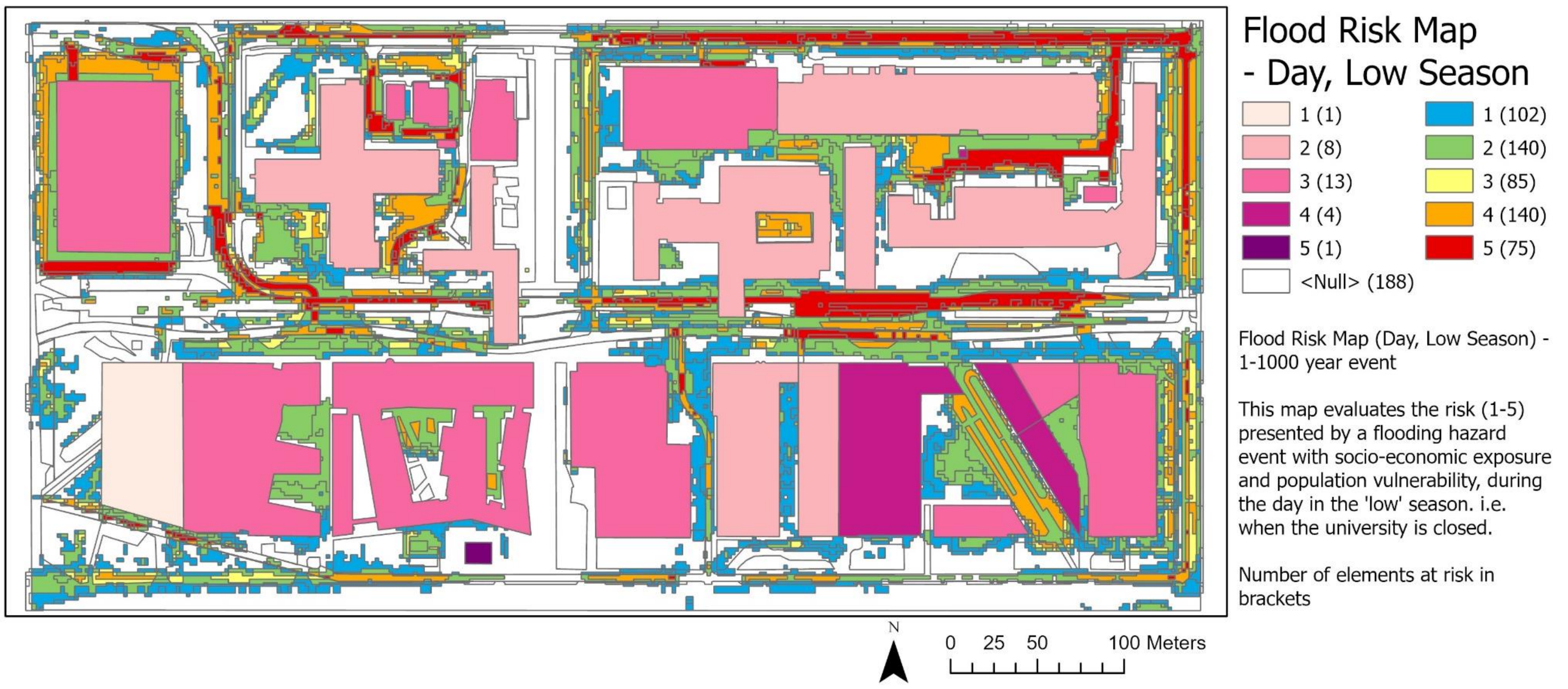
Appendix 2: Maps designed by GBO stakeholder session using the Climate Resilient City Toolbox



Flood Risk Map (Day, High Season) - 1-1000 year event

This risk map evaluates the risk (1-5) presented by a flooding hazard event with socio-economic exposure and population vulnerability, during the day in the 'high season'. i.e. when the university is open.

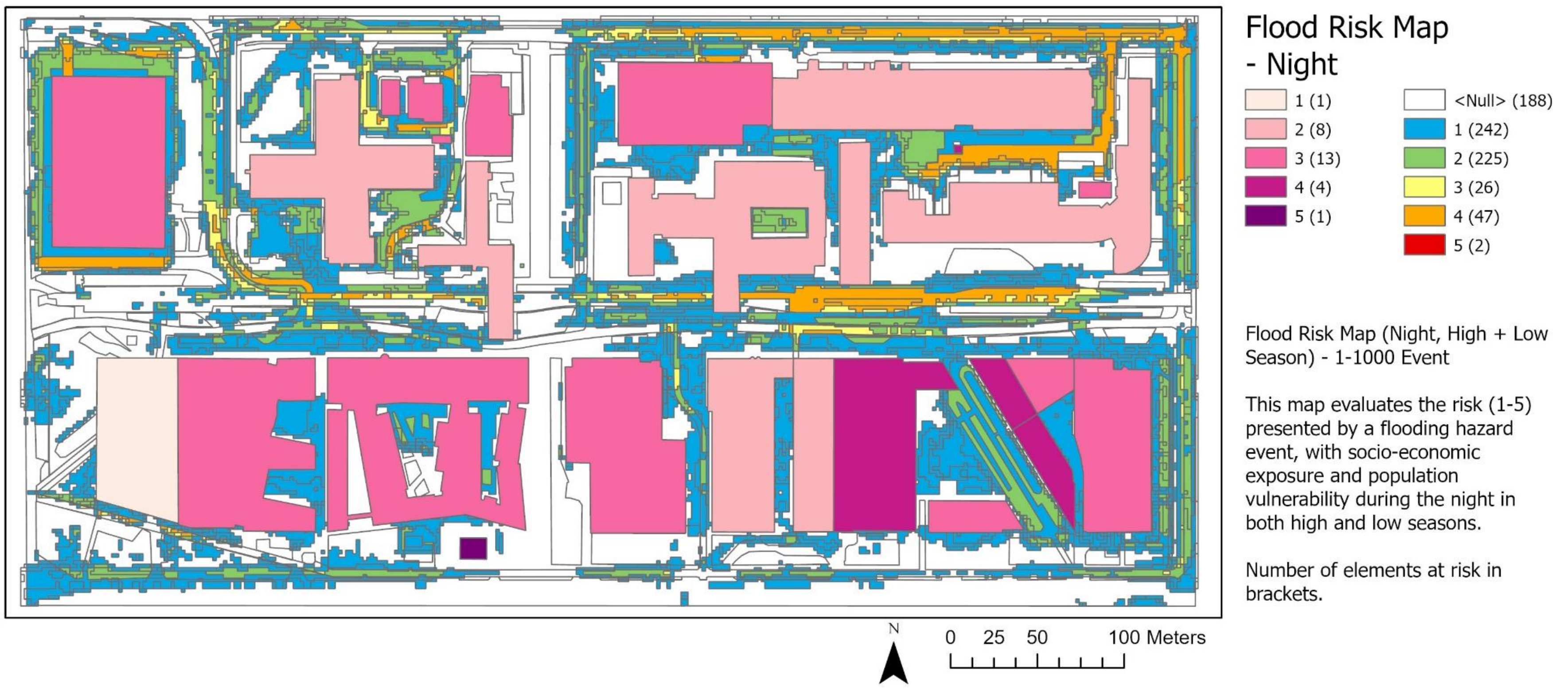
Number of elements at risk in brackets



Flood Risk Map (Day, Low Season) - 1-1000 year event

This map evaluates the risk (1-5) presented by a flooding hazard event with socio-economic exposure and population vulnerability, during the day in the 'low' season. i.e. when the university is closed.

Number of elements at risk in brackets

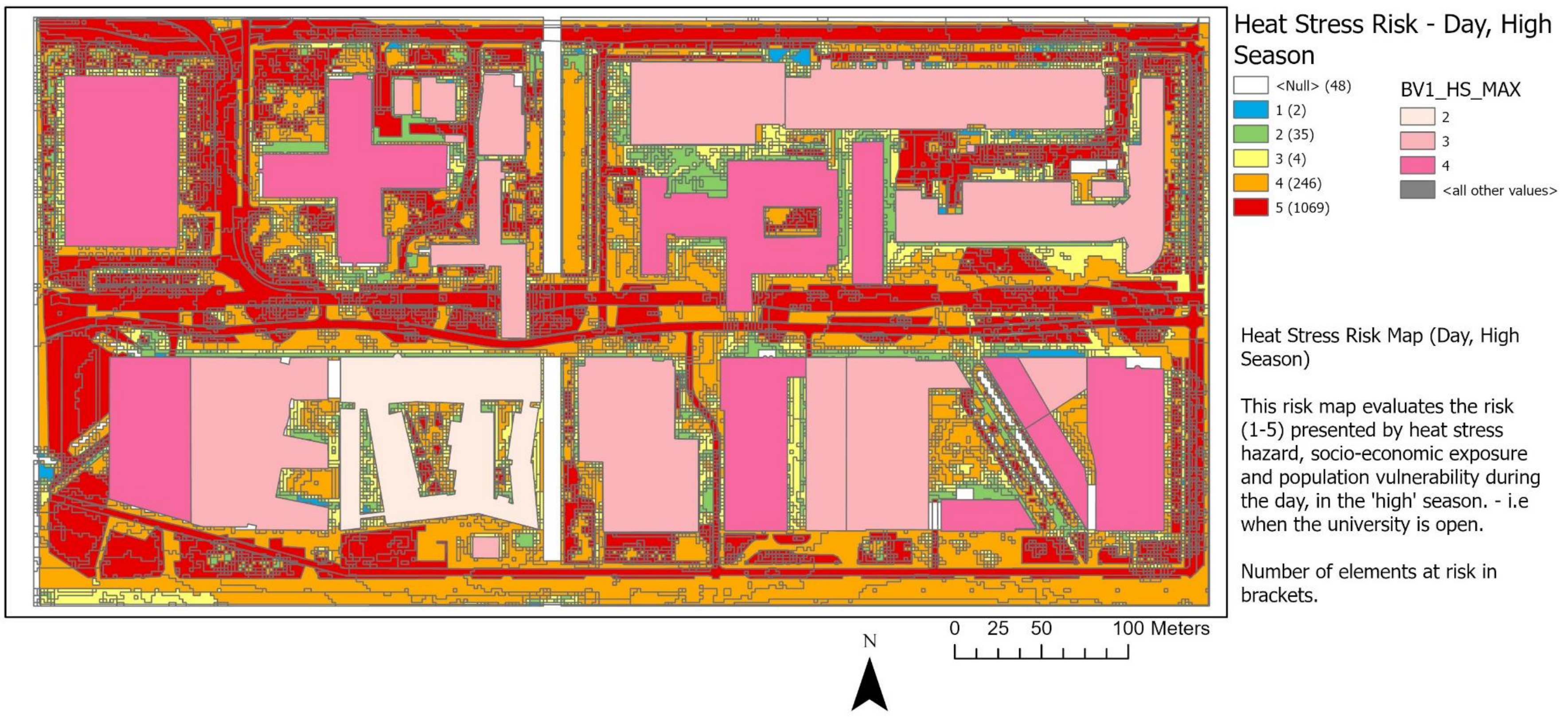


Flood Risk Map (Night, High + Low Season) - 1-1000 Event

This map evaluates the risk (1-5) presented by a flooding hazard event, with socio-economic exposure and population vulnerability during the night in both high and low seasons.

Number of elements at risk in brackets.

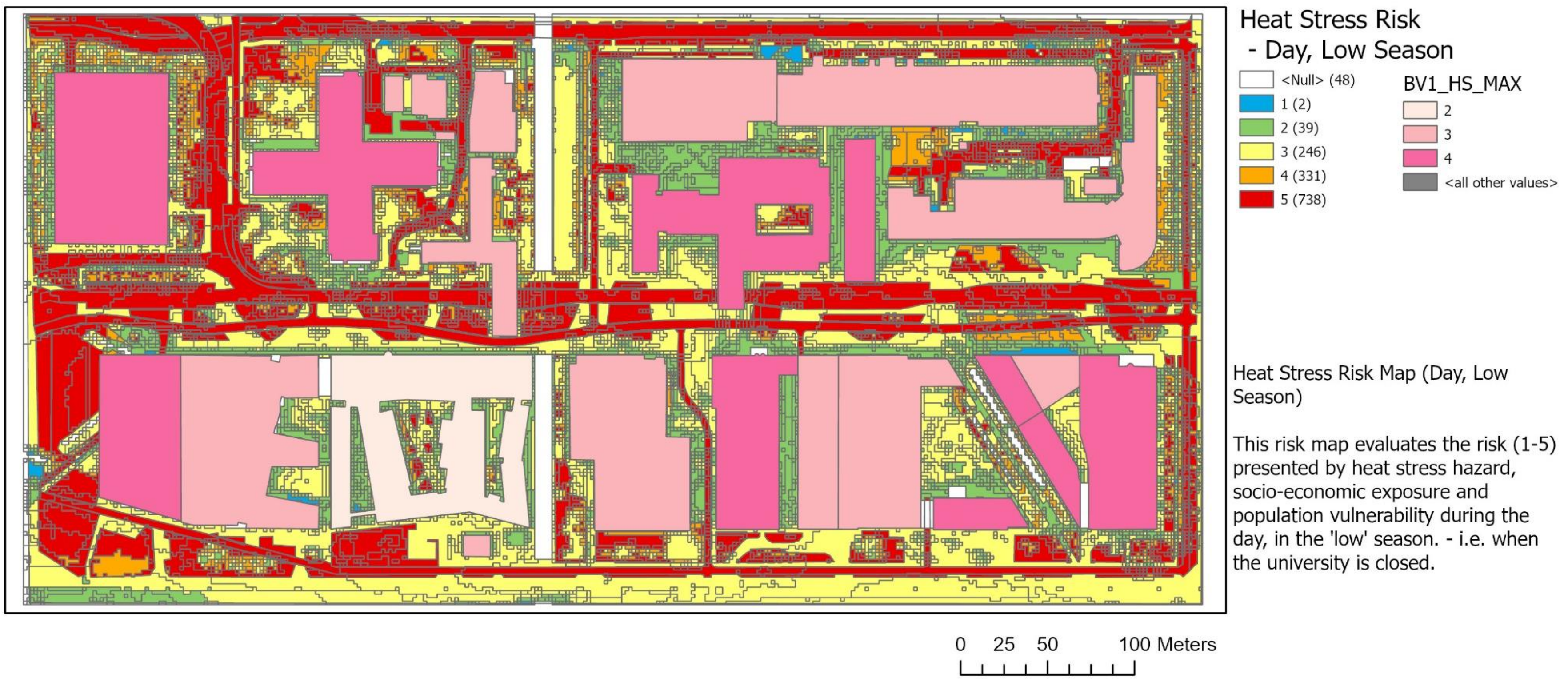
Appendix 3 - A: Demonstration how you can merge the building vulnerability layers with the risk map for the flooding (1-1000 year) to get an overview of how buildings relate to flooding risk. Unfortunately an integrated risk map including buildings was not possible, as the hazard maps did not include building areas in their calculations



Heat Stress Risk Map (Day, High Season)

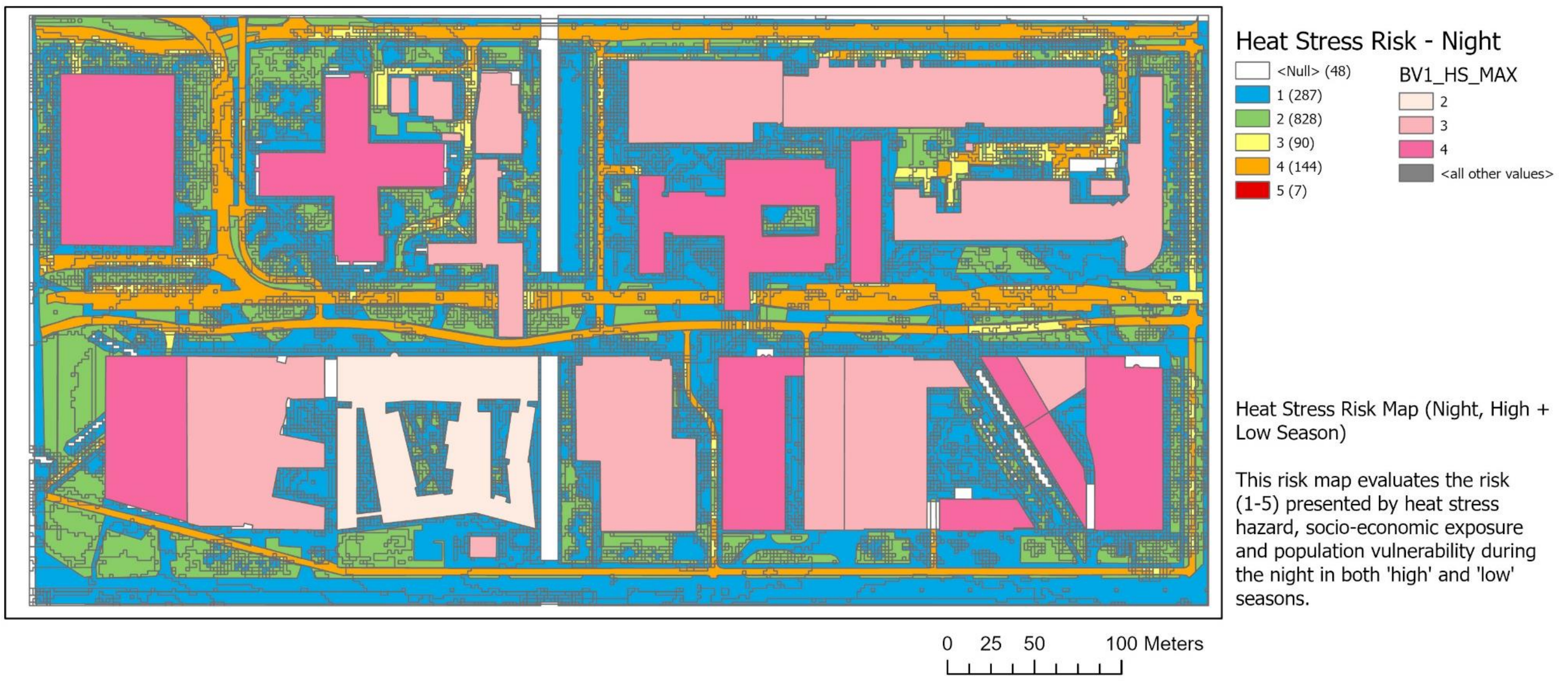
This risk map evaluates the risk (1-5) presented by heat stress hazard, socio-economic exposure and population vulnerability during the day, in the 'high' season. - i.e when the university is open.

Number of elements at risk in brackets.



Heat Stress Risk Map (Day, Low Season)

This risk map evaluates the risk (1-5) presented by heat stress hazard, socio-economic exposure and population vulnerability during the day, in the 'low' season. - i.e. when the university is closed.



Heat Stress Risk Map (Night, High + Low Season)

This risk map evaluates the risk (1-5) presented by heat stress hazard, socio-economic exposure and population vulnerability during the night in both 'high' and 'low' seasons.

Appendix 3 - B: Demonstration how you can merge the building vulnerability layers with the risk map for the heat stress (2050) to get an overview of how buildings relate to flooding risk. Unfortunately an integrated risk map including buildings was not possible, as the hazard maps did not include building areas in their calculations

Appendix 4: Nature Based Solution examples based on recommendations. Information adapted from the KBS toolbox.

1

Adding trees to streetscape

Pluvial flooding Heatstress

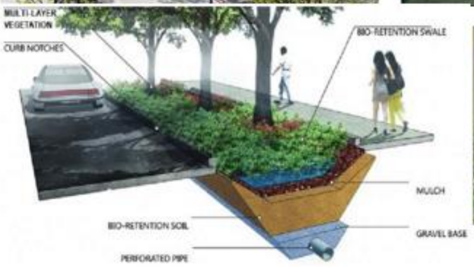
Planting trees on streets, squares and car parks creates shade and evapotranspiration and therefore has a cooling effect. Dense foliage over busy roads is not beneficial, since the emissions from the vehicles tend to become trapped under the foliage. The type of tree should be chosen to suit the local moisture system.

2

Bioswale (with drainage)

Pluvial flooding Drought Heatstress

A bioswale is a ditch with vegetation, a porous bottom and below that a layer of gravel, packed in geotextile with an infiltration pipe/drainpipe. It allows rainwater storage, infiltration and transport while helping to enhance biodiversity and quality of life.

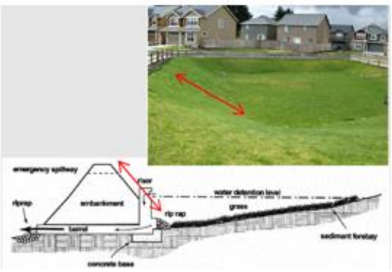


3

Rainwater detention pond (wet pond)

Pluvial flooding Drought Heatstress

Buffer ponds temporarily capture precipitation and allow it to drain off slowly. During rainfall, the rainwater is captured in the pond and subsequently drained off to create room for the next precipitation. Buffer ponds can be designed to have a mostly stony or a mostly natural appearance.



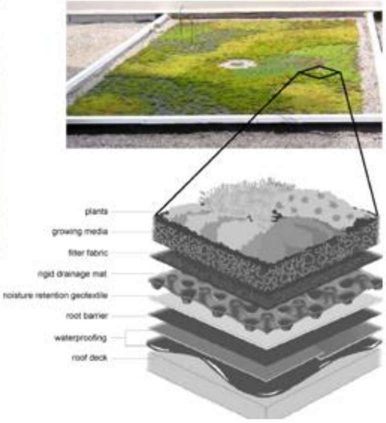
Appendix 5: Technical Solutions examples based on recommendations. Information adapted from the KBS toolbox.

1

Green roofs with drainage delay

Pluvial flooding Heatstress

Green roofs with drainage delay are also called retention roofs. It is a green roof that can store extra water in a substrate layer under the green planted layer and is drained delayed with a pinched drain. A polder roof is a retention roof where the control system is linked to the weather forecast.



2

Hollow roads

Pluvial flooding

Hollow roads allow water on the road instead of only in a gutter and can hold and drain much more water than gutters. Slopes are often less of an obstacle for covering distances greater than 50 metres because the road level can be varied.

3

Permeable pavement systems (infiltration)

Pluvial flooding Drought

Porous pavements consist of porous material through which water can pass; permeable pavements contain or create open parts through which water can infiltrate. These paving materials have several advantages: rainwater can be absorbed into the ground, replenishing the ground water and relieving the sewage system. Suitable materials are for example, open cell concrete blocks, grass concrete pavers, woodchips, shells or gravel.