

Dissertation

THE POTENTIAL OF ECOSYSTEM-BASED ADAPTATION:

Integration into Urban Planning and Effectiveness for Heat and Flood Mitigation

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“I took a walk in the woods and came out taller than the trees.”

Henry David Thoreau

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CONTENTS

ABSTRACT

Future climate change is expected to increase the frequency and intensity of extreme events such as heat and heavy rain. Cities are especially vulnerable to those climatic impacts due to their structural characteristics – the density of the urban environment, surface sealing and lack of greening –, population density, and their important role in the economy. Consequently, climate adaptation is a focus of urban planning and, especially, ecosystem-based approaches are gaining increasing attention. These approaches use ecosystem services, provided by urban green infrastructure elements, to support society's adaptation to climate change. However, the role of ecosystem-based adaptation and related measures in municipal adaptation activities remains unclear. Moreover, there is little comparative information available to support planners in the selection of effective ecosystem-based adaptation measures.

Against this background, this dissertation aims to increase the understanding of the current state of integration of ecosystem-based adaptation in Germany, and provide evidence-based knowledge of the potential of different types of green infrastructure to regulate climatic extreme events. This information can be used to support the implementation of ecosystem-based adaptation measures for the development of climate-resilient cities.

First, this thesis provides insights into the integration of ecosystem-based approaches and measures in current municipal adaptation strategies in Germany. It concludes that while the term itself is not referred to directly, references to the underlying components (i.e. ecosystem services, biodiversity and green infrastructure) can be identified. Greening measures of various types are included in many of the assessed adaptation strategies, which also acknowledge their multiple benefits for urban planning. At the same time, the results confirm that more studies are needed to provide evidence of these multiple benefits.

Second, a scenario modelling approach is developed to quantify the potential of ecosystem-based adaptation measures to regulate extreme climatic events. A set of scenarios based on various types and quantities of green infrastructure are developed, to provide comparable information on their potential to regulate heat and heavy rain events. A dense urban area in Munich, Germany is taken as a case study. The models show that under future climate conditions heat stress reaches extreme levels, and nearly all rainfall is discharged as surface runoff. It is shown that mitigating these effects is a function of the type of green infrastructure, and the quantity of its implementation. For heat mitigation, the quality of vegetation has the largest effect. Trees prove to be the most effective measure, as they provide both shading and evapotranspiration. With respect to runoff mitigation, increasing the quantity of green spaces, and consequently water storage capacities, is most influential. More specifically, trees can intercept, evapotranspire and infiltrate rain water, while green roof substrates increase retention

capacities. While all types of urban green infrastructure contribute to climate change adaptation, their role differs as a function of their ability to provide one of two functions: shading of open spaces and building surfaces (for heat mitigation), and infiltration capacities (for runoff mitigation).

These results have practical implications for urban planners who are seeking to enhance the integration of ecosystem-based adaptation into their work, and who must select the best ecosystem-based adaptation measures to reduce both heat stress and the volume of surface runoff. Hence, the results provide decision-makers with a sound base of evidence that they can draw upon when arguing for effective climate change adaptation using ecosystem-based approaches.

KURZFASSUNG

Durch den Klimawandel häufen und intensivieren sich aller Voraussicht nach extreme Hitze- und Starkregenereignisse. Von diesen Klimawandelauswirkungen sind Städte besonders betroffen aufgrund ihrer strukturellen Charakteristika: dichte Bebauungsstruktur, ausgedehnte Oberflächenversiegelung, geringer Grünanteil und hohe Bevölkerungsdichte. Klimaanpassung ist daher ein wichtiges Thema in der Stadtplanung und ins Zentrum des Interesses rücken dabei in zunehmendem Maße ökosystem-basierte Ansätze. Diese nutzen Ökosystemleistungen, welche von urbanen grünen Infrastrukturen bereitgestellt werden, um die Anpassung an klimatische Veränderungen zu unterstützen. Unklar ist noch, welche Rolle das Konzept der ökosystem-basierten Klimaanpassung und die daraus resultierenden Maßnahmen derzeit in städtischen Klimaanpassungsaktivitäten spielen. Weiterhin sind wenig vergleichbare Informationen verfügbar, die Planer bei der Auswahl effektiver ökosystem-basierter Klimaanpassungsmaßnahmen unterstützen.

Vor diesem Hintergrund ist es das Ziel der vorliegenden Dissertation, das Verständnis für die derzeitige Integration der ökosystem-basierten Klimaanpassung in Deutschland zu wecken sowie evidenz-basiertes Wissen über das Regulationspotential verschiedener grüner Infrastruktur-Typen zu generieren. Damit kann die Umsetzung ökosystem-basierter Anpassungsmaßnahmen zur Entwicklung klimaresilienter Städte unterstützt werden.

Zunächst vermittelt diese Thesis Einblick in die Integration von ökosystem-basierten Ansätzen und Maßnahmen in städtische Klimaanpassungsstrategien in Deutschland. Aus dieser Untersuchung ergibt sich, dass, obwohl dieser Terminus nicht explizit verwendet wird, Referenzen zu verwandten Konzepten (wie Ökosytemleistungen, Biodiversität und grüne Infrastruktur) identifiziert werden konnten. Begrünungsmaßnahmen verschiedenen Typs waren in vielen der untersuchten Anpassungsstrategien berücksichtigt, besonders in Zusammenhang mit ihren multiplen Nutzen für die Stadtplanung. Allerdings lassen die Ergebnisse deutlich werden, dass weitere Studien nötig sind, um diese Nutzen umfassend aufzuzeigen.

In einem zweiten Schritt wird daraufhin ein Ansatz zur Szenarienmodellierung entwickelt, um die Leistungen ökosystem-basierter Klimaanpassungsmaßnahmen zur Regulation von klimatischen Extremereignissen zu quantifizieren. Durch das Testen von Szenarien zu verschiedenen grünen Infrastruktur-Typen und deren Quantität werden vergleichbare Informationen zu ihrem Regulationspotential von Hitze- und Starkregenereignissen bereitgestellt. Unter zukünftigen Klimabedingungen zeigt sich, dass der Hitzestress im Außenraum eines dicht bebauten Innenstadtviertels in München extreme Belastungsstufen erreicht und fast der gesamte Niederschlag oberflächlich abfließt. Der Beitrag der Szenarien zur Verminderung dieser Effekte hängt vom Typ der grünen Infrastruktur und der Quantität ihrer Umsetzung ab. Für die Hitzeregulierung hat die Qualität

der Vegetation den größten Einfluss. Dabei sind Bäume durch die gleichzeitige Bereitstellung von Verschattung und Evapotranspiration die effektivste Maßnahme. Für die Abflussregulation sind das Erhöhen der Quantität des Grüns und die damit einhergehende Erhöhung der Wasserspeicherkapazität am einflussreichsten. Bäume ermöglichen hier Interzeption, Evapotranspiration und Infiltration von Regenwasser, während Gründächer die Retentionskapazitäten in ihren Substraten erhöhen. Folglich sind alle untersuchten Typen grüner Infrastruktur komplementär für das Erreichen von Klimaanpassung an extreme Hitze- und Starkregenereignisse, auch wenn ihr Beitrag dazu in Abhängigkeit von der Bereitstellung zweier verschiedener Funktionen variiert, zum einen der Verschattung von Freiflächen sowie Gebäudeoberflächen zur Hitzeregulation, zum anderen der Infiltration zur Abflussregulation.

Für die Stadtplanung haben die vorgestellten Ergebnisse praktische Auswirkungen, um die Integration von ökosystem-basierter Klimaanpassung in die Planung auszuweiten und die strategische Auswahl und Platzierung von Maßnahmen zu unterstützen, so dass Hitzestress und Abflussvolumen reduziert werden. Entscheidungsträger erhalten also eine Argumentationsgrundlage, um sich für eine effektive Klimaanpassung mithilfe ökosystem-basierter Ansätze einzusetzen.

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List of Abbreviations

ADI	Alternating directly implicit solution technique
BMBF	German Federal Ministry of Education and Research
CFD	Computational fluid dynamics
DEM	Digital elevation model
DWD	German Weather Service (Deutscher Wetterdienst)
EbA	Ecosystem-based adaptation
EC	European Commission
ES	Ecosystem services
ET_0	Reference evapotranspiration
FLL	Research Society for Landscape Development and Construction (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e. V.)
GALK	Heads of the German Parks Departments Conference (Deutsche Gartenamtsleiter-konferenz)
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
KLAM	Climate species matrix (Klimaartenmatrix)
LAD	Leaf area density
LAI	Leaf area index
LCZ	Local climate zone
LID	Low impact development
LMU	Ludwig-Maximilians Universität München
MA	Millennium ecosystem assessment
NBS	Nature-based solutions
NDVI	Normalized difference vegetation index
OUTSET	Outdoor standard effective temperature
PET	Physiologically equivalent temperature
PMV	Predicted mean vote

SUDS	Sustainable urban drainage systems
T_a	Air temperature
TEEB	The economics of ecosystems and biodiversity
T_{max}	Maximum air temperature
T_{min}	Minimum air temperature
T_{mrt}	Mean radiant temperature
UGI	Urban green infrastructure
UHI	Urban heat island
UNFCCC	United Nations Framework Convention for Climate Change
USA	United States of America
UTCI	Universal thermal climate index
WSUD	Water sensitive urban design

List of Publications

This cumulative thesis is based on the work published and submitted in the following three original articles. At the time of thesis submission two articles have already been published and one article was still under review.

Paper 1: Zölch, T., Wamsler, C., Pauleit, S. (2018). Integrating the ecosystem-based approach into municipal climate change adaptation strategies: The case of Germany. Journal of Cleaner Production, 170, 966-977. DOI: 10.1016/j.jclepro.2017.09.146.

Summary

Climate change impacts are a key challenge for sustainable urban development. To address this challenge, ecosystem-based adaptation (EbA), i.e., the use of ecosystem services and biodiversity to help people adapt to climate change, is increasingly being considered as an alternative or complement to traditional, engineering-based approaches. However, little research on ecosystem-based adaptation has been carried out in urban areas, and empirical evidence of its effectiveness and uptake in strategic adaptation planning is particularly lacking. Against this background, this study investigates the implementation of urban EbA in strategic adaptation planning. Based on a comparative analysis of all German municipalities with more than 100,000 inhabitants, it examines the integration of EbA into municipal adaptation strategies. The results show that there is, so far, no comprehensive uptake of the EbA concept. While current strategies differ significantly in their type, structure, scope, maturity and content, overall the EbA concept remains implicit. 76 % of the assessed strategies include some kind of ecosystem-based adaptation measures, which focus on enhancing the conservation, restoration, creation or sustainable management of ecosystems, but comprehensive approaches are missing, and only 25 % of all strategies highlight the multiple benefits of EbA measures. We conclude that better promotion and comprehensive mainstreaming of EbA (e.g., through more distributed urban governance and enhancing research, top-down policies and bottom-up activities) is urgently needed to foster sustainable urban development.

Author's contribution

The first author T. Zölch developed the research design and theoretical framework, compiled the desk work and composed and wrote the manuscript under the supervision of the co-authors. Both co-authors contributed to the manuscript by scientific advice and language editing.

Paper 2: Zölch, T., Maderspacher, J., Wamsler, C., Pauleit, S. (2016). Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale. Urban Forestry & Urban Greening, 20, 305-316. DOI: 10.1016/j.ufug.2016.09.011.

Summary

Urban green infrastructure (UGI) has been increasingly promoted as a key measure to mitigate heat stress in cities caused by the urban heat island effect and climate change impacts, including climate variability and extremes. However, comparable information concerning the performance of different UGI types to moderate such impacts is mostly lacking. This creates serious challenges for urban planners who need to decide on the most effective measures while considering spatial and administrative constraints. This study investigates how different types and quantities of UGI, i.e. trees, green roofs, and green facades, affect pedestrian thermal comfort. The study was applied to high-density residential areas under current and future climatic conditions. Climate change will on average increase afternoon Physiological Equivalent Temperature (PET) values by 2.4 K; however, this could be vastly reduced by different UGI scenarios. Planting trees had the strongest impact with an average PET reduction of 13 % compared with existing vegetation. Trees shade open spaces and provide evapotranspirative cooling. Another valuable adaptation option is green facades, which have mitigating effects of 5 %–10 %. In contrast, the effects of green roofs were negligible. Our results indicate that increasing the share of green cover did not directly correspond to the magnitude of the PET reduction. Placing vegetation strategically in heat-exposed areas is more effective than just aiming at a high percentage of green cover. We conclude that our extensive comparative analysis provides empirical evidence to support UGI on the micro-scale and assists planners and decision-makers to effectively select and prioritise concrete measures to adapt to climate change.

Author's contribution

The first author developed the methodological framework and scenario set-up in discussion with the co-authors. All modelling work, data analysis and writing of the manuscript was done by T. Zölch. J. Maderspacher supported the data analysis methodologically and all co-authors contributed to the manuscript by scientific advice and language editing.

Paper 3: Zölch, T., Henze, L., Keilholz, P., Pauleit, S. (2017). Regulating urban surface runoff through nature-based solutions - an assessment at the micro-scale. Environmental Research, 157, 135-144. DOI: 10.1016/j.envres.2017.05.023.

Summary

Urban development leads to changes of surface cover that disrupt the hydrological cycle in cities. In particular, impermeable surfaces and the removal of vegetation reduce the ability to intercept, store and infiltrate rainwater. Consequently, the volume of stormwater runoff and the risk of local flooding rises. This is further amplified by the anticipated effects of climate change leading to an increased frequency and intensity of heavy rain events. Hence, urban adaptation strategies are required to mitigate those impacts. A nature-based solution, more and more promoted in politics and academia, is urban green infrastructure as it contributes to the resilience of urban ecosystems by providing services to maintain or restore hydrological functions. However, this poses a challenge to urban planners in deciding upon effective adaptation measures as they often lack information on the performance of green infrastructure to moderate surface runoff. It remains unclear what type of green infrastructure (e.g. trees, green roofs) offers the highest potential to reduce discharge volumes and to what extent. Against this background, this study provides an approach to gather quantitative evidence on green infrastructure's regulation potential. We use a micro-scale scenario modelling approach of different variations of green cover under current and future climatic conditions. The scenarios are modelled with MIKE SHE, an integrated hydrological simulation tool, and applied to a high density residential area of perimeter blocks in Munich, Germany. The results reveal that both trees and green roofs increase water storage capacities and hence reduce surface runoff, although the main contribution of trees lies in increasing interception and evapotranspiration, whereas green roofs allow for more retention through water storage in their substrate. With increasing precipitation intensities as projected under climate change their regulating potential decreases due to limited water storage capacities. The performance of both types stays limited to a maximum reduction of 2.4 % compared to the baseline scenario, unless the coverage of vegetation and permeable surfaces is significantly increased as a 14.8 % reduction is achieved by greening all roof surfaces. We conclude that the study provides empirical support for the effectiveness of urban green infrastructure as nature-based solution to stormwater regulation and assists planners and operators of sewage systems in selecting the most effective measures for implementation and estimation of their effects.

Author’s contribution

The first author developed the methodological framework and research design of the manuscript supervised by S. Pauleit, and carried out the computational modelling as well as the composition and writing of the paper. L. Henze and P. Keilholz assisted in setting up and calibrating the modelling software. All co-authors contributed to the manuscript by discussing the work progress, giving scientific advice and language editing.

1. INTRODUCTION

1.1 Background and problem definition

Climate change is expected to increase climatic variability and extremes such as heat waves and heavy rain (IPCC, 2014). Recent weather records confirm a worldwide trend: the years 2014, 2015 and 2016 successively broke the record for the highest annual mean temperature globally, with an air temperature 1.1 °C higher than pre-industrial levels in 2016 (WMO, 2017). The situation in Germany followed this worldwide trend: warmer conditions were accompanied by severe heat waves with a maximum temperature of 37.8 °C in summer, and exceptionally low annual precipitation. When it did rain, it was exceptionally intense, with maximum daily volumes of up to 150.7 l/m^2 (DWD, 2016a). The German Weather Service (DWD) defines days with maximum air temperature exceeding 30 °C as heat days, while heavy rain is defined as precipitation that exceeds 10 mm/hour (DWD, 2015, 2016b). Over the course of the past century, almost all weather stations in Germany have registered an increasing number of heat waves in July and August, and extremely hot summers (notably 2003) are increasingly frequent. Similarly, heavy rain events have become more frequent and more intense over the past 50 years (Zebisch et al., 2005).

Vulnerability to climate change is commonly defined as a function of exposure, sensitivity and adaptive capacity (Solomon et al., 2007). It varies as a function of the spatial setting, population group and infrastructure type and the ecological, social and technical systems of cities are generally thought to be particularly exposed (Revi et al., 2014; Wamsler, 2014). The reasons for this situation include high population density, the number of built structures, the extent of sealed surfaces, and the lack of green space compared to rural areas (EEA, 2012; Kuttler, 2010; Wamsler et al., 2013).

On the one hand, built structures and human activities create an urban climate that shows specific characteristics compared to the regional climate (Oke, 1980). It is especially represented by higher air and surface temperatures, reduced wind speeds and a lack of air exchange and evapotranspiration due to altered energy exchanges (Kuttler, 2010; Oke, 1980). The thermal load found in cities is described as the urban heat island (UHI) effect. Artificial surfaces absorb incoming solar radiation and heat up more than natural surfaces due to higher albedo and thermal storage capacities (Oke, 1982). Built structures reduce wind speed and air exchange, and contribute to the problem of warmer air within the city boundaries (Oke, 2011). The UHI effect is both seasonal and diurnal (Scherer & Endlicher, 2013).

Artificial surfaces store heat during the day, and release it during the evening and night, which counterbalances nocturnal cooling. In Berlin, for example, the recorded difference has reached a maximum of 11 K (and an average of 4–5 K). The UHI effect is more intense in summer (Fenner et al., 2014; Oke, 2011).

For the urban inhabitants the UHI effect increases the risk of heat stress, a condition where the body is unable to release sufficient energy to prevent its temperature rising (Kovats & Hajat, 2008). The consequences can be severe. For example, the summer of 2003 is estimated to have led to over 70,000 deaths in Europe (Robine et al., 2008). It can also reduce productivity (Daanen et al., 2013) and increase demand for energy in order to cool the indoor climate (Akbari et al., 2001).

On the other hand, changes to surface cover disrupt the hydrological cycle, and reduce the capacity to intercept, evapotranspire, store and infiltrate rainwater (Bridgman et al., 1995; Douglas, 1983). High rainfall is transformed into surface runoff, and the urban hydrological system discharges water outside the city boundaries (Endreny, 2006). Other characteristics of the urban water balance are base flow losses, reduced groundwater recharge and higher concentrations of water-borne pollutants (Endreny, 2006; Fletcher et al., 2013; Miller et al., 2014; Oke, 1987). During a heavy rain event, the volume of runoff, especially peak runoff, increases (Loftus et al., 2011), as does the risk of overloading the sewage system. Sewage overflow can have severe impacts with negative consequences for health and infrastructure, especially when combined with the supply system (Endreny, 2006; Loftus et al., 2011). For example, in 2011, the Danish capital of Copenhagen experienced a severe cloudburst – over 150 mm of precipitation fell within three hours. Many of the city's streets and cellars were flooded. Citizens were put at risk, infrastructure was disrupted and high insurance claims followed (City of Copenhagen, 2011; Kruse, 2016).

In addition, climate change contributes to the degradation of the climatic and hydrological situation in cities (Coumou & Robinson, 2013). For example, in the German city of Munich, the regional climate model REMO indicates that the frequency and magnitude of both heat days and heavy rain events will increase (Jacob, 2009). Figure 1 illustrates the projected increase in heat days (left) and heavy rain events (right) under different Intergovernmental Panel on Climate Change (IPCC) emission scenarios, compared to the reference period of 1970 to 2000 (Nakicenovic et al., 2000). C20 represents the reference period, B1 an integrated and ecologically-friendly future world, A1B a balanced use of all energy sources, and A2 represents a growing population and economy (Nakicenovic et al., 2000). For the period 1970–2000, temperatures reach a maximum (T_{max}) of 37.6 °C, compared to 43.2 °C for the period 2060–2090 in scenario A1B. In the Munich region, the current average magnitude of a heavy rain event in the reference period is 14.6 mm/hour, with a return period of 0.5 years. In the climate change scenario A2, this is expected to increase to 17.8 mm/hour, with a return period of one year, for the period 2060–2090 (KOSTRA-DWD, 2000).

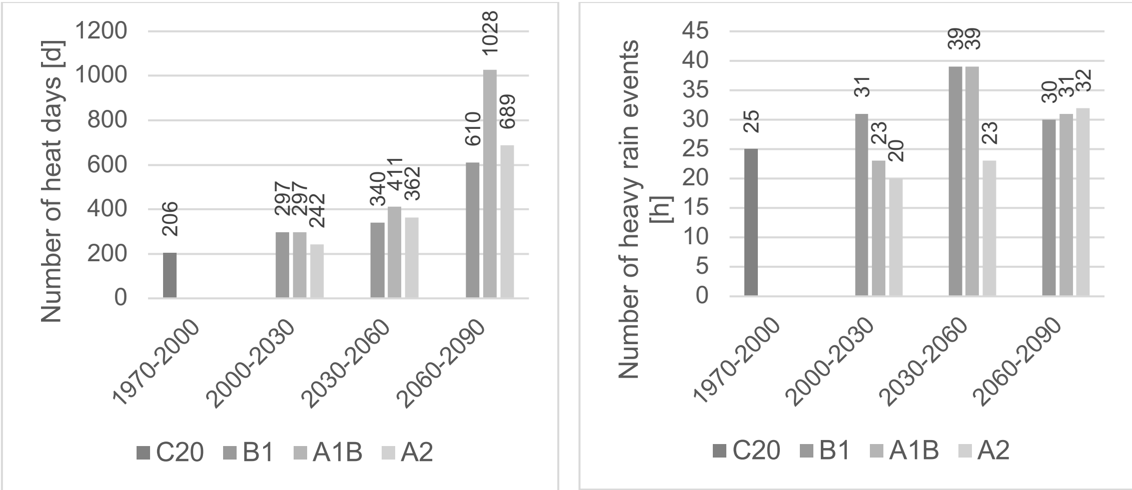

Figure 1: Projected increase in the number of heat days (left, T_{max} > 30 °C) and heavy rain events (right, precipitation > 10 mm/h) for IPCC Special Report on Emissions Scenarios (SRES) until 2090, compared to the reference period (C20, 1970–2000) for Munich, based on the REMO model.

Climate change impacts express themselves differently within a city, which makes a small-scale assessment beyond the cities' boundaries indispensable. Heterogeneous structures interact distinctively with the urban atmosphere. They can be classified into urban areas of similar size (e.g. a street block) that share the same morphological characteristics (Gill et al., 2008; Roth, 1980). These urban morphology types have also been called urban structural types, or urban fabric types (e.g. Pauleit & Breuste, 2011; Pauleit & Duhme, 2000; Stiles et al., 2014b). The typology is used to assess intra-urban variance due to the roughness of elements, building materials, surface sealing and evapotranspiration rates, which determine environmental performance and exposure to climate change impacts (Mathey et al., 2011; Pauleit & Duhme, 2000; Stewart & Oke, 2012). Scherer et al. (1999) showed how the concept of climatopes, representing areas with similar combinations of climatic factors could be used by urban planners to differentiate the effects of urban morphology on the urban climate. Stewart and Oke (2012) used the idea of climatopes to develop the concept of local climate zones (LCZ) to refer to areas that have a uniform surface cover, structure, materials, human activity and characterise a temperature regime. Their standardised approach to site selection and description is increasingly adopted in urban climate studies (Stewart et al., 2014). Similarly, several studies have assessed differences in the hydrological behaviour of urban morphologies (e.g. Gill et al., 2007; Pauleit & Duhme, 2000; Sjöman & Gill, 2014).

Cities need to adapt to climate change, and effective adaptation strategies are indispensable to achieve this (EEA, 2012; Perks, 2011; Revi et al., 2014). Climate change adaptation refers to adjustments that are made in response to actual or expected climate effects that aim to reduce the vulnerability of an ecological, social, economic or technical system, either by reducing exposure or sensitivity, or by increasing adaptive capacity (Noble et al., 2014). It enhances a system's resilience in the face of current or future impacts of climate change. Resilience describes the ability of urban systems to rebound, resist and recover from climate change impacts (IPCC, 2012). Adapting a system is an active process that includes the planning and implementation of measures to prevent, moderate, cope with and take advantage of climatic stimuli and their effects (Adger et al., 2005). Measures are included in municipal adaptation strategies that cities are gradually developing. The development passes through different phases and several guidelines describe this process (e.g. Hallegatte et al., 2011; ICLEI, 2010; Lehmann et al., 2015; Prutsch et al., 2014; Wamsler, 2017). For instance, ICLEI (2010) distinguishes five milestones:

1) Initiation of the process, including the identification of the problem and stakeholders;
2) Research on the problem, including risk and vulnerability assessments;
3) Plan of action, including strategy development and selection of measures;
4) Implementation of measures, including the evaluation of site conditions;
5) Monitoring of effectivity, including revisions of adaptation strategies.

It is important, in all phases, to sustainably mainstream adaptation activities into urban planning practices. Mainstreaming refers to the integration of considerations into all affected sectors, and is designed to holistically reduce climate change impacts and include all relevant stakeholders in the process (Wamsler, 2017; Wamsler & Pauleit, 2016).

Climate adaptation takes various forms of applied actions (Noble et al., 2014). Hard approaches (grey infrastructure) refer to engineering measures designed to withstand climatic variability and extremes (e.g. levees, technical shading, irrigation systems), while soft measures encourage adaptive behaviour by, for example, providing information and incentives (EEA, 2012; Noble et al., 2014). Green approaches increase urban resilience, as ecosystem services are provided by green and blue urban spaces (EC, 2009; Noble et al., 2014). Benedict and McMahon (2002) define this urban green infrastructure (UGI) as "an interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations", which embraces the ecosystem services approach (Daily, 1997; Doswald & Estrella, 2015; Hansen & Pauleit, 2014; MA, 2005). UGI can constitute of various types at different scales. For instance, parks are found at city scale, while trees are found at local scale (Gaffin et al., 2012).

Academia has adopted the term ecosystem-based adaptation (EbA) to refer to ecosystem services and biodiversity that help society to adapt to climate change impacts (CBD, 2009). Several authors have claimed that it provides a more flexible, cost-effective, participatory and broadly-applicable approach to climate change adaptation than conventional approaches (Chong, 2014; Girot et al., 2012; Jones et al., 2012; Revi et al., 2014; Vignola et al., 2009). In the context of urban climate change adaptation, it can provide services that regulate the urban climate and hydrology, for example by cooling the environment through shading and evapotranspiration, and reducing runoff rates (e.g. Akbari et al., 2001; Armson et al., 2013; Lafortezza et al., 2009; Rahman et al., 2011; Vanuytrecht et al., 2014). Moreover, the adoption of EbA has many potential co-benefits for urban planning (Doswald et al., 2014; Jones et al., 2012; Noble et al., 2014; Ojea, 2015; Wamsler et al., 2014). For instance, vegetation can sequester carbon and contribute to climate change mitigation; it can also filter noise and pollutants to enhance air quality, provide recreation opportunities by offering aesthetic values, improve quality of life, and increase biodiversity (e.g. Bolund & Hunhammar, 1999; Davies et al., 2011; Strohbach & Haase, 2012; Strohbach et al., 2013). Because of its multifunctionality EbA is gaining attention as a so-called 'no-regret' option, reflecting the uncertainties inherent in climate projections and the difficulty of effectively tailoring adaptation measures (Füssel, 2007; Hallegatte, 2009; Naumann et al., 2014).

Recent reviews of research into the potential contribution of EbA to effective climate change adaptation have concluded that a lack of knowledge of governance structures and the effectiveness of current applications have hindered its practical implementation (Brink et al., 2016; Doswald et al., 2014; Munroe et al., 2012; Naumann et al., 2011; Ojea, 2015). Both research and the integration of EbA into local adaptation planning, particularly urban planning, is still in its infancy (Brink et al., 2016), although there is increased political support and recognition as adaptation option (Wamsler, 2015; Wamsler et al., 2016). For that reason, Geneletti and Zardo (2016) carried out an initial, qualitative analysis of the impact of EbA measures on adaptation planning in pioneering European cities. At the same time, pathways for mainstreaming EbA in municipal governance, and at project level, have been investigated in case studies in South Africa, Sweden and Germany (Pasquini & Cowling, 2014; Wamsler, 2015; Wamsler et al., 2014; Wamsler et al., 2016; Wamsler & Pauleit, 2016). However, there is still a lack of systematic and quantitative analyses of how EbA and derived measures are integrated into municipal adaptation strategies in a single country (compare Geneletti & Zardo, 2016). The role of the EbA concept and related adaptation measures in municipal adaptation activities remains unclear (Wamsler et al., 2014).

At the same time, there is an increasing demand for knowledge and information about the climate adaptation benefits of EbA, notably whether EbA measures are actually effective when implemented. So far, most benefits have been shown by empirical and modelling studies that focus on single types of measures provided by UGI. For instance, many studies of heat stress have highlighted the importance of urban trees in providing shade and evapotranspiration. Hall et al. (2012) and Skelhorn et al. (2014) found a reduction in maximum air and surface temperatures from planting additional trees, while Moser et al. (2015) and Fahmy et al. (2010) found a relation between the magnitude of climatic benefits and tree dimension and leaf area. Other studies have shown that green facades can lower mean radiant temperatures (Jänicke et al., 2014) and that green roofs contribute to improving thermal comfort, although the effects are smaller than of street-level vegetation (Lobaccaro & Acero, 2015; Ng et al., 2012; Perini & Magliocco, 2014). In the context of regulating surface runoff, studies have found that the single types of UGI have positive effects (e.g. Armson et al., 2013; Czemiel Berndtsson, 2010; Gregoire & Clausen, 2011; Nagase & Dunnett, 2012; Schroll et al., 2011; Vanuytrecht et al., 2014; Wang et al., 2008). The potential of trees to reduce surface runoff through interception and infiltration was for instance assessed by Armson et al. (2013) who compared plots covered by asphalt with those planted with trees, while Wang et al. (2008) looked at complete catchments. The review carried out by Czemiel Berndtsson (2010) assessed the performance of green roofs and identified various influential factors, including the type of green roof and the selection of vegetation. Gregoire and Clausen (2011) found that extensive green roofs retained 50 % of rainfall, and Nagase and Dunnett (2012) found that grass is more effective than other vegetation. The performance of a single UGI type has only rarely been assessed under projected climate conditions (Hiemstra et al., 2017)

There is therefore little comparative information available to support planners in the selection of appropriate adaptation measures. Decision-makers need to identify the type and quantity of EbA measure that is most effective in moderating extreme events, while at the same time considering spatial and administrative constraints and balancing other sustainable urban planning priorities (Bowler et al., 2010). Planners often lack information on the performance of different types of UGI, while the regulating functions of EbA measures are not taken into account in urban planning (Ahiablame et al., 2012; Gill et al., 2007; Lee et al., 2012; Matthews et al., 2015). Norton et al. (2015) were the first to attempt to advise urban planners on how to prioritise greening interventions for a particular location. They argued that heat-stressed open spaces need to be planted with UGI types that maximally reduce solar exposure. However, their study did not assess the effectiveness of different interventions, or the regulating effects on surface runoff, or changes in climatic conditions. Hence, it remains unclear what type of UGI is best able to counteract the climate change impacts of both heat and heavy rain events, under current and future climate conditions, and to what extent.

1.2 Objectives of the thesis

The overall aim of this thesis is to increase knowledge on the effectiveness of different EbA measures, in order to support decision-making in the context of urban climate adaptation planning. It focuses on Germany, which is a leader in climate change governance (Wamsler, 2017). A comprehensive, tailored knowledge base that can be used by municipal administrations must begin with an understanding of the current state of knowledge and application of EbA in urban planning, and what information is lacking. Therefore, it is indispensable to assess the current status of EbA and its integration into the municipal adaptation strategies of selected German cities (Paper 1). This initial assessment confirmed the hypothesis that there is a lack of evidence of the adaptation potential of different types of UGI that could guide urban adaptation planning (Paper 2 and 3). Hence, the specific objectives of this thesis are:

- Objective 1:
  Assess the uptake of the EbA concept and EbA measures in the municipal adaptation strategies of selected German cities. The aim is to identify knowledge gaps in urban planning, and ways to improve the integration of EbA into strategic adaptation planning.

- Objective 2:
  Quantify the potential of different types of UGI for heat mitigation and, consequently, increased outdoor thermal comfort given current and future climate conditions.
- Objective 3:
  Quantify the potential of different types of UGI for runoff mitigation and, consequently, reduced discharge volumes given current and future climate conditions.
- Objective 4:
  Evaluate the potential of EbA to generate synergies for heat and runoff mitigation by comparing regulating effects and specific functions.

Finally, in order to translate the scientific results of this thesis into recommendations that can be used in decision-making and to prioritise the use of different types of UGI to mitigate climate change by EbA, the practical implications for urban planning are discussed.

Objectives 1, 2 and 3 relate directly to the research questions posed in Papers 1, 2 and 3, while Objective 4 is only addressed in the present thesis. The objectives of Papers 1, 2 and 3 are given below:

- Paper 1: How, and where, is the EbA concept integrated into municipal adaptation strategies? What types of EbA measures are considered? Why are these specific measures considered? What are their expected benefits?
- Paper 2: How does climate change affect the urban microclimate and pedestrians' thermal comfort? To what extent can the type and quantity of UGI improve pedestrian thermal comfort under current and future climate conditions?
- Paper 3: How does the intensity of summer rain events influence urban surface runoff? To what extent can the type and quantity of UGI regulate urban surface runoff after heavy rain events of varying intensities?

1.3 Structure of the thesis

To improve the decision-making for EbA in urban adaptation planning, Paper 1 develops an analytical framework to assess the current level of integration of the EbA concept, and EbA measures, into the adaptation strategies of large German cities. The findings support the hypothesis that integration could be more extensive, as they provide evidence of the effectiveness of EbA measures in the German context. Based on these results, Papers 2 and 3 examine the potential of different types of UGI that can be implemented as EbA measures to provide regulating ecosystem services, and to help in adapting to the impacts of either extreme heat (Paper 2) or heavy rain events (Paper 3). These Papers support the argument that EbA measures can contribute to improved adaptation. A set of greening scenarios is developed that distinguish different types and quantities of UGI. The results of Papers 2 and 3 are then discussed in terms of the synergies and multifunctional benefits of EbA for climate adaptation. Finally, practical implications for the implementation of EbA in urban planning are derived. Figure 2 illustrates the approach.

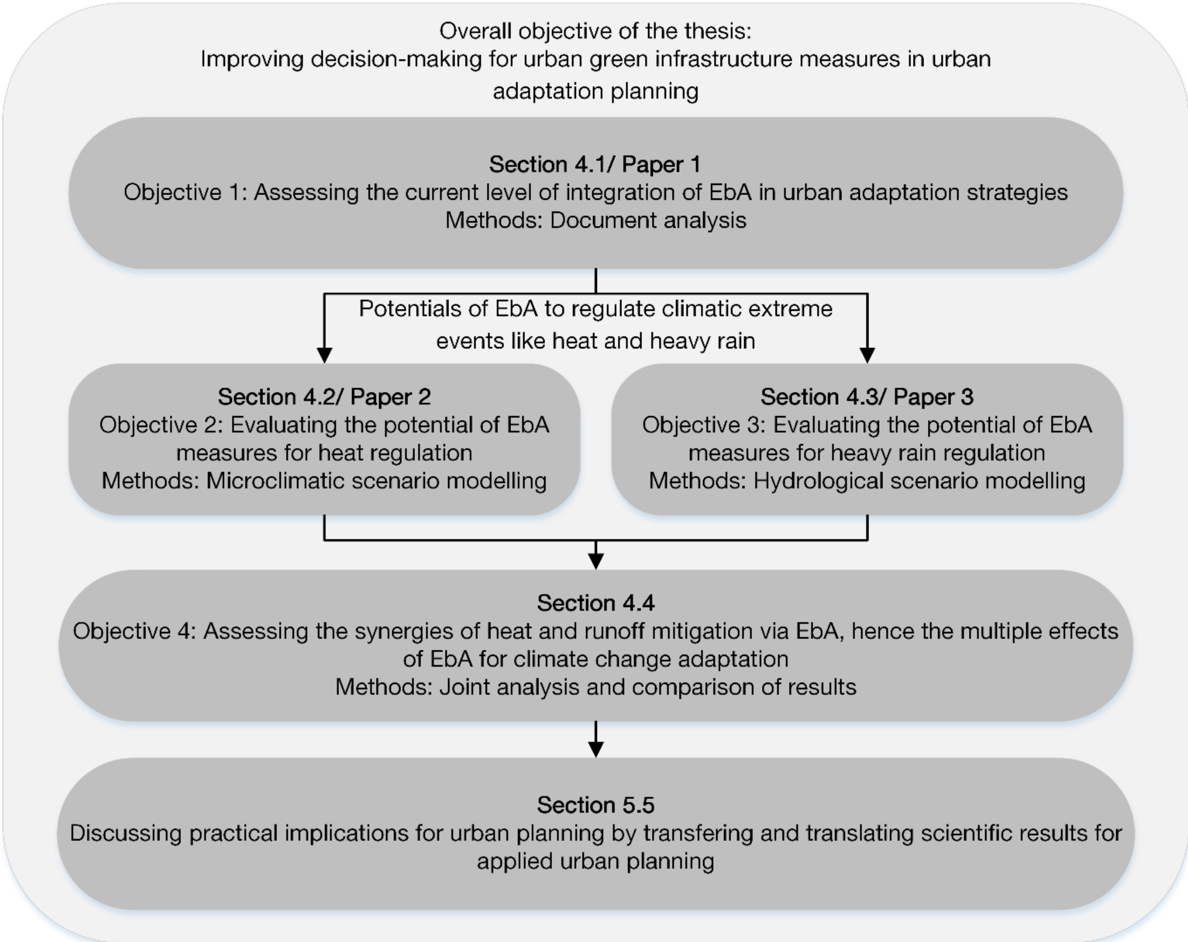

Figure 2: Structure and overview of the thesis and the related publications

The thesis is structured into the following, overall, sections: Section 2 reviews relevant concepts on climate adaptation in cities, and formulates the analytical framework that provides the background for this research. Section 3 presents the approaches and methods, and the results are summarized in Section 4. Section 5 discusses the results and the urban planning guidelines that are derived. Finally, Section 6 draws some conclusions regarding the adaptation potential of ecosystem-based approaches.

2. KEY CONCEPTS AND ANALYTICAL FRAMEWORK

This section begins with a presentation of the background needed to understand the concepts of adaptation to climatic extreme events in cities. It is followed by a presentation of the specific concepts found in the academic and political discourse related to climate adaptation by urban greening, i.e. with the help of urban ecosystems. The most relevant concepts, namely: ecosystem-based adaptation (EbA), ecosystem services (ES), urban green infrastructure (UGI), and nature-based solutions (NBS) are introduced, and finally an integrated analytical framework that draws upon these concepts is formulated.

2.1 Urban adaptation to climate change

Climate change adaptation is defined as "the process of adjustment to actual or expected climate and its effects" (Noble et al., 2014). It aims to reduce the vulnerability of a system to climate change impacts (Noble et al., 2014; Wamsler, 2014). To achieve this, either the exposure of the system to climate impacts, or its sensitivity, or its adaptive capacity need to be addressed (Solomon et al., 2007). As cities are composed of different systems that each have specific vulnerabilities to climate change, adaptation activities need to be tailored to the system and the expected climate change impact (Revi et al., 2014). The following sections thus introduce the characteristics of two urban systems – population and drainage – and show how they can adapt to two climate change impacts – extreme heat and heavy rain.

2.1.1 Adapting to heat

During heat events urban inhabitants suffer from heat stress, which can have severe consequences (Kovats & Hajat, 2008). The most dramatic impact is an increase in the mortality rate (Gabriel & Endlicher, 2011). Several studies have shown a relation between heat events and the number of fatalities. For example, Scherer et al. (2013) suggest that 5 % of all deaths between 2001 and 2010 in Berlin can be related to increased air temperature, and Robine et al. (2008) estimate that the extremely hot summer of 2003 caused 70,000 heat-related deaths in southern and western Europe. To stay healthy, the human body needs to maintain an internal temperature of 37 °C, and it achieves this by sweating, increasing cardiac output and directing blood flow to the skin (Kovats & Hajat, 2008). If this is not possible, the body reacts with cramps, exhaustion, heat stroke and, in the worst case, death (Buchin et al., 2016).

The highest thermal load in urban areas occurs on summerly heat days (maximum air temperature $T_a > 30$ °C) with high solar radiation and little wind. Heat stress reaches its maximum in the afternoon, when direct solar radiation hits the surfaces and the air is already heated up (Matzarakis et al., 2010; Parlow, 2003). Thus, this is the first priority to address. Humans also experience heat stress at night, when the UHI effect reduces nocturnal cooling and T_a remains high (Fenner et al., 2014; Santamouris, 2014). If T_a does not fall below 20 °C during the night, it is termed 'tropical' (DWD, 2015), and residents find it difficult to recover from the day (Harlan et al., 2006).

Vulnerability to heat is a function of personal sensitivity, which differs among social groups, and exposure, which differs from site to site. Age is a decisive factor for being negatively affected by heat. People aged over 65 have a limited capability to respond to high temperatures, and a higher probability of having pre-existing cardiovascular and pulmonary illnesses. Infants under three years old are also very sensitive, as their physiological capabilities are not yet fully developed (Loughnan et al., 2013). Finally, the extent to which an urban area overheats is a function of its spatial characteristics, and heat hotspots can be scattered around the city (Fenner et al., 2014; Harlan et al., 2006).

The above highlights that the urban population can be adapted to heat events either by reducing its sensitivity to heat or by reducing its exposure. Reducing sensitivity draws upon 'soft' adaptation measures, for example, improving the health of the population, or running campaigns to raise awareness of the need to drink sufficiently during heat events (EEA, 2012). Reducing exposure draws upon adaptation measures designed to improve the meteorological context, and hence reduce the likelihood that heat hotspots will develop (Bradford et al., 2015; EEA, 2012). This thesis focuses on the second strategy and, in particular, how it can be achieved by using ecosystem-based approaches with urban greening.

A first step is to be able to assess exposure to heat stress. For this, different methodological approaches can be applied. Some studies have analysed a single parameter, such as T_a, surface temperature, or mean radiant temperature (T_{mrt}), either by taking punctual measurements, or using remote-sensing or modelling-based approaches, which are spatially explicit (e.g. Alavipanah et al., 2015; Chen et al., 2014; Lindberg & Grimmond, 2011b; Loughnan et al., 2013). However, in reality, heat stress is determined by multiple parameters, the most important being T_a, T_{mrt}, wind patterns and humidity (from the meteorological perspective), and metabolic rate, activity, age and clothing (from the physiological perspective) (Höppe, 1999; VDI, 2008). Hence, various indices have been developed to describe outdoor and indoor thermal comfort that take into account the diverse factors that influence the human body (Jendritzky et al., 2012). The most popular outdoor indices are Predicted Mean Vote (PMV), Physiological Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI) and Outdoor Standard Effective Temperature (OUTSET). All are based on the calculation of the human energy balance, but vary in terms of the field of application, the thermo-physiological heat balance model, and unit of measurement (Mukherjee & Mahanta, 2014). The PET and UTCI are measured in °C, which is thought to be more easily understood by practitioners (Matzarakis et al., 1999). The PET, in particular, is described as the temperature experienced by a person outdoors, and is recommended in German guidelines for urban and regional planners (VDI, 2008). Therefore, it is used as the measure of heat stress in this thesis.

The PET index categorizes heat stress into classes of physiological stress. Humans experience thermal comfort at 18–23 °C PET. All values below this benchmark represent a form of cold stress, while values above 23 °C PET are experienced as heat stress. Heat stress increases as PET values rise – up to extreme heat stress levels at temperatures above 41 °C PET (Höppe, 1999; Matzarakis et al., 1999). The table below shows the classes of thermal comfort expressed by the PET.

Table 1: Classes of thermal stress of the thermal comfort index Physiological Equivalent Temperature (PET) (own representation after Matzarakis et al. (1999))

PET in °C	Thermal perception	Grade of physiological stress
Below 4	Very cold	Extreme cold stress
4–8	Cold	Strong cold stress
8–13	Cool	Moderate cold stress
13–18	Slightly cool	Slight cold stress
18–23	Comfortable	No thermal stress
23–29	Slightly warm	Slight heat stress
29–35	Warm	Moderate heat stress
35–41	Hot	Strong heat stress
Above 41	Very hot	Extreme heat stress

2.1.2 Adapting to heavy rain

When a heavy rain event occurs over an urban area, the water infrastructure, part of the technical system of a city, must handle the stormwater volume. In a city, where built-up or sealed surfaces reduce natural drainage, humans have developed technical systems to take over this role, and drain rainwater directly. This is the conventional rainwater management system that most western cities rely on, and which has been optimised over the past century (Libbe et al., 2017; Loftus et al., 2011). Typically, drainage inlets, set into street canyons, catch surface water and funnel it into an underground sewage network, where it is finally processed outside the city boundaries (Endreny, 2008). The water balance in these systems differs considerably from the natural water balance, as the direct drainage of rainwater means that less water is available for evapotranspiration and infiltration processes (Endreny, 2008; Pataki et al., 2011). Figure 3 illustrates these effects, in particular, increased runoff, and decreased evapotranspiration and infiltration.

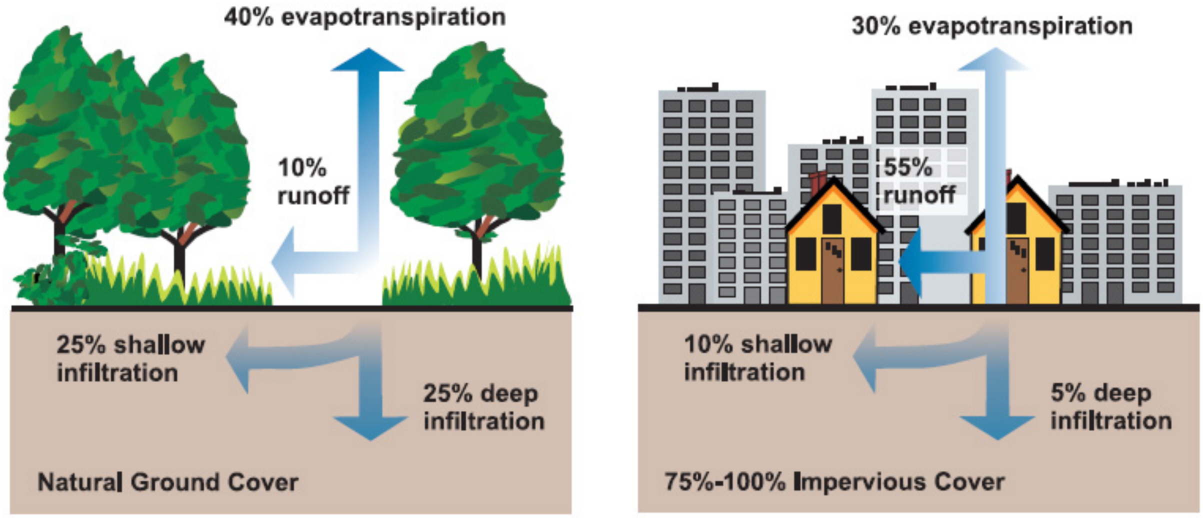

Figure 3: Difference between water balance processes in natural and urban areas (EPA, 2004)

Although conventional rainwater management has reduced the vulnerability of cities to flooding in general, at the same time, it has increased vulnerability to extreme precipitation events. Municipal sewage systems are designed to handle an exact amount of rainwater that occurs within a statistically-predicted return period (Willems et al., 2012). In Germany, the regulations DIN EN 752-2008 and DWA-A 118 state that drainage systems need to be capable of handling a heavy rain event that occurs with a one-year return period (for rural areas), and a two-year return period (for urban areas). These volumes are critical, as they represent the design limits of sewage systems. If the magnitude and frequency of extreme rain events increases (for example, due to climate change) these design criteria and, thus, sewage capacity can be exceeded (Willems et al., 2012). Similarly, the risk of urban flooding increases as surface water rapidly accumulates and travels down roads and other flow paths (EEA, 2012).

The collapse of the drainage system after a heavy rain event can have severe consequences for property, infrastructure, economic activities and human health (Reacher et al., 2004). Stormwater runoff can damage infrastructure, notably houses and the transport system, by entering basements and underground systems, creating severe disruption to everyday life. Flooding can also cause electricity blackouts, leading to economic losses because of production blackouts (EEA, 2012). The urban water system is often constructed as combined system, where stormwater and sewage systems are integrated. If these systems overflow, stormwater can be polluted by sewage, leading to contamination and a risk to public health (Loftus et al., 2011).

Effective adaptation to heavy rain events is important to ensure the correct functioning of the urban stormwater system. Here again, there are various ways to achieve this. On the one hand, the lack of capacity to manage future rain events can be addressed (Willems et al., 2012) – for example stormwater capacity can be increased by making technical adjustments. On the other hand, the overall water infrastructure can be transformed into a system that corresponds more closely to the natural water balance. The latter system has greater capacity to store, evapotranspire and infiltrate rainwater before it is discharged (EPA, 2004). Several approaches have been developed, which are closely related, including: water sensitive urban design (WSUD), sustainable urban drainage systems (SUDS), and low impact development (LID). Another popular approach is integrated stormwater management (Fletcher et al., 2014), which is designed to decrease the exposure of the urban sewage system to runoff after a heavy rain event. This thesis focuses on the latter system, as it can be achieved using ecosystem-based approaches with urban greening.

Integrated stormwater management is a holistic approach with objectives that extend beyond adaptation to future heavy rain events. It sees the urban water cycle as an integral part of the urban system and takes environmental, sanitary, social and economic considerations into account (Fletcher et al., 2014; Johannessen & Wamsler, 2017). By extending the focus beyond technical solutions, which focus the problem of channelling stormwater, and directly incorporating natural processes such as infiltration and evapotranspiration, the conventional urban drainage system becomes both more resilient and provides benefits that include consistent water quality, water conservation and the promotion of multiple uses of the infrastructure, e.g., recreation facilities and habitats for urban flora and fauna (Lloyd et al., 2002). Several planning principles have been derived to achieve this. For instance, in the WSUD context, Hoyer et al. (2011) summarize them as: restoration of the natural water balance, design for improving quality of life, application of techniques and maintenance practices ensuring long-lasting functionality, multifunctional usage, and public acceptance. Measures to achieve integrated stormwater management include: the restoration of river beds, the conservation and enhancement of urban green spaces, and the installation of natural depressions or low-lying vegetated beds (also called rain gardens) along runoff flow paths. All of these measures are designed to increase rainwater retention and infiltration capacities (Ahiablame et al., 2012; Endreny, 2008; EEA, 2012).

Despite these multi-purpose, integrated stormwater management practices, surface runoff remains the critical parameter in deciding how to reduce urban water volumes, and it is assessed in further detail in this thesis.

2.2 Concepts for climate change adaptation by urban greening

The following paragraphs present the various concepts that are used in this thesis to discuss climate change adaptation by urban greening. It should be noted that they are both interrelated, and sometimes even used synonymously (Naumann et al., 2014).

2.2.1 Ecosystem-based adaptation (EbA)

The concept of EbA is defined as "the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change" (CBD 2009, p.41). It was included in the 2008 Bali Action Plan that was presented at the United Nations Framework Convention for Climate Change (UNFCCC) (IUCN 2008; Girot et al. 2012). Today, EbA is used internationally (Munang et al., 2013; Naumann et al., 2011). It focuses on sustainable management, and the conservation and restoration of ecosystems that aim to provide services that support human adaptation to climate change (Munang et al., 2013; CBD, 2009). Consequently, it is embedded into two other concepts: ecosystem services and climate change adaptation (Chong, 2014; Wamsler et al., 2014).

EbA is considered to be multifunctional, as it also takes other potential social, economic and cultural co-benefits for local communities into account. By aiming at multifunctionality different functions are combined into one action in order to use limited space and capacity more effectively (Ahern, 2011; Hansen & Pauleit, 2014). Co-benefits are defined as solutions to both climate change and other urban planning challenges, through the simultaneous implementation of policies and strategies (Jiang et al., 2016).

The European Climate Change Adaptation Strategy, for example, encourages the implementation of EbA (EC 2013a). So far, it has mainly been used in the sectors of agriculture and forestry (Doswald et al., 2014; Vignola et al., 2009). Nevertheless, urban planners are taking a greater interest in EbA as a cost-efficient, comprehensive and multifunctional approach (Brink et al., 2016). In cities, EbA refers to the design and improvement of green and blue infrastructure for adaptation purposes (Doswald & Osti, 2011).

2.2.2 Ecosystem services (ES)

The concept of ecosystem services constitutes a foundation for EbA as it defines the services of ecosystems humans can benefit from for adapting to climate change. It emerged in the late 1970s, when ecosystem functions that benefitted humans were renamed as 'services' in an attempt to raise public awareness for biodiversity conservation (Gómez-Baggethun et al., 2010). Since then, the discourse has broadened to include assessment and valuation methods, ethical issues and mainstreaming approaches into policy making (e.g. Cowling et al., 2008; Norgaard, 2010). The 2005 Millennium Ecosystem Assessment (MA) report, led by the United Nations, represented the first global assessment of ecosystem services explicitly aimed at policymakers (MA, 2005). The concept is important in the urban sector, as its application can reduce the ecological footprint of cities and enhance their resilience (Gómez-Baggethun & Barton, 2013; TEEB DE, 2016).

Generally, ecosystem services are defined as the benefits humans obtain from ecosystems (MA, 2005). They are allocated into four broad categories: regulating, provisioning, cultural and habitat/ supporting (Figure 4). Each individual ecosystem service has direct effects on human wellbeing, while supporting services enable other services to be present and hence, have indirect effects (Gómez-Baggethun & Barton, 2013; MA, 2005; TEEB, 2011). Regulating services are especially relevant for climate adaptation as they can directly moderate the climate (Gaffin et al., 2012; Larondelle et al., 2014; Uy & Shaw, 2012).

Cities, seen as socio-ecological systems, depend on the smooth functioning of ecosystems to sustain good living conditions, security and the wellbeing of humans in the long-term. Although demand for ecosystem services is high, due to the density of the population, many services (e.g. food, energy and drinking water) are actually supplied from outside the city's boundaries. On the other hand, some ecosystem services are created within the city, notably the moderation of local microclimates, the promotion of biodiversity, and other aspects that directly affect human health (Gómez-Baggethun & Barton, 2013; TEEB DE, 2016).

The demand for different ecosystem services in urban planning leads to interactions and feedback among the services and systems that supply them. Synergies are created, as an increase in one ecosystem service leads to a mutual increase in another (Haase et al., 2012). This relates to the concept of multifunctionality, which is found when synergies between the provision of different ecosystem services are created (Hansen & Pauleit, 2014).

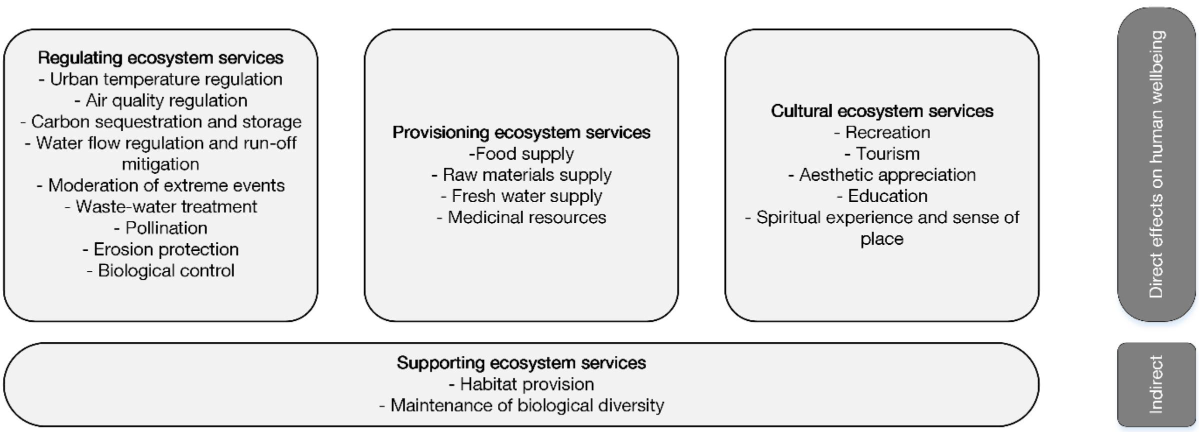

Figure 4: The concept of ecosystem services (adopted from Gómez-Baggethun & Barton, 2013; MA, 2005; TEEB, 2011)

2.2.3 Urban green infrastructure (UGI)

In urban areas, ecosystem services are provided by a network of natural and semi-natural, managed, green and blue spaces (Benedict & McMahon, 2006; Bolund & Hunhammar, 1999; BMUB, 2015; Gaffin et al., 2012; Kabisch & Haase, 2013; Noble et al., 2014). Urban green infrastructure (UGI) refers to vegetated areas within a city that are planned and maintained for the purpose of delivering a large amount of ecosystem services (Benedict & McMahon, 2006; Hansen et al., 2017).

UGI originated in the United States of America (USA), where it was intended to improve spatial planning and open space protection (Benedict & McMahon, 2002). In the USA, it is also applied to sustainable stormwater management and often used in conjunction with LID or SUDS approaches (Fletcher et al., 2014). At the local scale, the most commonly-implemented UGI for stormwater management are trees, green roofs, rain gardens or swale systems (EC, 2015; Jayasooriya & Ng, 2014). At European level, there is a policy aim to mainstream UGI into spatial planning and territorial development, in the context of the Biodiversity Strategy 2020 (EC, 2013b).

The concept is applied as planning approach that aims to develop coherent networks of green spaces and contributes to the resilience of urban ecosystems; the goal is to provide services to maintain or restore ecological functions (Pauleit et al., 2011). It understands vegetated areas of a city as essential urban infrastructure – equally as important as technical and social infrastructure (Hansen et al., 2017). UGI is a broader concept than EbA, and aims to improve human wellbeing in many ways, including the promotion of good health and social cohesion (Davies et al., 2015; EC, 2013b; Lafortezza et al., 2013; Lovell & Taylor, 2013). UGI principles such as multifunctionality, connectivity, integration, and a multi-scale and multi-object approach can be applied in spatial planning, and the concept has already found practical applications in urban planning (Pauleit et al., 2017a; Pauleit et al., 2017b).

2.2.4 Nature-based solutions (NBS)

Recently, the concept of nature-based solutions (NBS) aims to use nature to provide solutions to climate mitigation and adaptation challenges (Nesshöver et al., 2017). Originally, the concept was introduced by the World Bank and the International Union for Conservation of Nature (IUCN) to raise the profile of biodiversity conservation in tackling climate change (IUCN, 2009; MacKinnon et al., 2008). In Europe, it has been adopted into the Horizon 2020 framework programme for research and innovation (EC, 2015). NBS are defined as solutions that use nature and ecosystem services to provide economic, social and environmental benefits (EC, 2015; Maes & Jacobs, 2015). They include both natural ecosystems and novel ecosystems that are intentionally or unintentionally created by humans (Eggermont et al., 2015). Pauleit et al. (2017b) found many overlaps in the scope and definition of EbA, UGI and ecosystem services. At the same time, the latter authors found that the scope of the NBS concept is broader than EbA, more abstract (in terms of application to urban planning) than UGI, and based on ecosystem services' approaches to the benefits of nature for human wellbeing. Thus, NBS could be said to be an umbrella term for other concepts that is receiving increased attention at the political and academic level (Nesshöver et al., 2017; Pauleit et al., 2017b).

2.3 Analytical framework

The concepts that are introduced above were used to derive the analytical framework that forms the basis for the analyses and assessments presented here. The focus lies on the concept of EbA that is understood as a way to achieve climate change adaptation in urban planning. Figure 5 presents the main components of the analytical framework.

The EbA concept assumes that ecosystems provide services that help people to adapt to the impacts of climate change (Chong, 2014; CBD, 2009; Uy & Shaw, 2012; Wamsler et al., 2014). In urban areas these ecosystems are provided by various forms of UGI (Gaffin et al., 2012). Bolund and Hunhammar (1999) developed a classification consisting of: trees, parks/ lawns, urban forests, cultivated land and lakes/ streams. For the present case, this list was extended to include greening of buildings, i.e., green roofs and facades, street and backyard vegetation and other strategic measures following later work and taking up additional types that are commonly referred to as climate adaptation options (Benedict & McMahon, 2006; EEA, 2012; Gaffin et al., 2012; Pauleit et al., 2011).

Ecosystem services have been sub-divided into four broad categories as presented in Section 2.2.2 and Figure 4 (MA, 2005; TEEB, 2011). Biodiversity is integral to the functioning of ecosystems, and falls into the category of supporting services that provide habitats and maintain species diversity (Gómez-Baggethun & Barton, 2013; CBD, 2009; TEEB, 2011). It is explicitly included in the Convention of Biological Diversity's (CBD) definition of EbA. All four categories of ecosystem services have adaptation benefits for urban planning. Regulating services (e.g. local temperature regulation) are considered to deliver most benefits, as they directly moderate the local climate and are thought to be effective ways to mitigate heat and runoff (Gaffin et al., 2012; Larondelle et al., 2014; Uy & Shaw, 2012). Other services have indirect benefits. For example, the provision of recreation facilities in green spaces is considered to be a cultural service that contributes positively to physical and mental health, while the supply of fresh water that is stored and purified by ecosystems is deemed a provisioning service (Foster et al., 2011; MA, 2005; TEEB, 2011).

Finally, EbA measures refer to actions that use different UGI types leading to the provision of adaptation benefits at different scales, from individual buildings (e.g. green roofs) to an entire city (e.g. green corridors) (Doswald et al., 2014; Geneletti & Zardo, 2016; Munroe et al., 2012; Zandersen et al., 2014). EbA measures are designed to support climate change adaptation (e.g. adaptation to heat or flooding) through the provision of at least one ecosystem service (Brink et al., 2016; Doswald et al., 2014; Doswald & Osti, 2011). If they provide more than one ecosystem service, synergies are created and the action is multifunctional. Therefore, EbA measures rely on the presence of relevant UGI types, and concern the conservation, restoration, creation and/ or sustainable management of ecosystems (Doswald et al., 2014). They can be characterised in four ways:

- The aim and type of measure (e.g. the promotion of green roofs);
- The type of urban ecosystem or green infrastructure (e.g. a park);
- The ecosystem service that the measure is expected to provide for climate change adaptation, and the climate change impact it is designed to mitigate;
- The measure's multiple benefits, if mentioned.

In order to fully define the urban ecosystem that is affected or adopted by an EbA measure, the classification of UGI types is applicable and therewith, completes the presented analytical framework (Figure 5).

This framework illustrates the interrelations between the concepts of EbA, ecosystem services and UGI, and how they are used to assess the integration and effectiveness of EbA in urban adaptation to climate change.

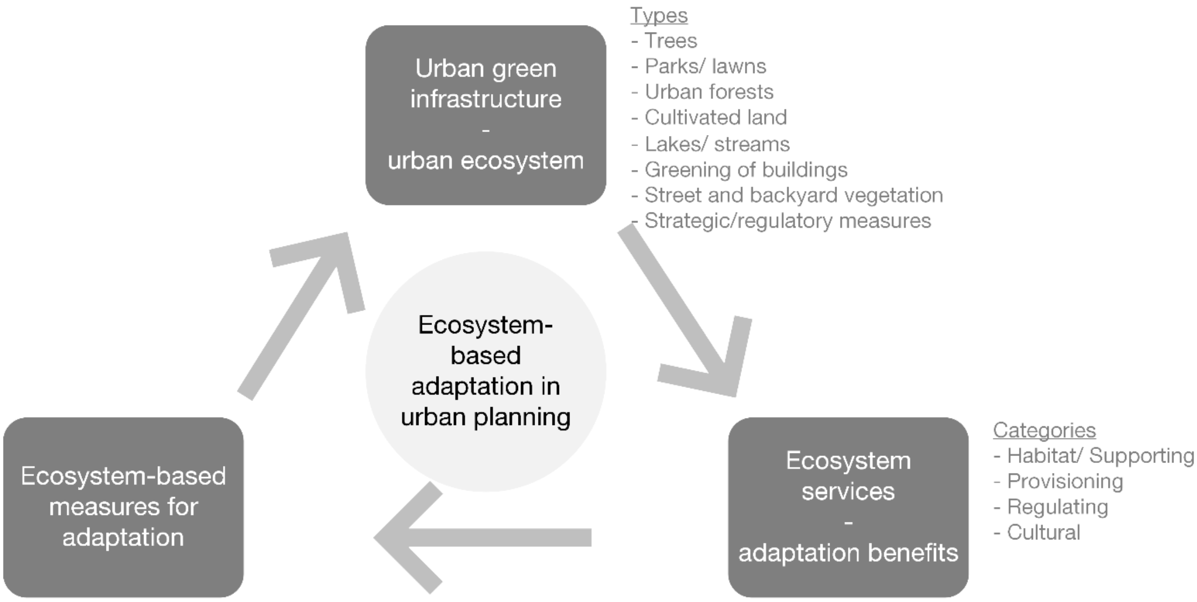

Figure 5: The analytical framework for climate change adaptation by urban greening – EbA.

3. METHODOLOGY

This section presents the methodology applied in this thesis. It begins with the overall approach and a presentation of the geographical focus area, then goes on to present details of the methodologies to: a) assess the integration of EbA into urban planning; and b) quantify the effectiveness of EbA for heat and flood mitigation.

3.1 Overall research approach

To achieve the different objectives presented for this research a mixed methods approach was applied. Each objective requires a different methodology, and addresses multiple disciplines (i.e. urban ecology, urban climatology and climate change governance). Paper 1 reviews EbA integration. Therefore, municipal adaptation strategies were evaluated at national level to provide an overall picture of the actions of different cities that are subject to the same regulatory conditions. Papers 2 and 3 examine the same study area. They take a computational approach, and model greening scenarios at the neighbourhood level to assess the effects of high-resolution vegetation. Modelling helps to simplify the real world, in this case urban climate and hydrology, without the need for resource-intensive empirical data acquisition. Furthermore, it makes it possible to assess future scenarios. Both approaches can be used to analyse single heat or heavy rain events. Finally, the results are compared and discussed to derive recommendations for urban planning.

3.2 Geographical focus

As multiple methods were adopted, assessments at different scales were necessary – the nationwide level for comparisons of cities within the same federal background, and the neighbourhood level, where urban adaptation measures are actually implemented.

Germany was selected as it is a pioneer in the domain of environmental and climate change governance: climate adaptation is a declared goal of the federal government (Deutsche Bundesregierung, 2011). German cities have been encouraged to develop municipal adaptation strategies, and several municipalities have already taken action. Assessing the EbA uptake in this context is particularly interesting as the political discourse has gained momentum in recent years. For example, the Federal Agency for Nature Conservation published a review on good ecosystem-based practices in various sectors (Doswald & Osti, 2011), and funded a national project on ecosystem-based approaches for adaptation and mitigation in different sectors from 2012 to 2014 (BfN, 2012). Moreover, the use of multifunctional green spaces for climate change adaptation was an important part of the Federal Government's 2011 Action Plan for Climate Change Adaptation, which recommends actions at lower policy levels (Deutsche Bundesregierung, 2011).

Among the German cities that are involved in climate adaptation activities, the city of Munich is considered as a frontrunner because of its engagement in this field (Wamsler, 2017). It had just begun the process of developing its climate adaptation strategy when the work on this thesis started and, thus, was not included with its adaptation strategy in the sample of cities that are reviewed in Paper 1. However, its integrated climate mitigation strategy contains several sections on climate adaptation, and it was therefore included (RGU, 2012). EbA is given high priority in its integrated climate change mitigation strategy. The city aims to increase the proportion of green space, and support the implementation of EbA measures (RGU, 2012). Its climate adaptation strategy was finally published at the end of 2016, and includes a separate section proposing measures that aim at increasing the use of different UGI types for adaptation purposes (Schneider et al., 2016). At the same time, the city is experiencing high population growth, high population density and increasing pressure on open spaces due to infill development (Artmann, 2014). Therefore, finding EbA solutions that can be effective in a limited space is important.

3.3 Analysis of municipal adaptation strategies

The assessment of the integration of EbA in municipal adaptation strategies was based on a nationwide sample of strategy documents. The approach consisted of a quantitative and qualitative content analysis (Roe, 1994) that, on the one hand, expressed the current situation numerically and, on the other hand, offered a way to interpret the content of individual strategies. The criteria for the analysis were derived from the conceptual framework given in Section 2.3. Figure 6 summarizes the methodological approach.

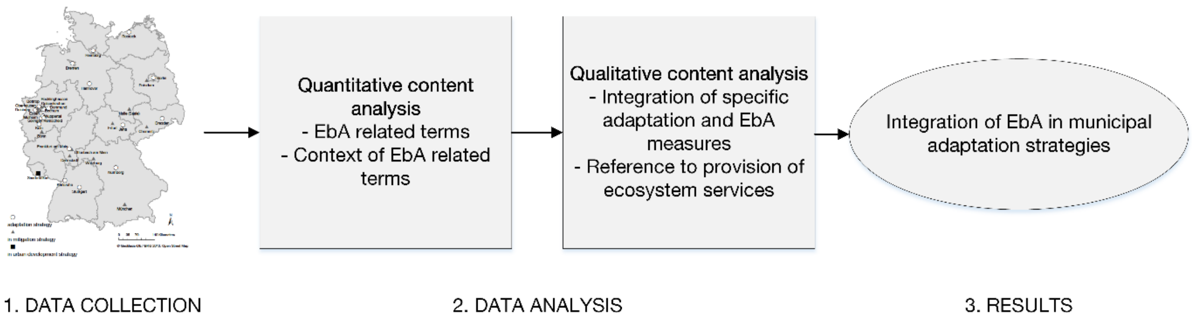

Figure 6: Methodological approach for assessing the integration of EbA into municipal adaptation strategies

3.3.1 Data collection

Larger cities are said to be especially vulnerable to climate change impacts, amongst other things due to the larger impact of the UHI effect (Zhou et al., 2013). Therefore, the analysis focused on municipal adaptation strategies in German cities with more than 100,000 inhabitants (Statistisches Bundesamt, 2014) that fulfilled the following criteria:

- The municipalities anticipated an increasing exposure to heat events and/ or flash floods in their adaptation strategies;
- The municipalities' adaptation strategies were either stand-alone strategies or an integrated part of their climate change mitigation or urban development programmes;
- These (stand-alone or integrated) adaptation strategies were publicly available as of January 2015.

Those criteria were chosen to ensure that the cities actually are affected by (a future increase of) climatic extreme events, hence need to undertake adaptation activities, as well as that their adaptation activities are documented and made accessible for the public.

On this basis, a total of 34 municipal adaptation strategies were finally identified and assessed. A list of the documents that were analysed is provided in Appendix A of Paper 1.

3.3.2 Data analysis

Data analysis began with a quantitative content analysis that identified passages of text that made reference to the EbA concept (Hansen et al., 2014; Roe, 1994). As the words used to describe EbA can differ within adaptation strategies, the following keywords were used in accordance with the developed framework and its integrative parts:

- Ecosystem-based
- Ecosystem service – Environmental service
- Biodiversity – Biological diversity
- Green infrastructure – Green structure – Natural balance – Urban ecology.

Each document was analysed with regard to the presence of these keywords. The related context was filled into an inventory document and coded in relation to the framework for the analysis and research questions. Explicit references, such as the direct use of the term 'ecosystem-based', were understood as a conscious uptake of the concept, whereas implicit references (i.e. the use of terms describing the underlying concepts) were taken as an indicator of a conceptual understanding of related objectives and benefits (Hansen et al., 2014).

The next step was to supplement the context of keywords with additional coding categories, in order to assess the relevance of EbA in municipal strategies. Codes related to the thematic sections the keywords were included in, or to which they referred. Following the work of Baker et al. (2012), five categories were selected that were also linked to the phases of developing adaptation strategies introduced in Section 1.1:

1) General background: what happens under climate change and definitions of terms;
2) Site-specific background: objectives and activities of the respective municipality;
3) Climate change impacts on ecosystems: climate change impacts and priorities for adapting to them;
4) General adaptation options: general description of possible adaptation options;
5) Specific adaptation measures: description of planned on-the-ground measures.

The second qualitative content analysis focused on those sections of municipal adaptation strategies that addressed specific adaptation measures (fifth bullet point above). A qualitative content analysis was performed. First, all measures that fulfilled the criteria of an EbA measure derived from the presented analytical framework (Section 2.3) were identified, irrespective of whether they were explicitly described as an EbA measure. Second, the contextual notations describing the identified measures were noted to assess the characteristics of EbA measures as described. UGI types were assigned according to the list presented above. In addition, the four types of ecosystem services (provisioning, regulating, supporting and cultural) were divided into 21, individual services, as specified in Figure 4.

3.4 Modelling approaches

Based on evaluating the integration of EbA into municipal adaptation strategies, the core of this thesis is to assess the effectiveness of different EbA measures for climate change adaptation. In the second stage, the focus moved from the national scale to the micro scale – a densely built-up urban neighbourhood. Two climatic extremes, a heat and a heavy rain event, were examined. There are several software packages available that can be used to model urban climate and hydrological events at the micro-scale. In particular, ENVI-met is applied as microclimatic modelling tool, and MIKE SHE is used for hydrological modelling. These models were applied and configured to match the situation in the case study area. In the following sections, their differences and similarities are discussed, and greening scenarios are presented. The aim was to hypothetically implement different types and quantities of UGI in the form of EbA measures, and assess their effects on heat and runoff regulation.

3.4.1 Study area

Munich is located at 48° 8’ 13’’ N, 11° 24’ 31’’ E and lies at 519 m above sea level. Its climate is classified as humid continental with no dry season, and warm summers with highest precipitation rates occurring during this season. A climate function map was developed to simulate data on air temperature, bioclimatic situation and wind patterns for the city, to provide an insight into thermal conditions in hot, high-pressure weather conditions (Landeshauptstadt München, 2017). The grid resolution for this map was 50 m, making it possible to differentiate the thermal conditions of different types of urban morphology. Especially in the inner city the thermal conditions are unfavourable, mainly due to high building densities, high surface sealing and low green shares.

The predominant urban morphology is perimeter blocks, which are very common both in Germany and other European cities. These blocks are characterised by high building and population density, a high level of surface sealing, and a lack of green areas (Pauleit & Duhme, 2000). According to the standardised local climate zone (LCZ) classification used in many urban climate studies, perimeter blocks are typically compact mid-rises (LCZ 2). This class is characterised by a high proportion of shaded areas, high building heat storage capacity, low backyard air ventilation potential, and a high potential for wind channelling effects within street canyons (Grothues et al., 2013; Stewart & Oke, 2012; Stiles et al., 2014a). Consequently, they can be particularly vulnerable to overheating, the UHI effect and flooding, and therefore deserve special attention when planning and implementing urban adaptation measures.

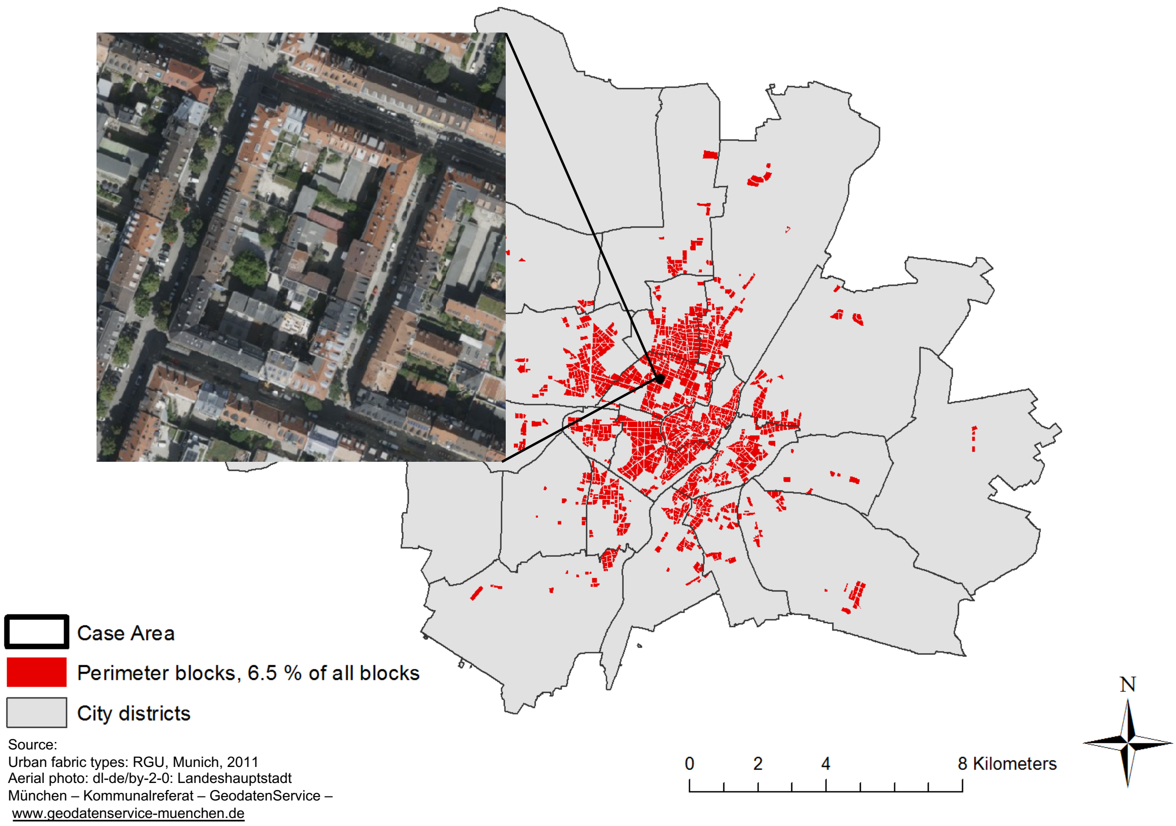

Figure 7: Perimeter blocks in Munich and the location of the case study area

More specifically, an assessment by the city administration in 2011 found that 6.5 % of all buildings can be defined as perimeter blocks (Landeshauptstadt München, 2015). An analysis of these blocks revealed that, on average, they are 72 % sealed, 28 % vegetated, and the building density is 57 %.

The case study area concerns one of these blocks. It is characterised by an above-average level of surface sealing and a below-average level of green areas, thus representing the worst-case situation for heat stress and flooding after heavy rain events. It covers an area of 3.5 ha (150 x 180 m) and is located in the central district of Maxvorstadt (Figure 7). Approximately 50 % of the case area is built-up. The main buildings are 17–25 m high, while buildings surrounding courtyards reach heights of 3–10 m. The block is oriented NE–SW, and the height–width (H/W) ratios of the NW–SE-oriented street canyons on the short edge of the block are 1.2 and 1.5, while the NE–SW-oriented canyons have H/W ratios of 0.9 and 1.3. An analysis of the Normalized Difference Vegetation Index (NDVI) and height classes based on aerial photos and field surveys found that 9.0 % of the area was covered with vegetation. This was further partitioned into 7.1 % tree cover (primarily along the streets and within courtyards), 1.6 % shrub and 0.3 % grass (in courtyards). The remaining 91.0 % was split into 44.2 % sealed and 46.8 % building surfaces. Figure 8 shows the spatial arrangement of the area, including the distribution of vegetation.

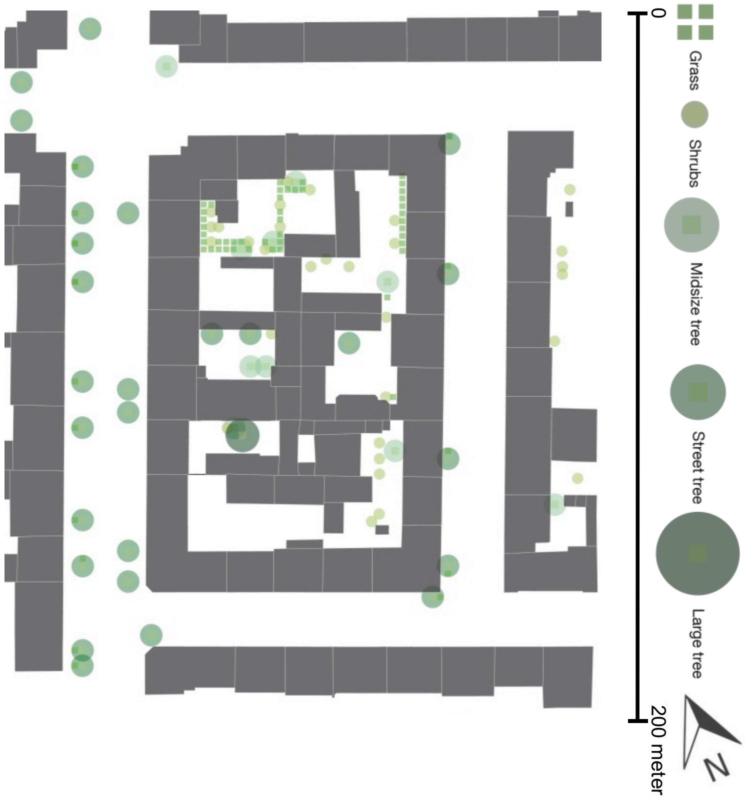

Figure 8: The case study area showing its current vegetation

3.4.2 Analysis of extreme weather events

Individual extreme heat and heavy rain events formed the primary input data for the quantitative analyses presented here and need to be analysed before the modelling work. Data on current climate conditions is drawn from weather stations and projections of future climate conditions from regional climate models.

For the analysis of the current climate conditions data for 2000 to 2010 was provided by the Ludwig-Maximilians-Universität München (LMU) weather station. This was chosen due to its location in the city centre (urban climate conditions) and its proximity to the case area. Future climate conditions were determined from projections provided by the REMO model, which are available in hourly resolution. REMO data is available at 10 km resolution for the whole of Germany, up to the year 2100, and for all IPCC greenhouse gas emission scenarios (SRES). Twelve grid boxes, covering the region of Munich, were averaged for scenario A1B and the period 2030 to 2060. This scenario represents a moderate situation that is closest to current global trends of greenhouse gas concentration (Nakicenovic et al., 2000). The period 2030 to 2060 was chosen for three reasons: a) any trees planted today would reach their optimal potential to provide ecosystem services; b) the effect of long-term municipal strategies would be seen (e.g. RGU, 2012; Schneider et al., 2016; Steinrücke et al., 2012); and c) the following time period (2060 to 2090) is too far in the future, as it is beyond the planning horizon of municipal administrations.

Selection of typical hot summer days in Munich

It is necessary to carry out a microclimatic assessment of heat days (maximum air temperature T_{max} > 30 °C; DWD, (2015)) because urban overheating and UHI effects are especially large due to high pressure, high solar radiation and low wind speeds (Parlow, 2003). Thus, for both datasets, diurnal cycles representing a typical heat day in Munich were selected. The selection of diurnal (24 hour) cycles was designed to focus on a particularly stressful situation.

The current average for heat days in Munich is T_{max} of 31.4 °C, reached in the late afternoon (4 pm), and occurs nine times per year. Under future climate T_{max} is 35.4 °C at 4 pm, occurring 14 times per year. As it is typical on heat days, wind speeds are relatively low (2.3 m/s and 1.9 m/s respectively from a south-easterly direction). On the basis of averaged T_{max} and diurnal cycles, two heat days (current and future) with comparable characteristics were selected. Figure 9 shows the diurnal cycle, and highlights that under future climate conditions T_a increases more steeply during the day, while at night they are more similar. Both curves have their lowest point around 20 °C, and hence can be called tropical nights (T_{min} > 20 °C).

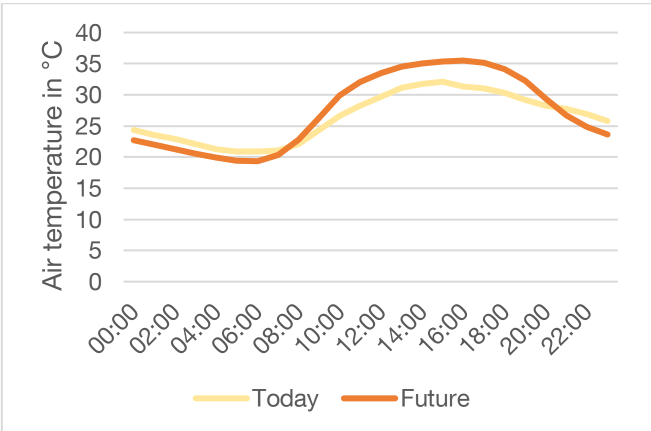

Figure 9: Diurnal cycle of air temperature of the selected heat days under current and future climate conditions (Data source: LMU weather station, the REMO climate model)

Selection of typical heavy rain events in Munich

Heavy rain events are defined as more than 10 mm of precipitation per hour, while extreme rain is precipitation of more than 25 mm per hour, which can lead to quickly-rising water levels and flooding (DWD, 2016b). Both datasets were analysed to identify those events and determine typical events in the current and future climates. Values were drawn from rain event statistics for German cities published by the German Weather Service (DWD), which are the standard reference (KOSTRA-DWD, 2000).

On average, the LMU weather station registers four heavy rain events per year, with a magnitude of 17.0 mm per hour. Most occur in the summer months, and in the late afternoon, representing an annual return period. As the design of drainage systems in urban areas is based on a two-year return period (24.7 mm/h; KOSTRA-DWD (2000)) an event representing this period was selected.

A typical extreme heavy rain event (i.e. 31.3 mm/h) of the weather station's dataset was chosen as the input to the model of future climate conditions, as the analysis of REMO data found that this value was similar to the average for the period of 2030 to 2060. The rain event reflects a five-year return period according to KOSTRA-DWD (2000). However, hourly precipitation projections for the coming decades are thought to be unreliable, as models still show significant errors, especially for highly variable, small-scale processes such as heavy rain events (IPCC, 2007; Pfeifer et al., 2015; Willems et al., 2012). Consequently, the REMO data was used as a reference point in the selection of an appropriate historical heavy rain event from the LMU dataset. Finally, both events were recorded between the months May and June, when vegetation is fully developed (Table 2).

Table 2: The two heavy rain events selected for the analysis

	Heavy rain event [mm/h]	**Date and time of occurrence**	**Return period determined from KOSTRA-DWD (2000) for Munich**
1.	24.7	05-06-2003 17:00	2 years
2.	30.9	05-05-2001 17:00	5 years

Not only does the diurnal, 24 hour, cycle needs to be considered, but also the soil moisture conditions and water storage capacity in the days surrounding the event. Therefore, a total period of two weeks (one week before and after the heavy rain event) formed the input to the hydrological model. In both cases these periods were dry, without any larger precipitation events than the heavy rain events (Figure 10). In this way, comparability is ensured.

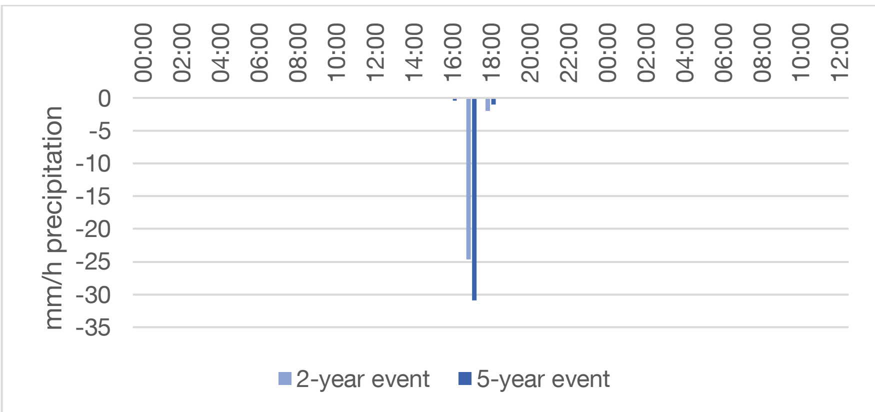

Figure 10: Precipitation patterns of selected heavy rain events (Data source: LMU weather station)

3.4.3 Microclimatic modelling with ENVI-met

ENVI-met V4 is a three-dimensional micro-scale model based on computational fluid dynamics (CFD) that simulates surface–plant–air interactions in the urban environment. It employs the non-hydrostatic incompressible Navier-Strokes equations to calculate the wind field, the k-epsilon turbulence model and the Alternating Directly Implicit (ADI) solution technique to calculate the interaction of air flow and surfaces (Bruse & Environmental Modelling Group, 2015a; Bruse & Fleer, 1998). Further details of the physical basis of ENVI-met have been described in literature (e.g. Ali-Toudert & Mayer, 2006; Bruse & Fleer, 1998; Huttner, 2012; Simon, 2016; Taleghani et al., 2015). The model operates at the micro-scale with spatial resolutions of 0.5–10 m and time frames of 24–48 hours.

ENVI-met is currently the only available urban microclimate model that offers sophisticated possibilities to include the effects of vegetation in its simulations and therefore it was selected for this study. It also offers several other benefits compared to, for example, RayMan or Solweig (Lindberg & Grimmond, 2011a; Matzarakis et al., 2010). It has a high spatial resolution, includes major atmospheric processes, such as the wind field, temperature, humidity, radiation, and turbulence, takes into account physiological vegetation processes, and represents vegetation in great detail (Ali-Toudert & Mayer, 2006; Jänicke et al., 2014; Lobaccaro & Acero, 2015; Skelhorn et al., 2014). An integrated plant database makes it possible to include vegetation profiles drawn from empirical data, or using default data. Default data includes various plant species, but no specific vegetation types, such as green roofs or facades (Jänicke et al., 2014).

This model has been applied in various studies examining the effects of urban form, vegetation, and surface materials on the microclimate, and has been validated for European climatic conditions (Jänicke et al., 2014; Lee et al., 2016; Skelhorn et al., 2014; Stiles et al., 2014a). In its current version V4 the evolution of temperature during the diurnal cycle has been improved via forcing (Bruse & Environmental Modelling Group, 2015a).

To assess outdoor thermal comfort, an integrated tool (BioMet) calculates the physiologically equivalent temperature (PET). Its application is especially useful for assessing heat regulation as it is explicitly developed for outdoor conditions and is given in °C, which makes it easily understandable for urban planners. Moreover, it is recommended in official German guidelines (VDI, 2008). To be able to compare results, and calculate the human energy balance, most studies refer to a standard person aged 35, 1.75 m tall, weighing 75 kg (Jendritzky, 1990; Jendritzky et al., 1979) who is assumed to walk quickly.

This thesis assesses the thermal situation on the afternoon of heat days (> 30 °C) when the thermal load is highest (Matzarakis et al., 2010). Hence, the analyses refer to 3 pm on an average heat day, at a height of 1.4 m, which represents the centre of the standard human body described above.

Configuration of ENVI-met V4

Table 1 summarizes the meteorological input data used in the simulations (see Section 3.4.2). Simulations were launched at 6 am for a total simulation time of 48 hours. Output data from the second day were used in the analysis, to exclude any initial, transient conditions (Bruse & Environmental Modelling Group, 2015a). Input parameters (Table 3) were selected following extensive preliminary analyses that tested the influence of the main input parameters on the modelling results. This iterative process was designed to reconstruct the real situation in the study area by providing accurate input data and producing the most reliable results possible.

Table 3: Meteorological input data for ENVI-met V4

Configuration of ENVI-met V4		
	Current climate	**Future climate**
Simulation time		
Start of simulation	06/18/2002, 6 am	06/01/2058, 6 am
Duration of simulation	48 h	
Meteorological conditions		
Wind speed (10 m above ground)	2.3 m/s	1.9 m/s
Wind direction	160°	192°
Roughness length at initialisation point of wind flow at model boundaries	0.01 m	
Mean air temperature	26.4 °C	27.4 °C
Max. air temperature	32.1 °C	35.5 °C
Specific humidity at model top at 2500 m	7 g/kg	
Initial temperature atmosphere	26.4 °C	27.4 °C
Relative humidity at 2 m	59 %	
Cloud cover	0	
Soil data		
Initial temperature at all levels	19.9 °C	
Relative humidity at all levels	60 %	

The study area was divided into a grid of 87 x 100 x 25 cells, plus 10 nesting grids, with an equidistant horizontal and vertical resolution of 2 m. The horizontal resolution of 2 m is a good compromise between computational effort and accuracy according to Salata et al. (2016). In the vertical dimension, the lowest grid cell is split into five sub-boxes (0.2, 0.6, 1.0, 1.4 and 1.8 m high) to increase the accuracy of the calculation of surface processes (Bruse & Fleer, 1998). The grid was rotated 24° from north to rectify the block structure, which simplified digitising. Existing vegetation was represented by plant profiles drawn from the integrated Albero database and based on the dominant tree species (Table 4). The most influential parameter describing the effect of vegetation is leaf area density (LAD) measured in m^2/m^3, representing one-sided foliage area per unit canopy volume.

Table 4: Vegetation classes used for the representation of current vegetation in the ENVI-met model

Vegetation class	**Street tree**	**Large tree**	**Medium-sized tree**	**Shrubs**	**Grass**
Type/ species	e.g. *Robinia pseudo-acacia, Acer platanoides*	e.g. *Pterocarya fraxinifolia, Fraxinus excelsior*	e.g. *Betula pendula, Acer campestre*	e.g. *Ligustrum spec.*	*e.g. Poa spec., Cyper spec.*
Plant height [m]	15.0	20.0	6.0	3.0	0.5
Plant width [m]	6.0	15.0	6.0	3.0	1.0
Root depth [m]	3.0	2.0	1.4	1.2	0.5
Leaf area density [m^2/m^3]	2.0	1.2	1.0	0.7	0.3
Leaf area index [-]	6.1	5.1	4.0	3.3	3.0
Dimension in ENVI-met	3D	3D	3D	3D	1D

3.4.4 Hydrological modelling with MIKE SHE

Objective 3 requires the use of a physical-based hydrological model that can determine all of the hydrological processes making up the urban water balance. This model must be raster-based, run as a small-scale application and include a detailed representation of vegetation characteristics. MIKE SHE is an integrated hydrological model, which fulfils these requirements and has been proven be able to correctly interpret hydrological processes in various applications (DHI Water & Environment, 2016; Jaber & Shukla, 2012; Ma et al.).

MIKE SHE has several advantages over other approaches such as SWMM, iTree Hydro or the more simplified runoff curve number approach (Jayasooriya & Ng, 2014; USDA, 1986; EPA, 2017; Wang et al., 2008). None of these alternatives are able to process detailed input parameters of plant characteristics, explicitly take into account processes driven by vegetation, run stable micro-scale simulations, or simulate continuous time series and hence soil moisture storage (Ahiablame et al., 2012; Fletcher et al., 2013; Jayasooriya & Ng, 2014; Wang et al., 2008; Zhou, 2014). Hence, it was selected for application in this thesis. The MIKE SHE model has already been successfully applied in studies of the impact of greening and future climate change on surface runoff (e.g. Keilholz et al., 2015; Trinh & Chui, 2013).

The following paragraphs describe the technical background, and the calculation of the most important processes (DHI Water & Environment, 2016).

- Overland flow: When precipitation is falling on sealed surfaces, the water is routed as two-dimensional overland flow. The shallow water equation (diffusive wave) is solved based on the finite difference method. The calculation of water flow depends on slopes defined by a digital elevation model (DEM). Furthermore, the roughness of surface materials is considered by the Manning-Strickler value (Perry, 1960). Additionally, if surface water can no longer infiltrate, or groundwater reaches the surface, this water contributes to overland flow (Butts & Graham, 2005). In urban areas, surface runoff is normally routed to a stormwater drainage system. The effects of these water processes can be calculated by coupling a one-dimensional hydraulic model such as MIKE 11 or MIKE Urban to MIKE SHE (e.g. City of Copenhagen, 2011). If detailed sewer data is not available, this calculation can be simplified by removing parts of the overland water automatically from the model using the paved area function.
- Unsaturated zone: Infiltration, soil moisture and recharge to the saturated zone are calculated with the unsaturated zone module. Input data are precipitation and soil data (pf-curves and saturated hydraulic conductivities). Soil data is presented in a soil map with multilayer soil types. The numerical approach is the Richards equation which is solved one-dimensionally (Richards, 1931), only considering vertical flow processes. Hydraulic conductivity changes with soil saturation. This effect is calculated by the van Genuchten formula (Van Genuchten, 1980) in combination with the Mualem function (Mualem, 1976). The representation of the lower boundary is the head of the saturated zone. By changing groundwater levels the length of the unsaturated zone is fitted automatically.
- Saturated zone: The calculation of three-dimensional groundwater flows is carried out by solving the Darcy equation using the finite difference method. Groundwater flows and heads are negligible for this study. However, the module is needed to define the lower boundary conditions for the unsaturated zone.
- Land use: To analyse the effects of vegetation, a land use module is integrated into the model. Inputs are potential evapotranspiration (ET_0), a land use map, and vegetation-specific data. MIKE SHE then calculates actual transpiration, soil evaporation and interception using the Kristensen & Jensen approach (Kristensen & Jensen, 1975). The equations (1), (2) and (3) include different functions for the leaf area index (LAI) and the distribution and depth of the roots.

- Evaporation from canopy [mm/dt]:

$$E_{can} = min(C_{int} \cdot LAI, ET_{ref} \cdot \Delta t) \qquad (1)$$

C_{int} = interception coefficient (≈ 0.05 mm)

ET_{ref} = potential reference evapotranspiration [mm/dt]

Δt = Simulation time step [dt]

- Plant transpiration [mm/dt]:

$$ET_{aT} = f_1(LAI) \cdot f_2(\theta) \cdot RDF \cdot ET_{ref} \qquad (2)$$

$f_i(LAI, \theta)$ = Functions for LAI or soil moisture (see Kristensen & Jensen, 1975)

RDF = Root distribution function (see Kristensen & Jensen, 1975)

- Soil evaporation [mm/dt]:

$$ET_{aS} = ET_{ref} \cdot f_3(\theta) + \Big(ET_{ref} - ET_{aT} - \big(ET_{ref} \cdot f_3(\theta)\big)\Big) \cdot f_4(\theta) \cdot \big(1 - f_1(LAI)\big) \qquad (3)$$

The strong coupling to the unsaturated zone makes it possible to analyse the actual evapotranspiration in relation to the actual soil moisture. This function is directly integrated into the Kristensen & Jensen approach and makes it possible, for example, to analyse vegetation water stress.

The software is organised into modules, which means that all assessed processes can be directly linked to each other.

Surface runoff, calculated as overland flow, is the decisive factor in the evaluation of the impact of heavy rain events on the urban system. Nevertheless, the urban water balance is a complex and interlinked system of contributing processes. The results presented in this thesis are averaged for the whole study area over a period of three days (one day before and after a day of heavy rain). To evaluate the temporal occurrence of surface runoff, time series for the hours before and after the heavy rain event are presented.

<u>Configuration of MIKE SHE</u>

The model requires detailed inputs in the form of meteorological and spatial data. Precipitation rates (Section 3.4.2) and reference evapotranspiration (ET_0), calculated using the Penman-Monteith equation (Allen et al., 1998; Monteith, 1981; Penman, 1956) were extracted from the climate datasets. Following this method, ET_0 was calculated based on hourly global radiation, air temperature, air humidity and wind speed. MIKE SHE was run for a simulation period of two weeks (one week before and after the heavy rain event) to overcome initial transient conditions in, for example, soil moisture, with adaptive output time steps of one-hour resolution. In both cases, a small rain event precedes the heavy rain event, only the intensity differs.

MIKE SHE is a raster-based model. Spatial input data consists of different layers, each at a 1 m grid resolution. Topography was extracted from a DEM provided by the city of Munich showing the elevation of surfaces and buildings, and other information regarding the surface roughness of different materials (Holschemacher, 2015). A land use map was derived from aerial photos and field surveys. The final model represented impermeable and permeable surfaces, together with any vegetation canopy. To ensure the comparability of results, the vegetation classes used in the microclimatic model were adopted, i.e. leaf area density (LAD), plant geometry, root depth and location (see Table 4). For ENVI-met simulations, LAD is pivotal in the calculation of the evapotranspirative behaviour of plants. In MIKE SHE, the leaf area index (LAI) is used instead. Both parameters describe the leaf area characteristics of the respective plant, and are related to each other. This relation can be expressed by empirical equations e.g. developed by Lalic and Mihailovic (2004). To generate the LAI values for the MIKE SHE simulations their approach was used as Bruse and Environmental Modelling Group (2015b) recommend. As vegetation is presented two-dimensionally in MIKE SHE, understorey vegetation could not be included. The final input parameters (Table 5) were selected following extensive preliminary analyses to test the influence of the main input parameters on the results.

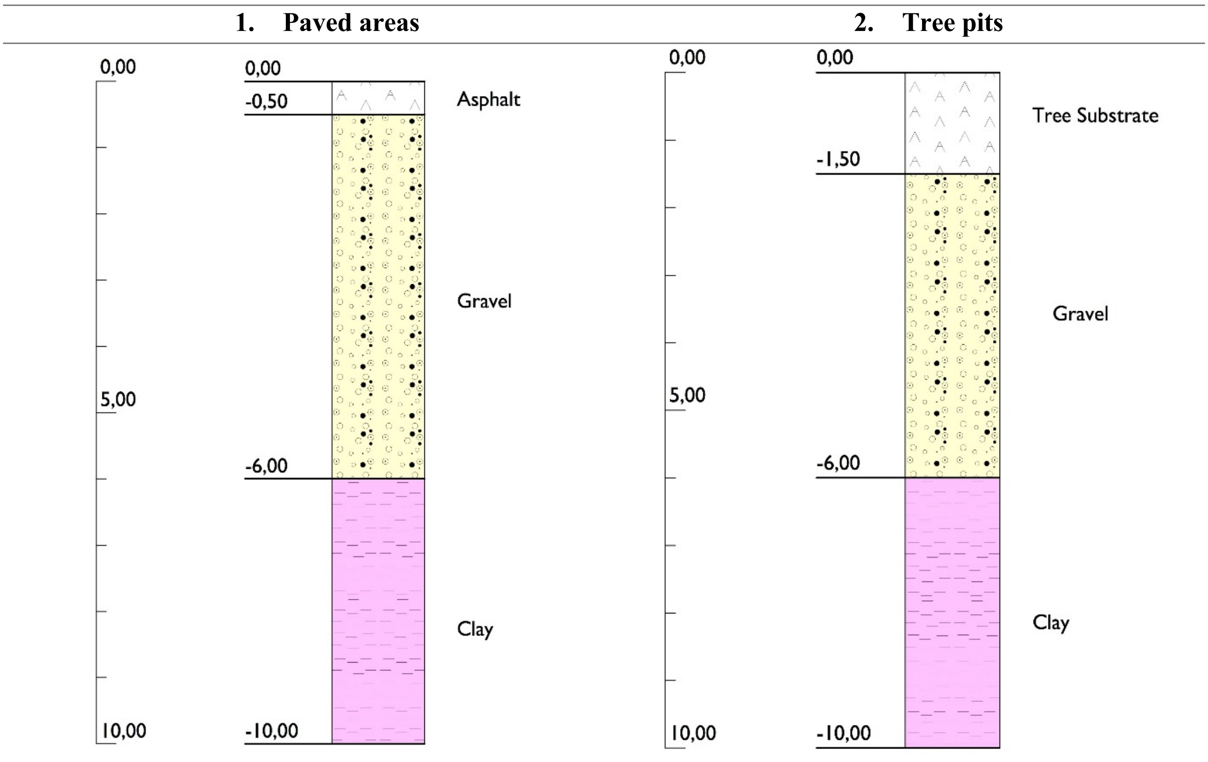

Figure 11: Soil profiles for paved areas and tree pits (Henze, 2016)

Two soil profiles were created based on borehole data provided by the Munich Water Management Office, the Munich soil atlas, and the regulation ZTV-Vegtra-Mü for paved areas and open soil, for example in tree pits (Landeshauptstadt München, 2016a, 2016b). The profiles are vertically subdivided into three layers (Figure 11):

- Paved areas: Asphalt (impermeable, artificial deposition), gravel (Pararendzina, enriched with carbonates) and clay;
- Tree pits: Tree substrate (humus, organic matter, coarse grained sand), gravel (Pararendzina, enriched with carbonates), clay.

Surface water can infiltrate permeable areas, while in paved areas water is channelled and removed from the model by activating the paved area function, and coupling the one-dimensional hydrodynamic MIKE 11 model. Hence, processes within the saturated zone are no longer considered, and are simplified using a fixed groundwater head for the overall project area. Table 5 is a summary of the relevant parameters used in the MIKE SHE model.

*Table 5: Parameter setup for the MIKE SHE model. Notes: * Saturated moisture content, ** Residual moisture content, *** Saturated hydraulic conductivity, **** Bulk density (adopted from i.e., Landeshauptstadt München, 2016b; Lösken et al., 2008; Twarakavi et al., 2010)*

Parameter	Value	Unit
Vegetation		
Leaf area index (LAI)	3–6.1	-
Canopy interception	0.05	mm * LAI
Root distribution	0.5–3	m
2D surface water		
Paved runoff coefficient	0–0.5	-
Resistance value (K_{st})	40–85	$m^{1/3}/s$
Detention storage	1	mm
Initial water depth	0	m
Surface-subsurface leakage coefficient	0.0001	l/s
Unsaturated and saturated zone		
Asphalt: θs*; θr**; K_s***; BD****	0.2; 0.001; 1e-009; 1700	-; -; -; kg/m^3
Substrate for trees: θs*; θr**; K_s***; BD****	0.347; 0.055; 0.001; 1150	-; -; -; kg/m^3
Green roof substrate: θs*; θr**; K_s***; BD****	0.347; 0.055; 0.0001; 1700	-; -; -; kg/m^3
Gravel: θs*; θr**; K_s***; BD****	0.45; 0.05; 0.005; 1700	-; -; -; kg/m^3
Clay: θs*; θr**; K_s***; BD****	0.475; 0.072; 1e-009; 1500	-; -; -; kg/m^3

3.4.5 Comparability of approaches

Figure 12 summarizes the characteristics of the two modelling approaches that are pivotal to enable the comparability of the results later on. Both take a physical approach. All calculations are based on physical equations describing natural processes and interactions within the urban microclimate and the urban water balance, for example, the calculation of evapotranspiration processes. In both models, spatial characteristics are represented as grid cells of variable resolution (2 and 1 m), which makes it possible to include small-scale information on the heterogeneous urban morphology and evaluate the results based on their spatial distribution. Concerning the temporal resolution, both approaches assess single events in hourly time steps. Although this requires very detailed meteorological input data, it provides detailed time series as output. As meteorological data for both heat and heavy rain events is available from the same sources (the LMU weather station and the regional climate model REMO), the quality and reliability of the data is comparable. Moreover, results can be derived for current and future climate conditions.

The most important factor in the quantitative assessment of EbA's regulating potential is how vegetation is represented. Both models allow for a very detailed characterisation of vegetation parameters, therefore the same vegetation profiles with the same parameters can be used as input data. To calculate the regulating effects of vegetation, the most influential parameter is the leaf area. This is considered in both models, but in different forms: ENVI-met uses the LAD, MIKE SHE uses the LAI. These parameters can be linked to each other via empirical equations (e.g. Lalic & Mihailovic, 2004). One major difference between the approaches is that ENVI-met operates in three dimensions, while MIKE SHE is limited to two. This is why the effects of facade greening can only be assessed with ENVI-met.

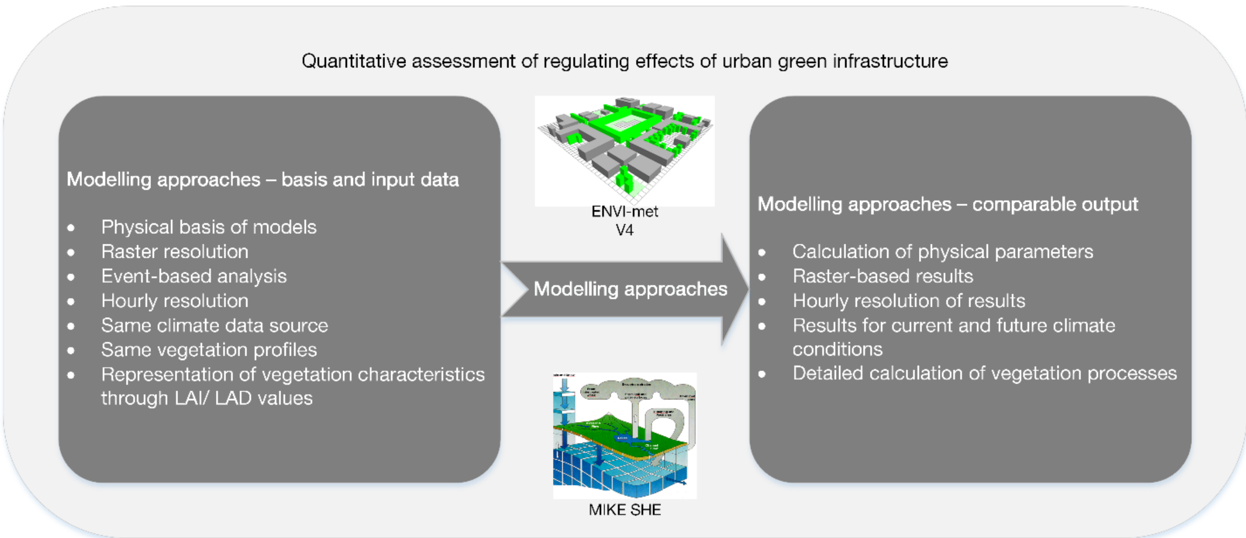

Figure 12: A comparison of the selected modelling approaches

3.5 Developing greening scenarios

Scenarios were developed to compare the regulating effects of EbA measures. Ideally, these should combine scenarios for different types and quantities of UGI, which can be implemented at micro-scale (Section 3.5.1). Quantities range from the extreme case of no vegetation cover to the highest possible percentage of green shares. Moreover, they should follow official planning guidelines to ensure transferability into practice. The greening scenarios presented in the following sections are the result of an iterative series of discussions with various experts from research and practice.

3.5.1 Selected types of urban green infrastructure

EbA measures can take the form of different types of urban greening from urban forests or parks at the city scale to green roofs and facades at the building scale (see list in Section 2.3). This thesis focuses on three types of UGI as those are the most feasible options for implementation at the micro-scale and within existing structures (e.g. Ahiablame et al., 2012). At the same time, the functions of the three types are different, which makes a comparison interesting. The following paragraphs introduce the selected UGI types in detail, with regard to their regulating functions and their implementation in cities.

<u>Trees</u>

Trees are an important element in urban ecosystems (Bolund & Hunhammar, 1999). They are planted along streets, in courtyards, in open spaces or in parks and gardens. To supply the trees with soil, water and root space they are planted in tree pits (FLL, 2015; Roloff, 2013). In addition to their aesthetic and ecological functions, urban trees provide regulating services for climate and stormwater management (Demuzere et al., 2014; Gaffin et al., 2012). The four main functions are: evapotranspiration, shading, interception and infiltration.

- Evapotranspiration is the combined process of evaporation from soils and surfaces and transpiration through leaf stomata. Both release water into the air and provide a cooling effect, as energy is needed to evaporate liquid water to water vapour (Taha, 1997).
- Shading reduces incoming solar radiation, which in turn lowers air and surface temperatures below the tree's crown (Armson et al., 2013).
- The storage of rain water in the canopy is called interception, and describes the fraction of precipitation that is held by the leaves of the canopy. The intercepted water then evaporates or, eventually, contributes to runoff with a time delay (Sanders, 1986; Xiao & McPherson, 2002).
- The surface of the tree pit is – at least to a certain extent – pervious and allows rainfall to infiltrate into the ground. From there, water is available for evaporation, transpiration or groundwater recharge (Konarska et al., 2016).

The functions of evapotranspiration, shading and interception are mainly determined by one factor – the density of the tree's leaves (e.g. Kristensen & Jensen, 1975; Moser et al., 2015). This is expressed by the leaf area index (LAI) or leaf area density (LAD). LAI expresses the one-sided green leaf area per unit surface area, and the LAD is the per unit canopy volume (Lalic & Mihailovic, 2004). The higher these values, the higher the transpiration rate, the less solar radiation is transmitted through the crown, and the more precipitation is retained (e.g. Fahmy et al., 2010; Rahman et al., 2011; Xiao et al., 2000). Infiltration depends on the permeability and size of the tree pit and its soil characteristics (e.g. Armson et al., 2013; Konarska et al., 2016).

In European cities, a wide range of tree species are typically planted (Roloff, 2013). However, in central and north-western European cities only a few genera predominate the species selection – among them *Platanus, Acer, Aesculus* and *Tilia* (Pauleit et al., 2002; Sæbø et al., 2005). Vital, healthy trees that can provide the above-mentioned services must be suitable for use in urban areas, and adapted to climate change. In Germany, two lists have been developed that evaluate the suitability of urban tree species – KLAM and GALK. KLAM was developed at the Technical University of Dresden, and evaluates tree species as a function of their resistance to drought stress and cold, with the aim of selecting trees that can be planted under future climate change conditions (Roloff, 2013). The GALK list was first introduced in 1976 by the Heads of the German Parks Departments Conference as a recommendation to municipal administrations, and has been updated regularly since then (GALK, 2012). Urban planners use these two lists to select tree species for new plantings, and are considered to ensure vital urban trees in the long term.

Green roofs

Green roofs are vegetated layers covering the rooftop. The construction is divided into four layers – a waterproof layer, a drainage layer, a filter layer and a substrate layer. The depth of the substrate layer depends on roof-carrying capacity, investment decisions and type of vegetation (Lösken et al., 2008). Generally, there are two types of green roofs, intensive or extensive. Intensive green roofs are designed as roof gardens with different types of vegetation and a thick substrate layer (> 0.2 m) (Lösken et al., 2008). This requires a complex construction, and the level of maintenance is high as irrigation is often needed. Extensive green roofs, on the other hand, are greened with undemanding vegetation and are suitable for large areas or sloped roofs, as their technical design and maintenance requirements are simple (Berardi et al., 2014; Getter & Rowe, 2006). For instance, roofs planted with low, dense and drought-resistant vegetation of little height are well-suited to residential buildings, and for retrofitting the existing building stock (Ahiablame et al., 2012). Like trees, green roofs provide regulating ecosystem services for cooling and rainfall retention by evapotranspiration, changes in surface albedo, interception and infiltration (Ansel et al., 2011; Pfoser et al., 2013). By greening rooftops their albedo changes, increasing reflection of incoming solar radiation, and reducing heat storage (Santamouris, 2014). Evapotranspiration, interception and infiltration vary as a function of the substrate's depth and hydraulic characteristics, and the LAI of vegetation (e.g. Czemiel Berndtsson, 2010). In urban areas, where space for additional greening is limited, green roofs have the advantage of occupying space that is normally unused (Stovin, 2010). Hence, city administrations support their implementation through different programmes and incentives, for example, directly by providing financial incentives and making them a legally-binding part of master plans, or indirectly by reductions in sewage fees (Ansel et al., 2011).

Green facades

Green facades are plants growing on a vertical surface, typically the walls of buildings. There may or may not be any further infrastructure, and vegetation is rooted either in the ground or in planters installed on the ground or within the facade. Some systems need irrigation (Pfoser et al., 2013). Green facades can technically be attached to a large proportion of walls in a city, and the space required for their implementation is low compared to, for example, trees (Köhler, 2008; Manso & Castro-Gomes, 2015). The regulating ecosystem services provided by green facades are evapotranspiration, shading, changes in surface albedo and infiltration (if rooted in the ground) (Pfoser et al., 2013). Unlike trees, there is no shading of open spaces, but building walls covered by vegetation have lower surface albedo; consequently, they prevent incoming solar radiation from heating up the building materials, and decrease long-wave radiation into the open space (Cameron et al., 2014; Jänicke et al., 2014). Like trees and green roofs, the evapotranspiration and shading capacities of green facades are contingent on the plant's LAI, and infiltration capacity on the size and hydraulic characteristics of their planting pits (if rooted in the ground). As for green roofs, cities can support the implementation of green facades directly with financial incentives (Pfoser et al., 2013).

3.5.2 Development of scenarios

To assess the regulating effects of different UGI types, a comprehensive set of greening scenarios was developed. This novel approach integrates different types and quantities of UGI, under varying initial conditions, while at the same time taking into account the planning guidelines practitioners must follow (Figure 13). Municipal representatives were invited to stakeholder workshops during the development of the approach, and provided feedback on complex local requirements and practices. Their comments were taken into account when parameterising the different scenarios.

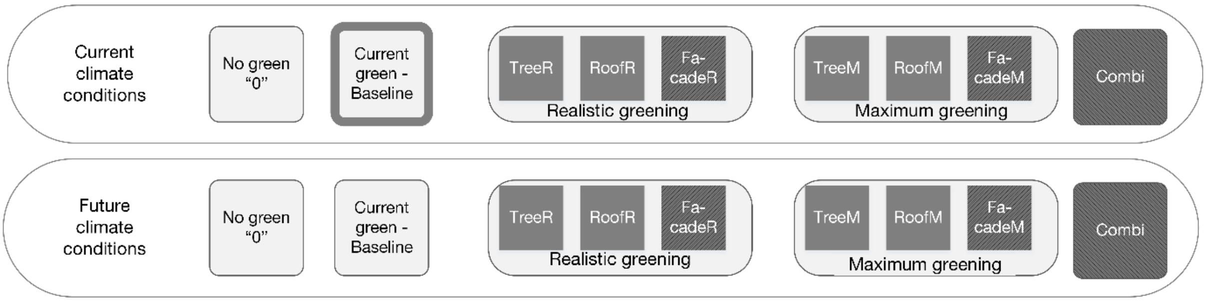

Figure 13: Green infrastructure scenarios tested with both modelling approaches. The Baseline scenario is highlighted. Facade greening was only simulated by the Microclimatic model, and the Combi scenario by the hydrological model. These scenarios are hatched.

The current greening situation (Section 3.4.1) forms the Baseline. The other scenarios range from the extreme cases of no vegetation ('0') to maximum greening for each proposed type of UGI (TreeM, RoofM, and FacadeM). The 'no green' scenario assumes the total loss of vegetation and completely sealed surfaces. The 'maximum greening' scenario assumes that vegetation is present in all available spaces except buildings. In this case, trees are planted in pits on pavements, on parking lots and courtyards, and all walls and roofs are greened. Between the Baseline and maximum scenarios, a set of presumably realistic scenarios (TreeR, RoofR and FacadeR) was created, representing greening interventions that are technically and spatially feasible. One objective was to place vegetation in areas that are most exposed to heat, notably those that are south-west oriented (e.g. Lee et al., 2016; Norton et al., 2015) as the location of the vegetation is assumed to have a large impact on heat mitigation. Other realistic interventions included planting trees on pavements and in courtyards at a minimum distance of 10 m from each other, only greening flat-roofed buildings (in courtyards) and greening two-thirds of facades. For individual trees, it was assumed that they would provide more cooling than tree stands per unit canopy area, because their canopies intercept light over a greater area (Ennos, 2010). Greening is most likely to be technically feasible on flat roofs, and approximately one third of a facade cannot be greened due to space requirements for windows (Pfoser et al., 2013). Facade greening was only tested in the microclimatic model, as the hydrological model is two-dimensional and cannot represent this situation. Finally, a combined, realistic scenario of green roofs and trees was developed ('Combi') and tested in the hydrologic model. For all scenarios, the existing Baseline vegetation was preserved (except for scenario '0'). In the case of overlapping vegetation types, priority was given to the type with the higher leaf area. To isolate the effects of vegetation from the effects of the urban form, the arrangement of streets, buildings and surface materials were kept constant in all scenarios. Figure 13 sums up the approach, and Figure 14 presents the location of the respective types of UGI in each scenario.

The extent of greening is 9.0 % in the Baseline scenario (see Section 3.4.1). Table 6 gives the respective percentages for all scenarios, and the percentage of permeable surfaces for scenarios tested in the hydrological model. Permeable surfaces are, to a certain extent, the same as greening (e.g. for green roofs). However, for trees the percentage of permeable surface is less than greening, as only the size of the tree pit is counted, while the crown is counted as green cover. For each modelling approach, these percentages were calculated using the respective software or analysis tools (R for microclimatic modelling, MIKE SHE for hydrological modelling), and from a two-dimensional perspective. For this reason, the proportion of green facades is lower than if their vertical coverage is included. Due to the different sizes of grid cells (ENVI-met 2 m, MIKE SHE 1 m) and the rotation from the north (in ENVI-met) the calculated percentages vary for the same spatial setups.

Table 6: Green share and permeable surfaces of all scenarios calculated by the two models

Scenario	**ENVI-met**	**MIKE SHE**	
	Green share %	Green share %	Permeable surfaces %
‘0’	0.0	0.0	0.0
Baseline	9.0	6.4	1.7
TreeR	23.6	14.9	3.9
TreeM	35.6	25.3	6.5
RoofR	17.8	14.6	10.1
RoofM	55.8	54.3	50.0
Combi	-	22.7	12.2
FacadeR	12.3	-	-
FacadeM	19.3	-	-

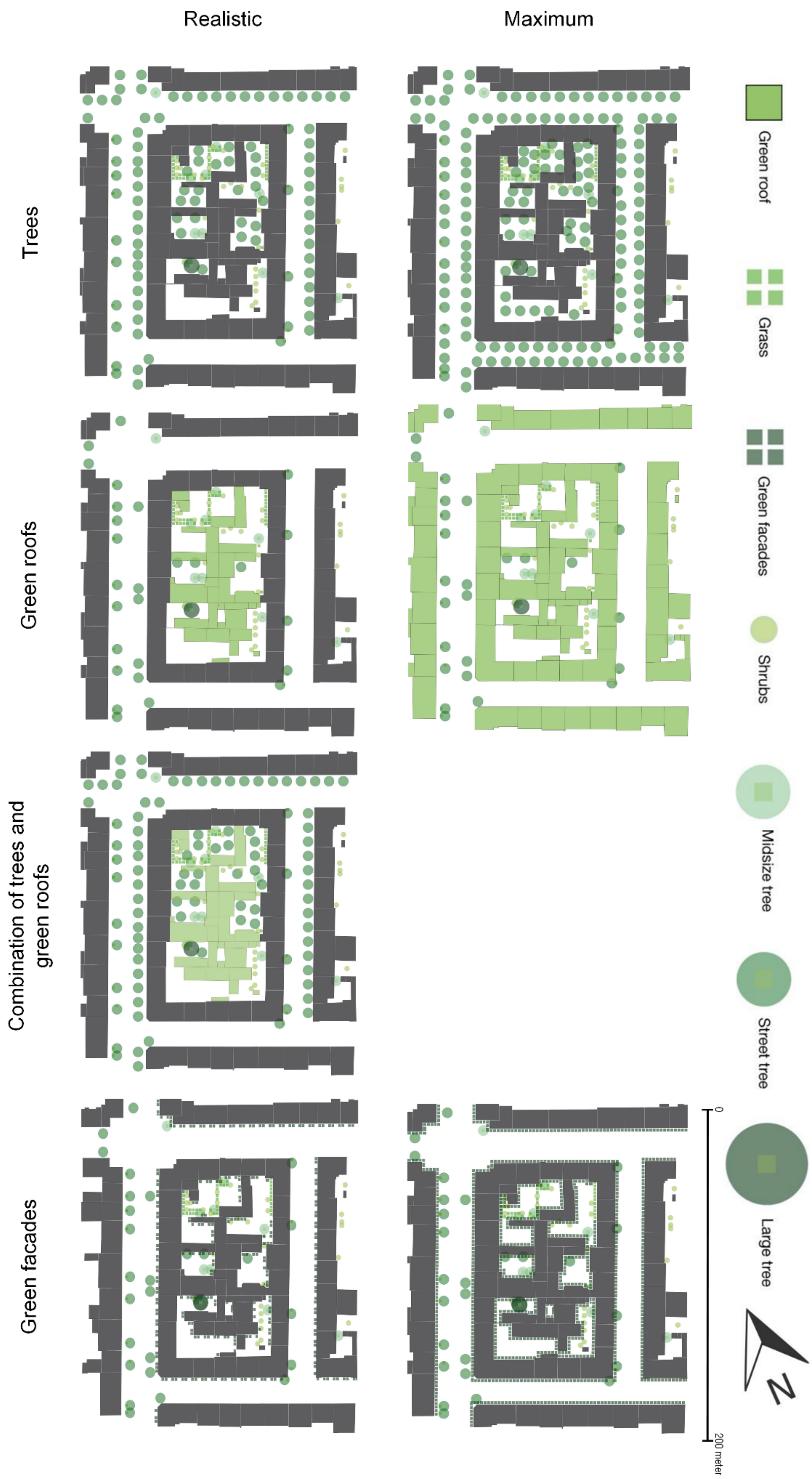

Figure 14: Overview of all greening scenarios with location and distribution of the respective UGI type

3.5.3 Definition of vegetation profiles

To build the scenarios within the two modelling approaches vegetation profiles were defined for each UGI type. The ENVI-met package includes a database of common European vegetation profiles that defines species, geometry and leaf area characteristics. As it was not possible to collect empirical data regarding existing vegetation on the ground, these profiles were used and supplemented by information from the literature on, for example, facade greening. Table 7 presents the three vegetation profiles that were selected, namely a type of tree frequently found in Munich and rated as suitable for urban areas by GALK and KLAM (GALK, 2012; Roloff, 2013), an extensive green roof covered by grass and a typical way of facade greening with creeper.

Table 7: Characteristics of the selected vegetation profiles used in greening scenarios. Adapted from ENVI-met Albero and Jänicke et al. (2014).

UGI type	**Tree**	**Green roof**	**Green facade**
Type/ species	*Acer platanoides*	Extensively greened	*Parthenocissus tricuspidata*
Plant height [m]	15.0	Max. 0.5	Depending on building height
Plant width [m]	6.0	1.0	1.0
Root depth [m]	3.0	0.5	1.0
Leaf area density [m^2/m^3]	2.0	0.3	1.9
Leaf area index	6.1	3.0	Depending on building height

Next to the leaf area other parameters regarding vegetation profiles were set. Consistent with municipal regulations of the city of Munich, the size of the trees' planting pits was set to 36 m^3 with a diameter of 3 m (Landeshauptstadt München, 2016b). The technical construction of the green roof consisted of a 0.2 m thick substrate layer as recommended by Lösken et al. (2008). This made the creation of a third soil profile for the green roof substrate necessary (compare Section 3.4.4). It consists of the 0.2 m substrate layer made up of coarse-grained material such as lava, pumice and expanded slate and an impermeable clay layer representing the roof construction (Lösken et al., 2008).

3.6 Assessment of multiple ecosystem services

The final step was to compare the results of the two models, in order to draw some conclusions on the synergies of EbA measures implemented to regulate both heat and runoff. First, the reduction potential of each scenario was compared and ranked. Only scenarios that were assessed in both models were used. Reduction potential for heat and runoff mitigation was expressed as the relative change in either PET values, or runoff volume as a percentage of the overall precipitation volume, compared to the Baseline scenario. The regulating effects of single types of UGI (trees and green roofs) were compared by referring to their specific functions (Section 3.5.1). The results and their comparison offer a better understanding of the key vegetation parameters needed to provide certain functions, and make it possible to optimise vegetation characteristics.

4. RESULTS

This section summarises the results presented in Papers 1 to 3, and the evaluation of EbA synergies for heat and runoff mitigation (Objective 4).

4.1 Integration of EbA into urban adaptation strategies

The 34 climate change adaptation strategies included in this analysis (Appendix A of Paper 1) are significantly different in terms of their type, structure, scope and presentation. Nineteen are stand-alone policies, 14 are part of municipal mitigation strategies, and one is part of an urban development strategy (Figure 15). Overall, stand-alone adaptation strategies were more comprehensive and detailed than others.

The context analysis showed that almost half of the keywords (47 %) appeared in the section of the documentation focused on specific adaptation measures. With respect to individual keywords, in all cases, most references to EbA related to specific adaptation measures, while 'biodiversity' was frequently included in the context of climate change impacts. This gives a first insight into the importance of EbA and its related concepts. Following from the fact that EbA receives its main attention, when specific adaptation measures are presented, a high relevance, clear understanding of the purpose of EbA and high chances for an actual implementation of measures are indicated.

Figure 15: Large German cities with adaptation strategies, either as a stand-alone policy, or as part of municipal mitigation or urban development strategies (as of January 2015)

Furthermore, the analysis showed that 76 % of climate change adaptation strategies include adaptation measures that can be related to EbA according to the analytical framework. The percentage of EbA measures compared to conventional, engineering-based measures ranges from 15 to 100 %. In three cities, all adaptation measures can be linked to EbA: Munich (integrated into a mitigation strategy), and Bremen and Mülheim (stand-alone adaptation strategies). Many cities provide a comprehensive list of planned adaptation measures (ranging from 0 to 157) together with more-or-less detailed explanations. The urban ecosystems used or created by EbA measures cover all classes of UGI from green buildings to urban forests. Parks/ lawns are the most frequent (93 instances) individual measures. In contrast, greening of buildings (19 instances) is least frequent. Typical EbA measures include: a) the creation of new ecosystems by planting trees, greening roofs and facades, or creating climate-regulating green spaces; b) measures that have an impact on parks/ lawns such as the conservation and extension of parks for fresh air exchange or the use of green areas as flood retention areas; and c) strategic and regulatory measures, for example, the implementation of a biodiversity strategy, the development of habitat connection plans, or the promotion of species diversity when planting trees.

Regarding the effectiveness of EbA measures, only Berlin and Köln had attempted to quantify their impact through microclimate simulations. These showed a reduction in air temperature as a result of implementing greening programmes (e.g. street trees or facade greening). No other evidence is available concerning the effectiveness of EbA (Grothues et al., 2013; Senatsverwaltung für Stadtentwicklung Berlin, 2011).

Regarding the expectations and reasons for integrating EbA measures into adaptation strategies, 14 of the 21 individual ecosystem service categories were mentioned. On average cities named 11 different ecosystem services as motivation for their EbA measures. Regulating services were cited most often (303 instances), which highlights the importance of local climate regulation as the main purpose of EbA measures. Except for Mühlheim, all cities that listed specific adaptation measures referred to regulating ecosystem services in their strategies. Among these services, ‘urban temperature regulation’ was used 121 times to refer to measures such as the conservation of fresh air corridors and greening facades. ‘Run-off mitigation’ was achieved by, for example, greening roofs and unsealing impermeable surfaces (54 instances), while ‘moderation of extreme events’ through, for example, climate-adapted species selection was used 59 times. With respect to individual adaptation strategies, 48 % included EbA measures with multiple objectives that aimed to provide more than one ecosystem service. In absolute terms, 25 % of descriptions of EbA measures refer to multiple objectives.

4.2 EbA potential to regulate heat events

On a hot summer day pedestrians experience moderate to extreme heat stress in all open spaces in the Baseline scenario. PET reaches 41.1 °C on average, with single values ranging from 34 °C to nearly 60 °C at 3 pm. Within the study area, thermal comfort varies. Highest discomfort occurs in the north-eastern courtyard, where there is no ventilation, wind speeds are close to 0 m/s, and south-western oriented facades and asphalt surfaces reflect incoming solar radiation (Figure 16, left side). The coolest spots are found in street canyons and courtyards shaded by trees and buildings, with PET values between 34 and 39 °C. Where streets are not shaded, PET is higher as a high proportion of incoming solar radiation is re-radiated from the asphalt.

Under climate change, thermal discomfort for pedestrians increases by 6 %, to an average PET of 43.5 °C (ranging from 37–62 °C PET). Spatial variability is similar to today's climate, as the north-eastern courtyard is still the area of highest discomfort, with PET values up to 62 °C. Even in shaded areas, PET increases to over 41 °C, leading to extreme heat stress. This is especially true for shaded courtyards, where there is little wind and hot air cannot escape (Figure 16, right side).

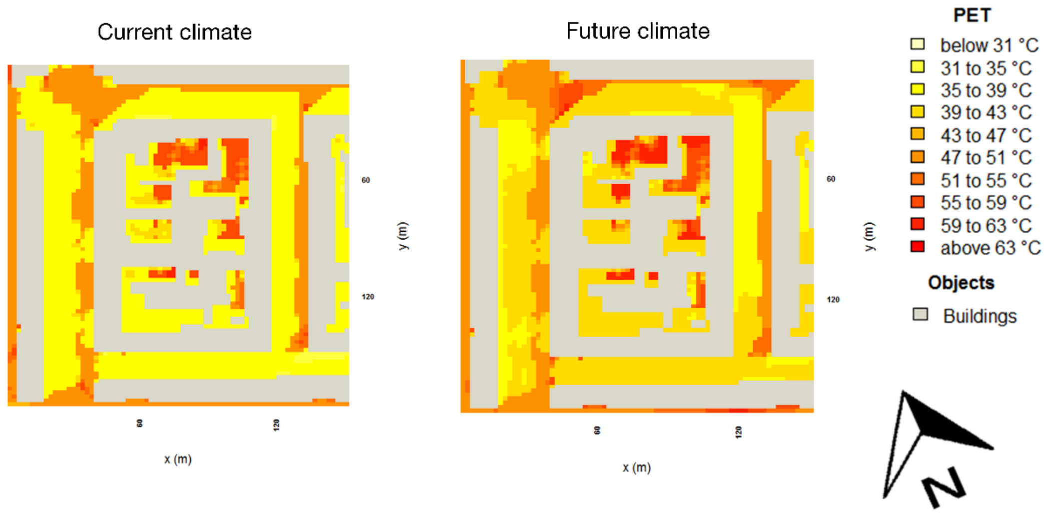

Figure 16: Simulated PET values for a height of 1.4 m at 3 p.m. for the Baseline scenario under current and future climate conditions.

Although all greening scenarios achieve an improvement in PET values compared to the current situation, thermal comfort remains low. Average PET values for all scenarios indicate strong (35–41 °C PET) to extreme (above 41 °C) heat stress. This shows that the regulating potential of the different scenarios varies as a function of the UGI type and quantity.

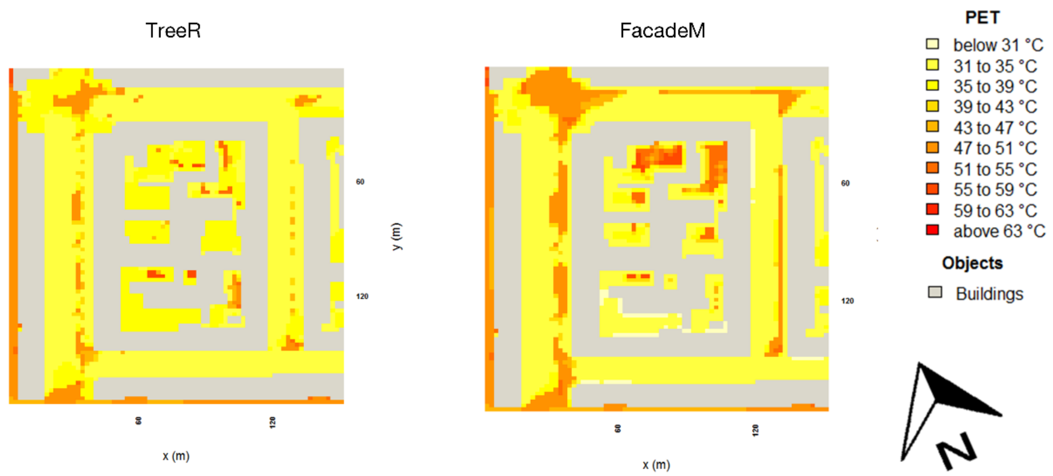

Figure 17: Simulated PET values for a height of 1.4 m at 3 p.m. for the TreeR and FacadeM scenarios. Although both show an average PET reduction of 10% compared to the Baseline, there are differences in local regulating effects.

Planting trees has the highest potential to mitigate thermal discomfort during heat days. Maximum tree planting (TreeM, 34 % tree cover) reduces PET by 13 % compared to the Baseline. TreeR has tree crown cover of only 24 %; however, it still achieves a PET reduction of 10 %. Most of this reduction comes from shading and evapotranspiration (e.g. Bowler et al., 2010; Konarska et al., 2014; Shashua-Bar & Hoffman, 2000). PET values reflect the pattern of solar radiation hitting surfaces, as expressed by T_{mrt}, which governs PET as a dominant factor during the daytime of calm and windless days (Lee et al., 2016). Local PET values under tree crowns decreased to a minimum of 31 °C in TreeM, representing moderate heat stress. The highest mitigating effect of trees occurred in the north-eastern courtyard, where PET was reduced up to 40 % compared to the Baseline (Figure 17, left side).

A comparison of green roofs and facades reveals significant differences in their heat mitigation capacity. Green roofs do not contribute to shading effects and are distant from street level. Their contribution to reducing PET at the 1.4 m level is small for RoofM (0.5 %) and zero for RoofR (no reduction). However, green facades achieve average PET reductions in the range of 10 % (for FacadeM) and 5 % (for FacadeR) under today's climate. Green facades decrease the heating of walls and the reflection of incoming solar radiation (Jänicke et al., 2014; Pfoser et al., 2013) leading to a reduction of T_{mrt} and PET in front of green facades. When facades are greened, minimum PET values in the study area dropped to 30 °C compared to 34 °C with current greening. However, this reduction is restricted to the immediate proximity of the green facades (Figure 17, right side). Further away (> 2 m), no effects were observed. Therefore, differences in thermal conditions between urban locations are closely related to the amount of solar radiation reaching the surface, i.e. the sky view and the proximity of vegetation (Oke, 1980).

The heat mitigating effects of trees, green roofs, and green facades are summarized in Table 9. Figure 17 compares the spatial cooling effects of trees and green facades. Both scenarios achieve a reduction of 10 %, but the heat maps reveal that trees increase the fraction of shaded open spaces, while green facades provide cooling by hindering the re-radiation of heat from building walls.

4.3 EbA potential to regulate heavy rain events

In both current and future climate conditions, precipitation represents the main water inflow into the study area. These inflows are converted into an outflow (i.e. surface runoff that is discharged into the sewage system, evapotranspiration, or subsurface flows), or an increase in the water stored by the system. All of these components are shown in Table 8.

For the smaller heavy rain event with a two-year return period, 95.7 % of precipitation is discharged, whereas 2.7 % contributes to evapotranspiration, and 0.8 % to groundwater recharge. The evapotranspiration rate is an aggregation of plant transpiration, soil evaporation and evaporation from ponded water, either from surface runoff or canopy interception. As only 6.4 % of the study area is greened, evapotranspiration from interception remains relatively low. Moreover, only 2 % of surfaces are permeable. For example, tree pits infiltrate water through the topsoil and contribute to soil evaporation, plant transpiration, or groundwater recharge.

*Table 8: Hydrological processes in m^3 and % for the Baseline scenario under current and future climate conditions. Note: * For example evaporation from detention storage, boundary outflows, model error.*

	Two-year return period		Five-year return period	
Hydrological process	m^3	%	m^3	%
Precipitation	−779.0	−100.0	−978.8	−100.0
Surface runoff	745.7	95.7	946.6	96.7
Evapotranspiration	20.8	2.7	15.7	1.6
Evaporation from interception	2.0	0.3	2.0	0.2
Soil evaporation	3.9	0.5	3.1	0.3
Plant transpiration	12.5	1.6	8.9	0.9
Evaporation from overland flow	2.5	0.3	1.6	0.2
Groundwater recharge	6.0	0.8	2.8	0.3
Storage change	−7.5	−1.0	−6.3	−0.6
Others*	14.0	-0.9	20.1	0.4

Under future climate change scenarios, rainfall intensity is higher and 96.7 % is discharged. The relation between the precipitation event and amount of surface runoff remains relatively stable. The rate of surface runoff is higher compared to current climate conditions due to higher levels of precipitation in the same time step, and immediate discharge from the surface. Figure 18 shows that most precipitation drains away within the hour of a heavy rain event. In return, water has proportionally less time to infiltrate, evapotranspire or be intercepted.

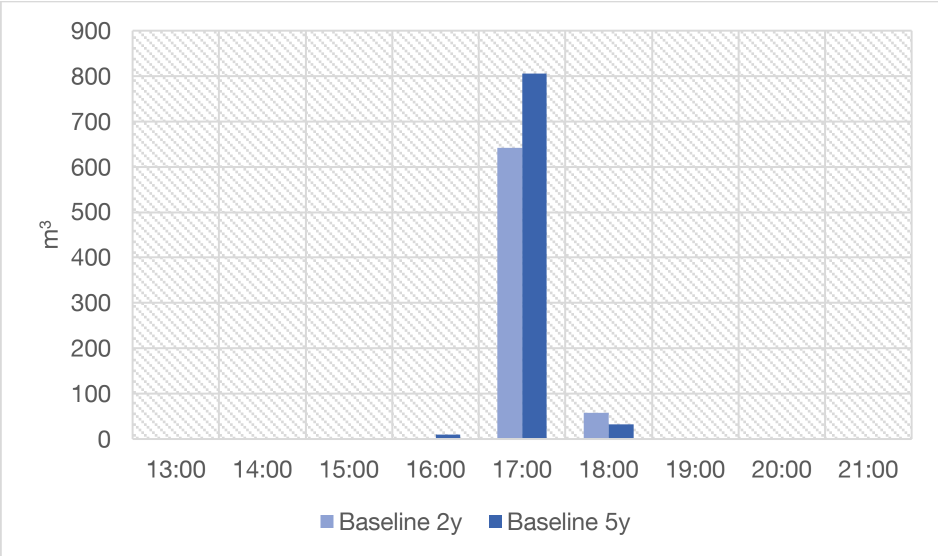

Figure 18: Surface runoff in the Baseline scenario in hourly time steps before and after heavy rain events (two- and five-year return period)

The addition of vegetation to the Baseline scenario decreases surface runoff and increases evapotranspiration. The biggest increase can be attributed to soil evaporation and plant transpiration. Another effect observed are the increased rates for water uptake from saturated and unsaturated zones needed for transpiration during dry summer months. This leads to a lack of storage in the unsaturated zone. This additional inflow means that increased evapotranspiration has more impact than reductions in surface runoff. Under future climate conditions (i.e. higher rainfall intensity), surface runoff reductions are slightly less than under current conditions, as less water is retained and made available for evapotranspiration and infiltration. The most effective runoff reduction scenario has the highest percentages of green cover and permeable surfaces (RoofM, 54.3 % greening). As for the other greening scenarios, a maximum difference of 2.4 % from the Baseline is reached in the Combi scenario (22.7 % greening). TreeR and RoofR have almost the same percentage of green cover (approximately 15 %), while their surface runoff rates are 94.8 % and 94.2 % respectively for the two-year return period. Small differences are found in evapotranspiration, groundwater recharge and storage change due to the higher percentage of permeable surfaces in the RoofR scenario. On the other hand, the result of the Combi scenario is almost the sum of the two individual scenarios RoofR and TreeR. The difference can be explained by the presence of tree crowns over green roofs in courtyards, and the inclusion of only the tree layer in the two-dimensional simulation.

4.4 Synergetic effects for heat and flood mitigation

The results of Papers 2 and 3 clearly show that all UGI types reduce both heat stress and surface runoff, independent of the quantity of their implementation. Nevertheless, regulating potential varies within the scenarios, as a function of the UGI type and quantity (Table 9). Trees are most effective for heat mitigation with PET reductions of up to 13 %, due to their ability to provide both shading for open spaces and building surfaces and evapotranspirative cooling. Shading is the more influential parameter, as it reduces incoming solar radiation and consequently the heating of artificial surfaces, which re-radiate heat (Akbari, 2002; Oke, 2011). With respect to runoff mitigation, increased evapotranspiration is beneficial, as is interception by the tree crown and infiltration into tree pits. Infiltration has the biggest impact on reducing runoff. However, the unsealed land available to plant trees and increase infiltration is limited, and the maximum reduction (2 %) is far less than that achieved by green roofs (14.8 %). This shows that in this case, permeable green roofs are the most effective UGI type due to their ability to provide large capacities for infiltration through their permeable surface. On the other hand, they are least effective for heat mitigation at pedestrian level due to their distance from the street.

Consequently, both trees and green roofs are complementary for achieving adaptation to extreme heat and heavy rain events, however their contribution differs as they provide two different functions: shading of open spaces and building surfaces (for heat mitigation) and infiltration capacity (for runoff mitigation).

Table 9: The potential for heat and runoff regulation expressed as relative change compared to the Baseline scenario under current climate for each greening scenario under current and future climate conditions

Scenario	**Heat regulation**		**Runoff regulation**	
	Current climate	*Future climate*	*Current climate*	*Future climate*
'0' = No greening	+ 4.3	+ 10.7	+ 0.7	+ 1.6
Baseline = Current greening	0.0	+ 6.3	0.0	+ 1.0
TreeR = Realistic trees	−10.3	−4.0	−0.9	+ 0.2
RoofR = Realistic green roofs	0.0	+ 6.3	−1.5	−0.4
FacadeR = Realistic green facades	−5.1	+ 0.9	(Not assessed)	(Not assessed)
TreeM = Maximum trees	−13.0	−7.1	−2.0	−0.9
RoofM = Maximum green roofs	−0.5	+ 6.3	−14.8	−13.4
FacadeM = Maximum green facades	−9.8	−4.1	(Not assessed)	(Not assessed)
Combi = Realistic trees and green roofs	(Not assessed)	(Not assessed)	−2.4	−1.2

Furthermore, the results show that the strategic placement of vegetation in heat-exposed areas increases its heat mitigation effects and reduces the need for additional green cover, while for runoff mitigation in flat areas (like the study area) the extent of green and permeable surfaces is key, resulting in a need for extensive green cover. While the maximum tree crown cover (34 %) reduces PET by 13 %, just 22 % cover can reduce PET by 10 % if hotspots are prioritized. With respect to runoff mitigation, there is a clear relation between green cover and runoff reduction, as maximum green cover (54 %) achieves the maximum runoff reduction (15 %). This is confirmed by comparing RoofR and TreeR scenarios, which both have 15 % green cover and a similar runoff reduction potential. Hence, to regulate heat events, vegetation needs to shade heat exposed areas, while to regulate heavy rain events, green cover must enable infiltration (expressed as the extent of permeable surfaces).

As the greening scenarios can only take account of one vegetation profile per UGI type, Table 10 summarizes the vegetation characteristics that contribute to either heat or runoff regulating ecosystem services, and which should be considered when selecting plants. These parameters were found to be influential during sensitivity testing before the model setup. Optimizing one service can positively influence the provision of other services, intensifying synergies. For instance, a tree with a high LAD not only has high shading potential, but also higher interception rates. Green roofs with deep substrate have a high capacity for retaining water, while also increasing the potential for evapotranspirative cooling.

Table 10: Vegetation characteristics for optimising heat and/or runoff mitigation

	Heat mitigation	**Runoff mitigation**
Trees	High evapotranspiration rates High leaf area density for shading High crown volume for shading Drought tolerance	High leaf area density for interception Large crown volume for interception High evapotranspiration rates Large tree pit for infiltration
Green roofs	High substrate depth for evapotranspirative cooling High evapotranspiration rates Drought tolerance	High substrate depth for infiltration and retention High evapotranspiration rate
Green facades	High leaf area density for shading Drought tolerance	(Not assessed)

To summarise, all of the assessed UGI types can contribute to climate change adaptation by mitigating both heat and runoff, so being synergetic. However, urban planners and decision-makers need to establish their priorities when choosing the most effective type of UGI for their situation – trees for heat mitigation, and green roofs for runoff mitigation – and optimise the UGI type accordingly.

5. DISCUSSION

The first part of this section discusses the relevance and general limitations of the main findings, first in terms of the current integration of EbA, then for its regulating potential to extreme heat and rain events. The next part is dedicated to the multifunctionality of EbA, followed by a discussion of the methodological limitations of the modelling approach to improve the understanding of the underlying assumptions when interpreting the study's results. Finally, some practical implications for urban planning are discussed.

5.1 Current status of EbA in strategic urban planning

The results of Paper 1, presented in Section 4.1, show that the EbA concept and terminology have not yet been disseminated to the local policy level in Germany, as none of the strategies included in the analysis took a comprehensive approach to EbA. While the importance of EbA is acknowledged at federal level (BfN, 2012; Doswald & Osti, 2011), this has not led directly to a successful uptake at local level. Wamsler et al. (2017) suggest some pathways for effective EbA mainstreaming at local, institutional and interinstitutional level, meaning that integration could become a standard procedure. The latter study finds that power relations and conflicts of interests at all levels can hinder implementation. For example, municipalities see climate change mitigation and adaptation as separate issues and, hence, miss sharing experiences or exploiting potential synergies. This is consistent with the results of Pasquini and Cowling (2014) and Wamsler et al. (2016) for South Africa and Sweden, which suggest that a lack of knowledge transfer and institutional fragmentation underlie the lack of integration of EbA into urban adaptation planning.

Nevertheless, most strategies included indirect references to the underlying principles of EbA (ecosystem services, biodiversity and green infrastructure), indicating a general understanding of the concept. Interestingly, the term 'ecosystem service', even though more closely related to EbA, receives less attention than the term 'biodiversity'. This may be due to the fact that the term 'ecosystem services' was created by academia (MA, 2005). This is seen in Dresden's strategy, which is the product of a large research project and contains most references to the term compared to all other assessed strategies (REGKLAM, 2013). Other reasons that the concept is not further acknowledged could include that: a) it is a recent development; b) some aspects of it (e.g. monetarisation) have been criticised by municipal staff (Wamsler, 2015) and c) ‘older’ concepts, such as ‘landscape’ or ‘ecological functions’ still exist in the German planning discourse (Albert et al., 2012). On the other hand, the importance given to biodiversity might in Germany be related to the fact that the country expects climate change to have severe impacts on biodiversity in the near future (Mosbrugger et al., 2013). It is interesting to note that in Sweden, biodiversity has been the driver of EbA approaches (Wamsler et al., 2016).

It is clear that in Germany, the EbA concept is more widely understood by the research community than by the municipal administrations or private companies who are the authors of the assessed adaptation strategies. The example of Dresden supports findings from studies in other regions, which reveal that progress in EbA integration is most often found in cities where climate change adaptation research is being carried out (Pasquini & Cowling, 2014; Wamsler, 2015). For instance, in South Africa, Pasquini and Cowling (2014) concluded that research activities facilitated collaboration for environmental goverance and consequently the mainstreaming of EbA in a city administration.

This raises the question of whether EbA is the best term to use (outside of academia) to promote climate change adaptation using ecosystems and biodiversity, given that it is not fully accepted by practitioners (Wamsler, 2015). Recently, the European Commission (EC) established the term nature-based solutions (NBS) as an alternative, and it is gaining increasing attention in research and practice (Nesshöver et al., 2017). NBS are defined as sustainable actions that help societies to tackle not only the challenge of climate change, but also other environmental, social and economic challenges (EC, 2015; EEA, 2015). It is possible that this term could be more easily accepted by a wider group of stakeholders than EbA is at the moment (Nesshöver et al., 2017).

The variation in the percentage and type of EbA measures presented in adaptation strategies suggests that a consistent and comprehensive approach to their selection and integration is lacking. In Germany, there is currently no legal requirement to develop an urban adaptation strategy, and various unofficial guidelines are available (e.g. ICLEI, 2010; Prutsch et al., 2014). Existing strategies are therefore the result of voluntary efforts. This has resulted in a wide array of approaches, different types of strategies and measures with different scopes, leading to a wide range of results. According to Geneletti and Zardo (2016), this is also the case for adaptation strategies adopted by large cities in other European countries.

The findings presented here suggest that clearer guidance for municipalities that are taking action in the area of climate change adaptation, together with increased emphasis on the importance of ecosystems for climate change adaptation might help to promote the integration of EbA into urban adaptation planning of German cities (Deutsche Bundesregierung, 2011; Hansen et al., 2014; Noble et al., 2014; Pramova et al., 2012). It should be noted that most of the adaptation strategies that were examined prioritised regulating ecosystem services. Moreover, almost half of the strategies emphasised the multiple functions of EbA. Unlike non-EbA measures that only have one adaptation benefit (e.g. mechanical shade devices or changing surface albedo), EbA measures can provide several benefits at the same time (EEA, 2012).The results also underline the need for further studies that provide evidence of the multiple benefits for both adaptation and other areas of urban planning of EbA (Doswald et al., 2014; Pasquini & Cowling, 2014).

Finally, to strengthen the approach and the results of this study, it would be interesting to interview decision-makers and include other urban planning documents, such as urban land use plans and biodiversity strategies in the analysis, as this would provide a deeper insight on the integration of EbA into urban adaptation planning in Germany. Moreover, further research could assess both the benefits and the cost-effectiveness of EbA measures compared to other climate change adaptation options.

5.2 The regulating potential of EbA

A prerequisite for the implementation of EbA measures is to acknowledge the importance of ecosystem services for effective climate change adaptation, and ensure that it is disseminated into municipal adaptation strategies (TEEB DE, 2014). To support this, the results of Papers 2 and 3 provide empirical evidence on the positive effects of EbA in regulating extreme climatic events. All of the assessed types of UGI contribute to both reducing the outdoor thermal load and the volume of surface runoff after heavy rain events.

Under future climate change scenarios, all three types of UGI have the potential to decrease expected impacts to, or even below, today's level of heat stress and surface runoff. Both trees and green facades can provide climate-proofing against heat stress, assuming a minimum of 10 % of the surface is covered by either trees or green facades (i.e. scenarios TreeR, TreeM and FacadeM with 24, 36 and 19 % greening respectively, Figure 19). UGI types can also compensate for surface runoff due to climate change, as shown in scenarios TreeM, RoofR, RoofM and Combi. In this case, outcomes are related to the extent of both greening and permeable surfaces, which need to be larger than a minimum of 6 % (6.5, 15, 54 and 23 % permeable cover in TreeM, RoofR, RoofM and Combi respectively). The results presented here support the study of Gill et al. (2007), who suggest that heat climate-proofing is achievable with a 10 % increase in greening in the Greater Manchester city centre, where the current green cover is 20 %.

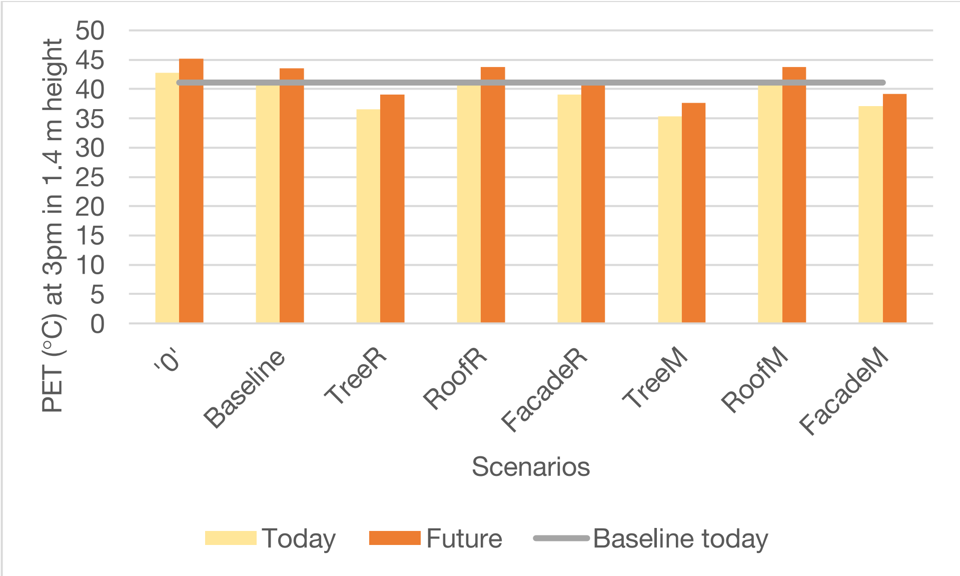

Figure 19: PET reduction potential for greening scenarios. The horizontal bar represents the PET Baseline scenario (the current climate). Under climate change, TreeR, TreeM, and FacadeM lead to a PET reduction of 4, 7, and 4 %, respectively, which is below the Baseline level.

There is often little space for additional vegetation in dense urban areas (such as the case study area), and thought needs to be given to how much green can be added. Also in Manchester, Hall et al. (2012) calculated that the potential increase in tree cover was only 5 %, given local regulations, which would fail to keep temperatures down to current levels under climate change. Consequently, a 10 % increase in green cover cannot be solely achieved by, for example, simply planting more trees. Another option is greening facades, because, although they do not contribute to shading of open space, they offer great cooling potential while requiring little space. Green roofs can regulate runoff, and offer the advantage of occupying space that is normally not used. This is relevant when there is a lack of space for greening, when the use of open space is controversial, or when radical changes to existing structures are not allowed.

At the same time, it is necessary to assess the effectiveness of combinations of different types of UGI, and when their joint implementation creates synergies and trade-offs. In the Combi scenario (tested for its runoff mitigation potential), the combination of trees and green roofs results in the summing of their regulating effects, while only the extent of green roofs overlaid by trees is missing. The combination leads to a greater reduction of runoff, as both measures increase storage capacity through interception, evapotranspiration and infiltration. Interception and evapotranspiration rates are higher with additional trees, which is the result of their higher LAI and larger root system. Green roofs, on the other hand, increase the percentage of permeable surface and increase infiltration. Consistent with the findings presented here, Trinh and Chui (2013) find a summing effect for runoff mitigation for green roofs and bio-retention systems tested first separately, and then in a combined scenario. Lobaccaro and Acero (2015) suggest that a similar positive correlation between different UGI types could also exist for heat regulation: the combination of grass, trees and green roofs was found to have lowest PET values in all scenarios examined.

The results of the microclimatic model show that the effectiveness of EbA measures is a function of their location within the area. Placing vegetation in heat-exposed hotspots increases its mitigating effects. This may be because there is a nonlinear relationship between green cover and PET reduction. However, this is not shown to be the case in studies such as Middel et al. (2015), who found a linear reduction in air temperature as the tree crown cover increased in hot and arid climates. This may be because the latter study used air temperature, rather than PET, and distributed additional trees evenly within the study area. Furthermore, the Middel et al. study used an earlier version of ENVI-met (V3.1). In this version of the software, vegetation could not yet be displayed as an individual object, meaning that transpiration processes were calculated differently (Bruse & Environmental Modelling Group, 2015a; Simon, 2016). Moreover, the study area used in this thesis has a higher building density, and consequently higher heat storage capacity and more shaded areas. It is possible that these factors have an impact on cooling potential that is different to the open, low-rise residential area assessed by Middel et al. (2015).

The hydrological model found no direct relation between the magnitude of runoff and the location of greening. Nevertheless, it can be assumed that it may be important to place it in natural overland channels, as additional surface water can infiltrate into pits of trees or green facades. This needs further research, for example in urban areas with larger differences in elevation than the study area, and an evaluation of the problems that might occur when polluted surface runoff directly infiltrates into the ground.

The effectiveness of EbA measures for heat and runoff mitigation can be optimised by species selection. This thesis only assessed one species per UGI type, however, differences between species in the provision of heat und runoff mitigation functions (shading, evapotranspiration) have been reported by several studies. For example, tree shading is dependent on the crown volume, geometry and LAD, which influences solar transmissivity through the crown (e.g. Moser et al., 2015; Shashua-Bar & Hoffman, 2000). Konarska et al. (2014) showed that average transmissivity of direct solar radiation during summertime (foliated tree crowns) ranged from 1.3 to 5.3 % depending on the tree species, which positively correlated with LAD values. *Tilia cordata* had the lowest transmissivity and highest LAD, while *Prunus* has the highest transmissivity. With respect to transpiration, Moser et al. (2015) found higher rates for fully grown (> 40 years old) *Tilia cordata* than *Robinia pseudoacacia* during the summer months. Konarska et al. (2016) supports the idea of inter-species variability in transpiration rates, while at the same time establishing a positive relation between the transpiration rate and the fraction of permeable surfaces, which provide trees with water. This, in turn, suggests that more extensive permeable surfaces increase rainwater infiltration, which becomes available for evapotranspiration (compare Table 10).

This thesis focuses on the regulating potential of EbA measures with micro-scale benefits. EbA can also have positive effects on a larger scale – for example a district of a city, or the whole city. Studies using remote sensing approaches (e.g. Alavipanah et al., 2015) or meso-scale climate modelling (e.g. Fallmann et al., 2014; Li et al., 2014) show that the UHI effect can be significantly reduced by increasing the vegetative cover within a city, e.g. through green roofs or parks. Changes in albedo change the radiation balance of the urban environment, and lower surface temperatures. Finally, changes in runoff rates may reduce discharge into the sewage system, leading to a reduction in storage capacities sewer operators are required to provide.

5.3 Multifunctionality of EbA

The importance of EbA measures in providing co-benefits for urban planning go beyond the adaptation benefits assessed in this thesis. Almost half of the adaptation strategies that were examined for Paper 1 emphasise multiple functions. For instance, urban vegetation can support climate change mitigation by sequestering and storing carbon emissions. Similarly, biodiversity not only provides a habitat, but also has social and health benefits, for example by providing recreation areas, filtering air pollutants and reducing noise pollution (Coombes et al., 2010; Demuzere et al., 2014; Hansen et al., 2016; Klemm et al., 2015; Strohbach et al., 2013). Therefore, it is likely that other ecosystem services are provided when EbA measures are implemented to mitigate heat or heavy rain events, which increases their effectiveness in urban planning. This observation supports arguments for the use of EbA when multiple demands need to be balanced, for example if social or economic requirements take priority over climatic issues in urban planning, and needs to be given sufficient attention.

To make full use of EbA and its services, the trade-off between ecosystem services and potential disservices needs to be considered. A trade-off occurs when one service is lost as another is gained. Hence, if certain ecosystem services are increased, their relation to others must be understood, to avoid any unintended negative consequences (Hansen & Pauleit, 2014). An ecosystem disservice describes ecosystems functions that are perceived as negative for human well-being (Lyytimäki & Sipilä, 2009). In the context of EbA, this could include health problems arising from more or different vegetation, e.g., higher pollen concentrations, damage to infrastructure such as roads, and costs related to the implementation and management of different UGI types, e.g., maintenance costs. Ecosystem disservices are difficult to assess as data on costs is often lacking, and negative perceptions are highly subjective (Lyytimäki & Sipilä, 2009). For instance, Delshammar et al. (2015) evaluate citizens' complaints about urban greening recorded by a municipal park department, while Lyytimäki (2014) assess the representation of vegetation disservices in newspapers. Current and future work in this field will help to enhance the planning and management of EbA measures.

5.4 Limitations of the modelling approach

This thesis applies a novel, quantitative modelling approach to evaluating the effectiveness of different UGI types in mitigating heat and surface runoff. The novelty is the result of the integration of: a) two climate change impacts; b) the evaluation of three UGI types that can be implemented as EbA measures; c) different quantities of greening; d) current and future climate conditions; and e) the inclusion of current planning guidelines that practitioners have to consider during implementation.

The approach consisted of microclimatic modelling (with ENVI-met) and hydrological modelling (with MIKE SHE) and, although it proved to be well-suited to the purpose of this thesis, there are some methodological limitations that are discussed in the following paragraphs to increase the understanding for underlying assumptions when interpreting the presented results.

The study was designed as solely model-based without any opportunities to collect empirical input data or to validate the modelling approaches. The lack of empirical input meant that rough estimates and standard values taken from the literature or the integrated ENVI-met database were chosen to represent, for example, building and surface materials. Soil characteristics are a key factor in calculating, for example, hydraulic conductivity, and for this more detailed data was needed. Fortunately, the Munich Water Management Office could provide data on bore holes in the area that was used to generate sophisticated soil profiles (compare Section 3.4.4). As the research focused on the effects of UGI types, vegetation characteristics were chosen particularly carefully. After site visits to the area, suitable vegetation types were created based on data taken from the Albero database integrated into ENVI-met. This database draws upon empirical data from various studies (Bruse & Environmental Modelling Group, 2015b), including, but not limited to, studies of urban vegetation. However, it was found that LAD values were significantly higher than those reported in Moser et al. (2015) and Sjöman et al. (2016). Therefore, it is possible that the chosen values are overestimates when applied to trees in a dense urban environment, which in turn could lead to a slight overestimation of, for example, transpiration rates calculated from LAD values. Empirical measurements of LAD for trees in the study area would clarify this issue.

The modelling approaches could be improved by collecting empirical data on heat and runoff, which would increase the precision of input parameters and confirm the validity of the results. With respect to heat regulation, a simple approach using temperature loggers at reference points within the case area is a suitable validation method as presented by e.g. Skelhorn et al. (2014). For runoff regulation, one approach is to measure surface roughness and drain level, and hence the volume of inflow into the sewage system at reference points (Jaber & Shukla, 2012).

Both modelling techniques are complex tools that require detailed input data and demand significant computational resources. For instance, the ENVI-met model ran for five days on an eight-core, high-performance computer to simulate one scenario. The grid resolution and size of the study area are determining factors for the running time. By increasing the grid resolution from 1 m to 2 m, it could be reduced from 11 to 5 days (compare Salata et al., 2016). Although this is not a problem for researchers, for practitioners, who need to quickly compare different scenarios before implementation, these approaches are too time-consuming. The initial test studies conducted at the beginning of this thesis may offer a solution, as some of the less-sensitive input parameters can be generalised, reducing the need to collect input data. Nevertheless, it is indispensable to develop new modelling approaches that are able to overcome these limitations, and work has already begun. The $[UC]^2$ project on 'Urban Climate Under Change', funded by the German Federal Ministry of Education and Research (BMBF) aims to develop a new urban climate model that can provide detailed, high-resolution results, with a user-friendly interface and low computational requirements (Scherer, 2017). Although estimates of runoff mitigation could be based on surface and soil characteristics, which might be an easy way to establish rough trends (Konarska et al. (2016), this is not a suitable option for heat mitigation. For example, the heat regulating services provided by trees are closely related to the location of the tree in the open space as Rahman et al. (2017) found for *Tilia cordata* trees in different urban environments. These complex interrelations are difficult to account for in estimating approaches.

A scenario approach was adopted to enable comparisons between different UGI types, which created other limitations. On the one hand, scenarios require the determination of assumptions regarding additional greening, based on the available literature and applicable regulations. For example, the technical construction of green roofs is based on guidelines provided by Lösken et al. (2008), but it is likely that performance could be improved by additional drainage layers or deeper substrates. The required substrate volume for the root zone of a street tree in Munich is 36 m^3 (Landeshauptstadt München, 2016b), which is high compared to other cities (for example, the standard set by the Research Society for Landscape Development and Construction (FLL) is 12 m^3 (FLL, 2015)). Consequently, water availability and transpiration rates could be overestimates compared to other cities (compare Konarska et al., 2016). Moreover, for each UGI type only one typically used species was selected: Norway maple as the urban tree, extensive vegetation for the green roof, and a creeper for the green facade. All vegetation types are assumed to be fully developed and vital, and at the optimal stage to provide ecosystem services. In reality, this optimum is only reached for short time periods, as plants can suffer drought stress or are not yet fully grown (Gillner et al., 2015; Kjelgren & Clark, 1992; Moser et al., 2015; Sjöman et al., 2015). Both this, and the interspecies differences discussed in Section 5.2 may have influenced the results.

Finally, the scenario approach did not address all possible UGI types and quantities, but this was necessarily limited by the scope of the thesis and time constraints. Future research could extend the approach by covering more UGI types, vegetation dynamics, combinations of UGI types, and spatial setups.

5.5 Implications for urban planning

The results of the study are not directly applicable to the implementation of EbA measures on the ground, but serve as an estimation of the potential for heat and runoff reduction offered by different UGI types. They show that EbA is a valuable way to counteract projected urban climate change impacts and reduce the vulnerability of the population and the sewage system. This quantitative assessment may help urban planners, and others, to decide which UGI type used for EbA measures has the highest potential to regulate either the thermal load or surface runoff, or both, in dense urban areas, when implemented as EbA measure. Planners can select the most suitable measures that meet their strategic needs, and decide where to locate them within the area of interest. The following summarises the most important considerations regarding UGI types and their local implementation:

For heat mitigation, effective measures include:

- Concentrating on specific areas – so called hotspots – where pedestrians experience extreme heat stress during hot summer days.
- Prioritizing the planting of tress in these hotspots to reduce incoming solar radiation on artificial surfaces and increase evapotranspirative cooling in places that are frequented by pedestrians.
- Adding green facades, in particular on south-west-facing surfaces to reinforce mitigation effects through shading building surfaces and evapotranspiration, in particular in areas where additional trees are not an option due to building density and competing uses.
- Assessing options to increase (or protect existing) ventilation in heat-exposed areas to reduce overheating.
- Considering of the mitigating effects of green roofs on a larger, (e.g. city) scale, by changing roof albedo.

For runoff mitigation, effective measures include:

- Increasing stormwater storage capacity and possibilities for evapotranspiration within the area of interest.
- Prioritizing the planting of trees to increase interception and evapotranspiration capacities, if sufficient open space is available.
- Implementing green roofs for rainwater retention and evapotranspiration on rooftops, where competition for open spaces is lower than at street level.

For both heat and runoff mitigation, effective measures include:

- Prioritizing which extreme climatic event has the largest impact in the area of interest and implementing EbA measures accordingly.
- Planting trees in hotspots and along surface runoff channels.

- Increasing the extent of permeable surfaces and the soil volume available for rooting in tree pits to increase infiltration and evapotranspirative cooling.
- Adding green roofs to increase rainwater retention capacity, while at the same time providing rooftop cooling.
- Assessing all the options for the implementation of EbA measures in the area of interest, as the use of different UGI types is shown to be effective for climate change adaptation as well as having co-benefits for urban planning.

Figure 20 merges all of these recommendations for effective heat and runoff regulation, and indicates the most effective strategic locations for their implementation, assuming an urban morphology consisting of perimeter blocks. In cases where there is a trade-off between heat regulation (via shading) and ventilation (as is for example the case for the courtyard in the north-west corner of the perimeter block), priorities have to be set based on local conditions and the tree species suitable for local conditions.

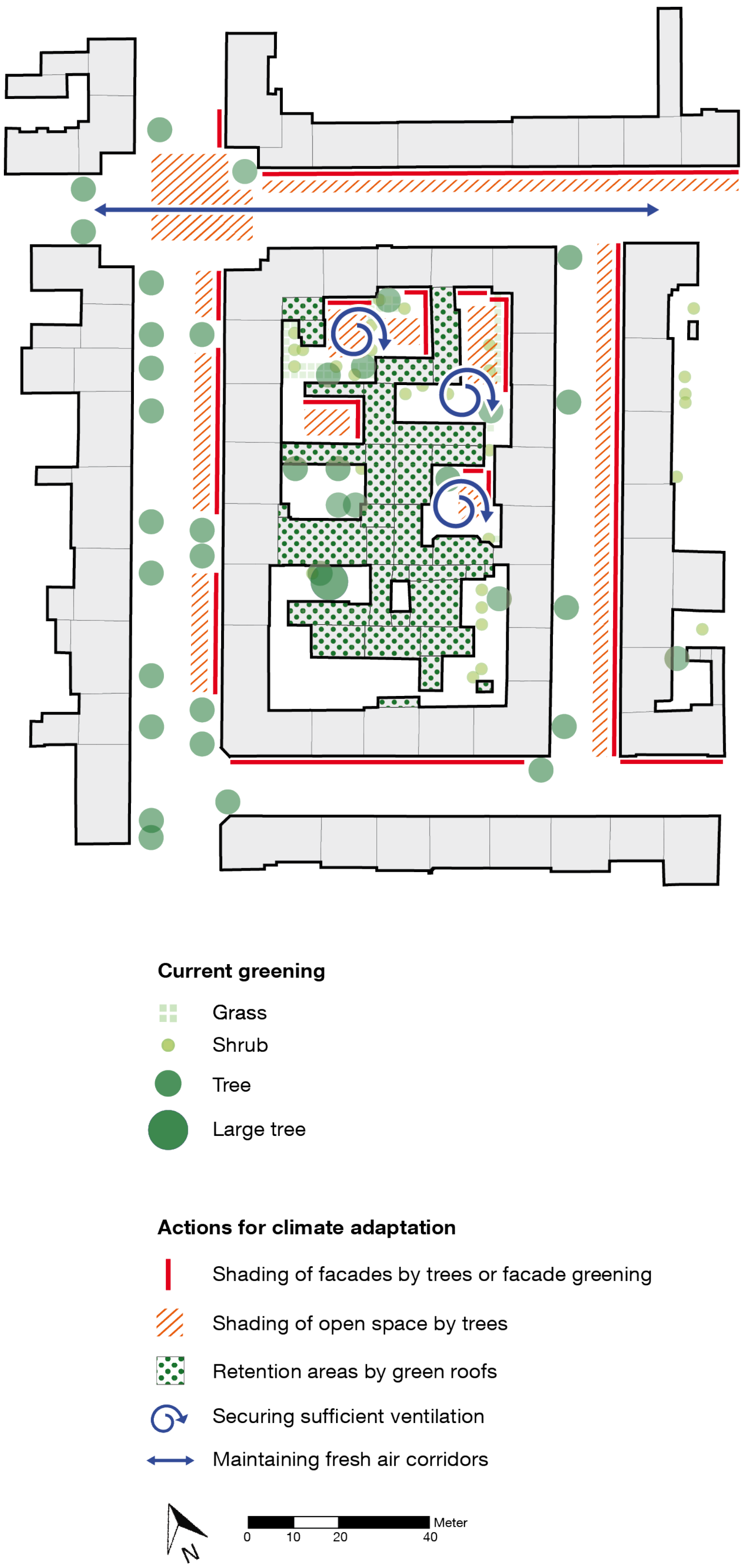

Figure 20: Location of EbA measures for effective climate change adaptation in a dense urban structure

Some other issues, which are not directly derived from the results of this thesis, need to be assessed before deciding to use certain EbA measures:

- The identification of possible locations for multifunctional EbA measures, by assessing the availability of open space and possible competing uses (e.g. Stovin, 2010).
- The location of below-ground infrastructure (i.e. cables, sewage system, underground parking) (e.g. FLL, 2015).
- The selection of climate-adapted vegetation, i.e. drought-tolerant species (GALK, 2012; Roloff, 2013).
- The selection of vegetation types that are suited to the location, in terms of, for example, soil type, water availability, or exposure to stressors (FLL, 2015; Lösken et al., 2008; Roloff, 2013).
- Early decision-making, as the benefits of EbA are only seen when the vegetation is fully grown. For example, for urban trees this may be 30 years after they are planted (Sæbø et al., 2005).

The here presented recommendations for urban planning fulfil two objectives: first, they allow urban planners to prioritise different UGI types as EbA measures change depending on the local characteristics of their area of interest and expected climate change impacts; secondly, they are backed-up by scientific evidence, which serves as a proof of effectiveness in decision-making processes, when various interests have to be balanced.

However, urban planners still have to bear in mind that although understanding the effectiveness of EbA measures is a decisive factor in their implementation, it is not the only one. As the results of Paper 1 show, there is a great need to increase acceptance of EbA approaches and mainstream them into urban planning processes. It is hence important for urban planners to consider the following aspects when adaptation activities using EbA are planned and implemented:

- Increasing the emphasis on the importance of ecosystems and their multiple benefits for adaptation and other fields of urban planning.
- Assessing the adaptation strategies of other municipalities and using good practice as a guide for own development processes.
- Identifying and applying synergies and experience from other areas of urban planning.
- Increasing the acceptance of EbA among stakeholders, for example, by adopting the term NBS (Nesshöver et al., 2017).
- Using participatory approaches to involve all relevant stakeholders (Wamsler, 2017).
- Assessing institutional processes and power relations to improve mainstreaming of EbA (Wamsler et al., 2017).

Transdisciplinary research efforts can support the understanding of barriers and opportunities within municipal planning processes, and improve knowledge transfer between science and practice for successful climate change adaptation by using the benefits of urban greening.

6. CONCLUSION

6.1 Summary of key results

Effective climate change adaptation is indispensable for sustainable urban development and increased urban resilience to climate change (Revi et al., 2014). In cities, where the main expected impacts are increases in climatic extreme events like heat and heavy rain, it is particularly important to reduce the vulnerability of the population to extreme heat, and the urban water infrastructure to heavy rain (EEA, 2012). Therefore, the recent academic and political discussion has paid particular attention to the use of urban greening and its ecosystem services in the context of EbA at the international, European and national levels. This thesis provides several insights into the integration of EbA into the municipal adaptation strategies of selected German cities. This aims at increasing the understanding of the current role of EbA in urban adaptation planning. It concludes that while the term EbA is not referred to directly, references to the underlying components (i.e. ecosystem services, biodiversity and green infrastructure) could be identified. Different EbA measures are included in many of the assessed adaptation strategies, and many acknowledge the multiple benefits for urban planning. Nevertheless, the findings suggest, and therewith support the original hypothesis, that greater awareness of the effectiveness of EbA measures could improve decision-making and extend their integration into strategic adaptation planning of German cities.

Based on these results, scenarios were developed to quantify the performance of EbA measures in regulating extreme climatic events. It is the first time a study has been able to compare information on the regulating potential of different UGI types and quantities, and the synergistic effects of EbA measures on both heat and runoff mitigation. Under future climate conditions heat stress will reach extreme levels, and nearly all rainfall will be discharged as surface runoff in dense urban areas. Hence, it is imperative to enhance the implementation of EbA measures that are shown to effectively regulate both heat and runoff. The type and quantity of UGI affects its contribution to climate adaptation. For heat mitigation, the quality of greening has the largest effect, as trees are shown to be the most effective measure through the provision of shading (for open spaces and building surfaces) together with evapotranspirative cooling. Green facades can also maintain heat stress for pedestrians at current levels, and have the advantage of lower open space requirements than trees. With respect to runoff mitigation, increasing the quantity of green spaces and providing water storage capacities is most influential. Trees can store water through interception, evapotranspiration and infiltration into pits, while the substrate of green roofs increases retention capacity. Compared to trees, green roofs require open space on often unused rooftops, and therefore have higher spatial potential for implementation.

The results presented here have practical implications for urban planning, notably the integration of EbA into strategic adaptation planning, together with the strategic selection and placement of UGI types to reduce both heat stress and surface runoff volumes. As they are backed by quantitative evidence, they provide urban planners with sound arguments that support climate adaptation using urban ecosystem services. Effective climate change adaptation is based on choosing the UGI type that is suited to the local situation, and the magnitude of services provided for heat and runoff regulation. Priority needs to be given to the type of UGI that can be implemented where it is needed. At the same time decision-makers need to continue to improve the mainstreaming and acceptance of EbA. The approach presented here helps to improve decision-making and the integration of EbA into urban climate adaptation planning.

6.2 Outlook and future research

This thesis presents a novel methodological approach that improves the integration of EbA measures into strategic urban adaptation planning by quantifying the effects of different UGI types for the regulation of heat and surface runoff. From the results some recommendations regarding how to implement EbA for climate adaptation are derived and discussed. The following paragraphs elaborate on possible extensions and amplifications of the methodological approach and assessment to further enhance the recommendations for urban planning.

Urban planners need information regarding the key factors that determine and influence the effectiveness of EbA measures for climate change adaptation. The scenario approach presented here offers the first comparative estimates of the adaptation potential of EbA. However, the study could be broadened to a larger scenario setup covering more types of UGI (e.g. rain gardens), and decentralised measures (e.g. the removal of impermeable surfaces for stormwater infiltration and changes to surface albedo), in order to assess combinations of types, understand interdependencies, and test different spatial preconditions (i.e. different morphology types, elevations and planting conditions). This could be extended to a larger-scale research programme that includes the collection of empirical data for model validation. In such a case, it would be interesting to include different species of one UGI type, and different climates (e.g. tropical or Mediterranean).

Furthermore, the focus of the analyses could be extended. For instance, nocturnal cooling rates are very important when studying the UHI effect and thermal comfort, as the thermal storage capacity of artificial materials prevents cooling especially at night (Oke, 2011), which in turn increases the population's exposure to tropical nights (T_{min} >20 °C). In addition, transpiration due to vegetation functions differs during the night (Konarska et al., 2016). Consequently, the nocturnal thermal load could be included in the assessment. With respect to runoff regulation, it would be interesting to provide information on spatial differences in surface runoff, and local flooding flashpoints. To achieve this, the models would need to be run with a shorter temporal resolution (e.g. 15 minutes), which requires rainfall data at this resolution. It also needs to be coupled in greater detail to the sewage system in order to be able to project system capacities at the same temporal resolution.

The assessment of heat and runoff mitigation synergies presented in this thesis is based on the application of two, comparable, modelling approaches that deliver comparable results on the regulating potential of EbA measures. Both the regulation of heat stress and the regulation of surface runoff are linked by evapotranspiration (compare Chen et al., 2011; Konarska et al., 2016). By taking a similar approach to the calculation of evapotranspirative processes, the simulations could be technically coupled and relevant parameters could be exchanged (i.e. evapotranspiration, soil moisture, water availability).

Moreover, there is increasing demand for research on the multifunctionality of EbA measures. An approach that integrates microclimatic modelling and a thermal building simulation, for example, could provide insights into how EbA measures that are implemented outdoors affect the inside of buildings (e.g. how indoor thermal comfort and energy demand for heating and cooling are affected by shading building surfaces and insulating the building). Such insights can, in turn, be used to calculate CO_2 emissions from buildings, and inform municipal climate mitigation efforts. Several studies have already begun to work on this topic, but are limited by the coverage of UGI types or seasonal differences in energy demand (e.g. Perini et al., 2017; Radhi et al., 2017; Skelhorn et al., 2016).

Finally, any scientific, or quantitative results on the climate change adaptation potential of EbA are insufficient if this knowledge is not transferred to practitioners and used for sustainable transformation in urban planning. There is an obvious need for greater exchange and communication with practitioners and decision-makers in cities to understand what kind of knowledge is actually needed, and at what point in urban planning processes. Changes to institutional frameworks could enable more inter- and transdisciplinary research, and improve mainstreaming pathways.

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