Universidade de Aveiro Departamento de Ambiente e Ordenamento
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BRUNO MIGUEL ROCHA AUGUSTO

Impactos diretos e indiretos no calor urbano de soluções baseadas na natureza

Direct and indirect impacts of nature-based solutions on urban heating

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia do Ambiente, realizada sob a orientação científica do Professor Doutor Peter Roebeling, Equiparado a Investigador Auxiliar no Departamento de Ambiente e Ordenamento da Universidade de Aveiro e coorientação da Doutora Joana Ferreira, Estagiária de Pós-Doutoramento no Departamento de Ambiente e Ordenamento da Universidade de Aveiro.

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“Happiness can be found even in the darkest of time, if one only remembers to turn on the light.” -Steven Kloves

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palavras-chave

soluções baseadas na natureza, calor urbano, expansão urbana, modelação.

resumo

O crescimento das cidades e o aumento da sua densidade populacional têm como consequência alterações no uso do solo, com um aumento das superfícies impermeáveis e uma perda substancial de espaços verdes. Estas alterações no ambiente urbano alteram a ecologia das cidades, causando efeitos como ilhas de calor urbano e um aumento generalizado do calor urbano. As soluções baseadas na natureza (NBS) são consideradas sustentáveis, custo-eficazes e multifuncionais para resolver estes problemas, no entanto, as NBS podem também levar a uma compactação urbana e aumento da densidade populacional.

O objetivo principal deste estudo é avaliar os impactos diretos (a curto prazo) e indiretos (médio a longo prazo) das soluções baseadas na natureza no calor urbano e na expansão urbana, tendo como caso de estudo a cidade de Eindhoven (Holanda). Pretende-se providenciar aos planeadores públicos, decisores e stakeholders uma ferramenta para ajudar a prever os efeitos das aplicações das NBS. Para isso, foi usada para uma abordagem de modelação integrada baseada no sistema WRF-SUEWS (com uma resolução de 1-km) e no modelo SULD para determinar o efeito de arrefecimento urbano (impactos diretos) e o efeito de compactação urbana (impactos indiretos), respetivamente.

Os resultados mostram que as NBS têm um efeito de arrefecimento a curto prazo, devido ao aumento de espaços verdes/azuis, e um efeito de compactação urbana a médio a longo prazo, devido à atração dos residentes de áreas periféricas para os espaços verdes/azuis. O efeito de compactação urbana reduz o efeito de arrefecimento direto, no entanto o balanço total é positivo.

Este estudo evidencia que as soluções baseadas na natureza podem ser usadas para reduzir os efeitos do calor urbano e expansão urbana, dependendo do tipo e tamanho das NBS. Também vem reforçar a ideia de que uma abordagem de modelação integrada permite uma melhor compreensão dos efeitos a curto e longo prazo das NBS e pode ser usada como uma ferramenta para os planeadores públicos e decisores.

keywords

Nature-based solutions, urban heat, urban sprawl, modelling.

abstract

Cities are growing and becoming more densely populated. This results in changes in land use, where there is an increase in impermeable surfaces and a substantial loss of green spaces. These changes in the urban environment alter the ecology of the cities, which can cause effects such as urban heat islands and overall urban heating. While nature-based solutions (NBS) are considered sustainable, cost-effective and multi-purpose solutions to address these problems, NBS may also lead to urban compaction and increase in population density.

The main objective of this study is to provide an assessment of the direct (short term) and indirect (medium to long term) impacts of nature-based solutions on urban heating and urban sprawl, having as a case study the city of Eindhoven (The Netherlands). The aim is to provide public planners, decision makers and stakeholders with a tool to help predict the effects of the applications of nature-based solutions. For this purpose, an integrated modelling approach composed of WRF-SUEWS (with a resolution of 1-km) and SULD was used to determine the urban cooling effect (direct impacts) and the urban compaction effect (indirect impacts), respectively.

Results show that nature-based solutions have a cooling effect in the short term, due to an increase in green/blue spaces, and an urban compaction effect in the medium to long term, due to attraction of residents from peripheral areas to attractive green/blue spaces. The latter reduces the direct urban cooling effect, though still results in an overall positive balance.

This study provides evidence that nature-based solutions can be used to reduce the effects of urban heating and urban sprawl, depending on the type and size of the nature-based solution. Also, it reinforces the idea that an integrated modelling approach allows to better understand the short to long term effects of NBS and can be used as tool for public planners and decision makers.

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Abbreviations

DIS	Direct impact scenario
ECMWF	European Centre for Medium-Range Weather Forecasts
EEA	European Environment Agency
EPA	Environmental Protection Agency
GIS	Geographical Information System
IIS	Indirect impact scenario
IPCC	International Panel for Climate Change
NBS	Nature-based solution
Q^*	Net all-wave radiation
Q_E	Latent heat flux
Q_F	Anthropogenic heat flux
Q_H	Sensible heat flux
ΔQ_S	Net storage heat flux
SULD	Sustainable Urbanizing Landscape Development
SUEWS	Surface Urban Energy and Water Balance Scheme
UHI	Urban heat island
USGS	United States Geological Survey
WRF	Weather Research Forecast

1. Introduction

1.1. Problem setting

Climate change is defined as a change in the state of the climate that can be identified (IPCC, 2013). It may be caused by natural processes or anthropogenic changes in the composition of the atmosphere and land use. Its effects are manifested in, for example, changes in temperatures, precipitation patterns and water levels (IPCC, 2014).

The main focus in planning for climate change is to reduce greenhouse-gas (GHG) emissions, which are considered the main driver of climate change (Gill *et al.*, 2007). Urban areas are, especially in developed countries, one of the main sources of GHG emissions (between 70-90% CO_2 emissions are generated in cities) (EEA, 2017a), which highly contribute to global climate change. If we consider that more than 95% of the increase in population will be in cities, we can expect that this problem is not solved easily (Grimm *et al.*, 2008).

One of the problems of the growing urbanization (Blanco *et al.*, 2009) is that it translates into a conversion of rural to more urban landscapes (Seto *et al.*, 2011) resulting in the rapid expansion of impermeable surfaces and substantial loss of green spaces (Estoque and Murayama, 2017). Also, it leads to an increased use of private and public transport, leading to increased CO_2 and air pollutant emissions (Kennedy *et al.*, 2011). These changes to the environment alter the ecology of cities which cause effects like the increase in temperature and subsequent creation of urban heat islands, increase in the production of carbon dioxide and decrease in the amounts of stored carbon (Whitford *et al.*, 2001). These effects can be divided into two main impacts: “urban heating” and “air pollution”. This situation seems to be ever growing and requires attention, since it can have negative effects for human health and well-being (IPCC, 2013).

One apparent solution to these problems comes in the form of Nature-based Solutions (NBS). These are, as defined by the European Commission (2015), actions, inspired by, supported by or copied from nature, that use features and complex system processes of nature, to achieve desired outcomes, while enhancing and maintaining the natural capital. They promote the maintenance, enhancement and restoration of biodiversity and ecosystems while addressing various concerns simultaneously (Kabisch *et al.*, 2016) and providing multiple ecosystem services, sometimes with low required physical resources (Everard and McInnes, 2013). The effects of NBS are increasingly recognized and include improved quality of life, mental and physical health (Keniger *et al.*, 2013), improvement of air quality and temperature reduction, improvement in stormwater management (European Commission, 2015), and urban compaction and real estate value appreciation (Roebeling *et al.*, 2017). These benefits can be achieved by the implementation of, for example, green roofs, green walls, green spaces (e.g. parks, community gardens, cemeteries, etc. …) and blue spaces (e.g. lakes, ponds, etc. …). These solutions are sustainable, cost-effective and multi-purpose, and help to define a path towards a more resource efficient, competitive and greener economy (European Commission, 2015).

The direct impacts of NBS, i.e. urban cooling, which is defined as the reduction of temperature in an urban setting, happen in the short-term in the area surrounding the NBS and is widely recognized (Zhang *et al.*, 2014, 2017; Rafael, 2017; Shih, 2017). The indirect impacts of NBS, most notable, urban sprawl, defined as the uncontrolled spread of cities into undeveloped areas (EEA, 2016), are however less well known. These also include population dynamics, gentrification and urban compaction (Wolch *et al.*, 2014; Roebeling *et al.*, 2017) that will impact urban temperature, as the implementation of NBS implies changes in the urban morphology (Rafael, 2017). These indirect impacts might not occur immediately, but in the medium to long-term and will influence the urban temperature in areas surrounding the NBS as well as other areas of the city. So, to better understand the net impact of NBS, it is important to understand the direct as well as the indirect impacts of NBS on urban temperature. This sequence of processes is better explained in Figure 1.

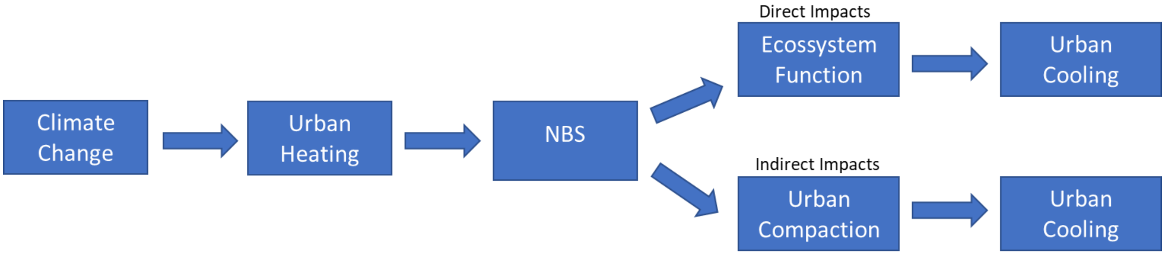

Figure 1: Process of the direct and indirect impacts of NBS.

In sum, it is important for public planners, decision makers and stakeholders to understand the full effects of their actions, in this case, the application of NBS, so that they can achieve their intended objectives in the most effective way – whether that be attenuating the effects of climate change, improving the social characteristics of a city or improving the well-being of the people.

1.1. Objective

The objective of this study is to assess the direct[1] and indirect[2] impacts of selected NBS on urban heat. To this end, the Weather Research and Forecasting (WRF), and Surface Urban Energy and Water Balance Scheme (SUEWS) modelling system (to simulate meteorological fields and energy/heat fluxes) in combination with the Sustainable Urbanising Landscape Development (SULD) model (to simulate population dynamics and urban sprawl) are used. A case study is provided for NBS in the city of Eindhoven (Netherlands), including daylighting rivers, de-paving requalifying an urban park. Results provide insight into how NBS will affect the city which, in theory, will assist public planners in achieving the desired effects when applying the NBS.

This research is developed in the context of the UNaLab project (http://www.unalab.eu/). UNaLab (Urban Nature Lab) is a network consisting of ten cities, partnered to face the challenges of climate change and growing urbanization, by developing an EU reference framework for nature-based solutions. Their objective is to "develop, via co-creation with stakeholders and implementation of 'living lab' demonstration areas, a robust evidence base and European framework of innovative, replicable, and locally-attuned nature-based solutions to enhance the climate and water resilience of cities". Three front-runner cities (Eindhoven, Tampere and Genova), with a history of making advances for sustainable development, will serve as a demonstration of the benefits, co-benefits, cost-effectiveness and economic viability of NBS, while developing a framework to help implement and replicate effective NBS systems. (UNaLab, 2016)

1.2. Outline

This dissertation is divided in 6 sections. The first section presents the literature review, which is based on a thorough research conducted using academic indexing and search engine (Scopus) for published articles and book chapters, and freely accessible internet search machines (Google) for grey-literature (reports, thesis). Keywords and search terms used to identify literature were green space, blue space, nature-based solutions, green infrastructures, blue infrastructures, urban, heat, heat

[1] Direct impact refers to the cooling functions provided by the NBS in the short term.

[2] Indirect impact refers to the urban compaction resulting from NBS implementation in the medium to long term.

island, urban sprawl, urban compactness and model. Keywords and search terms excluded to refine the search were agriculture, health, public, biodiversity. The publishing period was restricted to until 2017 (included). The language was restricted to English. The articles that were not available through Scopus were not reviewed. The following section focuses on the methodology used to reach the objective, i.e. the models used (WRF-SUEWS and SULD), their characteristics, how they relate to each other in the context of the problem, and their respective validation. The fourth section corresponds to the case study description of Eindhoven, based on socio-economic and bio-physical characteristics This section also includes the parametrization values for the city, and the description of the scenarios to be modelled. Section 5 encompasses the results of the different simulations, including the base scenario description for the city of Eindhoven. and the discussion of the results, and comparison of the different scenarios and available literature. Finally, the last section states the conclusions from this study, as well as suggestions for future research needs.

2. Literature Review

2.1. Nature-based Solutions

Defined by the European Commission (2015: p.5), nature-based solutions are “actions inspired by, supported by or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions, for example, mimicking how non-human organisms and communities cope with environmental extremes”. Put more simply, NBS refer to using nature to tackle challenges, like climate change, water resources or disaster risk management, facing not only ecological issues, but also societal factors, like socio-economic development and governance principles, among others (Balian and Eggermont, 2014).

NBS use features and complex system processes found in nature to achieve desired outcomes. For example, nature’s ability to store carbon or regulate water flows, can help develop climate change adaptation and mitigation, restore degraded ecosystems or even improve risk management and resilience (European Commission, 2015). One of the aspects of NBS that makes it so attractive is its capacity for multifunctionality. One NBS can, at the same time, improve quality of life, mental and physical health, and improve the ecosystem (Keniger *et al.*, 2013; Kabisch *et al.*, 2016). Because of this, NBS present, often, more efficient and cost-effective solutions to climate change threats, versus more traditional approaches (European Commission, 2015).

Depending on the NBS and its implementation, its effects may vary. Green spaces, in the form of parks, green roofs and walls, trees or even shrubs, have a cooling effect, especially in an urban environment, and can contribute to reducing the energy and resource demands and costs by reducing the need for heating and air conditioning. They have socioeconomic benefits, because they improve the value of the area, both visually and in terms of health. As another example, blue spaces, such as lakes, rivers and ponds have similar effects as well as, helping reduce the impacts of floods and the intensity of fires (Balian and Eggermont, 2014; European Commission, 2015).

Other examples of NBS include restoring salt marshes and other types of coastal restoration to improve coastal resilience, restoration of water bodies to improve water quality, afforestation for carbon sequestration and other green space related effects, sustainable agriculture practices to combat drought in rural areas, among others (Balian and Eggermont, 2014; European Commission, 2015; Kabisch *et al.*, 2016).

2.2. Urban heating

The incoming solar shortwave radiation powers the Earth's climate system and is balanced by the outgoing long wave radiation. As shown in Figure 2, about half of the incoming radiation is reflected back to space or absorbed in the atmosphere, the other half, however, is absorbed by the Earth's surface, heating it, and is then emitted back to the atmosphere, as terrestrial radiation, exhibiting a link between energy balance and climate change (EEA, 2017b).

The net all-wave radiation flux (Q^*) is the result of the radiation exchange and, the basic input to the surface energy balance. A combination of convective exchange to, or from the atmosphere, either as sensible heat (Q_H), latent heat (Q_E) or conduction to or from the underlying soil (Q_G), account, at any given time, for any surface radiative imbalance. This considered, the surface energy balance is given by:

$$Q^* = Q_H + Q_E + Q_G \qquad (1)$$

When the terms on the right side are positive, that represents losses of heat for the surface, and when they are negative, they represent gains (Oke, 1990).

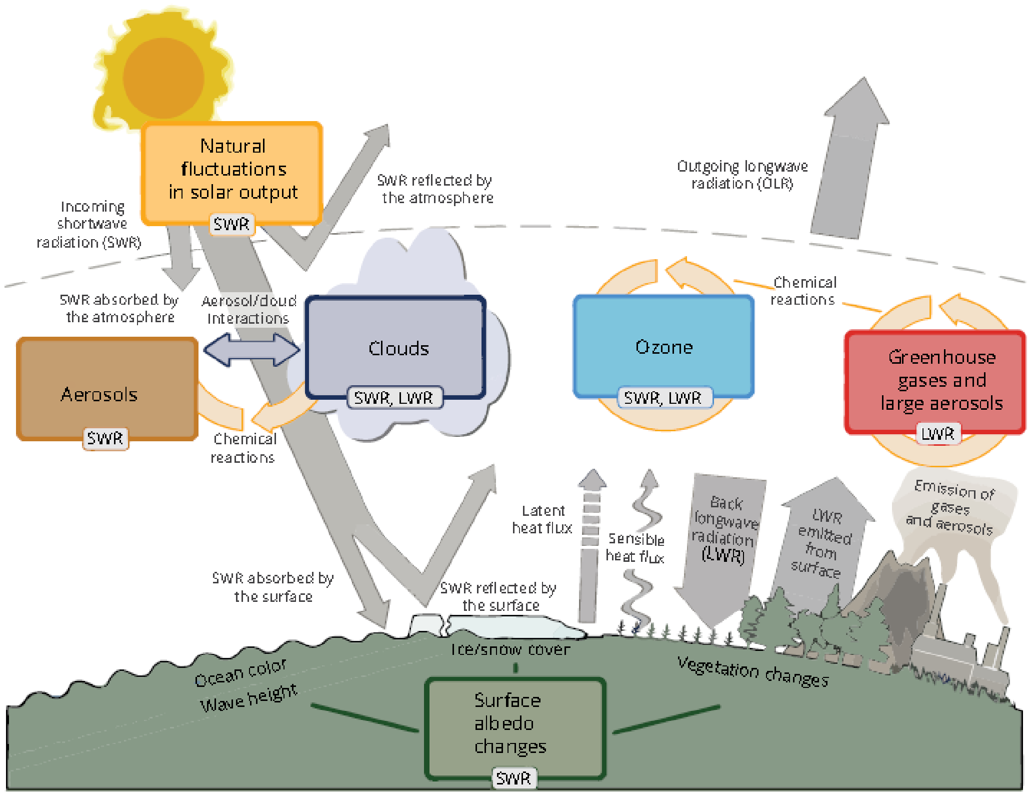

Figure 2: The Earth's energy balance and the drivers of climate change (EEA, 2017b).

The sensible heat flux can be defined as the energy transported by the atmosphere in its temperature and the latent heat flux is the energy that is lost from the surface by the process of evaporation of the surface water. Other important fluxes are the anthropogenic heat flux, that is the energy released by human activities and the net storage heat flux, that includes soil heat flux and the heating and cooling of the complete urban structure (Oke, 1990).

As urbanization grows, the climate and the hydrological cycle are affected, because of the changes in land cover and surface albedo (fraction of solar energy reflected from the Earth back into space), causing additional heat released to the atmosphere, influencing weather conditions (atmospheric temperatures and humidity) and climate, at street level (EPA, 2008; Flagg and Taylor, 2011; EEA, 2017b).

The most notable impact of urban land-use change is the urban heat island (UHI) (Zhong *et al.*, 2017). This is a phenomenon where urban regions experience higher temperatures than their surrounding rural areas (Howard, 1833) which causes negative impacts on the quality of life and sustainability (EPA, 2008). UHI are one of the secondary effects of urbanization. The urban expansion, pollution growth and the development of industrial activities are all factors that help with the formation of UHI. (Ghazanfari *et al.*, 2009), which helps explain why this effect is more connected with urban areas, than rural areas. Summarized by (Voogt and Oke, 2003), the causes and factors that contribute to the formation of UHI include: i) Canyon Radiative Geometry (decreased long-wave radiation loss from within street canyons due to the complex exchange between buildings and the screening of the skyline and multiple reflections of short-wave radiation between the canyon surfaces decreasing the effective albedo of the system); ii) Thermal properties, such as the increased storage of sensible heat in the fabric of the city; iii) Anthropogenic heat; iv) Urban “Greenhouse” (increased incoming long-wave radiation from urban atmosphere, which is more polluted and warmer); v) Evapotranspiration (the reduction of evaporating surfaces increases the sensible heat); Shelter (reduced turbulent transfer of heat within streets).

Effects of NBS on urban heating

One of the main strategies to mitigate these effect is the implementation of urban green spaces, that have the best cooling effect, when compared to other solutions, (Chen and Wong, 2006; Qiu *et al.*, 2017) specially at nighttime. This cooling effect is more pronounced in cities with UHI and during hot and dry days in cities with a Mediterranean climate (Oliveira *et al*., 2011). The effect of green surfaces and areas on temperature depends on several factors, such as urban features of the city and the climatic envelop of the study area.

This cooling effect is effective at macro- and micro- levels. For example, trees can reduce temperature by increase shaded area (Kabisch *et al.*, 2016), vegetation planted around a building can alter the energy balance and cooling energy requirements of the building, and when the green spaces are arranged throughout the city in the form of urban parks, natural reserves, and so forth, it can modify the energy balance of the entire city through adding more evaporating surfaces (Chen and Wong, 2006).

Assessing the effects of urban heating

Assessing the effects of NBS on urban heat is important to make sure the actions implemented are adequate and will have the desired effect in the short term as well as in the long term. There are various ways to assess these effects, such as quantitative studies based on remote sensing of satellites, local meteorological stations or mobile traverse measurements. However, as the urban environment is quite complex, there is a lack of detailed measurements and, thus, most studies use qualitative approaches (Qiu *et al.*, 2017).

As aforementioned, one of the most used techniques to investigate the cooling effects of green infrastructures is remote sensing because large areas can be monitored and analysed simultaneously and continuously (Liwen *et al.*, 2015). These methods have been mostly used at meso-scales using satellite imagery to map and quantify the cooling effects of green infrastructures (Koc *et al.*, 2017). However, remote sensing does not allow to predict the effects of possible NBS, or to predict how the NBS will develop in the future. For this purpose, modelling approaches are useful tools, that allow to simulate non-existing/future scenarios. The literature review performed revealed that there are several studies that followed this methodology. Table 1 summarizes the reviewed studies that analysed NBS and urban temperature.

Table 1. Summary of the reviewed studies that analysed NBS and Urban temperature.

Studies	Objective	Model
Wu & Chen, 2017	Investigate how different spatial arrangements of trees in residential neighbourhoods affect the cooling effects of vegetation	ENVI-Met
Sun et al., 2017	Assess the impacts of modifications in a park on the thermal comfort improving-effect of urban green spaces	ENVI-Met

Wai et al., 2017	Study aerosol impacts (in terms of aerosol optic depth variations) on physiological equivalent temperature	RayMan and SBDART
Alvizuri, et al., 2017	Study the ability of green roofs to insulate a building	Physical Model
Kuang et al., 2017	Developed the model to regulate urban land cover structure and thermal environment, and established the eco-regulation thresholds of urban surface thermal environments	EcoCity
Nielsen, et al., 2017	Explore the spatial configuration of forests across cities located within landscapes characterised by different levels of anthropogenic modification and socio-political contexts	Geographic Information Systems
Wai et al., 2017	Determine the change in evapotranspiration from the new ecosystems	Variable Infiltration Capacity
Žuvela-Aloise, 2017	Simulate the urban climate to demonstrate that the residential areas with deprived socio-economic conditions can exhibit an enhanced heat load at night	numerical model MUKLIMO_3
Meerow & Newell, 2017	Represent a spatial planning approach for evaluating competing and complementary ecosystem service priorities for a landscape	Green Infrastructure Spatial Planning (GISP)
Rafael *et al.*, 2017	Estimate energy fluxes and evaluate the effect of climate change	WRF-SUEWS
Takebayashi, 2017	Examine air temperature rise in urban areas that are on the leeward side of green areas	Numerical Model
Koc et al., 2017	Methodological framework for a more accurate assessment of the thermal performance of green infrastructure	Remote Sensing
Žuvela-Aloise, 2017	Evaluate the cooling potential of the blue and green infrastructure to reduce the UHI effect when applied to large areas of the city	MUKLIMO_3
Kong et al., 2016	Examine the outdoor 3D thermal environmental patterns with and without green spaces	ENVI-Met
Lin & Lin, 2016	Characterize the influence of the spatial arrangement of urban parks on local temperature reduction	ENVI-Met
Ward et al. 2016	Asses the model performance at two locations, a dense urban site and a residential suburban site	SUEWS
Zölch, et al., 2016	Quantify the effectiveness of three types of UGI in increasing outdoor thermal comfort in a comparative analysis	ENVI-Met
Kim et al., 2016	Calculate values of several landscape indices used to measure neighbourhood landscape spatial patterns	FRAGSTATS
He, et al., 2016	Investigate the thermal and energy performance of an extensive green roof under free-floating and air-conditioned conditions	Physical Model
Hu, et al., 2016	Quantify land surface temperature	MODIS LST

Liu et al., 2016	Investigate the relationship between Land surface temperature and the land-cover types and associated landscape components	STARFM
Kim et al. , 2016	Understand the cooling effect of changes in land cover on surface and air temperatures in urban micro-scale environments	ENVI-Met
Zhang et al., 2014	Estimate the energy-savings and emission-reduction contribution of urban green spaces	Empirical Model
Feyisa et al., 2014	Examine the relationship between characteristics of the vegetation and observed temperature	Linear Mixed-Effect Model
Ketterer and Matzarakis, 2014	Assess thermal human-biometeorological conditions of the current urban environment	ENVI-Met and RayMan
Kong et al., 2014	Explore and quantify the combined effects of factors related to the urban cooling islands intensity	Linear Regression Models
Smalls-Mantey et al., 2013	Evaluate Temperature Dependent and Temperature Independent models in the estimation of soil heat flux at night and during the dusk-dawn period	Temperature Dependent and Temperature Independent soil heat flux models
Vidrih & Medved, 2013	Study the effect of size, density and age of trees on the cooling effect of the park	TRNSYS
Vanos et al., 2012	Assess the moderating effects of urban parks in contrast to streets	COMFA
Liu et al., 2012	Analyse the influence of different land use types on the surface heat fluxes and energy balance	PCACA model
Mackey et al., 2012	Attempt to analyse a real large-scale application by observing recent vegetated and reflective surfaces in LANDSAT images	LANDSAT
Ng et al., 2012	Simulate 33 cases with different combinations of factors (different greening strategies and building heights for example)	ENVI-Met
Boukhabla and Alkama, 2012	Study the impact of vegetation on air temperature	ENVI-Met
Hongbing et al., 2010	Study tree layout in green space between buildings	Autocad; Sketch-up
Man Sing et al., 2009	Analyse the urban heat island effect at sites with different geometries, land use, and environments	Mathematical Models

As evidenced by the table there is a plethora of models to study the effects of NBS on urban heating, however, not all models are adequate for all objectives, and given a specific purpose, the models should be chosen accordingly.

To properly assess the urban heat component of a site, there is a need to analyse the heat fluxes (EEA, 2017b). According to Rafael *et al.*, (2016) the study of energy fluxes can be conducted in three main approaches: i) studies that only consider the measurements of energy fluxes through the eddy covariance method, and usually compare different types of land; ii) studies that combine flux measurements with model simulations; iii) Studies that use models designed to simulate the key processes governing heat, moisture and momentum exchanges of the urban canopy for different applications. All these approaches offer different benefits and present different challenges, and the chosen method should be dependent on the case study.

2.3. Urban Sprawl

The global urbanization phenomenon is one of the most complex processes concerning land use (Haase and Schwarz, 2009), and it is not only a societal problem but also an environmental one. Its impacts result in a reduction in ecosystem functions, that are defined as "the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly" (De Groot *et al.*, 2002). So, human actions have been known to have an effect on land use, as population growth has led to an ascending occupation of land for residential purposes and other exploitations of land cover (Veldkamp and Lambin, 2001; Haase and Schwarz, 2009)

Urban sprawl can be defined as an uncontrolled spread of cities into undeveloped areas (Agency, 2016). It is a result of economic development and environmental variation and it can affect the way society is organized (Wu, 2006), by having urban land use occupy natural and agricultural land uses, thus resulting in a new landscape with city features (Pinto, 2008).

It can be stated that urban sprawl is a natural process and results directly from population and economic growth, and it can have both beneficial and harmful impacts, but ultimately, is a concern among the most diverse countries (Agency, 2016).

Effects of NBS on urban sprawl

The social characteristics of communities are influenced by the level (i.e. number, size, accessibility and/or quality) of environmental amenities, that are considered a major factor for household location preferences (Brueckner *et al.*, 1999). More amenity locations in a community result in the attraction of higher income households. Therefore, those communities can provide better public services (Wu, 2006). NBS can influence the population dynamics in cities, by impacting the distribution of residential land use, property values and social-mix (Roebeling *et al.*, 2017; Wolch *et al.*, 2014). There is also a relationship between access to green spaces, that include those environmental amenities, and social characteristics such as, income, ethnicity and race, age and gender (Byrne *et al.*, 2009; McConnachie and Shackleton, 2010). Because of the added value of these amenities, provided by the green/blue spaces, households are willing to pay more rental values and live in smaller spaces when living near an urban park, and other attractive areas, so, cities are expected to become more compact, suffer an increase in population density and rental values, and overall changes in the demographic distributions patterns are expected to occur. However, these effects depend on other factors, such as: quality and size of the intervention; the location of the intervention; social classes attracted to the intervention areas (Roebeling *et al.*, 2017).

One issue with the effect of NBS on urban sprawl is that it can accentuate the difference in society at the varied levels of income. With more green spaces, there is an increase in the attractiveness of the area, thus increasing the value of housing costs, which can lead to displacement and/or exclusion of the residents for which the green space was originally implemented (Wolch *et al.*, 2014).

There is a debate whether a compact city or a sprawled city makes for a better urban environment, but the consensus is that there is a relationship between the city's form, size, density and land use and its sustainability, however, this relationship is not quite well understood (Williams *et al.*, 2013). At a city level, reaching a regional balance would translate in a balance between compactness and sprawl, and thus making sure cities are green enough to prevent them for overheating but still compact enough to ensure efficient transportation and infrastructural systems (Icaza and van der Hoeven, 2017).

Assessing the effects of urban sprawl

Non-economic land use models are mainly used in environmental and geographical literature to describe land-use patterns at a regional, national or even global level (Irwin & Geoghegan, 2001; Roebeling *et al.*, 2014), though lack a conceptual economic structure (Roebeling *et al*., 2017). This implies that they cannot distinguish endogenous interactions with spatially correlated exogenous forces or landscape features, they only come up with a possible pattern-interaction solution, they rarely consider that the external features may change over time, but are spatially static and they don't explain individual behaviour (Irwin & Geoghegan, 2001; Roebeling *et al*., 2014). These non-economic models can be: i) heuristic models, that represent the decision process that led to a specific land use pattern; ii) cellular automata, that are spatially explicit discrete cell-based models, that consists of cells, neighbourhoods, states and transition rules; iii) multi-agent systems, which are similar to cellular automata models, but focus more on human actions and interactions instead of landscape and their transitions; iv) hybrid models, that combine both the estimation and simulation capacity of previous models (Irwin & Geoghegan, 2001; Roebeling *et al*., 2014, 2017).

Economic land use models usually represent small scale processes that depend on the decision-maker's choice to maximize their utility, profit and/or income. This enables policy evaluation, by allowing the assessment and understanding of the decision-maker's response to incentive changes. They are used to investigate urban sprawl, optimal city size and urban concentration, timing of land development and land management policy measures. (Irwin and Geoghegan, 2001; Roebeling *et al.*, 2017). These economic land use models can be divided in spatially or non-spatially explicit (Irwin & Geoghegan, 2001; Roebeling *et al.*, 2014). The non-spatially explicit models assume that the landscape is a featureless plane, which allows an analytical tractability and have been criticized for failing to explain the impact of heterogeneous landscape features, and spatially explicit models are based on the individuals' willingness to pay for various aspects of a house and its surroundings (Roebeling *et al.*, 2017). The spatially explicit models take into account landscape features/characteristics and can be divided into hedonic pricing regression and hedonic pricing simulation models. The former base their property values estimation on observed data, however the data they require may be insufficient, missing or hard to find. The latter, without any observed data required, assess the value planned amenities will add, building on information from hedonic regression models (Roebeling *et al*., 2017).

Summarized in Table 2 are the studies that analysed land use and urban restructuring, sprawl or compactness, through modelling.

Table 2: Summary of the reviewed studies that analyse land use and urban sprawl/compactness.

Studies	Objective	Model
Sushinsky et al., 2017	Quantify the impact of compact and sprawling urban growth on opportunities to experience nature by measuring changes in backyard size, public green space provision, and bird species richness as a city grows	GIS (Google Earth)
Roebeling *et al.*, 2017	Assess and compare the socio-economic impacts of potential green/blue space, urban residential and road-infrastructure development scenarios in the Lyon Confluence project area (France)	Sustainable Urbanizing Landscape Development (SULD)
Saraiva *et al.*, 2017	Project, assess and compare changes in land-use, household type distribution, real estate values and household densities, in three different scenarios of population decline (-5%, -10% and -15%)	Sustainable Urbanizing Landscape Development (SULD)
Wang et al., 2017	Examine the patterns and interrelations among three types of boundary (metropolitan boundaries, natural boundaries, and urban boundaries)	GIS (Google Earth)

Oh et al., 2017	Determine ways to better understand ecological problems in urban areas, and to develop an UENP process and land use strategies to resolve those problems	Urban Ecology Network Planning (UENP)
Conedera et al., 2015	Assess the preferences and uses of urban and peri-urban green spaces	General Linear Model
Buck et al., 2015	Study the relationship between accessibility of green spaces to physical activity of children	Gama log-regression model
Schindler & Caruso, 2014	Study how urban structure impacts traffic-induced pollutant emissions and the exposure of residents to those pollutants	S-GHOST
Zhao et al., 2013	Investigate the temporal trend in green space coverage and its relationship with urbanization	Multiple regression model
Melichar & Kaprov, 2013	Trace the value of urban greenery amenities on the housing market in the newly transformed economy using a hedonic price model and capture the distance and size joint effect of green space on the property market by interaction effects	Hedonic pricing regression models
La Greca et al., 2011	Propose a land use suitability strategy model to orient Land Uses of Non-Urbanized Areas, based on integration of Land Cover Analysis and Fragmentation Analysis	GIS
Rahman et al., 2011	Assess urban sprawl for one of the fastest growing city of South India	Shannon's Entropy Model, GIS (IRS P-6)
Kong et al., 2007	Address the previous absence of the application of hedonic price models to the valuation of urban green space amenities	Hedonic pricing regression models, GIS
Roebeling *et al.*, 2007	Explore welfare gains that can be obtained from population growth and associated residential development, in a linked terrestrial and marine ecosystem	Spatially explicit model

As evident from Table 4, the most popular approach to study the impacts of urban environmental amenities on the distribution of residential land use, property values and the social-mix is the application of hedonic pricing models. These are used to determine property values as a function of distance to urban centres, while also taking into account other spatially explicit landscape characteristics (Roebeling *et al.*, 2017). It can also reveal preferences for specific amenities at small spatial scales, which allows to capture the accessibility, distance and visibility of the amenities (Waltert and Schläpfer, 2010).

3. Methodology

To better understand the process that was undertaken to achieve the results of this study, an outline of the methodology adopted for this dissertation is represented in Figure 3. It started with a literature review to assess the state of the art on NBS, urban heat and urban sprawl, followed by a review of the relevant models for evaluating NBS effects, both for urban heat and for urban sprawl.

After the literature review, the process of creating a database was undertaken to prepare for the models' inputs, which led to the preparation of the models, with tests to adjust some parametrizations as needed. When the models were ready, the scenario simulations began followed by the analysis of the results. Finally, the results were evaluated and reviewed, which allowed to reach conclusions.

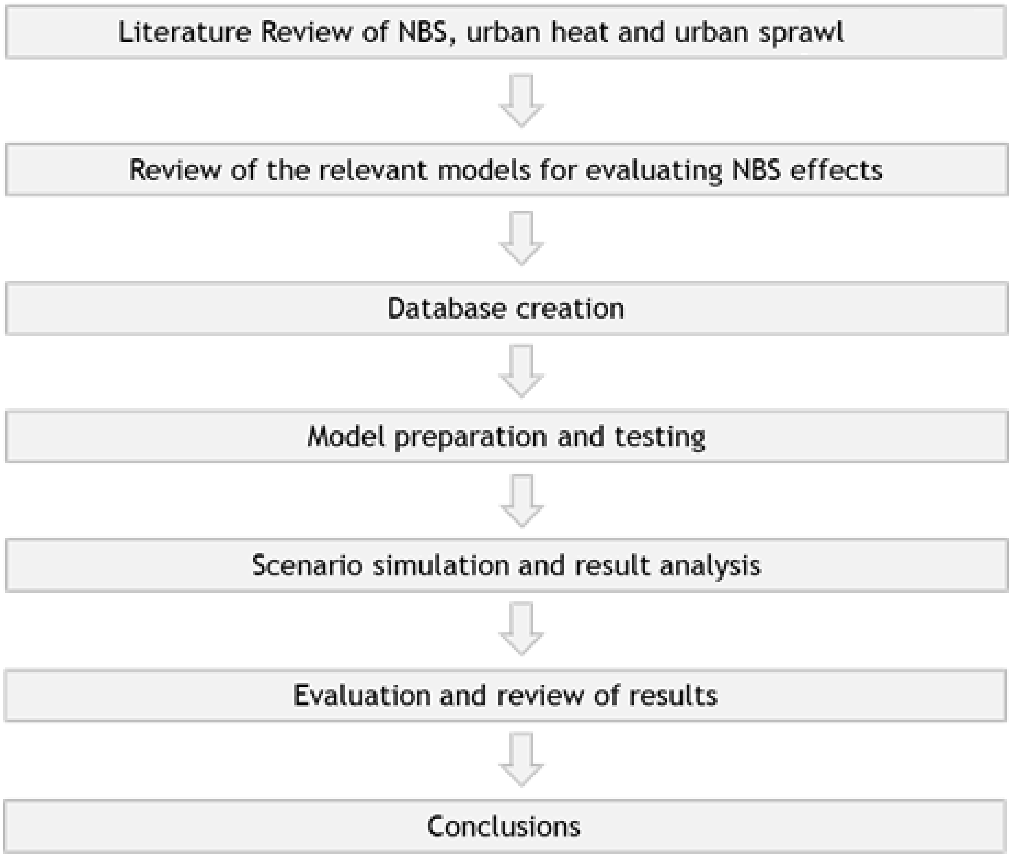

Figure 3: Schematic outline the methodology adopted for the dissertation.

3.1. Integrated modelling approach

Most modelling approaches/studies assess the direct impacts of NBS on urban heat and well-being. However, the indirect impacts associated are not well represented in literature, or they are represented in a disconnected way. So, this study is attempting to fill a gap in the knowledge regarding the implementation of NBS in an urban environment, to help to better understand its effects and consequences, and support the decision-making process of stakeholders.

WRF-SUEWS is used to simulate meteorological fields and energy/heat fluxes and SULD is used to simulate population dynamics and urban sprawl, so, since the models have different, but complementary purposes, by using and integrated approach, it is possible to simulate the urban-surface atmosphere exchanges and the socioeconomic exchanges caused by the implementation of the NBS at the same time, while also, simplifying the interpretation of the results. Figure 4 represents the inputs and outputs of the models chosen to be applied in the current study (WRF, SUEWS and SULD) and shows a relationship between them.

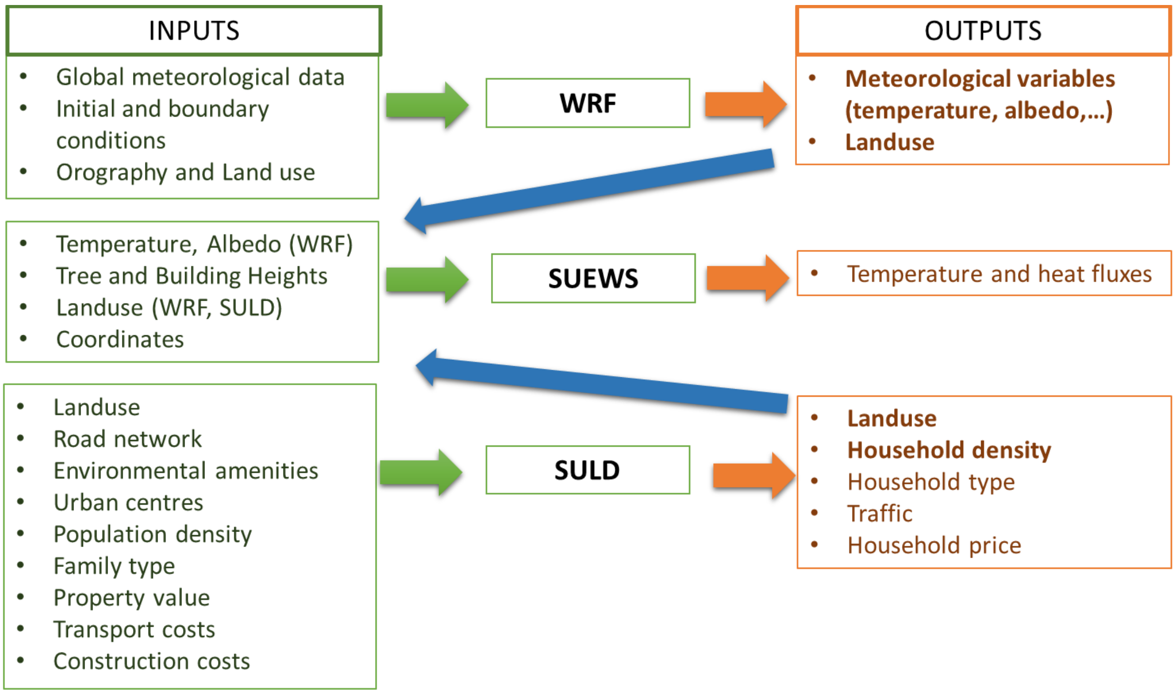

Figure 4: Relationship between the model's inputs and outputs.

The models influence each other directly, i.e. the outputs of SULD for the direct impacts simulation, will give information about the population density and land use, which will be used as the input values for SUEWS application to assess the indirect impacts. This interaction between the models can help better understand the relationship between the city's form, size, density and land use.

3.2. WRF-SUEWS

The Surface Urban Energy and Water Balance Scheme (SUEWS) model can simulate both energy and water fluxes at a neighbourhood scale, and it will be used to simulate the urban fluxes of the case study. SUEWS requires a relatively small set of inputs like common hourly meteorological variables (mean wind speed, relative humidity, air temperature, station air pressure, precipitation and incoming shortwave radiation), the plan area surface fractions, building and tree heights, albedo, emissivity, moisture storage capacity and population density. In return, it calculates complete energy balance (radiative, convective and conductive fluxes) at the interface between the urban surface layer and the atmosphere (Järvi *et al.*, 2011).

SUEWS utilizes several sub-models to minimize the number of variables required. These sub-models are, as summarized by (Rafael *et al.*, 2017):

- The Objective Hysteresis Model (Grimmond and Oke, 1991) to calculate the net storage heat flux, which includes soil heat flux and also the heating and cooling of the complete urban structure;
- The Net All-wave Radiation Parameterisation (Offerle and Grimmond, 2003) to supply the net all-wave radiation, which is the net incoming and outgoing radiative fluxes;
- The urban evaporation-interception scheme of (Grimmond and Oke, 1991) to calculate the latent heat flux, which is the energy released with the phase change of water;
- The sensible heat, which is the energy that heats the air, is estimated as the residual of the energy balance;
- A change version of the (Sailor and Vasireddy, 2006) approach is used to calculate the anthropogenic heat flux, which is the energy released by human activities;
- The Local-scale Urban Meteorological Parameterisation Scheme (Grimmond and Oke, 1991) to provide an initial estimation of the atmospheric stability.

The model is centred on the urban energy balance by (Oke, 1990),

$$Q^{*} + Q_{F} = Q_{H} + Q_{E} + \Delta Q_{S} \quad [W\ m^{-2}] \qquad (2)$$

where $Q^{*}$is the net all-wave radiation, Q_F the anthropogenic heat flux, Q_h the turbulent sensible heat flux, Q_E the latent heat flux and ΔQ_S the net storage heat flux.

SUEWS was parametrized using observational data from suburban areas in Vancouver, in the summer (Ward *et al.*, 2016), and that would be the ideal scenario to simulate, for better results. The meteorological data required to run SUEWS was obtained from the Weather Research Forecast Model (WRF- version 3.7.1)

WRF is a three-dimensional, compressible and non-hydrostatic meteorological model (Skamarock *et al.*, 2008) that has been used in a wide range of applications and research and found to have good performance regarding temperature and precipitation (Man Sing *et al.*, 2009; Liao *et al.*, 2014; Rafael, 2017; Zhong *et al.*, 2017). The WRF model configuration for 1-km grid spacing includes: the Noah land surface model (Tewari *et al.*, 2016), the Rapid Radiative Transfer Model (RRTM) longwave radiation scheme (Mlawer *et al.*, 1997), the Mellor-Yamada-Janjic planetary boundary-layer scheme (Janjic, 2002)

It presents 38 vertical layers with the lowest model sigma level at approximately 10-m of height and model top at 50 hPa. It uses the 24 land use categories from the United States Geological Survey (USGS) to remap the Corine Land Cover data (http://land.copernicus.eu/pan-european/corine-land-cover). The WRF model was used to provide the input meteorological data for SUEWS application.

3.3. SULD

SULD is a GIS-based hedonic pricing simulation model used as a support tool and developed to allow a more informed and unbiased decision-making regarding sustainable urban, and peri-urban, development and green/blue space management. (Roebeling *et al.*, 2017) It is based on analytical urban economic model with environmental and urban amenities. The model assesses the impacts of urban sprawl and the impacts of green/blue spaces, infrastructure and social-economic scenarios in an economic and well-being context, by determining the location of residential development, population density, housing quantity, living space, and real estate value as a function of distance to urban centres and environmental amenities. It has also been used to assess the environmental-economic impacts of population growth and urban development on marine ecosystems (Roebeling *et al.*, 2007). It provides valuable information to the stakeholders that is usually not available during the urban planning process, and is best suited to be used by regional/local decision makers and stakeholders in spatial development (Roebeling *et al.*, 2014).

The model is divided into a "demand" side, and a "supply" side. The households, and their preferences for a certain set of goods, services, residential space (S) and environmental amenities (e), represent the demand side (Eq. 3). Households try to maximise their utility (U) at a particular location (i), with a function depending on their preferences, the distance to environmental amenities and their income that is split between housing expenses (${p_i}^h S$), goods and services (Z), and transportation between the location (residential area) and the closest urban centre ($p_x x$).

$$Max_{S_i,Z_i} U_i(S_i, Z_i) = S_i^{\eta} Z_i^{(1-\eta)} e_i^{\varepsilon} \qquad (3)$$

$$\text{subject to } y = p_i^h S_i + Z_i + p_x x_i \qquad (3a)$$

The supply side (Eq. 4) is represented by developers who look to maximise their profit (π) at a particular location which is dependent on the rental price of housing, the opportunity cost of land, the constructions costs, the household density (n_i) and the residential space. The maximising of the profit (π) results in a minimum rental price that the developer is willing to accept at a particular location.

$$Max_{D_i} \pi_i(D_i) = p_i^h D_i - \left(l_i + D_i^{\eta}\right) \qquad (4)$$

$$\text{with } D_i = N_i S_i \qquad (4a)$$

where $p_i{}^h$ is the rental price of housing, l_i is the opportunity cost of land, $D_i{}^{\eta}$ is the construction cost function, and η is the ratio of housing value to non-land construction costs.

Equilibrium (Eq. 5) between the demand and the supply side occurs when supply for housing equals demand for housing. The equilibrium land rent price (r_i) is given by

$$r_i = \left(\frac{k e_i^{\varepsilon}(y - p_x x_i)}{u}\right)^{\frac{\eta}{\mu(\eta-1)}} \qquad (5)$$

$$\text{with } k = (\mu m)^{\mu}(1-\mu)^{(1-\mu)} \qquad (5a)$$

and hence development patterns for a certain population size and composition are determined, given the location of urban centres and environmental amenities (Roebeling *et al.,* 2017).

SULD has been parameterized, calibrated and validated for the city of Eindhoven (Netherlands) by Roebeling *et al.*, (2014).

4. Case study description

A case study is provided for the city of Eindhoven, located in the south-east of the Netherlands and an example of economic and demographic growth (Westerink *et al.*, 2017). This translates in the highest values of urban sprawl among all European countries (Agency, 2016). Eindhoven is the fifth largest city in the country, with 224,755 inhabitants at the start of 2016 and an area of 89 km^2 (CBS, 2017), resulting in a population density of 2530 inhabitants/km^2. It is situated at the confluence of various small rivers (e.g. Gender, Dommel) and streams.

The Eindhoven case study focuses on the inner-section of the city of Eindhoven, which comprises 23 neighbourhoods and is surrounded by a ring road (Figure 5). Eindhoven is serviced by 4 highways (A2, A58, A67 and A270), 8 provincial roads, a railway station and an international airport (Roebeling *et al.*, 2014). Twenty-one environmental amenities can be found in the city, including 6 urban parks, 4 neighbourhood parks, 10 local parks and water bodies. There are also 12 urban centres, marked in Figure 5, in red. These include a central shopping centre, five local shopping centres, three industrial areas, railway station, town hall and the Technical University of Eindhoven (Roebeling *et al.*, 2014).

Figure 5: Neighbourhoods (black borders) and urban areas (red dots) in the city of Eindhoven (based on Roebeling et al., 2014) .

4.1. WRF-SUEWS

The meteorological model (WRF; Grell *et al.*, 2005) is applied to three domains, using two-way nesting technique for the study period (July of 2013). Figure 6 shows the model domain setup: Domain 1 (D1) at 25-km grid spacing, covering Europe and a part of the north of Africa (180x155 horizontal grid cells); Domain 2 (D2) at 5-km grid spacing, covering The Netherlands and parts of Germany, France, Belgium and the United Kingdom (96x91) horizontal grid cells; Domain 3 (D3) at 1-km grid spacing, covering Eindhoven (51x41 horizontal grid cells).

Figure 6: WRF meteorological modelling domains, D1: Europe and part of the North of Africa; D2: The Netherlands, and other parts western Europe; D3: The Netherlands.

The meteorological initial and boundary conditions for WRF was initialized with ERA-Interim data from the European Centre for Medium-Range Weather Forecasts (ECMWF) global analysis (Rafael, 2017), with a horizontal resolution of 1°x1° and with a temporal resolution of 6-hour intervals.

SUEWS (version 2014b; Järvi *et al.*, 2011) uses a fourth domain, D4 at 1-km grid spacing, a sub-domain of D3 covering the centre of Eindhoven (4x4 horizontal grid cells), which is the study area. Due to its formulation and approach, SUEWS must be applied to each one of those 16 grid cells, represented in Figure 7. SUEWS parameterization by Rafael (2017) for the city of Porto, was adapted for the city of Eindhoven, which included changes to land use cover fractions, albedo, population density and precipitation. This modelling system was applied successfully to the city of Porto (Portugal) and verified against measured data (Rafael, 2017).

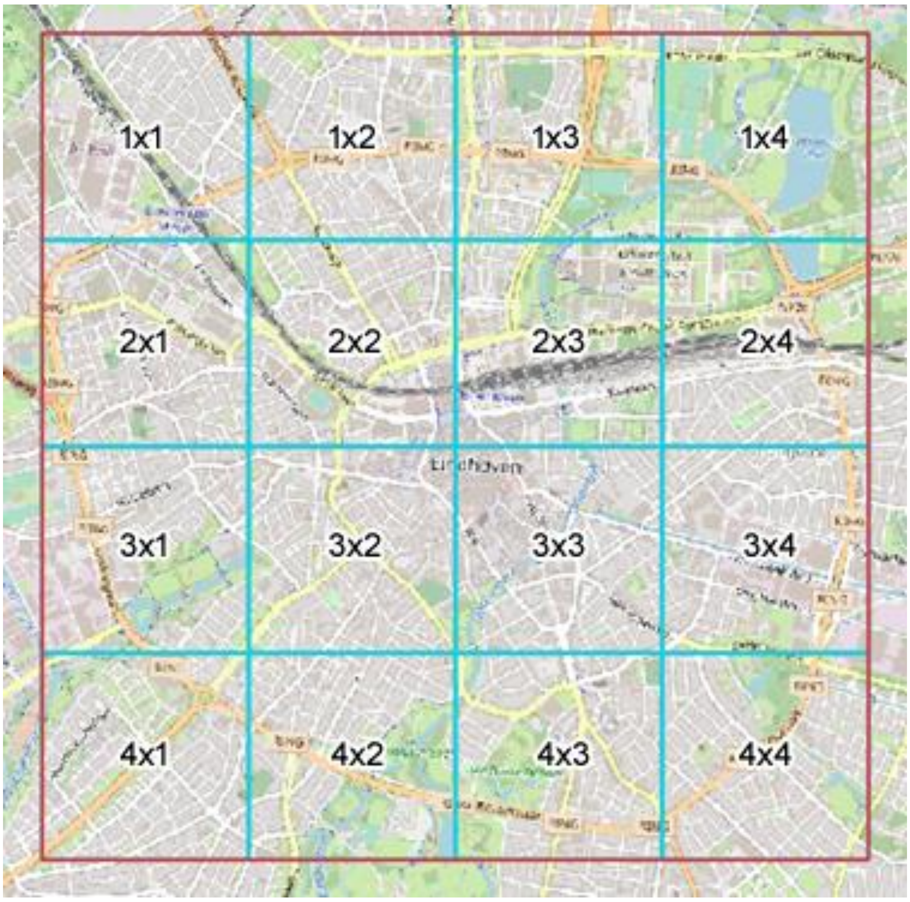

Figure 7: Sub-domain 4, that includes the city of Eindhoven, composed of 16 1kmx1km cells.

Data is compiled for population density for the neighbourhoods (CBS, 2017), building heights (Eindhoven, 2018), tree heights (https://www.pdok.nl/) and blue space areas (https://portal.eindhoven.nl). The data used is for the month of July in the year 2013.

The geographical and built area data is accessed using the open source database OpenStreetMaps (www.openstreetmap.org), and processed using the open source GIS tool, QGIS (version 2.14.21; https://qgis.org/en/site//). As this data is update regularly, it is not possible to access it for the base year 2013 but given the urban morphology hasn't changed significantly over the last few years this is not considered an issue.

As the model is applied for each individual cell of the domain, individual inputs were required. A pre-processor was developed by Rafael (2017) to automatically create SUEWS inputs, for example, the meteorological information provided by WRF, as represented in Figure 8.

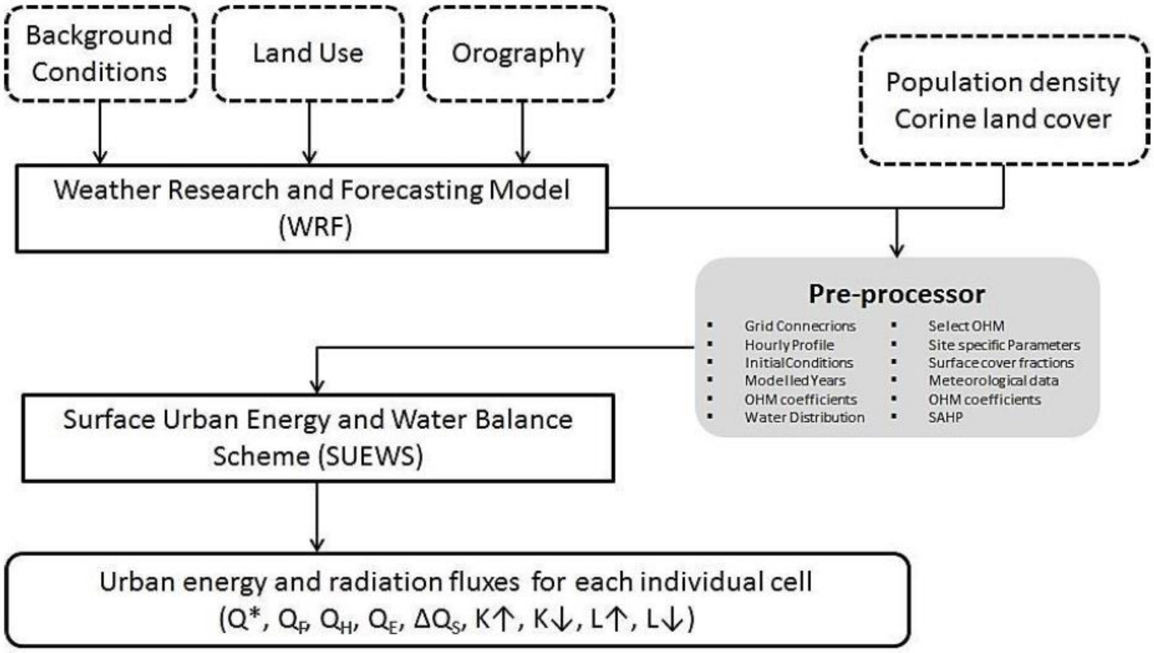

Figure 8: SUEWS Modelling system (source: Rafael, 2017).

Note: Q is the net all-wave radiation, QF is the anthropogenic heat flux, QE is the latent heat flux, QH is the turbulent sensible heat flux, ΔQS is the net storage heat flux, K↓ is the incoming shortwave radiation, K↑ is the outgoing shortwave radiation, L↓ is the incoming long-wave radiation, and L↑ is the outgoing long-wave radiation.*

As a tool to represent reality, models always carry uncertainties, so it is important to assess and evaluate if the chosen model represents the intended case study and situation with a certain degree of trust. The modelled meteorological values (temperature) were compared against measured data for the study period (July of 2013; daily time scale). The statistical analysis for temperature, shown in Table 3, exhibits a good relation between the measured and modelled data. The correlation factor (r) is greater than 0.9 and the root-mean-square deviation is close to 1.

Table 3: WRF statistical analysis.

	Measured	Modelled	RMSE	r	Bias
Temperature (Mean ºC)	19.9968	19.5738	1.112739	0.935094	0.422926

The obtained statistical metrics are in accordance with (Chang and Hanna, 2004). These findings guarantee that the most important meteorological variables are well modelled by WRF model, and therefore, the modelling results will be more reliable.

For the energy balance, there are no measured data available to compare, however, there are many studies where SUEWS has been used and validated (Rafael, 2017; Ward *et al.*, 2016)

4.2. SULD

The model study area consists of the inner-city ring of Eindhoven, represented in Figure 9, comprising 23 neighbourhoods. It encompasses an area of 4.070 km by 4.070 km (=16.56 km^2), covered by a grid layer of 185 by 185 (=34,225) cells of 22m by 22m. The results are based on available data for 2010-2011 (Roebeling et al., 2014).

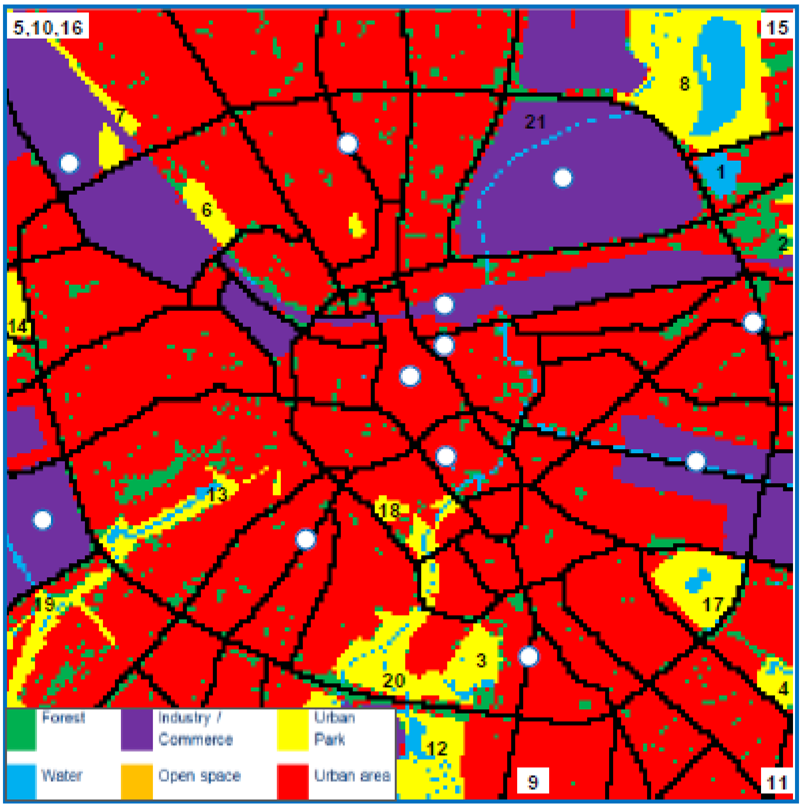

Figure 9: Land use in and around the city of Eindhoven (source: Roebeling et al., 2014).

The household characteristics for the case study area were based on household survey data, BioInfo (2013). Three income household groups were identified: low (household type 1), medium (household type 2) and high (household type 3). In Table 4 is summarized the household characteristics data (Roebeling et al., 2014).

Table 4: Household characteristics data (source: Roebeling et al., 2014).

	Unit	Household type 1	Household type 2	Household type 3	Total
Demographics					
Population	#	15,240	29,092	43,692	88,023
Household size	#/household	2.16	2.16	2.16	2.16
Households (Q)	#	7,056	13,469	20,228	40,751
Household budget					
Expendable income (y)	€/yr	11,576	22,333	35,362	$1{,}098.8*10^6$
Housing expenditures (μ)	%	29.8%	28.7%	28.2%	28.5%

4.3. Scenarios description

To evaluate the direct and indirect impacts of the NBS to be implemented, two main scenarios are simulated: i) Base scenario, that models the baseline in terms of temperature and heat fluxes, based on the current characteristics of land use; ii) NBS scenarios, that models the implementation of the NBS. Within the NBS scenarios, three different sub-scenarios are developed as to allow for the assessment of the direct and/or indirect impacts of NBS on urban heating. In particular:

- The direct impact scenario (DIS), aims to represent the direct impacts on urban heating caused by the implementation of the NBS;
- The indirect impact scenario (IIS), aims to represent the urban compactness that occurs after the implementation of the NBS (i.e. the indirect impacts) and that result in a change in land use and the population density (i.e. these indicators are representative of the changes in the urban morphology);
- The direct and indirect impact scenario (DIS+IIS), aims to represent the combined effects of the direct impact scenario and the indirect impact scenario.

The meteorological variables were kept constant for all scenarios, therefore the changes obtained are just the result of the land use and population density changes.

Baseline scenario (BS)

The baseline scenario aims to represent the state of the study area for the base year (2013). This serves as a starting point and the results are used to validate the model (in terms of meteorological data) against measured data. For this scenario, it was necessary to determine the population density, the surface characteristics assigned to each land use cover, the temperature and the albedo, for every individual grid cell as shown in Figure 7. The temperature, albedo and type of land use cover are WRF outputs and are the same for every simulation (Table 5)

Table 5: Data provided by WRF.

Grid Cell	Land use cover category	Temperature (K)	Temperature(ºC)	Albedo
1x1	Cropland/Woodland mosaic	293.616	20.466	0.1556
1x2	Urban and built-up land	294.012	20.862	0.15
1x3		294.018	20.868	
1x4		293.983	20.833	
2x1		294.013	20.863	
2x2		294.057	20.907	
2x3		294.059	20.909	
2x4		294.031	20.881	
3x1		294.071	20.921	
3x2		294.092	20.942	
3x3		294.092	20.942	
3x4		294.072	20.922	
4x1		294.092	20.942	
4x2		294.114	20.964	
4x3		294.117	20.967	
4x4		294.095	20.945	

The land use classifications are based on CORINE land cover categories (http://land.copernicus.eu/pan-european/corine-land-cover). The land use cover fractions were taken from Rafael (2017; see Table 6).

Table 6: Surface characteristics assigned to each land use cover (fraction of the plan area) based on Porto Urban Atlas information. Build: Surface fraction of buildings; paved: paved areas; unman: unmanaged land: ET_sh: evergreen trees; DT_sh: deciduous trees; UG: non-irrigated grass; IG: irrigated grass; wtr: water. (Rafael, 2017).

Land use classification based on CORINE land cover categories	build	paved	unman	ET_sh	DT_sh	Ug	IG	wtr
1 – Urban and built-up land	0.21	0.21	0.06	0.11	0.11	0.10	0.13	0.06
2 – Dryland cropland and pasture	0.14	0.17	0.07	0.15	0.15	0.13	0.12	0.07
3 – Irrigated cropland and pasture	0.15	0.17	0.07	0.15	0.15	0.10	0.14	0.07
4 – Mixed dryland/irrigated cropland and pasture	0.12	0.15	0.08	0.17	0.17	0.12	0.12	0.08
5 – Cropland/grassland mosaic	0.10	0.12	0.08	0.15	0.15	0.16	0.16	0.09
6 – Cropland/Woodland Mosaic	0.05	0.07	0.10	0.26	0.26	0.09	0.08	0.09
7 – Grassland	0.05	0.06	0.08	0.19	0.19	0.16	0.16	0.11
8 – Shrubland	0.07	0.09	0.13	0.27	0.27	0.07	0.06	0.04
9 – Mixed shrubland/grassland	0.03	0.05	0.09	0.26	0.26	0.12	0.12	0.07
10 – Savanna	0.04	0.07	0.13	0.27	0.27	0.06	0.05	0.11
11 – Deciduous broadleaf forest	0.07	0.09	0.12	0.17	0.35	0.07	0.07	0.06
12 – Deciduous needleleaf forest	0.08	0.10	0.10	0.17	0.29	0.10	0.09	0.07
13 – Evergreen broadleaf	0.08	0.10	0.10	0.27	0.19	0.10	0.10	0.07
14 – Evergreen needleleaf	0.06	0.08	0.10	0.31	0.15	0.09	0.09	0.12
15 – Mixed forest	0.17	0.20	0.05	0.11	0.11	0.16	0.14	0.06
16 – Water bodies	0.14	0.14	0.02	0.06	0.06	0.07	0.09	0.42
17 – Herbaceous wetland	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.4
18 – Wooden wetland	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.4
19 – Barren or sparsely vegetated	0.0	0.0	0.7	0.1	0.1	0.1	0.0	0.0

Due to lack of land use information, only “build” and “water” areas were available or able to be determined. By using the above Table 6, it was possible to determine the remaining areas for the base scenario.

NBS scenarios

To prepare the DIS, it is required to change the land-use, to represent the NBS implemented. In Figure 10 the NBS to be implemented in the city are represented and are the ones being simulated.

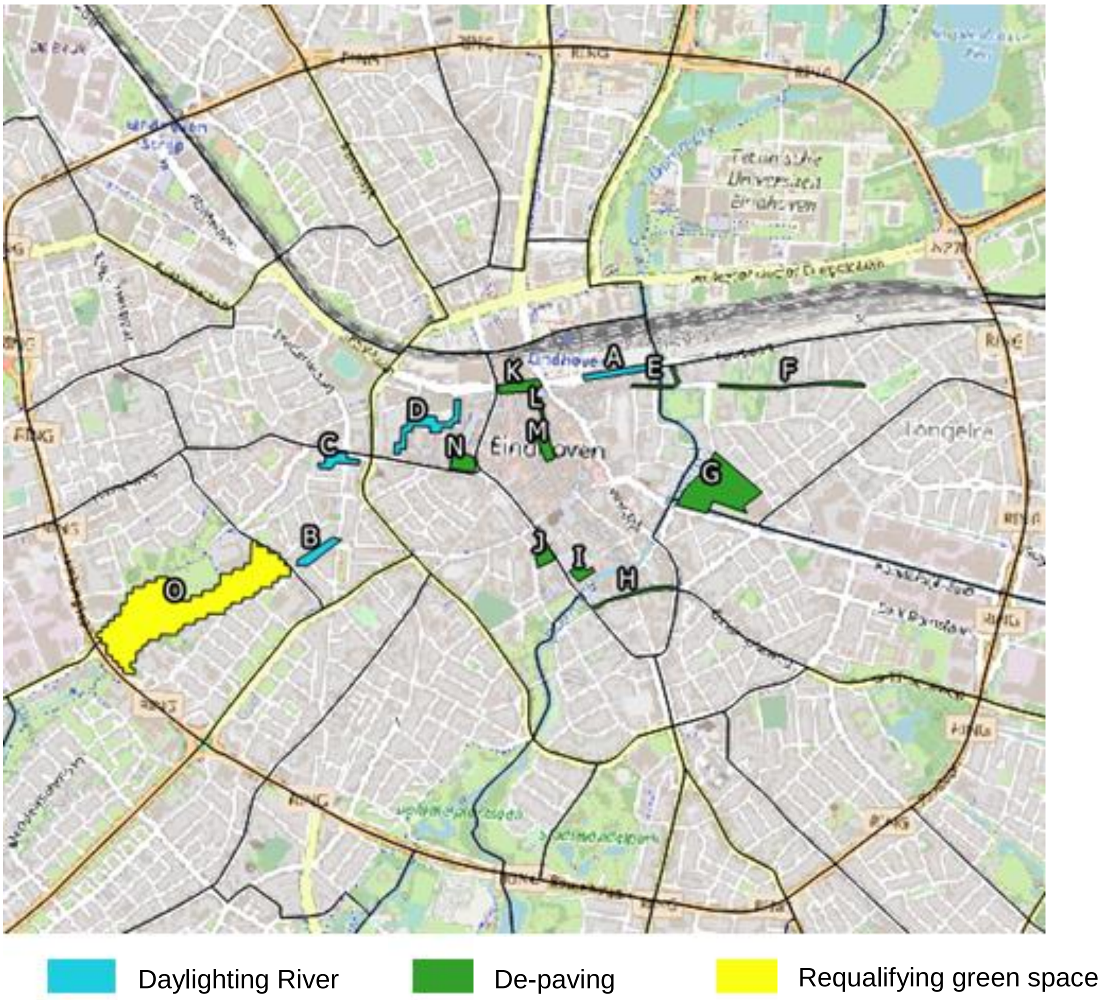

Figure 10: The 15 NBS (A to O) planned to be implemented in the case study area.

Some of the NBS will not have a direct effect on urban heat (because they do not change land use; i.e. O) or urban compaction (because they don't make the area more attractive; i.e. E-N) and, hence, not all NBS are simulated by all models. Table 7 lists the NBS and the model(s) that will simulate them, as well as a short description of what each NBS consists of.

Table 7: Description of the NBS to be implemented in the case study (Roebeling *et al.*, 2014a; Postmes, 2017).

NBS ID	ID	SUEWS	SULD	Description
Daylighting River	A	✓	✓	Make a section of the river Gender visible.
Daylighting River	B	✓	✓	Make the river run through the middle of a green area, thus providing storm water control and recreation areas.
Daylighting River	C	✓	✓	Construction of several houses and daylight the river Gender,

				creating an open water course, making this an attractive area.
Daylighting River/GS development	D	✓	✓	Daylighting the river Gender and creating a park.
De-Paving	E	✓	✗	De-paving the area, replacing an impermeable soil with a permeable soil.
De-Paving	F	✓	✗	
De-Paving	G	✓	✗	
De-Paving	H	✓	✗	
De-Paving	I	✓	✗	
De-Paving	J	✓	✗	
De-Paving	K	✓	✗	
De-Paving	L	✓	✗	
De-Paving	M	✓	✗	
De-Paving	N	✓	✗	
Requalify green space	O	✗	✓	Clean the river, improving ecological value and the water quality and improve visual value of the park.

Regarding the calculations of the input information for modelling, the changes in the DIS are in the land use cover fractions. So, for each cell, the area of NBS implemented was calculated and divided according to the type of land use it refers to. For example, “Daylighting river” adds blue area (water) and “De-paving” adds green area (evergreen trees, deciduous trees, unirrigated and irrigated grass) while decreasing the built and/or and paved area. This results in the changes represented in Table 8 for both DIS (green) and IIS (blue).

Table 8: Land use fraction and population density changes for the direct impact scenario (green) and the indirect impact scenario (blue).

Grid Cell	build	wtr	unman	ET_sh	DT_sh	Ug	IG	paved	population density
1x1	-5.412%					5.412%			-8.89%
1x2	-2.647%					2.647%			-3.79%
1x3	-1.229%					1.229%			-1.80%
1x4	-0.378%					0.378%			-0.67%
2x1	-0.226%					0.226%			0.35%
2x2		0.463%		0.195%	0.195%	0.068%	0.060%	-0.981%	10.35%
2x3		0.680%		0.393%	0.393%	0.136%	0.121%	-1.724%	6.10%
2x4				0.139%	0.139%	0.048%	0.043%	-0.370%	1.15%
3x1									1.76%
3x2	0.278%	1.265%		0.063%	0.063%	0.022%	0.019%	-1.710%	4.61%
3x3				2.033%	2.033%	0.704%	0.626%	-5.395%	0.89%
3x4									0.53%

4x1	-0.740%			0.017%	0.017%	0.700%	0.005%		-0.86%
4x2	-0.047%					0.047%			-0.13%
4x3	-1.843%					1.843%			-3.03%
4x4	-3.875%					3.875%			-5.83%

To prepare IIS it is necessary to change the land use and the population density. These indicators are representative of the changes in the urban morphology. The changes in land use and population density are calculated from the SULD outputs. While modelling the aforementioned NBS, the differences between the SULD base scenario and the NBS scenario results in Figure 11.

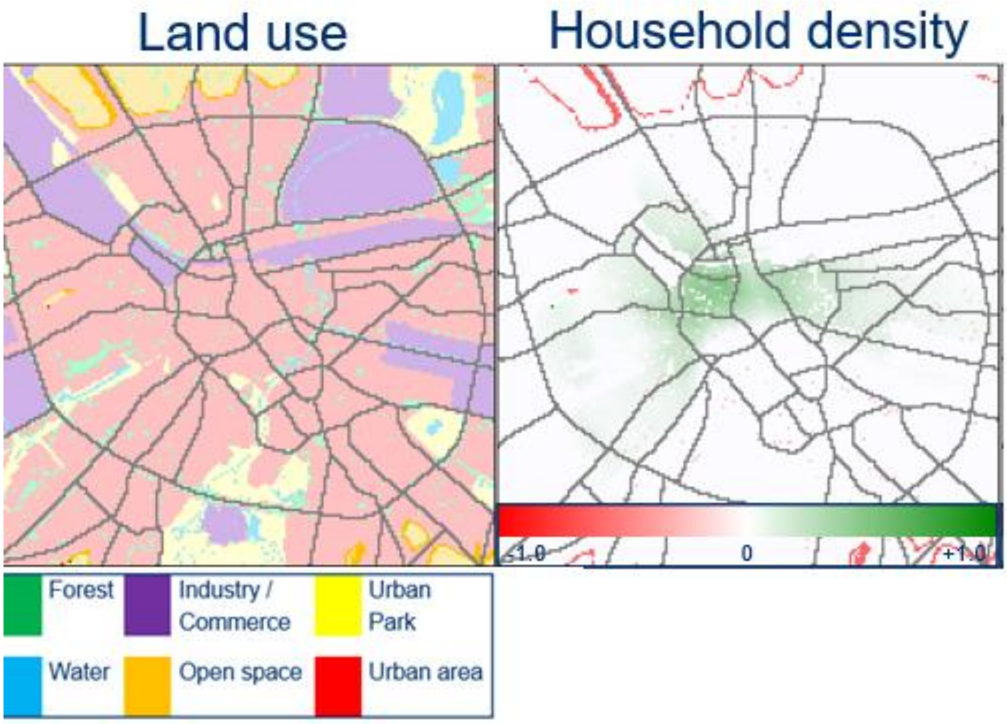

Figure 11: Land use and household density changes as outputs of SULD for the indirect impacts scenario (source: Roebeling et al., 2014).

By distributing these changes to the SUEWS grid cells, it translates to the land use and population density changes represented in Table 8 (highlighted in blue). To prepare the DIS+IIS, and thus representing both the direct and indirect impacts, it is necessary to include both the land use and population density changes from both DIS and IIS.

5. Results and discussion

This chapter presents the results of the simulations for the different scenarios. As SUEWS is better suited to analyse fluxes, the results are divided into heat fluxes and temperature. First, the monthly averages of the differences between the scenarios are presented (Figures 13-15 for heat fluxes, Figure 20 for temperature), then the diurnal average and differences between scenarios over the course of the month are presented (Figures 16-17 for heat fluxes, Figure 21 for temperature) and, finally, the hourly average and differences between scenarios over the day are presented (Figures 18-19 for heat fluxes, Figure 22 for temperature).

For some results, because the average for the sub-domain area (D4) diluted the results, the results are divided into the cells that contain the NBS (cells 2x2, 2x3, 2x4, 3x2 and 3x3), hereby denominated "A", and "B" the cells that do not contain NBS (Figure 12), and also to allow for a better differentiation between direct and indirect impacts.

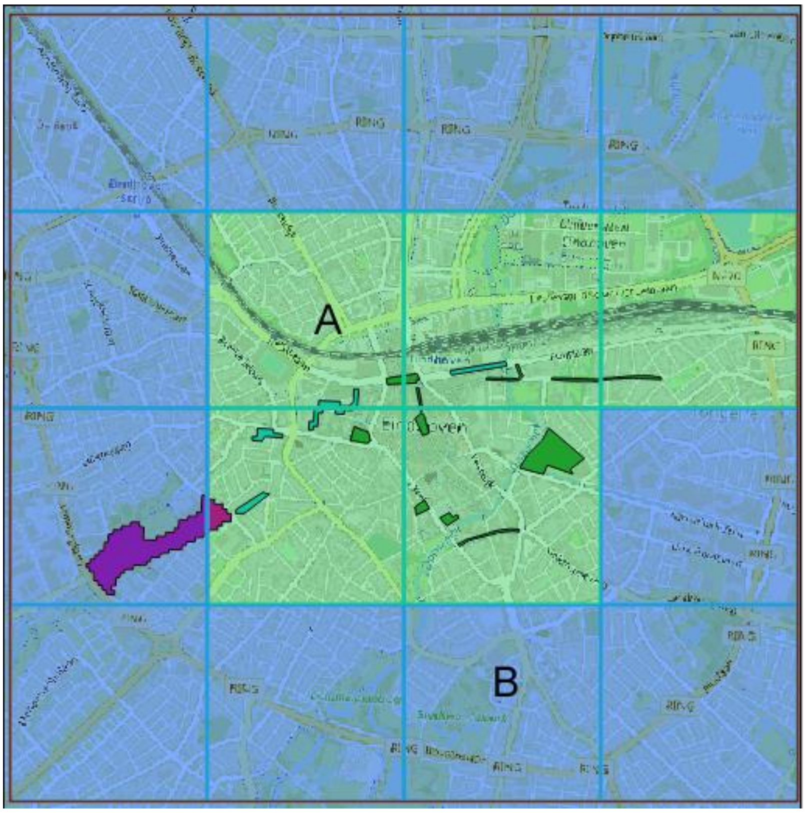

Figure 12: Cells that contain NBS (A; green) and cells that do not contain NBS (B; blue).

5.1. Heat fluxes

The following maps (Figures 13-15) exhibit the differences of the monthly average values of the scenarios with the base scenario following the simple equation:

$$Scenario\ X - \ Base\ scenario \qquad (5)$$

where X is the DIS, IIS or DIS+IIS (Figure 13).

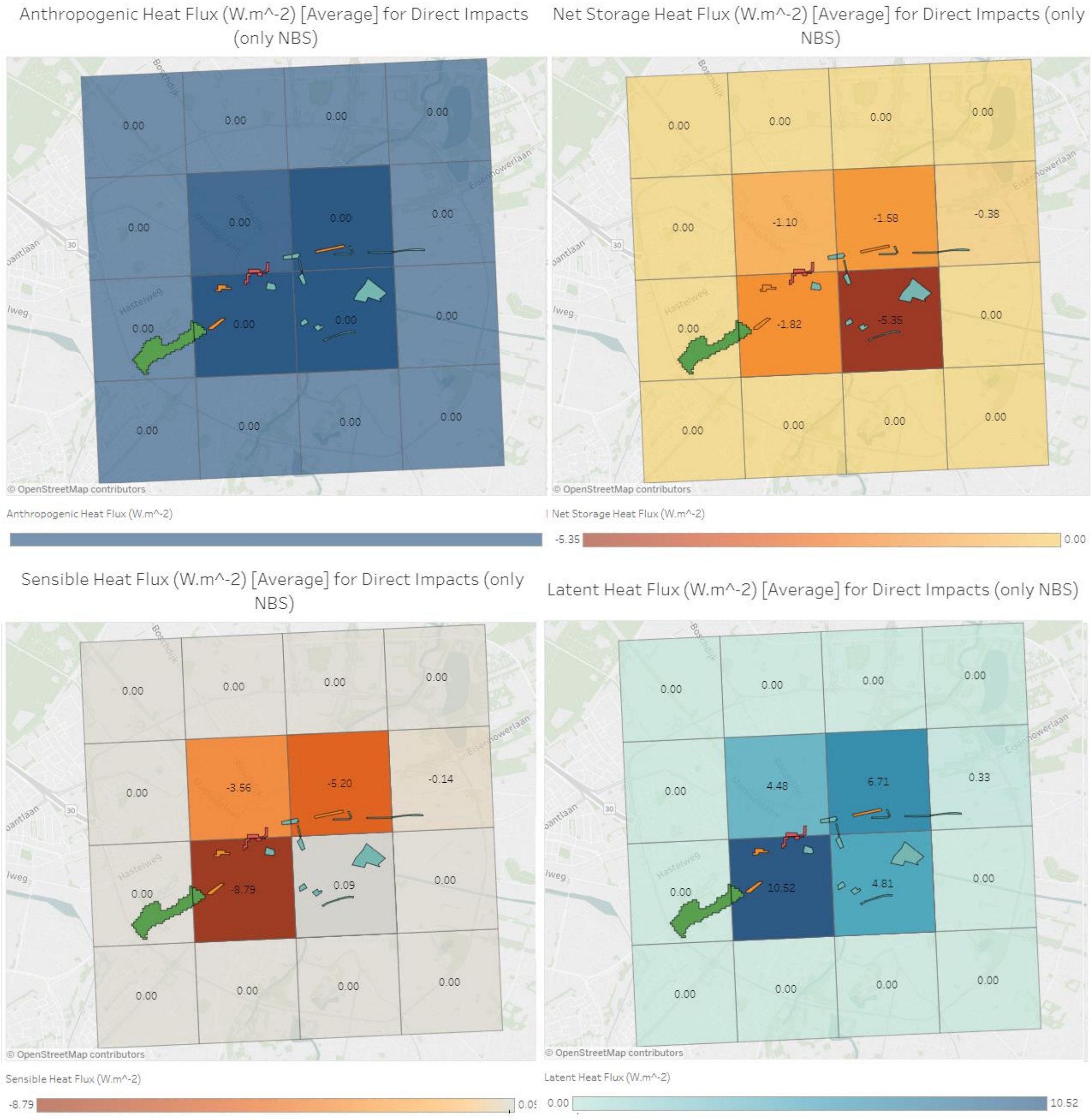

Figure 13: Monthly (July) differences in average heat fluxes for the direct impact scenario (DIS), relative to the base scenario.

The changes applied to represent the DIS are only applied to the A cells and, hence, there are only differences in fluxes in those cells. For anthropogenic heat flux (Q_F), there is no difference between both scenarios, which was expected because there was no change in population density (on which the estimation of Q_F is based). For the net storage heat flux (ΔQ_S), there is a decrease compared to the base scenario when the NBS are implemented – thereby noting that larger NBS (in terms of area) result in larger decreases in ΔQ_S. Regarding the sensible heat flux (Q_H), there is a decrease in particular in those cells where blue spaces were implemented. For the latent heat flux (Q_E), and balancing Q_H, the difference is positive, which means there is an increase in values. This was expected because of the increase in permeable area and vegetation.

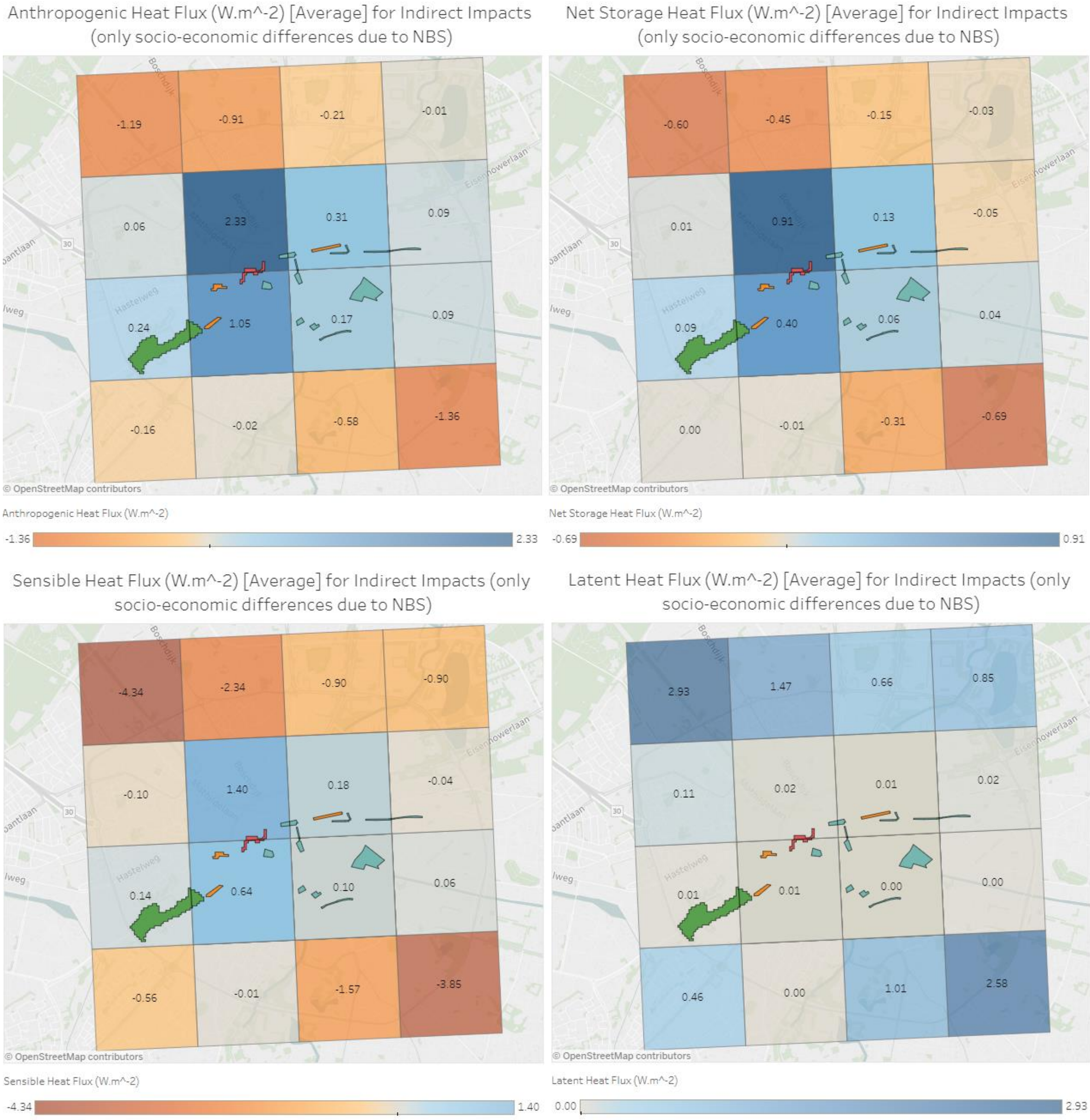

Figure 14: Monthly (July) differences in average heat fluxes for the direct impact scenario (IIS), relative to the base scenario.

The changes to represent the IIS are applied to both A and B cells, where changes in the A cells refer to changes in population density and where changes in B cells refer to changes in both land use and population density. So as expected, there are differences in all of the cells. For anthropogenic heat flux (Q_F), there is an increase (decrease) where the population density increased (decreased), which makes sense considering the estimation of Q_F is based on population density. For the net storage heat flux (ΔQ_S), there is a decrease in B compared to the base scenario, and an increase in A. This suggests that the increase in population density (A) increases ΔQ_S and the decrease in built area (B) decreases ΔQ_S. Given that statement, the decrease shown in B is the accumulated effect of both the reduction in population density and built area. Regarding the sensible heat flux (Q_H) there is a decrease in B and an increase in A. This shows that both the population density and the built area have an effect on Q_H. Furthermore, it is possible to note that the higher the population density, the higher the increase in sensible heat flux. For the latent heat flux (Q_E) the differences are mostly visible in B, where there is a bigger change in land use. As seen also in the DIS, less built area/more vegetation results in higher latent heat flux. It is also possible to verify that population density as little to no effect on Q_E.

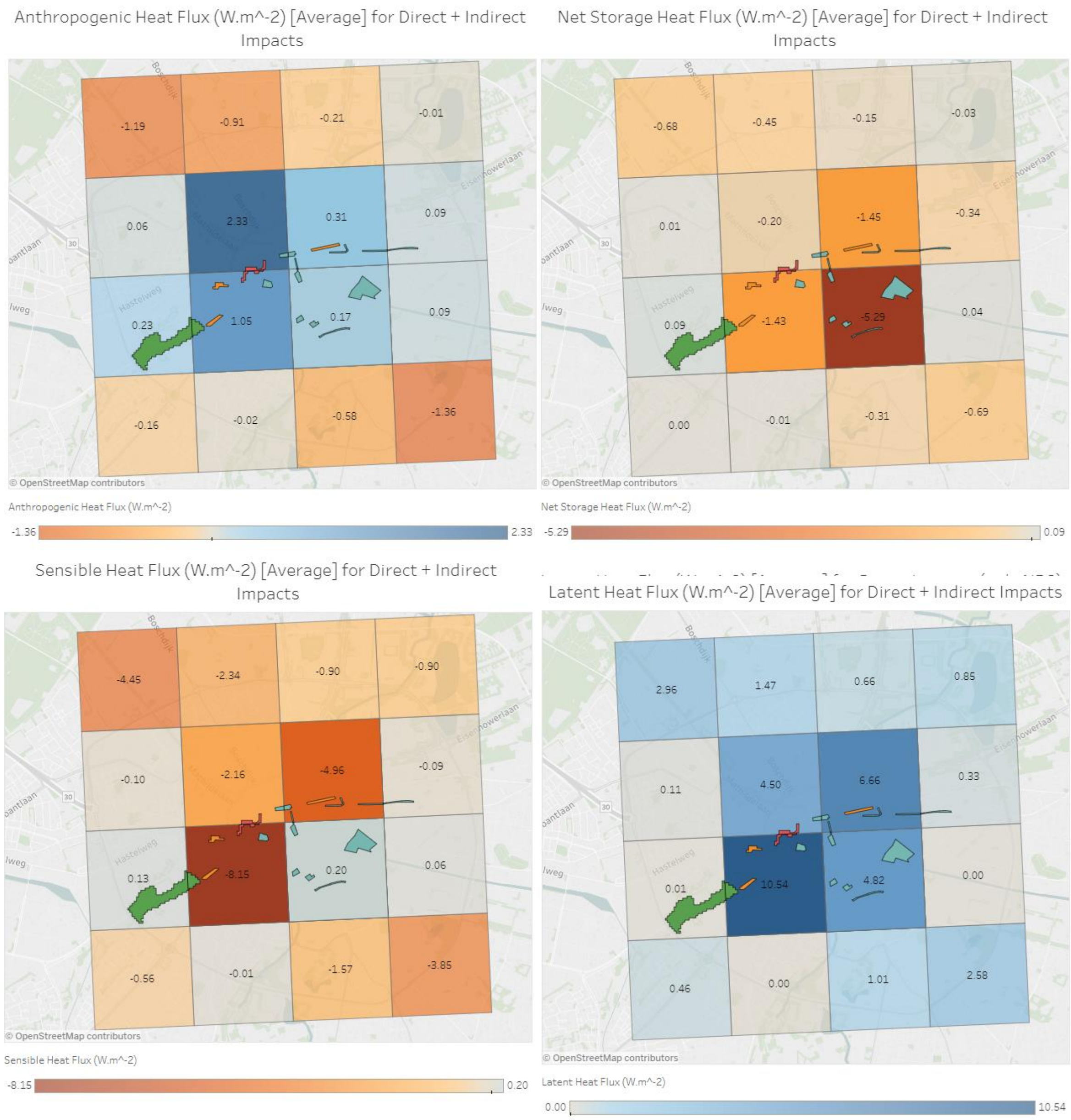

Figure 15: Monthly (July) differences in average heat fluxes for the direct impact scenario (DIS+IIS), relative to the base scenario.

For the DIS+IIS, these results show the cumulative effect of both DIS and IIS. For the anthropogenic heat flux the changes represent only the IIS, because in the DIS the difference is zero. For the net storage heat flux in the A cells, the cumulative impact attenuated the difference caused by the direct impacts or vice-versa. This means that, if the objective is to have a smaller ΔQ_S, the indirect impacts of the NBS are counterproductive. For Q_H in the A cells the same effect occurs, where the DIS shows a decrease and the IIS shows an increase and, overall, there is a smaller decrease as compared to the

DIS. For Q_E, as the effects in the IIS across A cells are close to zero, the cumulative effect exhibits the results for the DIS (and, thus, little difference).

For Q_E the biggest changes occur in the A cells, in the DIS where there is a significant increase as compared to the base scenario. This reinforces the strong dependence of the latent heat flux and the existence/absence of green/blue areas (Rafael, 2017), because, as stated previously: more vegetation and more water result in a higher latent heat flux, which is visible in the results. It is also possible to observe an increase in Q_E for the IIS, in B cells, which is also expected as there is a decrease in built area due to the urban compaction. Given the turbulent heat fluxes, sensible and latent, are intrinsically related by the Bowen ratio (Q_H/Q_E) (Oke, 1982), the increase in latent heat flux implies a decrease in sensible heat flux, which is observed in the data. This contributes to a reduction in the energy released into the atmosphere, promoting the cooling of the surface, and an increase in soil moisture, as the heat from the air is used to evaporate water (Rafael, 2017).

Regarding the net storage heat flux (ΔQ_S), the DIS shows, for A cells, a decrease compared to the base scenario, which is expected, as vegetated areas (in this case, the NBS) have a higher albedo than the urban areas, and have a shading effect over the ground (Coutts *et al.*, 2007; Rafael, 2017). For IIS, in B cells, there is also a decrease in net storage heat flux, because there is less built area (urban compaction), and in A cells, there is a small increase. This is the result of the increase in built area and also the increase in population density, because Q_F is incorporated in the calculation of ΔQ_S (Grimmond and Oke, 1991; Ward *et al.*, 2016).

For the DIS, there is no change in population density, so, for Q_E the difference is zero, as shown in figure 13. For IIS, there is a difference in population density, that exhibits the expected, aforementioned, pattern. However, Q_F is strongly dependent on the behaviour of the people in that area as well as onsite characteristics, which means different people/cultures will have different energy consumptions based on the need for heating/cooling, and that will affect Q_F (Sailor *et al.*, 2015). This effect of the heating/cooling is evident in the results (Figure 18).

By analysing the DIS+IIS, it is possible to observe that for the most part, the DIS and IIS do not interconnect with each other, especially for both Q_F and Q_E, because these are only affected by population density (IIS) and land use (DIS), respectively. However, for ΔQ_S and Q_H, there are significant effects that overlap, in A cells. As both fluxes are affected by population density and land use (because ΔQ_S is calculated using Q_F), it makes sense that the DIS and IIS overlap. For both fluxes, this means that the reduction (in A cells) caused by the NBS will be upset by the increase in population density (urban compaction), but there will still be, in these cases, a reduction, in both net storage heat flux and sensible heat flux, due to the decrease in built/paved area.

After examining the monthly average results for each cell, it is important to analyse the diurnal average, for the month, to check the effect of the scenarios on days with higher and lower values. The left axis corresponds to the base scenario (black line), and the right axis corresponds to the differences between the base scenario and the direct (DIS), indirect (IIS) and direct+indirect (DIS+IIS) scenarios (green, blue, red lines, respectively).

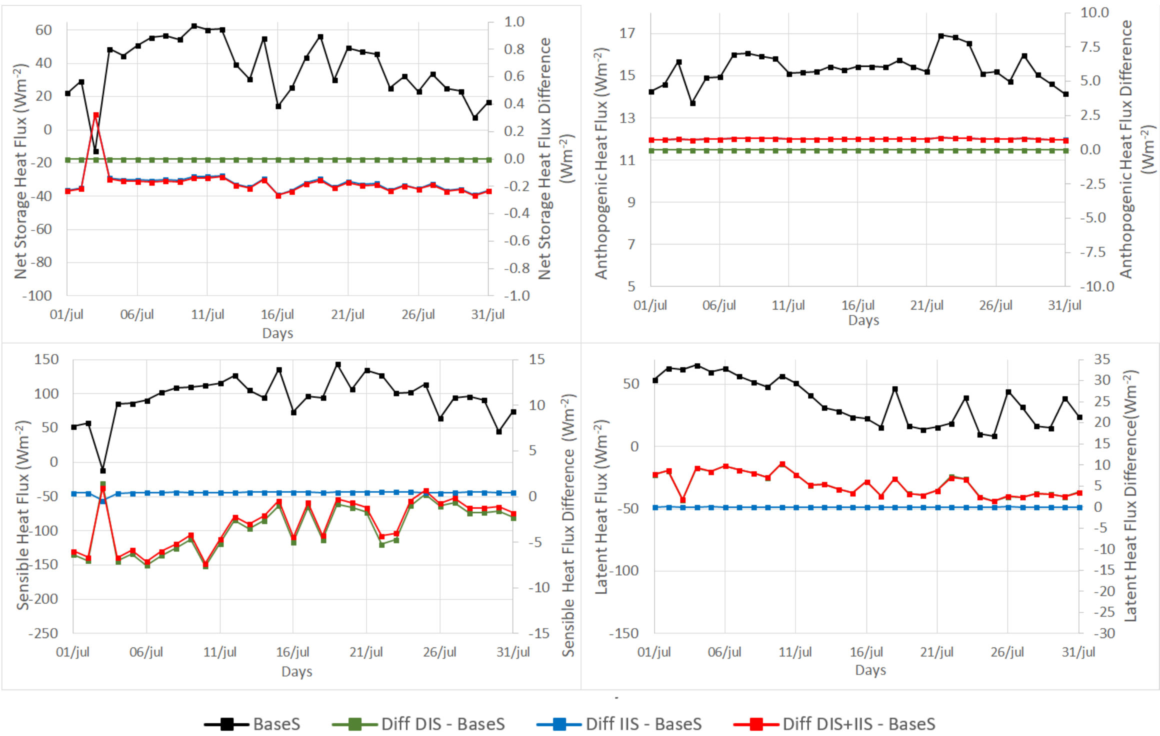

Figure 16: Daily average heat fluxes (ΔQ_S, Q_F, Q_H, Q_E) over the month (July) across A cells, for baseline (BaseS; black line), direct (DIS; green line), indirect (IIS; blue line) and direct+indirect (DIS+IIS; red line) scenarios.

For A cells (Figure 16), a decrease in ΔQ_S is observed for the DIS and DIS+IIS as compared to the base scenario. For IIS, the difference is positive, meaning an increase in net storage heat flux. It is possible to observe the attenuation of the effect the IIS has on the DIS by analysing DIS+IIS, which shows a lower decrease as compared to the DIS. For the anthropogenic heat flux, the IIS and DIS+IIS show an increase as compared to the base scenario and the DIS, because, as mentioned before, there is an increase in population density in A cells. Q_H shows a very similar pattern to ΔQ_S, where it is also possible to see the effect of the IIS and the DIS. For Q_E, there is an increase (expected, since Q_H decreases) in the DIS and DIS+IIS, which is in accordance with the monthly average results. This increase is more evident in the first half of the month, opposing the sensible heat flux, that shows a higher decrease in the first half of the month, when Q_H is higher.

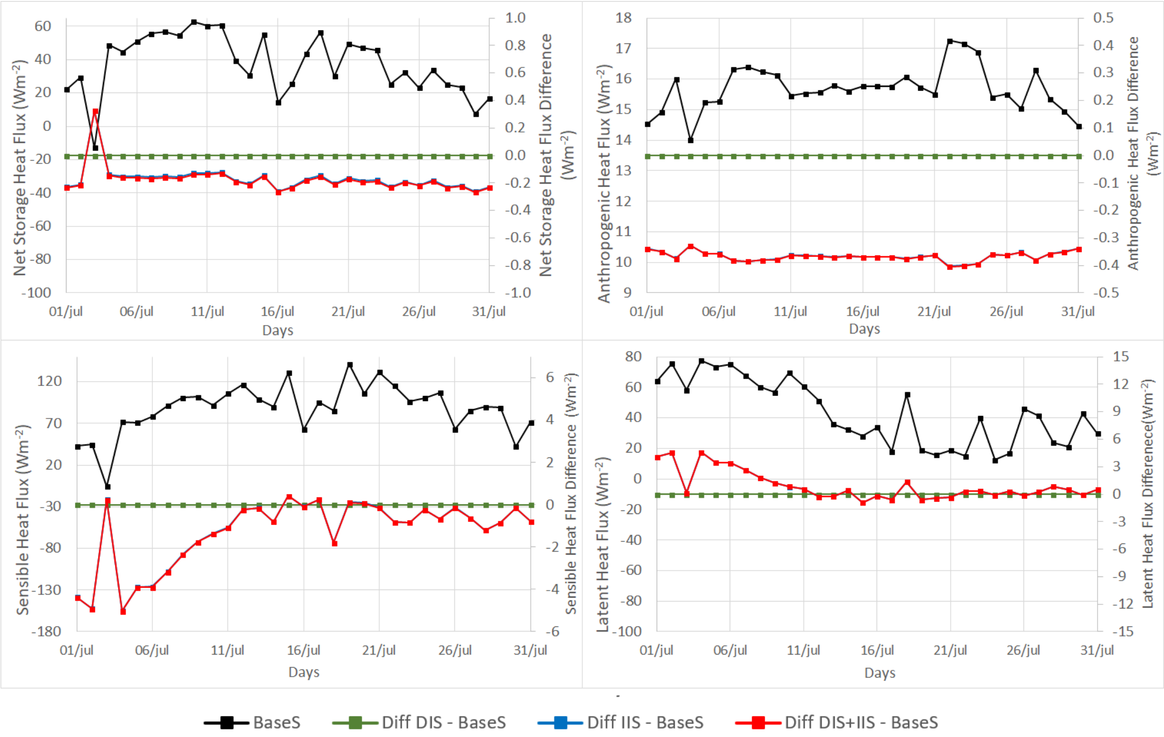

Figure 17: Daily average heat fluxes (ΔQ_S, Q_F, Q_H, Q_E) over the month (July) across B cells, for baseline (BaseS; black line), direct (DIS; green line), indirect (IIS; blue line) and direct+indirect (DIS+IIS; red line) scenarios.

For B cells (Figure 17), the differences are smaller across all fluxes, since the DIS does not have an effect (shown in the figures, by the difference being zero across all fluxes). For ΔQ_S, the differences between scenarios are very close to zero, but follow a similar pattern as in A. For the anthropogenic heat flux, there is a decrease, because of the decrease in population density, however the differences are smaller than in A (because it includes more cells). For Q_H, like for A, there is a decrease for IIS and DIS+IIS. Q_E shows and increase for IIS and DIS+IIS in the first half of the month, which coincide with the highest values of latent heat flux.

The results of the diurnal average for the month are as expected and in accordance with the results shown in the maps. The difference between A and B is especially apparent in the anthropogenic heat flux. The increase in A and decrease in B was expected, since there is an increase/decrease in population density, respectively, but since B includes a bigger area (more cells), the decrease in population density is somewhat diluted, which results in smaller decrease in Q_F. One thing to note is the behaviour on July 3rd. This day had the highest precipitation, which caused a very pronounced decrease in the Q_H and ΔQ_S (Rafael, 2017).

Finally, energy fluxes vary over the year and especially over the day, following the diurnal cycle of solar heating and urban activities. The proper way to show and analyse these is by analysing the hourly average for the month, that should look similar to a bell-shaped curve (Oke, 1990). These also allow to analyse the behaviour of the fluxes during the day. Figures 18 and 19 present the daily profiles obtained for the A and B cells, respectively.

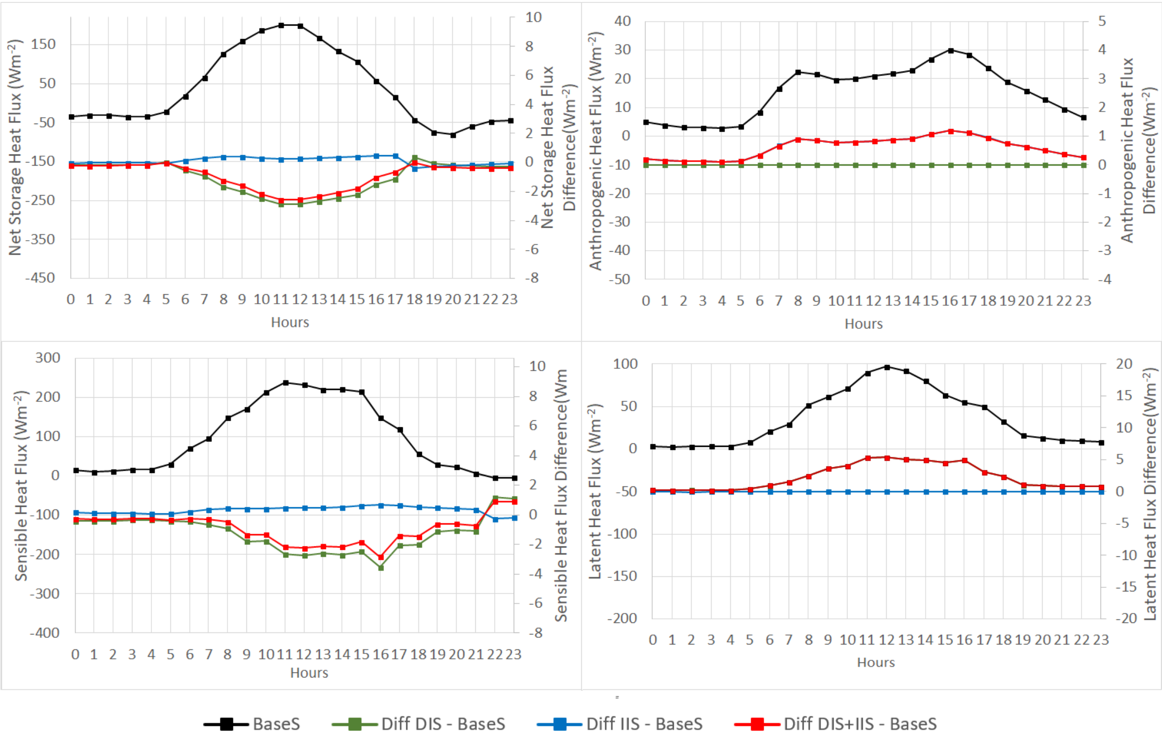

Figure 18: Hourly average heat fluxes (ΔQ_S, Q_F, Q_H, Q_E) over the month (July) across A cells, for baseline (BaseS; black line), direct (DIS; green line), indirect (IIS; blue line) and direct+indirect (DIS+IIS; red line) scenarios.

For the A cells (Figure 18), ΔQ_S and Q_H show, again, similar patterns. There is a small decrease for the DIS and DIS+IIS (most apparent during the day) and a small increase for the IIS (that upsets the effect of the DIS), in accordance with the previous results. Regarding the anthropogenic heat flux and the latent heat flux, these show an increase, that follows the pattern of the base scenario (higher values during the day, higher differences). This makes sense, because during the hottest hours, there is more evaporation and transpiration, and thus a bigger need for cooling.

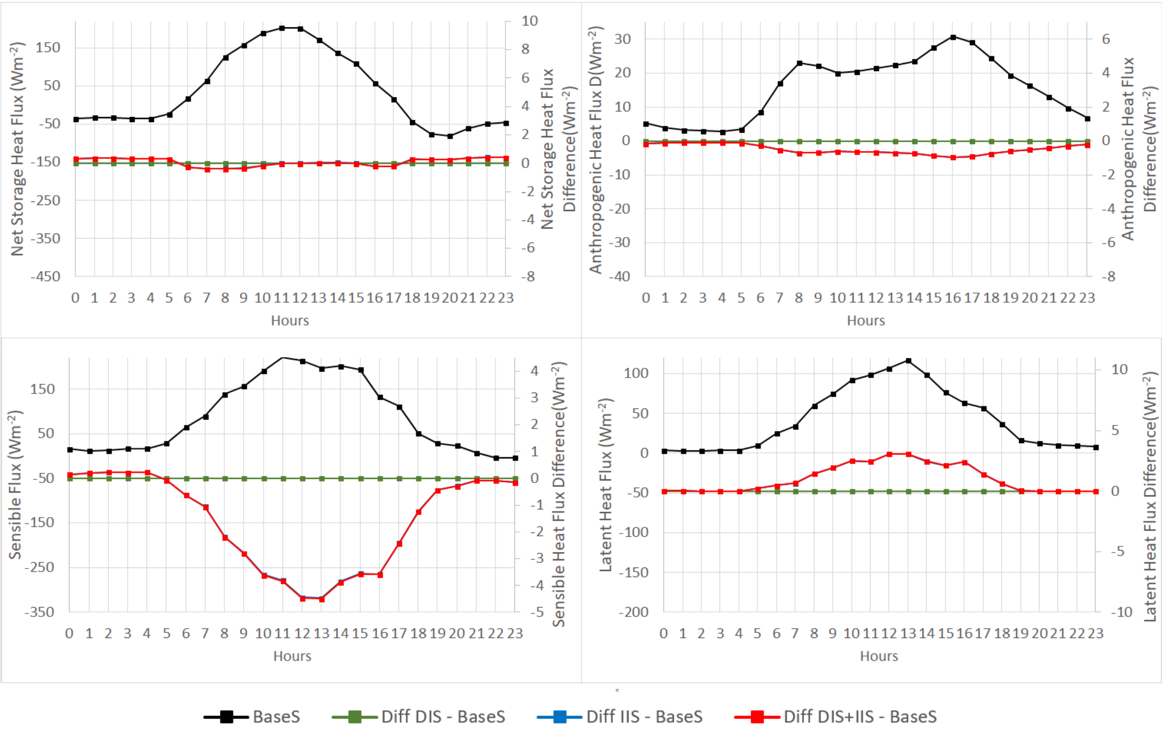

Figure 19: Daily average heat fluxes (ΔQ_S, Q_F, Q_H, Q_E) over the month (July) across B cells, for baseline (BaseS; black line), direct (DIS; green line), indirect (IIS; blue line) and direct+indirect (DIS+IIS; red line) scenarios.

For the B cells (Figure 19), the differences, as previously mentioned, are smaller due to the absence of the effect of the DIS. Q_F shows a decrease during the day, because there is a decrease in population density and, therefore, less energy cooling requirements. For ΔQ_S there is a small increase during the night and a small decrease during the day, due to the connection with Q_F. For the sensible heat flux, these is a decrease during the day. Finally, for Q_E, there is an increase due to the IIS, also during the day.

As shown in Figures 16-19, the sensible heat flux presents higher values across all fluxes, which is in accordance with observations in more densely built areas (Coutts *et al.*, 2007). However, SUEWS underestimates the latent heat flux and causes an overestimation of the sensible heat flux (Järvi *et al.*, 2011). This dominance of the sensible heat flux is expected because, as the study area is densely built and characterized by extensive impervious surfaces (including buildings and pavements) where runoff water drains quickly leaving less surface water available for evapotranspiration.

One aspect that is common to all fluxes is that the differences are relatively small. The most likely reason for this is the size of the NBS. In similar studies, where bigger NBS were simulated, the differences were also larger (Rafael, 2017).

5.2. Temperature

The analysis of the temperature follows the same order as for the fluxes. First, the monthly average differences, compared to the base scenario, for each cell, for the three scenarios (Figure 20).

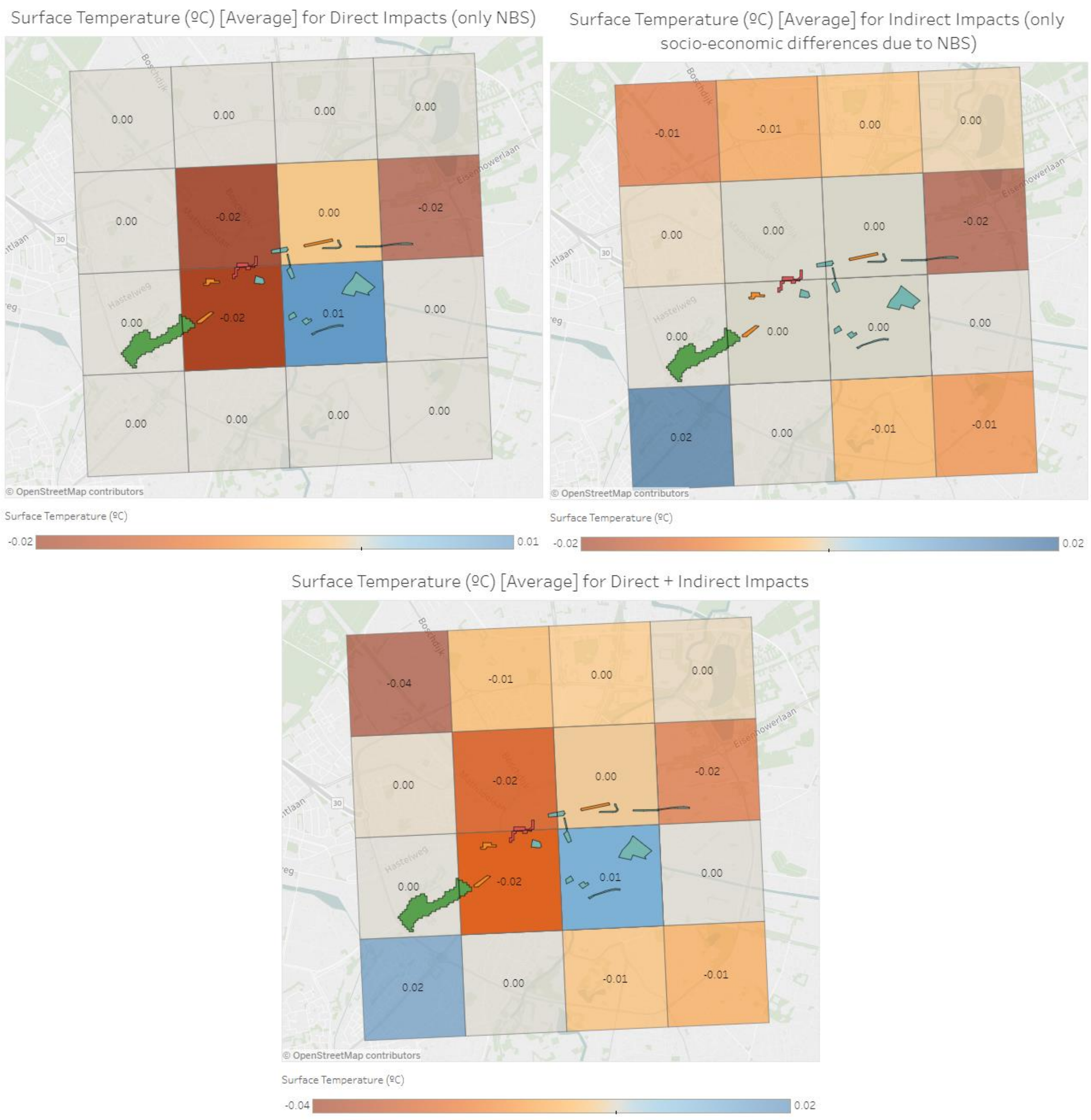

Figure 20: Monthly (July) differences in average temperatures for the direct impact scenario (DIS) indirect impact scenario (IIS), and direct + indirect impact scenario (DIS+IIS) relative to the base scenario.

As evidenced in Figure 20, for both A and B cells, there is a very small difference between the scenarios (-0.04-0.02 ºC). Note, however, that SUEWS is a model best suited to model heat fluxes, and thus, when analysing the results for temperature, this needs to be taken into account, meaning that the interpretation of the results should focus on the pattern shown and not the values themselves, specially since the magnitude of values is so small. It can be observed that, for the most part, less built area results in a decrease in temperature.

For the diurnal average temperature for the month, there is a small difference between A and B cells. There is a, relatively, larger decrease in temperature in A cells (up to -0.015ºC) than in B cells (up to -0.006ºC), due to the direct effect of the NBS. (Figure 21).

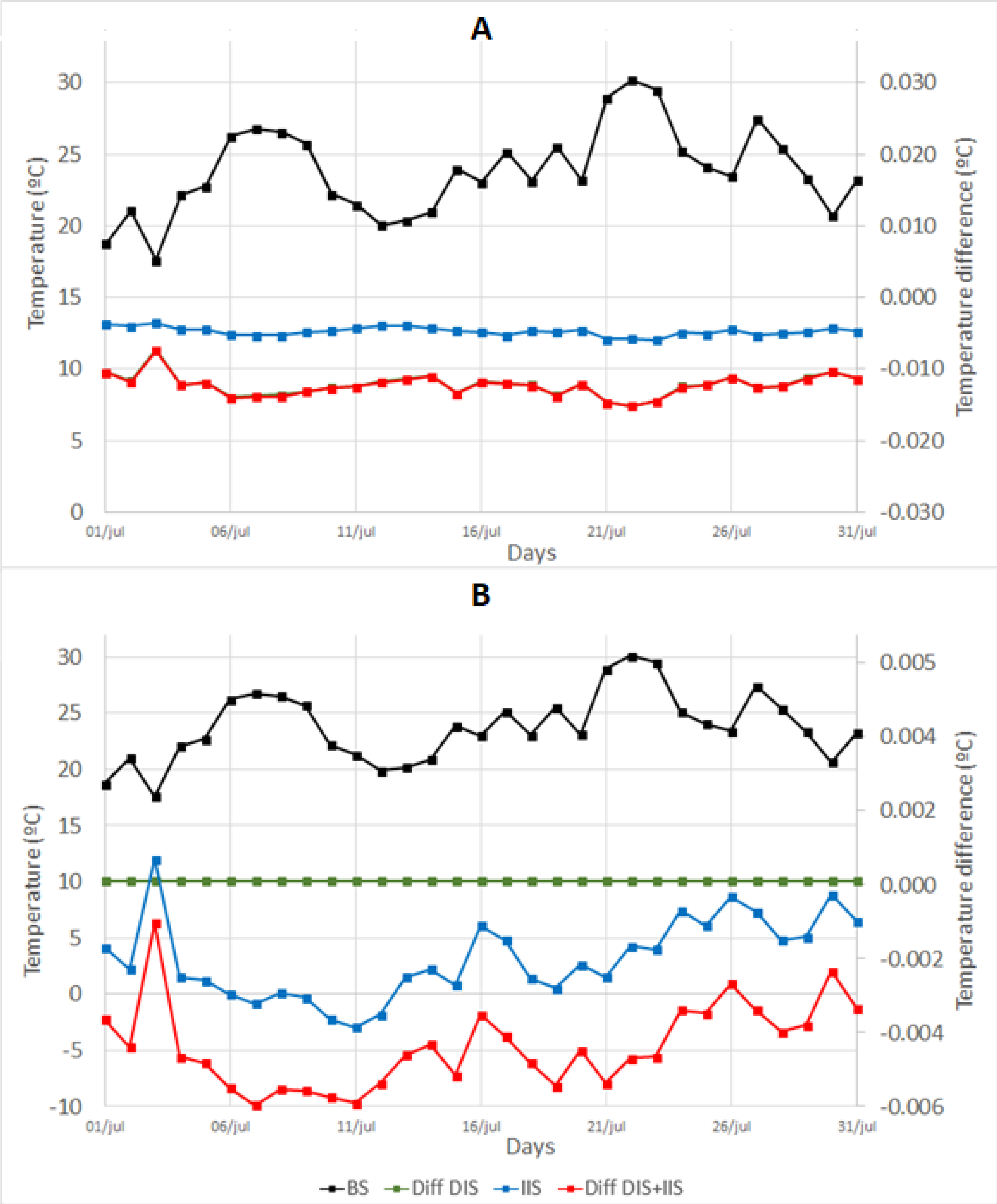

Figure 21: Daily average temperatures over the month (July) across A and B cells, for baseline (BaseS; black line), direct (DIS; green line), indirect (IIS; blue line) and direct+indirect (DIS+IIS; red line) scenarios.

For the hourly average of the temperature, it follows an expected pattern, with higher temperatures during daytime and lower temperatures during night-time. For A cells, there are no differences in temperature for the IIS, while largest differences in temperature are observed for the DIS and the

DIS+IIS (up to -1.5ºC at night). For B cells, there is no apparent difference in temperature (Figure 22).

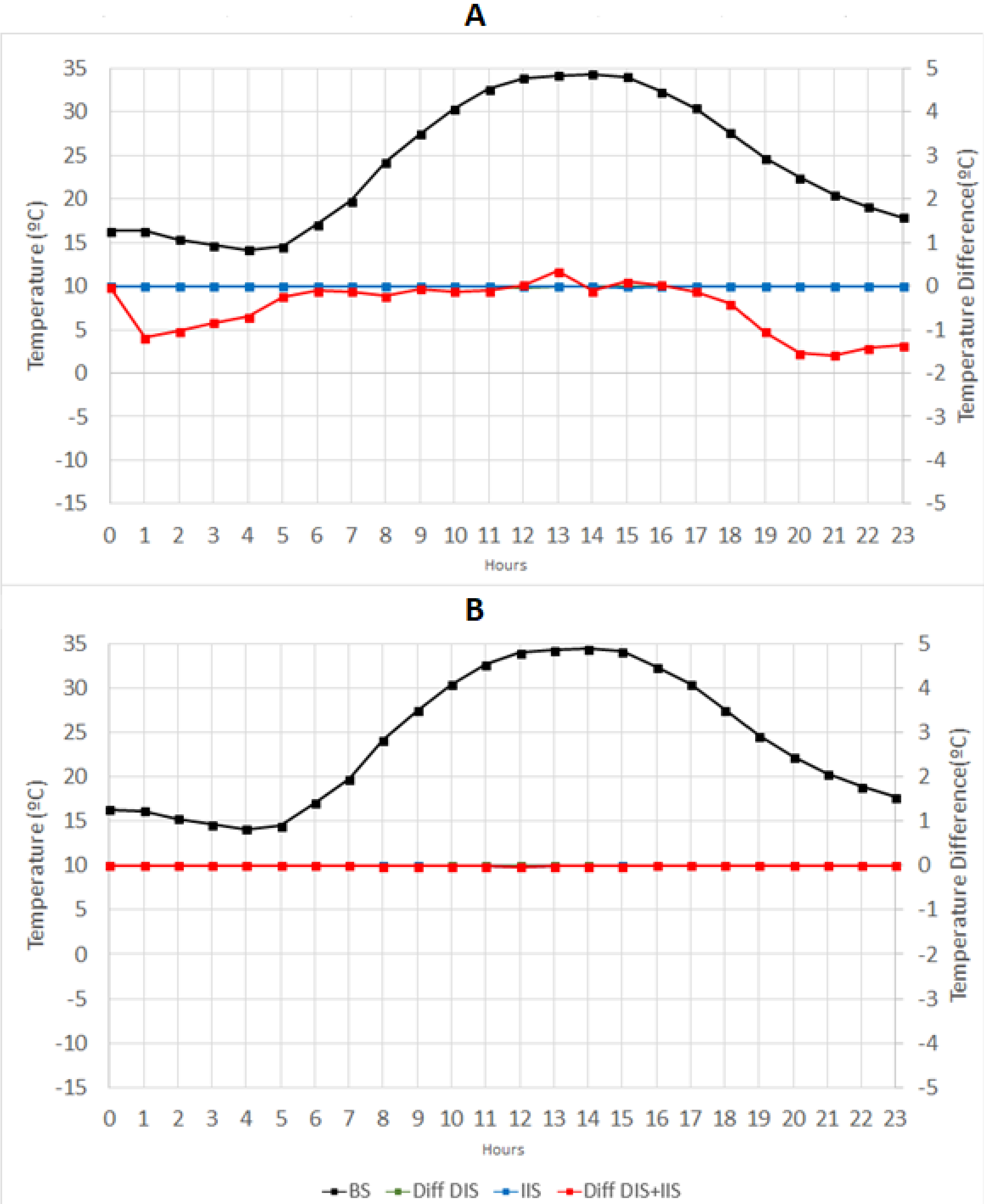

Figure 22: Hourly average temperatures over the month (July) across A and B cells, for baseline (BaseS; black line), direct (DIS; green line), indirect (IIS; blue line) and direct+indirect (DIS+IIS; red line) scenarios.

Temperature is a measure of the sensible heat content of the air, so, with a reduction in Q_H, a decrease in temperature is expected, however the changes in temperature are close to zero. The reasons are twofold: i) SUEWS is a flux model and less suited to model temperature; ii) the changes in Q_H, although significant, considering the small changes in land use, are still very small to influence significantly the temperature values. Nevertheless, for A cells, it is possible to discern the effect of the NBS, causing a decrease in temperature of almost 2 degrees during the night-time – in line with Chen & Wong (2006) and Qiu *et al.*, (2017).

6. Conclusions and recommendations

The work presented in this dissertation had as main objective the evaluation of the direct and indirect impacts of nature-based solutions on urban heat in the city of Eindhoven, in the Netherlands, using an integrated modelling approach, composed of WRF-SUEWS (to simulate meteorological fields and energy/heat fluxes) in combination with the Sustainable Urbanising Landscape Development (SULD) model (to simulate population dynamics and urban sprawl). The relevance of this study comes from the fact that although there are many studies modelling the effects of nature-based solutions on urban heat and on population dynamics and urban sprawl, there are no studies evaluating the interconnecting and/or cumulative effect of both. From this study, the following can be concluded.

Nature-based solutions, in the short term, can be used to reduce the net storage heat flux and the sensible heat flux, by increasing the area of vegetation and blue areas, and increase the latent heat flux, near the area of the nature-based solutions, while having no effect in the anthropogenic heat flux. In the long term, nature-based solutions lead to urban compaction, where the population density will increase near these amenities. This will have an opposite effect in the areas near the nature-based solutions (city centre), where the sensible heat flux, the net storage heat flux and the anthropogenic heat flux, will increase, reducing the short-term effects but not cancelling it. In the areas outside the city, away from the nature-based solutions, since there will be a decrease in built area and a consequent increase in vegetation, the sensible heat flux, net storage heat flux and anthropogenic heat flux all reduce. This helps understand why there is a debate between if it is better to have urban sprawl or urban compaction (see Williams *et al.*, 2013). In this study, it is concluded that nature-based solutions help contradict urban sprawl, which leads to a positive outcome, regarding the urban heat fluxes. These results were in line with other studies (Rafael, 2017; Ward *et al*., 2016).

The aim of this study was to serve as a tool, to help stakeholders understand the impacts, short term and long term, of nature-based solutions. It was possible to determine that the type and dimension of nature-based solution affect its efficacy, and that the long-term impacts can, sometimes, offset the intended objectives. As it was not possible to fully grasp the effects of the nature-based solutions on temperature, it is advised that more studies should be done, with different scales of nature-based solutions implementation and, perhaps, different models, to better sense the direct and indirect impacts of NBS on temperature. However, it is important to note that the integrated modelling approach used was successful in connecting the direct and indirect impacts of NBS and should be used as a valuable tool.

Three main policy implications can be derived from this study. First, the implementation of NBS can, when adequately designed, have positive socioeconomic and environmental benefits so it should be perceived as an opportunity to achieve a sustainable development. Second, the monitoring and evaluation of the implementation process and the resulting consequences (intended or not) can provide an important framework for future projects, so that these can achieve their full potential. Finally the implementation of NBS is conducive to a participatory planning process and public discussion, which should be encouraged because it promotes transparency, that will ultimately lead to a more clear set of environmental and socioeconomic target goals, that achieve a better societal well-being.

After the completion of this study, there are a few caveats that remain. First, SUEWS had a base parameterization for Porto, and not Eindhoven, which could have some effect on the results, especially since some of the land use cover fractions had to be estimated based on this parametrization. Second, the size of the simulated nature-based solutions (approximately 107,000 m^2 in total) was relatively small when compared to the study area (16 km^2) and, hence, it was difficult to observe significant changes in, particularly, temperatures. Third, and related to the previous point, SUEWS is designed to model fluxes and, less so, to model temperature and, hence, small/insignificant changes in temperatures were obtained. Finally, reduced anthropogenic emissions from reduced commuting distance, due to the relocation of households from the periphery to the area surrounding attractive NBS, were not considered and are likely to lead to reductions in anthropogenic heat flux as well as temperature.

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