Dynamics of Flood-Regulating Ecosystem Services in Urban Areas

Modelling Heavy Rainfall, Climate Change Impacts and Benefits of Nature-based Solutions

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Referent: Prof. Dr. rer. nat Benjamin Burkhard

Korreferent: Prof. Dr.-Ing. Kristian Förster

Korreferent: Dr. habil. Karsten Grunewald

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ABSTRACT

Urban areas are particularly affected by pluvial flooding caused by heavy rainfall. To protect humans against flooding, ecosystems can provide important natural flood-regulating functions as services, so-called ecosystem services (ES). However, due to climate change, heavy rainfall is projected to increase in intensity and frequency in the future. While ES are affected by climate change, they simultaneously serve as part of the solution to mitigate climate change. ES can be enhanced by further actions such as Nature-based Solutions.

In this light, there is a need to go beyond common flood-regulating ES assessment of fluvial floods more towards urban flood-regulating ES assessment for heavy rainfall. Therefore, the overreaching objective of this study is to improve the knowledge and methods of urban flood-regulating ES for heavy rainfall under changing climate conditions and the contribution of Nature-based Solutions. More specifically, this thesis 1) identifies limitations of existing methods and proposes approaches to overcome these for flood-regulating ES in urban areas, 2) presents a framework to conduct a mismatch analysis of urban flood-regulating ES supply and demand for heavy rainfall, and 3) investigates the future functionality of flood-regulating ES and contribution of Nature-based Solutions under todays and possible future climate conditions.

The first part of the thesis discusses and compares a hydraulic model and an area-based indicator approach to quantify fluvial flood-regulating ES. The approaches are not transferable to the urban environment and pluvial flood events, since they miss some crucial hydrological processes for flood regulation, such as infiltration and interception. Therefore, a hydrological model was developed that considers vegetation-related hydrological processes and a 2D surface runoff simulation on the scale of single landscape elements. A calibration and validation of the model showed a good match of peak flow, interception, and a plausible surface routing. Based on these findings, a framework for a mismatch analysis of flood-regulating ES supply and demand at the urban scale of heavy rainfall events is presented. ES supply indicators are interception and infiltration from the hydrological model output. The supply by interception was higher than infiltration. ES potential demand was assessed by a comprehensive set of different socio-economic indicators and turned into an actual demand when the area was flooded. A supply surplus was indicated in green areas, while sealed land uses had a surplus of demand. Lastly, a scenario analysis showed that land use structures reached a capacity limit of flood-regulating ES for current climate conditions. Although Nature-based Solutions increased the ES supply, reduced runoff, and consequently ES demand, their capacity under higher rainfall events was limited, since they could not completely prevent flooding.

Finally, flood-regulating ES assessment for urban areas and heavy rainfall under changing climate conditions is emphasized. Nature-based Solutions can be used for adapting to climate change but they need to be tested for their future functional suitability under changing climate conditions. Mapping ES supply and demand and their changes are particularly important for urban planning to better understand the impact of climate change and to improve the knowledge of Nature-based Solutions contribution.

Keywords: Ecosystem Contribution, Supply and Demand, Ecosystem Services Mismatches, Cities, Extreme Rainfall, Hydrological Modelling, Climate adaptation

ZUSAMMENFASSUNG

Städte sind besonders anfällig für Überschwemmungen verursacht durch Starkregen. Um Schäden zu vermeide oder zu verringern und Menschen zu schützen, können Ökosysteme wichtige natürliche Hochwasserregulierungsleistungen erbringen - sogenannte Ökosystemleistungen (ÖSL). Zukünftige Starkniederschläge werden aufgrund des Klimawandels in Intensität und Häufigkeit zunehmen, wodurch die Anpassung an diese Folgen an Bedeutung gewinnt. Dabei können flutregulierende ÖSL durch weitere Maßnahmen verbessert werden.

Das übergreifende Ziel dieser Arbeit ist daher, den aktuellen Kenntnisstand und Methoden zur Bewertung flutregulierender ÖSL für Starkregenereignisse im städtischen Umfeld unter veränderten Klimabedingungen und den Beitrag von Anpassungsmaßnahmen auszubauen. Konkret werden in dieser Arbeit 1) die Grenzen bestehender Methoden zur Erfassung flutregulierender ÖSL aufgezeigt und Ansätze zur weiteren Entwicklung vorgeschlagen, 2) ein methodisches Konzept zur Durchführung einer Vergleichsanalyse von Angebot und Nachfrage flutregulierender ÖSL für Starkregen in Städten vorgestellt, und 3) die Funktionstauglichkeit flutregulierender ÖSL und weiteren Anpassungsmaßnahmen unter veränderten Klimabedingungen untersucht.

Im ersten Schritt wird ein hydraulisches Modell und ein flächenbasierter Indikatoransatz zur Quantifizierung von Flusshochwasser-regulierenden ÖSL verglichen. Beide Ansätze können nicht direkt in den städtischen Raum übertragen werden, da wichtige hydrologische Prozesse, wie Interzeption und Infiltration, unberücksichtigt bleiben. Deshalb wurde ein hydrologisches Modell entwickelt, das Interzeption, Infiltration und Oberflächenabflussprozesse auf der Basis einzelner Landschaftselemente berücksichtigt. Auf dieser Grundlage wurde ein Konzept zur Analyse von Ungleichheiten in Angebot und Nachfrage flutregulierender ÖSL im städtischen Raum für Starkniederschläge erstellt. Als Indikatoren für das ÖSL-Angebot dienten Interzeption und Bodenwasser, berechnet mit dem hydrologischen Modell. Die potenzielle Nachfrage leitet sich aus verschiedenen sozioökonomischen Indikatoren ab. Aus der potentiellen Nachfrage wird eine aktuelle Nachfrage, wenn die zugehörige Fläche tatsächlich überschwemmt wird. Die Ergebnisse im Untersuchungsgebiet zeigen ein größeres Angebot durch Interzeption, als durch Bodenwasserspeicherung. Grünflächen wiesen generell ein Angebotsüberschuss, versiegelte Flächen hingegen eine erhöhte Nachfrage auf. Szenario Analysen zeigten, dass heutige Landnutzungsstrukturen bereits ihre flutregulierende ÖSL Kapazität erreicht haben und intensivere Starkregen zu extremeren Überschwemmungen und folglich einer erhöhten aktuellen Nachfrage führen. ÖSL-Angebote konnten durch weitere Anpassungsmaßnahmen erhöht werden, wodurch sich der Abfluss und die aktuelle ÖSL-Nachfrage verringerten. Allerdings ist auch die ÖSL Kapazität der gewählten Anpassungsmaßnahmen begrenzt, so dass Überflutungen unter intensiveren Starkregen nicht gänzlich zu verhindern sind.

Die Ergebnisse zeigen, dass die Kartierung von ÖSL Angebot und Nachfrage für die Stadtplanung von Bedeutung sein kann, um den Einfluss des Klimawandels und Effekte von Anpassungsmaßnahmen besser zu verstehen und entsprechend anpassen zu können.

Schlagwörter: Ökosystemleistungen, Angebot und Nachfrage, Städte, Starkniederschlag, Hydrologische Modellierung, Klimawandelanpassung

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LIST OF ABBREVIATIONS

CICES	Common International Classification of Ecosystem Services
CMF	Catchment Modelling Framework
DPSIR	Driver-Pressure-State-Impact-Response
DWD	Deutscher Wetterdienst
EPA	Environmental Protection Agency
ES	Ecosystem Services
ESTIMAP	Ecosystem Service Mapping Tool
FAIR	Findable, Accessible, Interoperable, Reusable
GI	Green Infrastructure
GIS	Geographical Information System
HEC-RAS	Hydrological Engineering Centre – River Analysis System
HRU	Hydrological Response Unit
INTEK	Integriertes Entwässerungskonzept
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPBES	Intergovernmental Panel on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
KINEROS	Kinematic Runoff and Erosion Model
LEAFlood	Landscape and vEgetAtion-dependent Flood model
LID	Low Impact Development
MAES	Mapping and Assessment of Ecosystem of their services
MA	Millennium Ecosystem Assessment
NbS	Nature-based Solutions
RCP	Representative Concentration Pathway
RoGeR	Runoff Generation Research
SCS	Soil Conservation Service)
SSP	Share Socio-economic Pathways
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
TEEB	The Economic of Ecosystems and Biodiversity
Wetspa	Water and Energy Transfer between Soil Plants and Atmosphere
WMO	World Meteorological Organisation

1

INTRODUCTION

This Chapter describes the research design and starts with the motivation of the thesis. Afterward, the objectives and research questions are presented. The Chapter concludes with an outline and structure that includes an overview of the four publications that form the main body of this dissertation.

1.1 Motivation

The IPCC report (2021) highlighted that climate change has increased the intensity and frequency of extreme weather events in the past and will further increase them in the future. Accordingly, heavy rainfall is projected to increase in intensity and frequency. One consequence is potentially more pluvial flooding. Short-duration events of less than 9 hours tend to occur more often and cause more damage than long events of more than 12 hours (GDV and DWD, 2019). Pluvial flooding caused by heavy rainfall has four important characteristics that differ from fluvial flooding: 1) they can occur everywhere also far away from rivers (GDV and DWD, 2019), 2) they are mainly caused by convective rainfall events and therefore occur highly localized 3) the warning time is relatively short, and 4) the effectiveness of pluvial flood risk management actions, which are widely employed along rivers, is studied less (Bronstert et al., 2018). Urban areas are particularly vulnerable and exposed to pluvial flooding for two main reasons. First, high population densities and a large potential for social and economic damages characterize urban areas. In 2018, approximately 55 % of the world's population lived in cities. This number is projected to increase to 68 % in 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2019). Second, the high degree of soil sealing modifies the natural water cycle resulting in a high percentage of surface runoff and less infiltration.

In this context, ecosystems can fulfil important natural functions in the water cycle to reduce flooding that result in ecosystem services (ES). ES link the ecological and socio-economic system and are the benefits people obtain from ecosystems (Millennium Ecosystem Assessment, 2005; TEEB, 2010). Flood-regulating ES support human well-being and security by protecting humans against flooding and damage. To ensure the effective protection of vulnerable elements, the effects of ecosystems needs to be quantified (Fletcher et al., 2013). Most flood-regulating ES studies focus on fluvial floods on the larger scales of river catchments (Nedkov and Burkhard, 2012; Logsdon and Chaubey, 2013; Stürck et al., 2014; Albert et al., 2015; Syrbe and Grunewald, 2017; Gaglio et al., 2019; Shen et al., 2021; Mori et al., 2022). Although, heavy rainfall can cause great damage in urban areas, pluvial flood-regulating ES have been studied to a lesser degree (Haase et al., 2014; Shen et al., 2019). Besides the spatial resolution and expansion, the physical regulating processes for pluvial flooding differ from river flood regulation. In this light, there is a need for further development and assessment of flood-regulating ES in urban areas for heavy rainfall.

Hydrological modelling offers the most complex but best representation of heterogeneous and hydrological complex urban areas. The few existing research studies on flood-regulating ES modelling in urban areas are usually based on hydrological response units (HRU), sub-catchments (Shen et al., 2019), or raster cells of 1 km² resolution (Xiong and Wang, 2022). Local effects cannot be detected on these scales, since landscape elements are aggregated into one unit. In heterogeneous urban areas, however, this local information of individual elements is crucial to understand the complex urban hydrological system and the ES contribution of important flood-regulating processes of, such as canopy interception or infiltration. Therefore, a model with an appropriate high spatial resolution based on single elements that consider important vertical and horizontal hydrological processes is necessary for the assessment of flood-regulating ES in urban areas.

ES become relevant if there is a demand by society. However, the major share of studies focus on ES supply, while there is a quantitative and qualitative gap in ES demand assessment (Wolff et al., 2015; Campagne et al., 2020; Dworczyk and Burkhard, 2021). Analysing the differences between supply and demand is important to understand the contribution of ES supply to human well-being. This is particularly relevant to identify unmet demand and missing ES supply to enhance ES contribution and ensure sustainable urban planning (Geijzendorffer et al., 2015), including urban drainage and green and blue infrastructure. In the context of flood-regulating ES, this means understanding the contribution of ecosystems to flood risk reduction. Indeed, some studies on flood-regulating ES consider the ES demand (Nedkov and Burkhard, 2012; Stürck et al., 2014; Shen et al., 2019; Shen et al., 2021). However, the spatial resolution or river catchments does not correspond to that of urban areas. Besides, simplified approaches and single indicators are used, while multidisciplinarity of demand is often neglected (Geijzendorffer et al., 2015; Dworczyk and Burkhard, 2021).

Ecosystems provide flood-regulating services that can be part of the solution for flood-related climate change effects. Further actions such as Nature-based Solutions (NbS) can additionally enhance ES supply and thereby support climate adaptation. The objective of flood-regulating ES is to increase the flood-regulating ES supply while reducing the flood hazard and consequently negative impacts on the socio-economic system. The new EU Biodiversity Strategy 2030 additionally highlighted the importance of NbS by aiming to integrate them more strongly into urban planning (European Commission, 2020). At the same time, climate change constitutes one of the most important pressures on the functionality of ES (Locatelli, 2016; Oesterwind et al., 2016; World Economic Forum, 2019). For this reason, flood-regulating ES in combination with measures to conserve or improve ES supply urgently need to be examined under changing climate conditions (Maes et al., 2020). However, there is a gap in research on the impact of climate change on flood-regulating ES and the performance of NbS under changing climate conditions. In this light, the knowledge of the future functionality of flood-regulating ES under changing climate conditions and the contribution of NbS must be enhanced (Kabisch et al., 2016; Kabisch et al., 2017). Only in this manner, the long-term functionality of ES and nature-based adaptation to climate change can be ensured and effective and sustainable urban planning can be guaranteed (Dwarakish and Ganasri, 2015).

1.2 Objectives and Research Questions

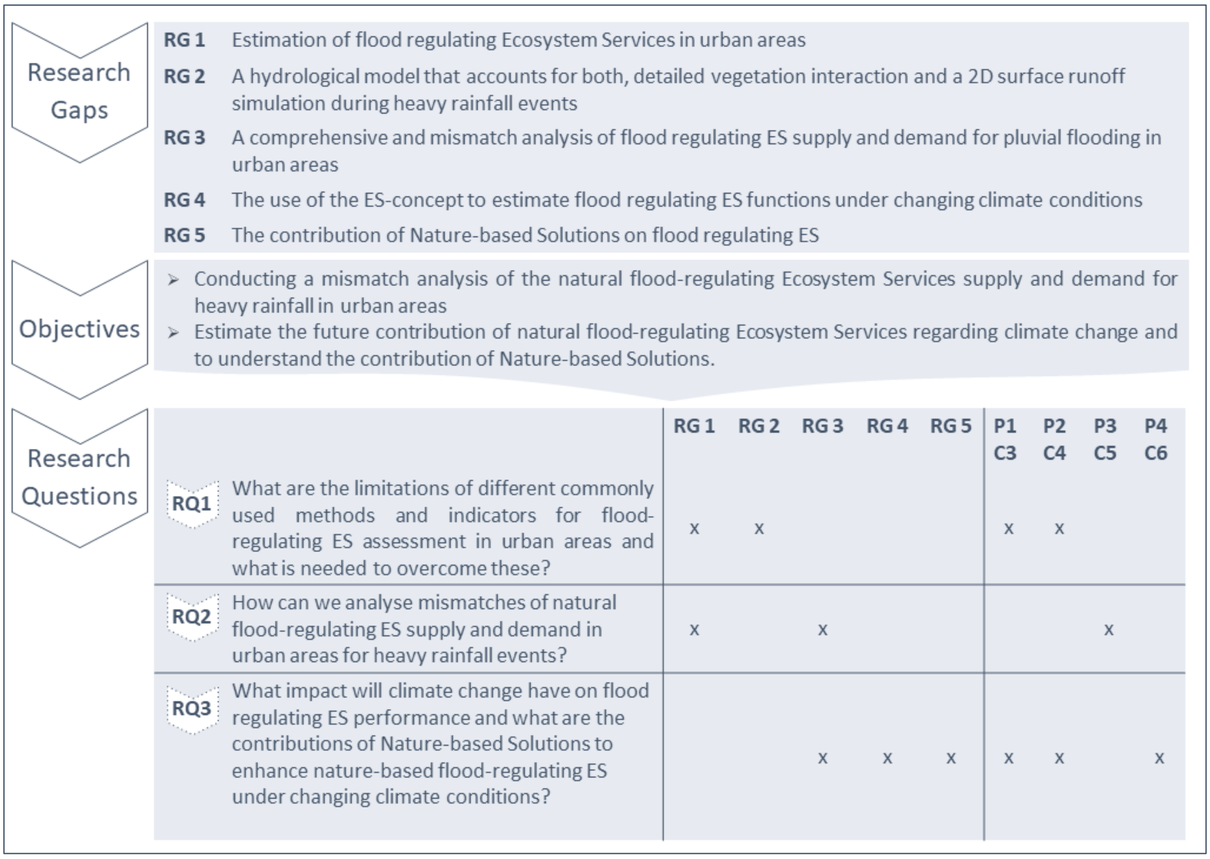
This thesis focuses on flood-regulating ES in urban areas for pluvial flooding under changing climate conditions. Based on the motivation, the listed research gaps in Figure 1 are identified followed by derived objectives and research questions. The research that addresses the individual research questions is presented in the following chapters of this thesis.

Together, the research gaps lead to the overall main objective, to develop and test a methodological framework and selected indicators for the evaluation of natural flood-regulating ES supply, demand, and their mismatches in urban areas for heavy rainfall events. Furthermore, the ES functionality and the contribution of NbS on ES are analysed under present and future climate conditions.

Three following objectives could be defined. The first objective was to understand the limitations of different commonly used methods and indicators for fluvial flood-regulating ES assessments for the transfer to urban areas. Under this objective, missing elements and approaches for the application of flood-regulating ES assessments for heavy rainfall in urban areas were identified and methods to overcome these were developed. This provides the theoretical fundament and knowledge of needed approaches for flood-regulating ES assessments in urban areas. For the second objective, a mismatch analysis of the natural flood-regulating ES supply and demand for pluvial flooding in urban areas was conducted at an exemplary study area for the current climate and land use conditions. Thirdly, the future functionality of natural flood-regulating ES under changing climate conditions was investigated. In addition, the benefits of NbS to enhance flood-regulating ES and their future functionality under changing climate conditions were studied.

The thesis aims to answer the following three research questions:

1) What are the limitations of different commonly used methods and indicators for flood-regulating ES assessments in urban areas and what is needed to overcome these?
2) How can we analyse mismatches of natural flood-regulating ES supply and demand in urban areas for heavy rainfall events?
3) What impact will climate change have on the performance of flood-regulating ES and what are the contribution of Nature-based Solutions to enhance nature-based flood-regulating ES under changing climate change?



Research Gaps

RG 1 Estimation of flood regulating Ecosystem Services in urban areas

RG 2 A hydrological model that accounts for both, detailed vegetation interaction and a 2D surface runoff simulation during heavy rainfall events

RG 3 A comprehensive and mismatch analysis of flood regulating ES supply and demand for pluvial flooding in urban areas

RG 4 The use of the ES-concept to estimate flood regulating ES functions under changing climate conditions

RG 5 The contribution of Nature-based Solutions on flood regulating ES

Objectives

- Conducting a mismatch analysis of the natural flood-regulating Ecosystem Services supply and demand for heavy rainfall in urban areas
- Estimate the future contribution of natural flood-regulating Ecosystem Services regarding climate change and to understand the contribution of Nature-based Solutions.

Research Questions

		RG 1	RG 2	RG 3	RG 4	RG 5	P1 C3	P2 C4	P3 C5	P4 C6
RQ1	What are the limitations of different commonly used methods and indicators for flood-regulating ES assessment in urban areas and what is needed to overcome these?	x	x				x	x		
RQ2	How can we analyse mismatches of natural flood-regulating ES supply and demand in urban areas for heavy rainfall events?	x		x					x	
RQ3	What impact will climate change have on flood regulating ES performance and what are the contributions of Nature-based Solutions to enhance nature-based flood-regulating ES under changing climate conditions?			x	x	x	x	x		x

Figure 1: Overview of the research design, based on the Research Gaps (RG), the derived Objectives, and the answer of the Research Questions (RQ) by the Publications (P) and their respective Chapters (C) including the contribution to the Research Gaps.

1.3 Outline and Overview of the Chapters

The thesis was prepared as a cumulative dissertation based on four peer-reviewed publications, which are presented in the corresponding Chapters 3 to 6 and one software publication (Chapter 2.2.3.2). The publications build on each other and each contributes to several research questions (Figure 1). Figure 2 shows the structure, content, and linkage of the individual chapters. Chapters 3, 5, and 6 have a clear focus on flood-regulating ES. While Chapter 3 addresses fluvial flood-regulating ES, Chapters 5 and 6 focus on pluvial flood-regulating ES. Chapter 4 includes a short excurse on hydrological modelling in urban areas for pluvial floods as the methodological basis for Chapters 5 and 6. The detailed content of each chapter is described in the following.

The introduction in **Chapter 1** outlines the research design of the thesis. It includes the motivation, the objectives, and the research questions.

Chapter 2 offers background information on concepts, definitions in the context of this work, the used methods, and the study areas. First, the general concept of ES is described followed by a detailed description of flood-regulating ES, the focus of this study. Next, a theoretical understanding of hydrological modelling and the challenges thereof in urban areas is given. In addition, the applied hydrological models are presented, including the hydrological model that was developed and published in the frame of this study (Chapter 2.2.3.2). This is followed by theoretical background information about climate change and NbS. Lastly, the case study areas are introduced.

The first objective of **Chapter 3** was to compare different methods to quantify flood-regulating ES for fluvial floods in river floodplains. A hydraulic model and an existing area based indicator for flood-regulating ES quantification were applied. Second, the impact of higher floods due to climate change and the benefits of NbS were analysed. Altogether, the evaluation and discussion of the existing methods and applied spatial scale provided the base for future work. The chapter outlines missing elements, parameters, and processes to transfer existing methods for flood-regulating ES assessment from fluvial to pluvial floods in urban areas. Therefore, the chapter contributes answers to research questions 1 and 3.

In **Chapter 4**, the developed hydrological model (presented in Chapter 2.2.3.2) was tested, calibrated, and validated with observation data in the Vauban area (city of Freiburg in Breisgau, Germany). This relates to research question 1. In addition, the role of trees in runoff generation for a pluvial flood event on the quarter scale was estimated. This delivers further insights into the benefits of NbS contribution (research question 3).

Chapter 5 presents a methodological framework to assess urban flood-regulating ES for heavy rainfall events using the outputs of the developed hydrological model LEAFlood as input indicators in the ES assessment framework. The chapter proposes relevant indicators of supply and demand for a comprehensive flood-regulating ES analysis in urban areas. With these indications, a mismatch analysis of ES supply and demand was carried out to identify areas and amounts of unmet demand and supply surplus. This chapter focuses on research question 2.

In **Chapter 6**, the future dynamics of flood-regulating ES are analysed by applying the framework and indicators from Chapter 5. First, the future functionality of current flood-regulating ES under more intense extreme rainfall events was studied. Second, the contribution of NbS on urban flood-regulating ES and their future functionality under higher rainfall intensities were estimated. This provides further information to answer research question 3 with a focus on urban areas.

Finally, **Chapter 7** aggregates all findings from the research in a synthesis. The three research questions are resolved. It also contains subchapters about limitations and uncertainties, the contributions of the findings for practical application, and an outlook for future research.

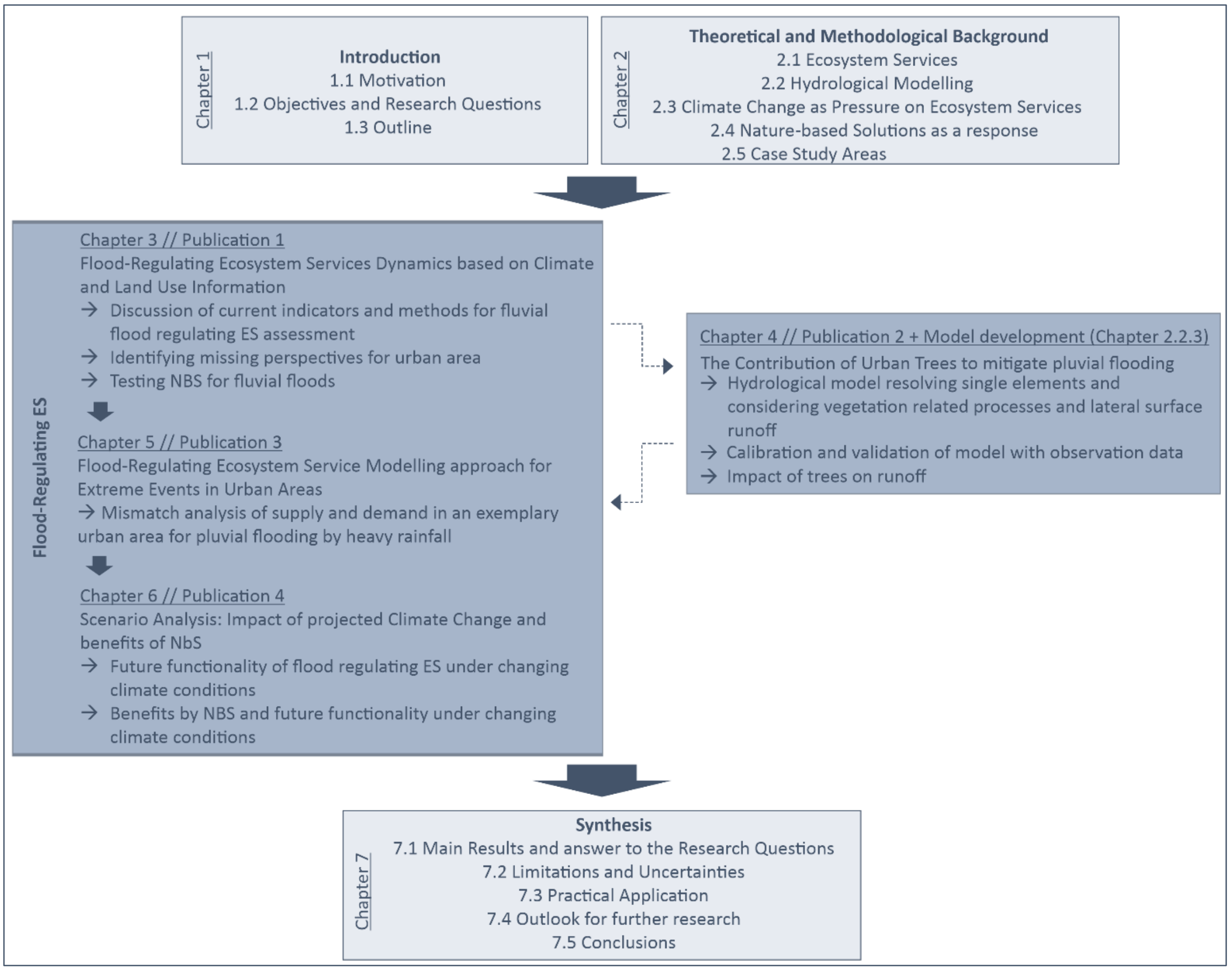


Figure 2: Structure and outline of the thesis including an overview of the content of the individual chapters.

2

THEORETICAL AND METHODOLOGICAL BACKGROUND

The second Chapter provides fundamental information on the concepts and definitions on which this thesis is based on. It provides more background information to the previous motivation chapter and builds up the base to answer the research questions.

In addition, background information on materials and methods, which were used in the individual research projects, is presented. The two applied hydrological models are described. An overview of the three study areas is given in the last subchapter.

2.1 Ecosystem Services

In the following, background information on the concept of Ecosystem Services (ES) is given, including a focus on flood-regulating ES.

2.1.1 Overview of the Ecosystem Services Concept

ES are defined as the direct and indirect contributions of ecosystems to human well-being (TEEB, 2010). They emphasise the linkage between the natural world with its biophysical elements and the human world in its socio-economic system. ES are integrated into the DPSIR (Driver-Pressure-State-Impact-Response) framework that connects the human-environmental system, where ES are placed in the centre as an impact (further details in Chapter 2.1.2, Figure 3; (Müller and Burkhard, 2012)). ES can be distinguished between supply, demand, and flow (see Box 1) (Burkhard and Maes, 2017). The functions of ecosystem and biodiversity structures provide ES supply that turn into ES flow if there is a demand by society. Demand types are multidisciplinary such as security or risk reduction, well-being as preferences, values or health, and direct or indirect use or consumption of resources (see Box 1; (Haines-Yong and Potschin, 2013; Geijzendorffer et al., 2015; Wolff et al., 2015). A comparison of ES supply and ES demand can indicate imbalances, whether there is an unmet demand or unsustainable use of ES (demand exceeds supply), or a supply surplus (supply exceeds demand) (Geijzendorffer et al., 2015; Dworczyk and Burkhard, 2021). The feedback on ecosystems and biodiversity by a socio-economic system depends on the valuation of ecosystem benefits by humans and the economy. The response of a socio-economic system acts as a driver, which causes pressures such as climate or land use change (Wolff et al., 2015; Oesterwind et al., 2016; Burkhard and Maes, 2017).

Box 1: Definition of Ecosystem Services terms (detailed definitions in Chapter 5 and 6)

Ecosystem Services: the direct and indirect contributions of ecosystem structures and functions to human wellbeing (TEEB, 2010)

Ecosystem Service Supply: the provision of service by an ecosystem, irrespective of its actual use (Burkhard and Maes, 2017)

Ecosystem Service Demand: the need, consumption, security, or preferences of ecosystem goods or services by society, irrespective of their provision or supply (Wolff et al., 2015; Burkhard and Maes, 2017). In the context of flood-regulating ES, Chapter 5 and 6 further divide the demand in potential demand (as the always-existing demand, irrespectively of the flooding) and actual demand (area that was actually used/flooded for a specific rainfall event).

Ecosystem Service Flow: the amount of ES that is mobilized in a specific area and time. It is driven by demand (Burkhard and Maes, 2017)

Ecosystem Service Mismatch: differences and imbalances in quantity or quality of ES supply and ES demand (Geijzendorffer et al., 2015)

In the past years, the ES concept has received increasing attention in science and policy. In 2005, it was part of the policy agenda by the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005). Based on this, the TEEB (The Economics of Ecosystem Services and biodiversity) recommended taking into account the economic value of ecosystems in decision-making processes (TEEB, 2010). To counteract the loss of ecosystems, the European Union committed to reduce biodiversity loss and avoid the degradation of ecosystems by 2020 in the EU-Biodiversity Strategy 2020. Action 5 of the EU Biodiversity Strategy 2020 Target 2 called for all EU member states to improve their knowledge on ecosystems and their services by mapping and assessing them (European Commission, 2011). For an efficient implementation of the goals of Action 5, the EU working group “Mapping and Assessment of Ecosystem of their services” (MAES) was established (European Commission, 2014) to develop indicators to monitor and assess the status and development of ES.

To classify ES, several ES classification systems exist. One example to define and delineate ES is the Common International Classification of Ecosystem Services (CICES, (Haines-Yong and Potschin, 2013; Haines-Young and Potschin, 2018). This classification system was intended to generate a uniform basis from the previously individually existing classifications. Today it is the basis for many research projects. The commonly used CICES classification system divides ES into three sections, namely ‘provisioning’, ‘regulation and maintenance’, and ‘cultural’ ES, which are further divided into divisions, groups, and classes of ES. ‘Provisioning services’ are material and energetic outputs from ecosystems as goods and products (e.g., livestock, drinking water, and water for agricultural or industrial use or biotic mass). The section ‘regulation and maintenance’ identifies ecosystem contributions to mediate or moderate the environment that affects humans. It focuses on benefits in terms of health and security, such as water flow regulation, water quality, or climate regulation. And lastly, the section ‘cultural services’ covers non-material characteristics of ecosystems for humans’ mental or intellectual well-being, such as recreation, aesthetics or education (Haines-Yong and Potschin, 2013; Burkhard and Maes, 2017; Haines-Young and Potschin, 2018).

To assess ES, multiple techniques and methods coexist. The tiered approach is a conceptual framework that classifies ES assessment methods regarding their level of detail and complexity (Grêt-Regamey et al., 2015). The choice of method should be based on the purpose of the ES assessment, stakeholder perspective, data availability, measurement technique, and spatial-temporal scale. TIER 1 usually provides a rough overview to raise awareness. It is based on links between land cover and constant ES value (Grêt-Regamey et al., 2015). A well-known example is the matrix approach by Burkhard et al. (2009). It consists of a look-up table with ES and, for instance, land cover classes. Methods to define ES proxies of land cover are expert evaluations or statistical data on a scale ranging from zero to five. TIER 2 estimates ES based on known relationships between ES and spatial information from literature or statistics. Besides, ES can be assessed by linking primary data such as field data to spatial information. For instance, harvesting statistics and forest types provide information on timber production (Grêt-Regamey et al., 2015). TIER 3 involves quantitative and social-ecological system models that link field and statistical data, literature information, and spatial data (Grêt-Regamey et al., 2015; Burkhard and Maes, 2017; Burkhard et al., 2018). A well-known ES assessment tool is InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) (Natural Capital Project, 2020; Nedkov et al., 2022). Depending on the assessed ES, InVEST covers TIER 2 or 3. Other biophysical models (mainly TIER 3) usually focus on one environmental component and consider complex processes of nature (Burkhard and Maes, 2017). Models are useful to fill spatial and temporal gaps, for extrapolation of measurements, or for scenario analysis. In particular, to quantify regulating services, models are important and sometimes the only option for an assessment (Burkhard and Maes, 2017). Model outputs and results, among other methodological approaches, provide indicators to assess, describe, and communicate states and trends of ES. Indicators can be for instance scores, percentages, biophysical quantification, or monetary values (Egoh et al., 2012; Boerema et al., 2017; Burkhard and Maes, 2017; Czúcz et al., 2018).

This thesis focuses on flood-regulating ES and mainly on assessments based on hydrological modelling (TIER 3). The ES and the methodological approaches and backgrounds are explained in more detail in Chapters 2.1.2 and 2.2.

2.1.2 In Detail: Flood-Regulating Ecosystem Services

Figure 3 shows the integration of flood-regulating ES in the DPSIR framework. Biophysical structures that can perform regulation functions to store water and reduce surface runoff are interception by vegetation, storage in surface depressions, infiltration in the soil, or percolation to the groundwater (Burkhard and Maes, 2017). They are indicated as the ‘State’ in the DPSIR framework (Figure 3) and can turn into an ‘Impact’ as flood-regulating ES. Flood-regulating ES are expected to lower flood hazards by reducing the runoff (Stürck et al., 2014) and thus, to lower potential social and economic damages (Vallecillo et al., 2019). Therefore, the resulting social benefits are the protection of property, houses, infrastructure, and human life as a further ‘Impact’ on the socio-economic system. The ‘Response’ by social and economic ‘Drivers’ causes ‘Pressures’ such as climate change or land use change. Pressures, change the State of the ecosystem, including biodiversity and biophysical structures (Müller and Burkhard, 2012). In the context of flood-regulating ES, consequences from climate change might be more frequent and intense rainfall events causing more frequent flooding. Land-use changes can either cause additional flood hazards by increased sealing and urbanization or function as adaptation measures to reduce flooding.

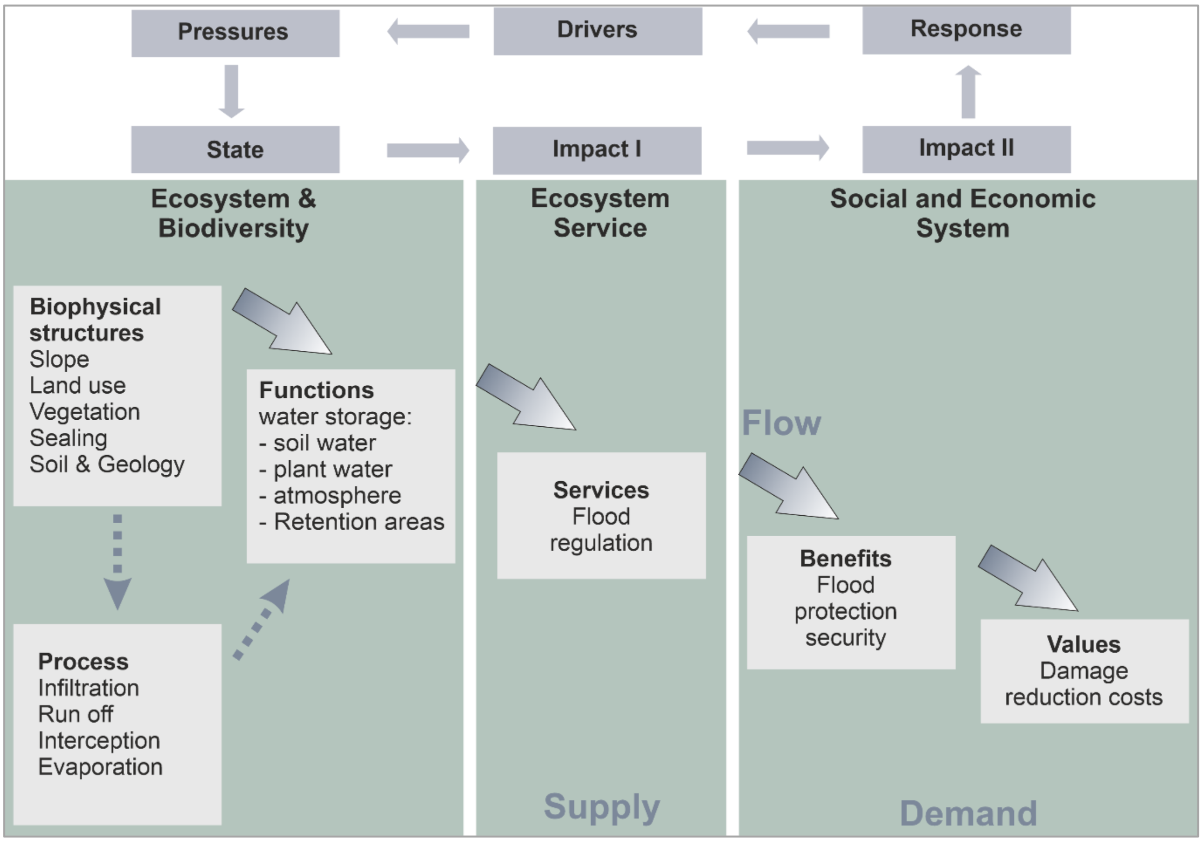


Figure 3: The ES-cascade model presenting ES in the DPSIR framework adapted for flood-regulating ecosystem services (adapted after Potschin and Haines-Yong (2011) and Müller and Burkhard (2012)).

In the following, various methods to assess flood-regulating ES are introduced. For a simple overview of flood-regulating ES, the matrix method can be applied (Burkhard et al., 2009; Goldenberg et al., 2017). Quantitative assessments can be based on indicators derived from spatial data evaluation such as land use, topography, or soil classes (Liyun et al., 2018; Shen et al., 2019). The German MAES working group proposed a flood-regulating ES supply indicator to quantify water storage capacity based on river floodplain areas. The indicator "area for flood retention" (Ger.: "Fläche für Hochwasserretention" (FHR)) considers all non-artificial land areas (e.g. pasture, forests, wetlands) that are not protected from flooding by dikes or other measures (see Chapter 3) (Albert et al., 2015). To consider related processes and interactions several model approaches exist. The InVEST model "Urban Flood Risk Mitigation model" that delivers runoff retention on the spatial scale of watersheds. The calculation is based on the SCS (Soil Conservation Service) Curve Number infiltration approach (Gaglio et al., 2019; Sharp et al., 2020). A more complex modelling but often applied approach is hydrological modelling (Nedkov et al., 2022). Studies exist mainly for fluvial flood-regulating ES assessment based on the spatial resolution of catchments (Nedkov and Burkhard, 2012; Stürck et al., 2014).

As the methodological focus to quantify flood-regulating ES is on hydrological models, a detailed overview is given in Chapter 2.2.

2.2 Hydrological Modelling

A model is a simplification of reality and represents the relationship, functions, and processes of different factors and components (Burkhard and Maes, 2017). A hydrological model is the representation of hydrological functions, processes, and characteristics to estimate flows within a hydrological system defined by various components and boundary conditions. While hydrological modelling focuses on hydrological processes, such as precipitation, evapotranspiration, infiltration, and surface runoff, hydraulic modelling is the study of the mechanical behaviour of water to predict the spatial and temporal characteristics of flow, like velocity and water depth, along a river or over surfaces (Mohd Talha Anees et al., 2016; DUDEK, 2022).

2.2.1 Classification of Hydrological Models

There is a wide range of hydrological models that differ in terms of the research question or practical application they address. The model selection depends on the investigated natural processes, landscape characteristics, scope of application, and the spatial and temporal scale (e.g. event-based, forecasting, or long-term studies) (Bach et al., 2014; Horton et al., 2021). Figure 4 shows a simplified classification of the spatial and temporal resolution to which models can be assigned, including related hydrological processes. In the following, two clusters of hydrological modelling that vary in the level of hydrological process and in the level of spatial representation are described.

On the level of hydrological processes, a distinction is made between empirical, conceptual or physical models. Empirical models are based on non-linear relationships of model input and output. They are rather simple in process description with a comparably small number of input parameters (Sitterson et al., 2017). One example of an empirical model is the commonly used Curve Number method (United States Department of Agriculture and Natural Resource Conservation Service, 2004). Conceptual models are based on simple model structures with simplified equations. The exchange of water among the atmosphere, hydrological components, and storage reservoirs are based on the water balance equation but physical processes are not included (Sitterson et al., 2017). Physical models, on the other hand, follow physical equations based on hydrological process knowledge. These models also take into account temporal-spatial variability and are more suitable for smaller scales (Sitterson et al., 2017). The high accuracy and complexity are associated with the requirement of a high number of input data, the need for higher computation power, and longer computing times (Cristiano et al., 2017).

Furthermore, models differ in the spatial presentation. Geology, soil, vegetation, and topography describe and define the spatial variability of a catchment (Sitterson et al., 2017). In lumped models, the spatial variability is neglected and the entire catchment is defined as one homogenous unit with average biophysical and (hydro) geological data (upper right corner in Figure 4). This results in the loss of information of extreme values (temporal resolution) and parameter changes on the short distance (spatial resolution), whereas the computational time is comparably low. These models are more suitable for long-term studies of the water balance in a catchment with a focus on mean budgets and values since the spatial distinction of water flow can be neglected over long periods (Sitterson et al., 2017). Semi-distributed models represent the landscape in more detail by using sub-catchments or HRUs of similar hydrologic characteristics regarding slopes, soil groups, and vegetation zones (centre of Figure 4) (Salvadore et al., 2015; Sitterson et al., 2017). A sub-catchment is defined by average data and is modelled in a lumped way (Cristiano et al., 2017). This also results in a loss of spatial information. The last option with a detailed spatial representation are the so-called distributed models. These models are spatially variable by grid cells or small elements defined by spatial heterogenic input parameters, thus their spatial limitation depends on the input data. Each cell has a hydrological response and is calculated separately (lower left corner of Figure 4) (Sitterson et al., 2017). The water flow is routed from each cell to the neighbouring cells, wherefore the flow can be calculated at any location. Distributed models are better for the representation of the spatial variability but require many input data of high resolution and spatial variability, such as a digital elevation model to describe the topography, land cover information, soil characteristics, and the spatial distribution of precipitation (Cristiano et al., 2017; Sitterson et al., 2017).

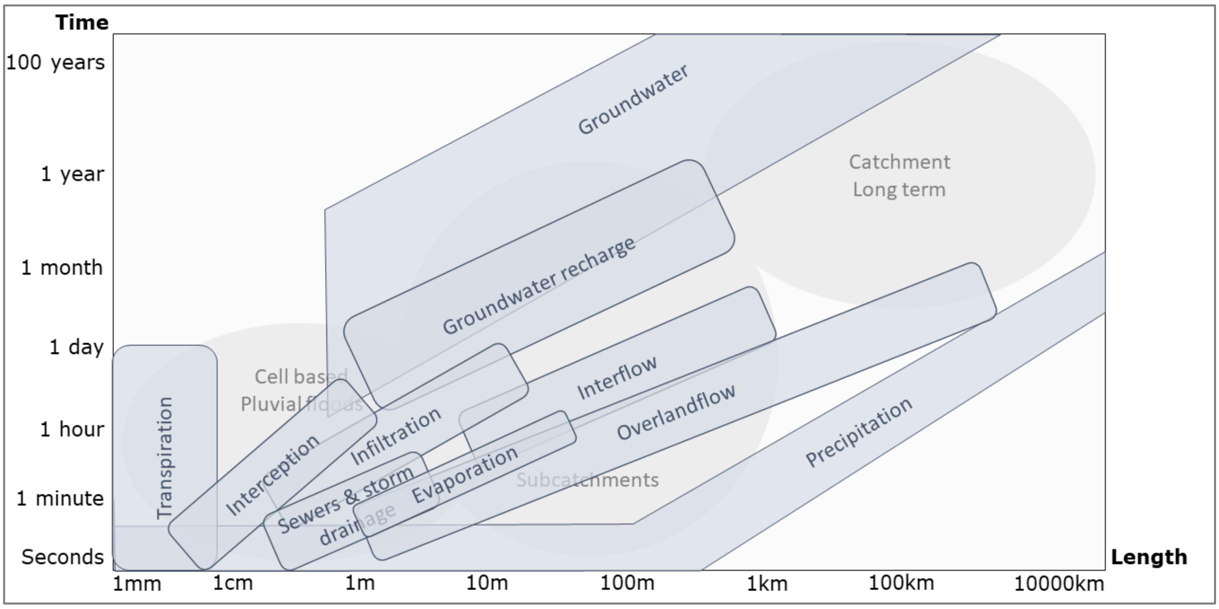


Figure 4: Spatial and temporal scales of hydrological processes (adapted after Salvadore et al., 2015).

In order to address a scientific question properly, the spatial and temporal components play a decisive role in the model choice. Table 1 gives an overview of frequently used models including their characteristics and resolutions classified according to Figure 4. Hydraulic models such as HEC-RAS (U.S. Army Corps of Engineers) or Flood Area (geomer, 2020) are hydrodynamic models, in which spatial resolutions are mainly cell-based (e.g. 1 m²) and the temporal resolutions are variable from events to long-term studies. They simulate the spatial distribution of water, e.g. on the surface, but rather consider hydrological processes. The model MIKE URBAN focuses on water distribution explicitly in urban areas, but also includes water quality. Another model cluster is lumped hydrological models for large catchments and long-term studies of the water balance (upper right corner of Figure 4). SWAT is a well-known example and the most popular hydrological model to quantify flood-regulating ES (Nedkov et al., 2022). Models based on the use of sub-catchments can be used for either single-event simulations or long-term studies (in the middle of Figure 4; e.g. KINEROS or WETSPA-Urban). For instance, SWMM is based on a simplified interception approach via depression storage. It is a one-dimensional model. The lateral surface runoff can only be routed in lower-laying neighbour cells (Rossman and Simon, 2022). The advantage of SWMM is the inclusion of Green Infrastructure (GI) and Low Impact Development (LID). Urban RoGeR is a water balance model for continuous simulations of hydrological processes in urban areas. While interception is simulated, the lateral surface runoff is not considered (Steinbrich et al., 2018). In summary, the model selection depends on the spatial resolution and considered processes. Accordingly, they are limited in terms of their application purpose as each model deals with a specific practical problem (Horton et al., 2021).

Table 1: Overview of commonly used hydrological models

Model	Source	Spatial resolution	Temporal resolution	Interception	Other comments
SWAT	Neitsch et al., 2009	Large Catchment	Long term	No	
SWMM	Rossman and Simon, 2022	Sub-catchments	Single event to long-term	Simplified by depression storage	
KINEROS	Woolhiser et al., 1990	Sub-catchments	Event-based	Yes	
Wetspa-Urban	Rezazadeh Helmi et al., 2019	Sub-catchments	Event - Continuous	Yes	
MIKE URBAN +	DHI, nY	Raster based	Event-based	unclear	Rainfall-Runoff Focus, Cost intensive
Urban RoGeR	Steinbrich et al., 2018	Cell-based	Long term	Yes	
Flood Area	geomer, 2020	Cell-based	variable	No	Hydraulic

2.2.2 Challenges of Hydrological Modelling in Urban Areas

Hydrological processes in urban areas are strongly altered by anthropogenic modifications. Soil sealing and soil compaction reduce infiltration and consequently increase surface runoff (Cristiano et al., 2017). Modelling hydrological processes in heterogeneous urban areas is mainly used for evaluating the effects of urbanization on the natural water system, to compensate lack of measurements, and for scenario predictions, such as the impact of land use or climate change (Salvadore et al., 2015).

Hydrological modelling in urban areas is still challenging. Multiple hydrological interactions of naturally and anthropogenically modified processes and their temporal and spatial variability result in a highly complex system (Fletcher et al., 2013; Salvadore et al., 2015). To represent hydrological processes on the urban scale for heavy rainfalls high spatial and temporal resolutions are needed (see Figure 4, lower left corner). The model review in Chapter 2.2.1 illustrated that resolutions of existing models on the catchment scale are usually too coarse to adequately represent urban hydrological processes (Salvadore et al., 2015; Wang et al., 2019). Instead, rainfall-runoff models designed for urban areas tend to separate vertical and horizontal hydrological processes and focus on surface runoff, while vegetation-related hydrological processes are neglected (e.g. MIKE URBAN or Urban RoGeR) (Wang et al., 2019). A model that resolves vertical hydrological processes, in particularly vegetation related processes, and lateral surface runoff on a sub-daily and cell resolution is missing.

Additionally, validation and calibration are still challenging. Due to the lack of measured data and the micro-climatic and micro-hydrological effects, it is difficult to prove model set-ups (Fletcher et al., 2013; Salvadore et al., 2015; Cristiano et al., 2017).

2.2.3 Hydrological Models Applied in this Study

Hydrological models were included in all parts of this thesis. Since hydrological models are designed for different purposes (Horton et al., 2021), two different models were applied. The hydraulic model HEC-RAS was used in Chapter 3 to estimate fluvial flood-regulating ES. Based on the outcomes of the hydrological model review, LEAFlood was developed and published (Wübbelmann and Förster, 2022) in the frame of this thesis. It was applied in Chapters 4, 5, and 6 for pluvial flood-regulating ES analyses in urban areas.

ArcGIS Pro 2.8.0 by ESRI and Python 3.7 was utilized for data preparation, pre and post-processing.

2.2.3.1 HEC-RAS

The U.S. Army Corp of Engineers developed the hydraulic model HEC-RAS (Hydrological Engineering Centre – River Analysis System). It has a user-friendly interface with a graphical display and an integrated geo data mapper to edit input and output data. Different water runoff simulations are available: one-dimensional steady flow, one- and two-dimensional unsteady flow, sediment transport, and water temperature and quality. The first version was released in 1995 and the newest version is from 2021 (Brunner, 2022a).

Two-dimensional unsteady flow simulations in version 5.0.7 were used in this thesis (Chapter 3; (Wübbelmann et al., 2021). While the older version only considered surface runoff and channel flow, newer versions also include different infiltration process approaches such as the SCS Curve Number or the Green-Ampt approach (Brunner, 2022b). For a two-dimensional model, the geometry is set in the first step. Input data are the elevation, the roughness coefficient by Manning, and boundary conditions for inflows and outflows. In the second step, the discharge data are adjusted. Either spatial homogenous rainfall dataset or discharge data at the boundaries as inflow can be applied. Lastly, the time steps for the calculation and simulation are defined (Brunner, 2022c).

2.2.3.2 LEAFlood

The LEAFlood model (Landscape and vEgetAtion-dependent Flood model) (Wübbelmann and Förster, 2022) is based on the modular programming library CMF (Catchment Modelling Framework) for hydrological modelling (Kraft et al., 2011; Kraft, 2020b). CMF is an open-source Python package to create individual hydrological models. Different hydrological processes and equations can be selected. The modularity and flexibility of this programming library enables to create different hydrological models depending on the research questions or practical application (Salvadore et al., 2015).

LEAFlood is a distributed model between a conceptual and physical-based approach. The objective of the model is to obtain a detailed representation of interception and lateral 2D surface runoff based on single landscape elements. Thus, the model simultaneously considers hydrological and hydraulic processes on the urban scale. Figure 5 shows the hydrological processes and a possible spatial resolution. The geometry is defined by irregular polygons from a shapefile. These can be based either on land use information or on smaller irregular polygons. LEAFlood considers processes of canopy interception, canopy evaporation, through fall, soil infiltration, and surface runoff (Wübbelmann and Förster, 2022). The canopy interception follows the Rutter approach (Rutter et al., 1971; Kraft, 2020e). Each cell is defined by a LAI, the interception capacity, and canopy closure. The canopy closure determines how much water is intercepted. A canopy closure of one means that all precipitation is intercepted and zero indicates direct routing to the surface. Up to now, LEAFlood considers one soil layer but can be adapted to multiple layers. The infiltration process follows the Green-Ampt infiltration method (Kraft, 2020c) and the Brooks-Corey Retention Curve (Kraft, 2020a). Besides the porosity, the saturated conductivity and initial saturated depth are the main input parameters for soil. The surface runoff is kinematic (Kraft, 2020d) and is therefore based on the topography and surface roughness (Manning's n). Depending on the available data and resolution, all input parameters can be defined individually for each cell with a few adjustments in LEAFlood (see Figure 5). Drivers are meteorological data as time series of rainfall, temperature, wind speed, relative humidity, and solar radiation. The temporal resolution is flexible depending on the purpose.

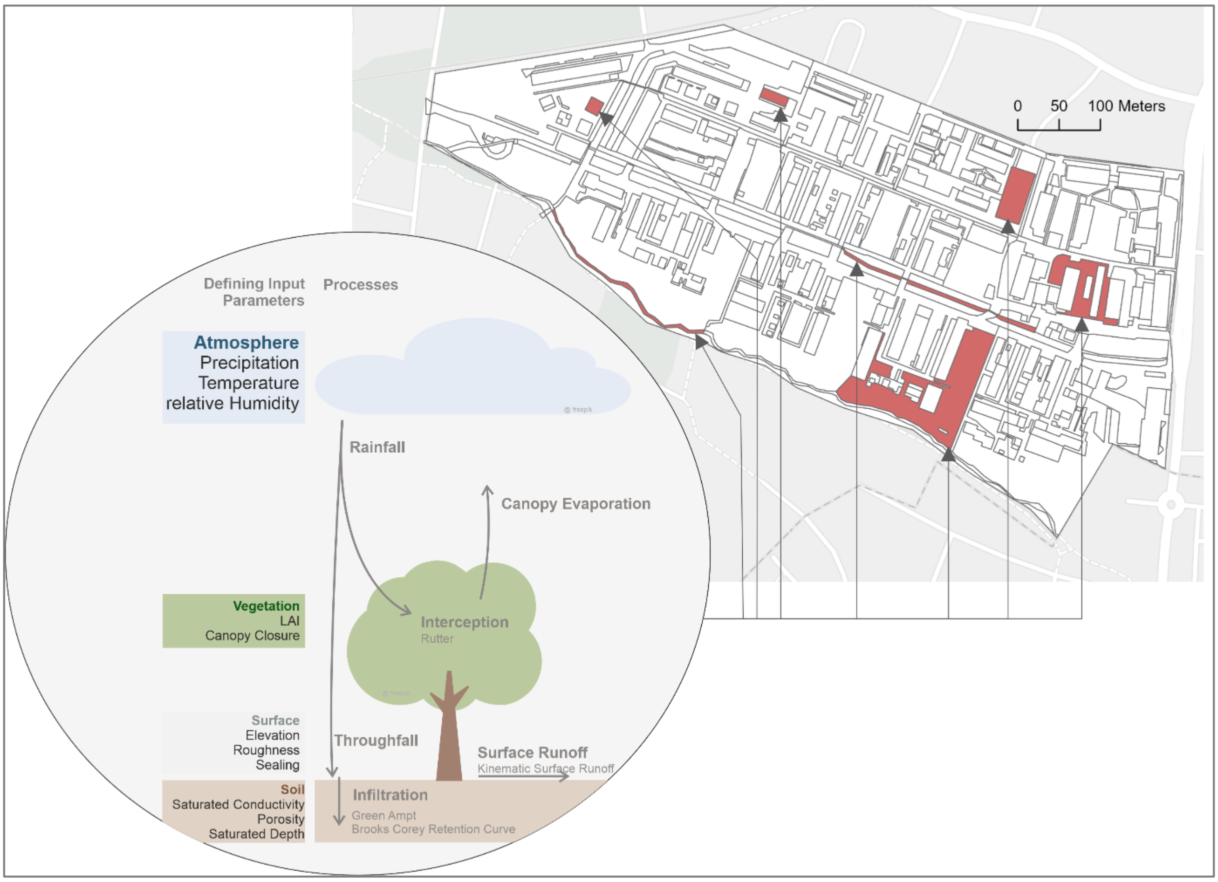


Figure 5: Processes and defining parameters in the hydrological model LEAFlood and an exemplary representation of the possible individual cell sizes of the geo-input data set using the example of Vauban (adapted afterWübbelmann and Förster, 2022).

LEAFlood was developed and published as part of this dissertation as an open-source Python script (Wübbelmann and Förster, 2022). The model follows the FAIR principles of being findable, accessible, interoperable, and reusable (Wilkinson et al., 2016). The principles were first declared for data and later pushed forward for software publishing (Lamprecht et al., 2020). The software quality of LEAFlood is warranted by maintenance due to the published open-source code and proven by the calibration with observation data in Chapter 4. The open source accessibility fulfils a FAIR principle and additionally differs in comparison to many other models that may consider many hydrological processes and details, but are comparatively costly (e.g. MIKE URBAN). A survey among hydrological model users confirmed the importance of a freely available model as a significant reason to choose that model (Horton et al., 2021).

LEAFlood was applied in the course of this dissertation by Medina Camarena et al. (2022) (Chapter 4), Wübbelmann et al. (2022a) (Chapter 5), and Wübbelmann et al. (2022b) (Chapter 6). Medina Camarena et al. (2022) calibrated and validated LEAFlood with observation measurements in Vauban to prove its plausibility in surface runoff and interception simulation. In a next step, Wübbelmann et al. (2022a) created a framework for pluvial flood-regulating ES in urban areas and used outputs of LEAFlood as indicators for the ES assessment. Finally, Wübbelmann et al. (2022a) also derived flood-regulating ES indicators from the output of the hydrological modelling with LEAFlood for a scenario analysis of pluvial flood-regulating ES in urban areas.

2.3 Climate Change as Pressure on Ecosystem Services

Anthropogenic induced climate change exerts an important anthropogenic pressure on ecosystems (Millennium Ecosystem Assessment, 2005; World Economic Forum, 2019). It increases the loss and degradation of ecosystems, reduces their functions, and ultimately ecosystem services and related benefits for the socio-economic system. Therefore, the future functionality and contribution of ES to human well-being urgently need to be assessed (Maes et al., 2020).

Since the 1970s, the global surface temperature has increased more quickly than during any time in the last 2,000 years. The anthropogenic influence on global warming is proven and many consequences are irreversible (IPCC, 2021). In the 21st century, global warming will exceed 2°C unless a drastic reduction in greenhouse gas emissions is made. While climate projections show a global temperature increase below 2°C for the sustainable SSP[1]1-2.6 scenario, the increase would be below 3°C for the moderate scenario SSP2-4.5 and up to almost to 5°C for the high fossil fuel scenario SSP5-8.5 (IPCC, 2021).

For Germany, a robust and significant increase in the annual mean temperature is projected for the period 2071-2100 compared to the reference period 1971-2000. The bandwidth of the emissions scenario RCP8.5[2] is between +3.7°C and +5.2°C, while the mean temperature increase for RCP4.5 is projected between +1.6°C and +3.2°C. The change in the mean annual precipitation sum varies between -5% and +25% for RCP 4.5 (Jacob et al., 2014).

Although mean annual precipitation amounts may decrease in some parts of Germany, IPCC (2021) has shown that human-induced climate change is already influencing extreme events and thus also the water cycle and related extreme events. This is particularly relevant for urban flood risk. Since the 1950s, the frequency and intensity of heavy precipitation events have increased over most land areas and will increase further in the future (IPCC, 2021). According to regional climate models, higher daily precipitation intensities can be expected with a shift from weak to moderate and high intensities (Jacob et al., 2014). On the global scale, precipitation intensities may increase by 7 % for each 1°C warming (IPCC, 2021), whereby global and regional climate model projections potentially underestimate the changes of short-duration rainfall events. Indeed, some studies show that the increase for extreme events could be as high as 14 % per 1°C warming (Lenderink and van Meijgaard, 2008; Westra et al., 2014; Dahm et al., 2019; Förster and Thiele, 2020). Consequently, current precipitation events with a 1h duration of 10 and 100-year return period will likely become more frequent (Dahm et al., 2019).

2.4 Nature-based Solutions as a Response

Using nature's potential is one way to adapt to climate change by enhancing the state of ecosystems and their functions. The objective is to counteract pressures from climate change and urbanisation (Kabisch et al., 2017).

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[1] Share Socio-economic Pathways (SSPs): This is the designation in newer IPCC reports. They have been developed to complete the Representative Concentration Pathways (see footnote below). A certain socio-economic development is included within the SSPs IPCC (2021).

[2] Representative Concentration Pathways (RCP): Different time series scenarios of emission and concentration of greenhouse gases, aerosols and chemically active gases. The existing RCPs are only one of many possible scenarios (representative) Moss et al. (2010).

One frequently used definition that has received more attention in recent years is Nature-Based Solutions (NbS). The term was first introduced by the World Bank and the International Union for Conservation of Nature (IUCN) (The World Bank, 2008; Cohen-Shacham et al., 2016). NbS are defined as "actions which are inspired by, supported by or copied from nature" (European Commission, 2015). NbS consider nature services by conserving, retrieving, or creating natural processes in modified ecosystems to address societal and biodiversity benefits to contribute to human well-being (Cohen-Shacham et al., 2016; Kabisch et al., 2017; WWAP, 2018). Therefore, NbS use features and complex natural processes to maintain and enhance biodiversity and ecosystems, and related natural capital (European Commission, 2015). NbS increase resilience against environmental risks and provide multiple co-benefits, such as water regulation, climate regulation, biodiversity conservation, and pollution reduction (European Commission, 2015; WWAP, 2018). Well-known NbS in urban areas are for instance green infrastructures, green roofs or rain gardens (WWAP, 2018).

The concept of NbS has many overlaps with coexisting definitions such as ecosystem-based adaptation or urban green-infrastructure. NbS can be seen as the umbrella of other concepts, as it is broader and more abstract (Kabisch et al., 2017).

2.5 Case Study Areas

The work this thesis was carried out in three different case study areas. One is located in the Biosphere Reserve Lower Saxonian Elbe Valley. This study area was used for flood-regulating ES assessment of fluvial flood events (Chapter 3). The area was mainly chosen, because of the numerous river floods that have taken place in this area in the past.

The second study area is Vauban, an urban district of the city of Freiburg (im Breisgau) in southern Germany. The area provides a detailed network of hydrological data including observation data, which are usually hard to obtain for cities. Datasets of runoff and interception amount were used for calibration and validation of the hydrological model LEAFlood (Chapter 4).

The third area is an urban district of the city of Rostock. It served as a case study in Chapters 5 and 6 for a pluvial flood-regulating ES assessment in urban areas. It was selected because of several heavy rainfall events and the resulting consequences in 2011 (Miegel, 2011). Since then, the awareness of this issue increased in this city, and several projects were implemented (Biota, 2013, 2014; Tränckner and Walter, 2018).

2.5.1 Biosphere Reserve Lower Saxonian Elbe Valley, Germany

The study area along the Elbe River is part of the Biosphere Reserve Lower Saxonian Elbe Valley, near Schnackenburg in the county Lüchow-Dannenberg (see Figure 6). The area has a size of 24 km² and is dominated by pasture (36 %) and farmland (32 %). Forests cover 13 % of the area and settlements cover 2.5 %. The main soil type in the study area is gleys with loamy to clayey alluvial sediments (BGR, 2022).

The prevailing climate is maritime in the west and shifts to a more continental climate in the east. The annual mean temperature at the DWD climate station in Dömitz is 9.3 °C for the reference period 1981-2010 with a mean maximum temperature of 18 °C in July and a minimum of 0.9 °C in January (DWD, 2022b). The average annual precipitation sum is 578 mm, with a maximum of 69 mm in July (DWD, 2022a).

Climate projections of 85 regional climate models show an increase in the annual mean temperature until the end of the century (2069 – 2098) between 0.3°C (RCP2.6) and up to 5.0 °C (RCP8.5) compared to the reference period 1971-2000. The projected bandwidth of precipitation change is between -7.8 (RCP2.6) and +30.1 % (RCP8.5). The number of days with more than 20 mm precipitation per day is projected to change between -0.8 days (RCP2.6) and +2.5 days (RCP8.5) (Pfeifer et al., 2021b).

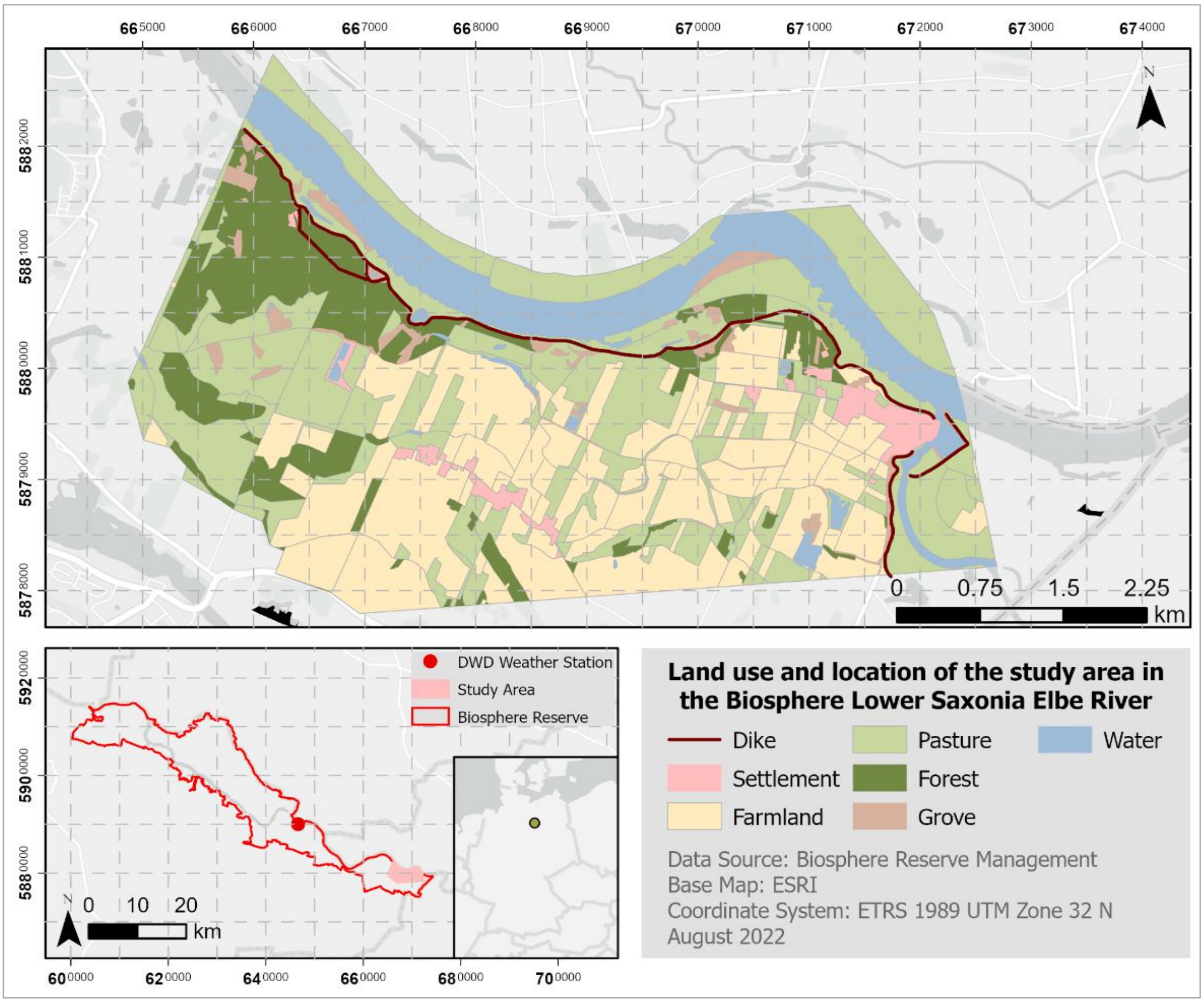

Figure 6: The study area and its land use in the Biosphere Reserve Lower Saxonian Elbe River.

2.5.2 Vauban – a district of Freiburg im Breisgau, Germany

Vauban is a district of the city of Freiburg in southern Germany (see Figure 7) with a size of 30.8 ha and 5500 inhabitants (Jackisch et al., 2013). It was built on the site of a former French military base from the 20th century. Vauban is a sustainability-oriented urban district with, for instance, ecological stormwater management system and low-energy passive solar houses. The design of the district aims to maximize green infrastructure, including extensive green areas, green roofs, walking paths with permeable pavements, rainwater harvesting, and intensive private gardening (Coates, 2013; Jackisch et al., 2013). A swale system manages the runoff. Two parallel swales run along the main streets. A downstream swale collects the discharge of these both swales in the northwest of the study area. The collecting swale flows into a creek at the southern edge of the district.

Due to the maximization of green infrastructure, 65.3 % of the total area is covered by green structures, including swales and green roofs. 33.8 % are sealed areas and 1 % consist of water bodies (land use dataset provided by the University of Freiburg). Vauban has a tree coverage with canopies of about 14 %. The soil type is partly gley on sandy to loamy river sediment and partly cambisol (BGR, 2022).

The climate conditions in Vauban are maritime to semi-continental. The mean temperature from 1981-2010 was 10.7 °C, with a maximum mean temperature of 19.9 °C in July and a minimum mean temperature of 1.8 °C in January (DWD, 2022b). The average precipitation sum is 940 mm, with a maximum of 109 mm in May (DWD, 2022a).

For Freiburg, the climate models project a robust increase of the annual mean temperature between 0.5 °C (RCP2.6) and 5.5 °C (RCP8.5) for the end of the century (2069 - 2098), relative to the reference period of 1971 – 2000. The bandwidths of precipitation are projected to be between -7.6 % (RCP2.6) and +28.1 % (RCP8.5). The number of days with 20 mm precipitation or more per day is projected to change between -2.8 days (RCP2.6) and +11.1 days per year (RCP8.5) (Pfeifer et al., 2021a).

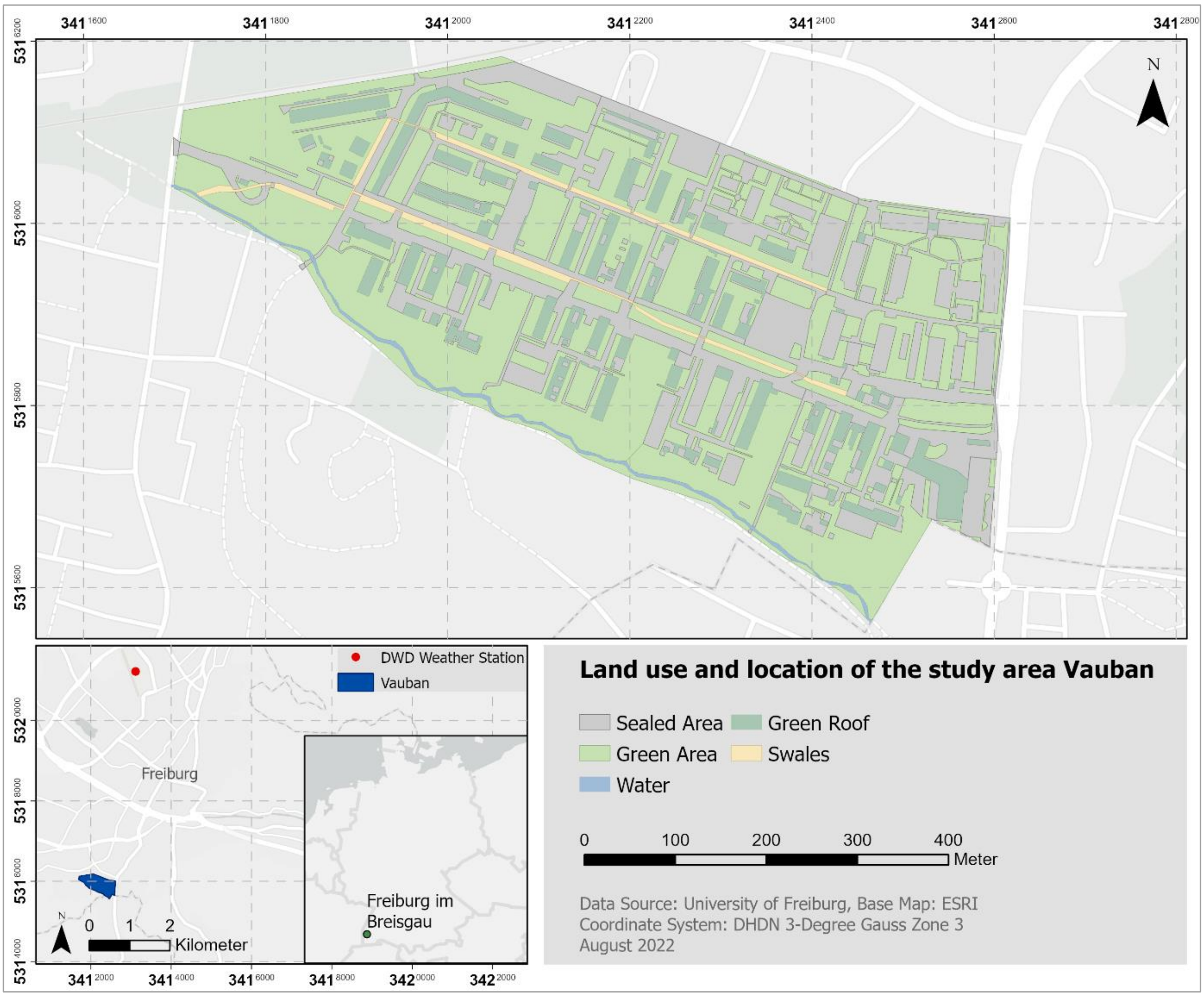

Figure 7: The study area Vauban (Freiburg im Breisgau) and its land use.

2.5.3 City of Rostock, Germany

Rostock is located in the northeast of Germany at the estuary of the river Warnow in the Baltic Sea (Figure 8). The city and its surroundings have a size of 182 km² with a terrain height ranging from 0 to 55 m over sea level (Landesamt Mecklenburg-Vorpommern, 2019).

The investigated study area covers 4.5 km² in the southwest of Rostock (Figure 8). The predominant land uses are green areas of parks, forests, and woodlands with a coverage of 50 %. Traffic areas cover 23 % of the area and settlements and industry 25 % (Steinbeis-Transferzentrum Geoinformatik, 2017). The soil types are luvisol-pseudogley and regosol of wet sandy loams or loamy sands (Hanse- und Universitätsstadt Rostock – Amt für Umwelt- und Klimaschutz, 2019a, 2019b).

The climate in Rostock is mild maritime, with annual mean temperatures of 9.4 °C (1981 – 2010). The warmest month is July (18.1 °C) and the coldest month is January (1.5 °C) (DWD, 2022b). The average precipitation amount per year is 613 mm (1981 – 2010), with a maximum average precipitation sum in June of 70 mm (DWD, 2022a).

A robust temperature increase is projected for Rostock until the end of the century (2069 – 2098) between 0.3 °C (RCP2.6) and 5.0 °C (RCP8.5) compared to the reference period (1971 – 2000). The changes in the precipitation is projected between -13.7 % (RCP2.6) and up to +32.3 % (RCP8.5). The number of days with more than 20 mm precipitation per day is projected to change between -0.9 (RCP2.6) and +9 days per year (RCP8.5) (Pfeifer et al., 2021c).

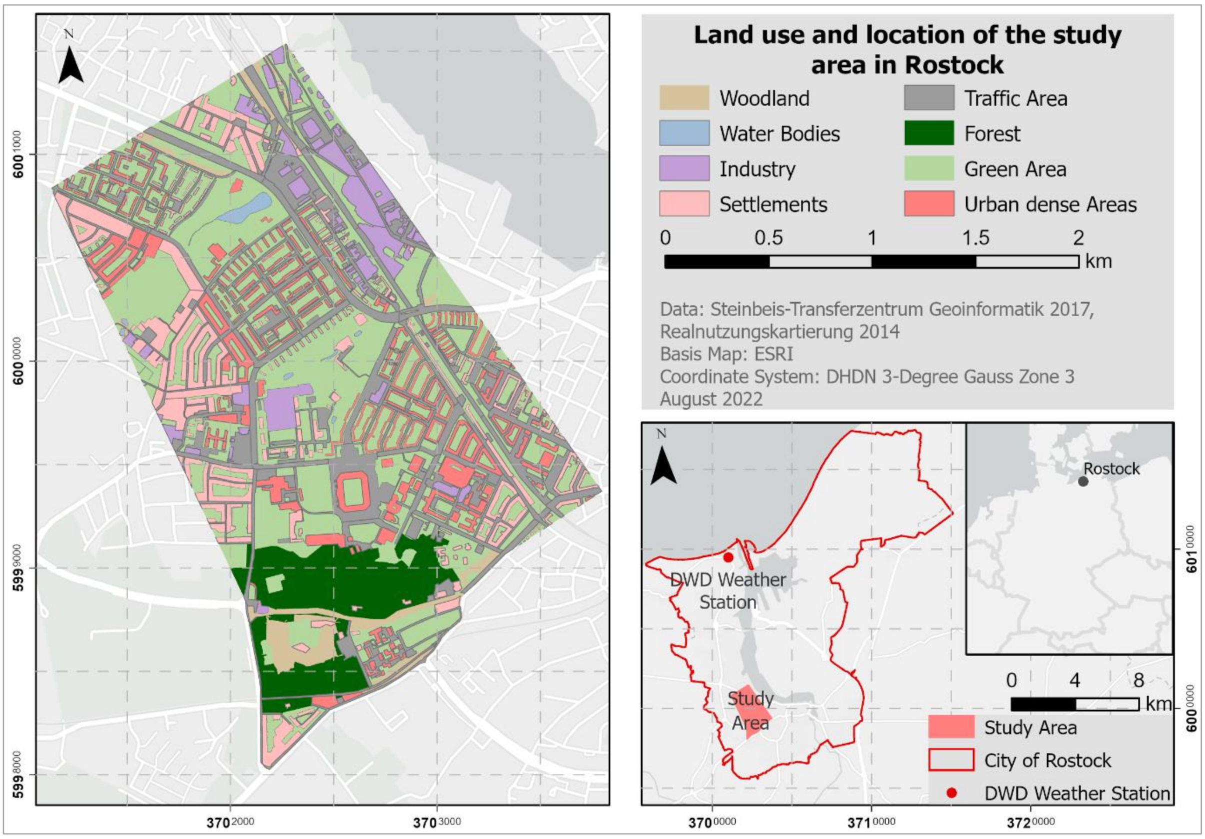

Figure 8: The study area in the city of Rostock and its land use.

3

PUBLICATION 1

FLUVIAL FLOOD-REGULATING ECOSYSTEM SERVICES DYNAMICS BASED ON CLIMATE AND LAND USE INFORMATION

This Chapter compares, evaluates, and discusses the results of two different approaches – the MAES indicator and hydraulic modelling - to assess fluvial flood-regulating ES. It analyses the contribution of Nature-based Solutions and the impacts of increased flooding due to changing climate to fluvial flood-regulating ES supply. The publication provides the basis for future research by highlighting missing scales, elements, parameters, and processes in flood-regulating ES assessments.

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RESEARCH PAPER Page 1

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Modelling flood regulation ecosystem services dynamics based on climate and land use information

Abstract

The concept of ecosystem service (ES) identifies benefits that people obtain from ecosystems with contributions to human well-being. One important ES under external pressure is “flood regulation” that describes an ecosystem’s capacity to reduce flood hazards.

Several related studies estimate current flood regulation ES. However, regional climate projections indicate a shift in precipitation patterns. Therefore, Climate and land use changes make it necessary to assess future supply in order to test functionality and adaptation measures. This study focuses on surface retention ES. We used two methods to show the relevance of different landscape scenarios and climate information for flood regulation ES supply: 1) hydraulic simulations with the model HEC-RAS 2) the flood retention capacity indicator suggested by the German MAES-Working group. We simulated two events: the historic flood of 2013 and future hypothetically 10% higher water levels. Furthermore, three land use change scenarios were evaluated.

The model results indicate water accumulation by vegetation. Higher water levels of future climate scenarios lead to an increase in flooded areas and higher water volumes. To evaluate flood regulation capacities, an approach solely based on 2D retention areas, such as the MAES-indicator, is not sufficient. Modelling approaches deliver the opportunity for future scenario simulations.

Thea Wübbelmann[1,2*], Steffen Bender[1], Benjamin Burkhard[2,3]

[1] Climate Service Center Germany (GERICS), Helmholtz-Zentrum Geesthacht (HZG), Hamburg, Germany

[2] Leibniz University Hannover, Institute of Physical Geography and Landscape Ecology, Hannover, Germany

[3] Leibniz Centre for Agricultural Landscape Research ZALF, Müncheberg, Germany

*Corresponding author: Thea Wübbelmann, Climate Service Center Germany (GERICS), Helmholtz-Zentrum Geesthacht (HZG), Fischertwiete 1; 20095 Hamburg, Germany, Email: thea.wuebbelmann@hzg.de

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1 Introduction

The loss and degradation of biodiversity and ecosystems is one of the main global risks (WEF 2019). Changes in land use, climate conditions and matter fluxes are key pressures for biodiversity loss (Baessler and Klotz 2019). However, the supply of ecosystem services (ES) must be ensured in order to safeguard the direct and indirect contributions of ecosystems to human well-being (MEA 2005; Burkhard and Maes 2017; TEEB 2010). The concept of ES links social and environmental systems to achieve a sustainable use of natural resources (Engel and Schaefer 2013; Burkhard and Maes 2017) and helps to discover synergies and trade-offs between different ES (Liu et al. 2013; Engel and Schaefer 2013).

To assess one of the most important pressures (“ […] pressure […] as a result of a driver-initiated mechanism (human activity/ natural process) causing an effect on any part of an ecosystem that may alter the environmental state” (Oesterwind et al. 2016, p. 11) for local and regional loss of biodiversity, increase in natural disasters and extreme events, it is becoming increasingly important to focus on changing climate parameters (WEF 2019). These changes influence many components of the water cycle and thus, flood characteristics. Because of a worldwide observed rise in flood events that also increasingly impacts people (Swiss Re Institute 2019), flood regulation ES are becoming more important (Paprotny et al. 2018; WEF 2019). Regional climate information can provide significant information (Jacob et al. 2014) to support the assessment of flood regulation ES.

1.1 Flood regulation ES and related indicators

„Flood regulation ES supply “addresses the ecosystem’s capacity to lower flood hazards caused by heavy precipitation events by reducing the runoff fraction” (Stürck et al. 2014, p.198) and thus reduces potential economic and social damages (Vallecillo et al. 2019; Müller et al. 2016). Usually, it is determined by the water retention function of terrain, soil or vegetation. Main pressures for flood retention loss are changes of land use and climate conditions. With regard of these pressures, the reduction of retention areas and the modification of water-related functions such as evapotranspiration, vegetation-soil interactions and surface roughness, and with that flow rates and flow velocity, are important varied processes. As a consequence, the annual water availability changes which can lead to periods of water scarcity and an increase in flood risk and water pollution (Engel and Schaefer 2013).

To quantify ecosystem service supply, indica- tor-based approaches are commonly applied, us- ing different parameters and dimensions (Vigerstol and Aukema 2011; Stürck et al. 2014). The initiative “Mapping and Assessment of Ecosystem and their Services” (MAES) has gained increasing importance in the context of the EU Biodiversity Strategy 2020 (European Commission 2011). In Germany, the national MAES working group has developed an ar- ea-based indicator for the evaluation of the surface flood retention capacity of floodplains (Grunewald et al. 2016; Albert et al. 2015), which was analysed for the practicability compared to results from hydraulic models in this study. De Groot et al. (2010) proposed a water volume-based assessment that considers the water storage capacity including the retention capacity in the soil or at surface depressions. Logsdon and Chaubey (2013) used a three-component function to estimate flood regulation, based on the flood duration [days], the number of flooding events per time period and the average magnitude [m^3/s] of the flood. In the past, model-based approaches of various complexity have become more common, for example to improve the consideration of complex physical processes. While hydrological models deliver more detailed results related to the involved processes, special ES tools (e.g. InVEST (Sharp et al. 2018) and ARIES (ARIES n.d.) are more accessible also to non-experts and can reflect trade-offs between ES (Vigerstol and Aukema 2011). Another methodis to combine hydrological parameters of model re- sults (e.g. infiltration, surface runoff, peak flow) with landscape information (e.g. land use, soil types) for spatial analysis (Nedkov and Burkhard 2012). Most of the studies analyse the flood regulation capacities for current climate conditions. Gaglio et al. (2019) have considered climate change with InVest, referring to the increasing drought in a catchment area in Portugal. With regard to the mentioned pressures, it is necessary to include regional climate projections for the next decades to estimate ES functionality in the future.

1.2 Climate change as pressures of ESchanges

The carbon emissions, caused by human activities such as fossil fuel burning or land use change, have a high impact on the global climate that affect ecosystem condition and ES supply (IPCC 2013, 2019). Future climate projections are based on ensembles of dynamic and statistic regional climate models with different emission scenarios (Representative Concentration Pathways (RCP)), driven by anthropogenic radiation propulsion (Moss et al. 2010; Bender and Jacob 2016; Bender and Bülow 2018). Three classes of pathway emission scenarios are commonly used: RCP2.6 (“climate protecting”) low emission scenario, reduction of the greenhouse gas emissions; RCP4.5 (“moderate emission scenario”); RCP8.5 (“busi-ness-as-usual scenario”) increasing emissions (Mosset al. 2010; DKRZ n.d.; van Vuuren et al. 2011).

Results of regional climate projections indicate a robust and significant temperature increase for all scenarios in continental Europe until the end of the 21st century (RCP4.5: +1.6 °C to +3.2 °C; RCP 8.5: +3.7 °C to +5.2 °C) (Bender and Bülow 2018; Jacob et al. 2014). As a result, there is a higher potential evaporation (IPCC 2013). Furthermore, an inter-annual shift towards more precipitation and runoff during winter and decreasing summer precipitation months is to be assumed (IPCC 2013; Bender and Jacob 2016) causing higher flood risks in winter season. Regional climate projections for Germany show a local, robust and significant increase of heavy precipitation frequency by about 25 % for the RCP 8.5 (period 2071-2100, reference period 1971-2000) for autumn and winter. For RCP 4.5, no significant changes are obvious (Jacob et al. 2014).

1.3 Objectives of the study

Our study focused on the derivation of flood regulation ES by hydraulic modelling for extreme flood events. Hydraulic modelling delivers information on the extent and depth of flooding and therefore on the surface retention capacity of a floodplain. With this method, we investigated the importance of flood regulation ES due to changing climate and land uses. To classify the model results, a simple retention area based indicator of the German MAES-working group was used. The two methods and their results were compared and the limitations and advantages were identified. Following research questions were answered by this study:

- Is HEC-RAS suitable to model flood regulation ES?
- What does the assessment of future flood regulation ES show?
- What are the advantages of flood regulation ES modelling compared to retention area-based indication?

2 Research area

The research area (24 km²) is located in the Biosphere Reserve Lower Saxonia Elbe Valley, close to the city of Schnackenburg (Figure 1). The area was chosen because it was flooded several times in the past years. The land use types pastures or grassland (36%) and farmland (32 %) are dominant. Forest areas cover 13 % and only 2.5 % of the area belong to settlements. The remaining area includes, for example, water bodies. In the entire floodplain, flood deposits of alluvial clay and sands can be found. The main soil types are gleys and pseudogleys (LBEGn.d.; BGR 2013).

The region is characterized by continental and maritime climate conditions. The annual mean temperature (1951-1980) is 8 °C. The maximum temperature is 17 °C in July and the minimum is -0.3 °C in January. The mean annual precipitation at the Station Dömitz amounts to 564 mm (1961-1990). Precipitation decreases from west to east (BrNE-Management 2009). In winter, snow melting and heavy rainfalls can cause surface water run-offs and river floods. In summer, prolonged precipitation periods lead to high water levels in the Elbe river (Meyer 2017; NLWKN 2017). For the end of the century (2070-2099) relative to 1971 - 2000, regional climate projections show a significant increase of annual temperatures: 0.2 - 2.0 °C (RCP2.6), 1.2 - 3.1 °C (RCP4.5), and 2.6 - 5.0 °C (RCP8.5) for the region of the Biosphere Reserve Lower Saxonia Elbe Valley. For the projected annual mean precipitation amounts, changes range between -9.9 and +7.4 % (RCP2.6), -1.7 and +17.2 % (RCP4.5), and -7.0 and 27.9 % (RCP8.5). These changes are not significant, but show an increasing tendency (Pfeifer et al. 2015). This trend can be at-

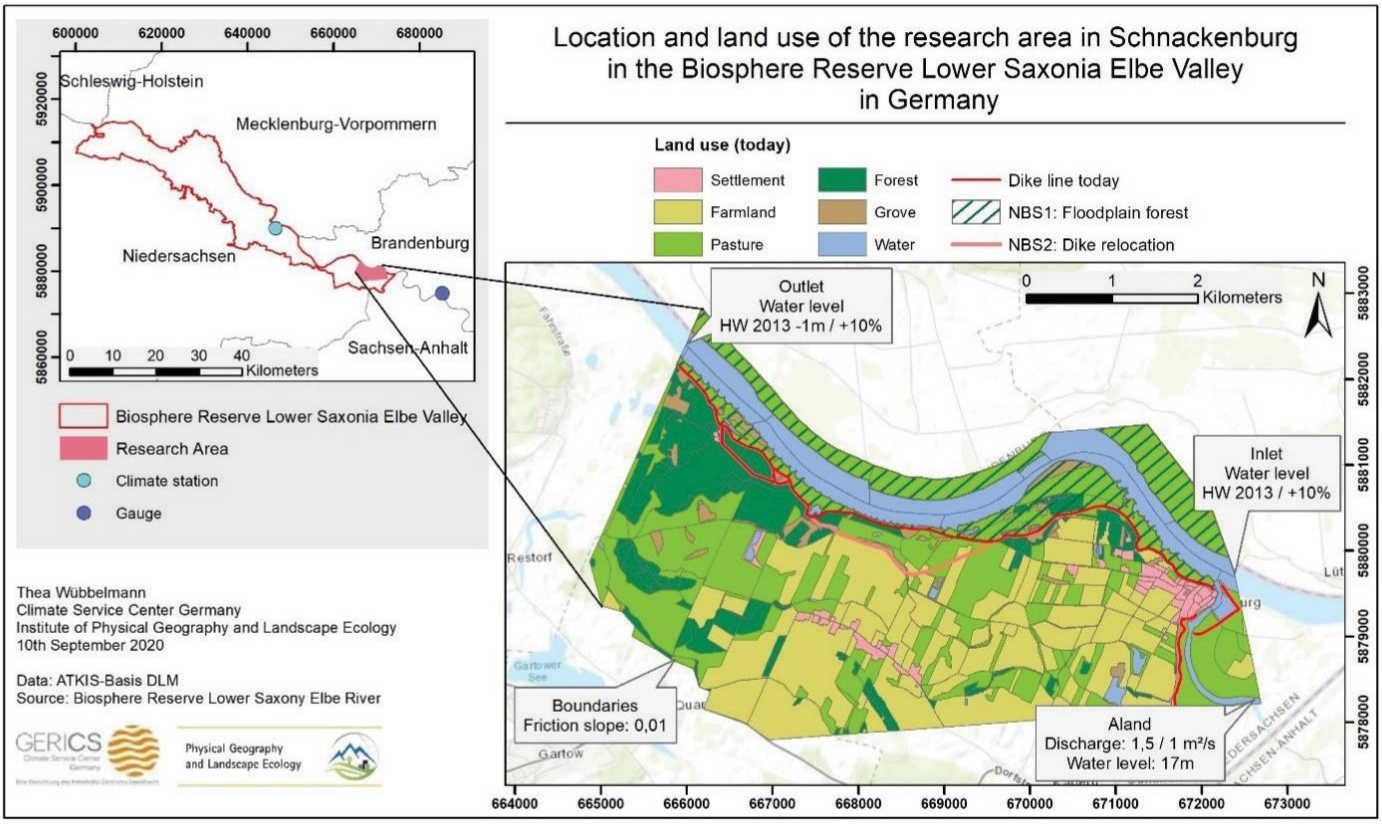


Figure 1. Location and land use of the research area in the Biosphere Reserve Lower Saxonia Elbe Valley in Germany. Also the tested land use scenarios and the boundary conditions for the hydraulic modelling with HEC-RAS are shown.

tributed to projected higher precipitation amounts in the winter half year. While no clear trend can be discerned in summer (Bowyer et al. 2020).

3 Materials and Methods

3.1 Hydraulic Modelling with HEC-RAS

Hydraulic models simulate the flow, amount and availability of surface water on different scales. They can assess effects of changes, like topography, vegetation and land use or meteorological variations (Sitterson et al. 2017). We used the HEC-RAS model (**H**ydrologic **E**ngineering **C**entre - **R**iver **A**nalysis **S**ystem), developed by the U.S. Army Corp of Engineers. It provides different possibilities for water run-off simulations, for instance two-dimensional unsteady flow simulations. For detailed information see Brunner (2016d, 2016b, 2016a, 2016c).

Basic input data are the geometry of the area (channel cross sections or a digital elevation model (DEM)), the roughness coefficient by Manning derived from land use data, and discharge information. The setup of the modelling with HEC-RAS follows three main steps (Figure 2): 1) setting the geometry, 2) adjusting the unsteady flow analysis, and 3) defining the time steps for the computation and runoff simulation. The boundary conditions of the inlet and outlet as well as the other edges of the research area are shown in Figure 1. The upstream and downstream boundary conditions were based on the discharge measurements of the flood of 2013 at gauge Wittenberge (chapter 3.3; Figure 1). To ensure a flow gradient the water level of the outflow was lowered by 1 m. The future flooding scenario was based on the water levels from the flood of 2013 elevated by 10 %, according to projections of future runoff scenarios (Nilson et al. 2014). To consider a high groundwater level because of rainfall and previous high discharge values, the initial water level conditions were set to 16 m above sea level in the whole research area. For the given computed time steps, single raster data sets were exported to 1) visualize the temporal development of water depths and flooded areas and 2) further processing in GIS. Besides the flood extent

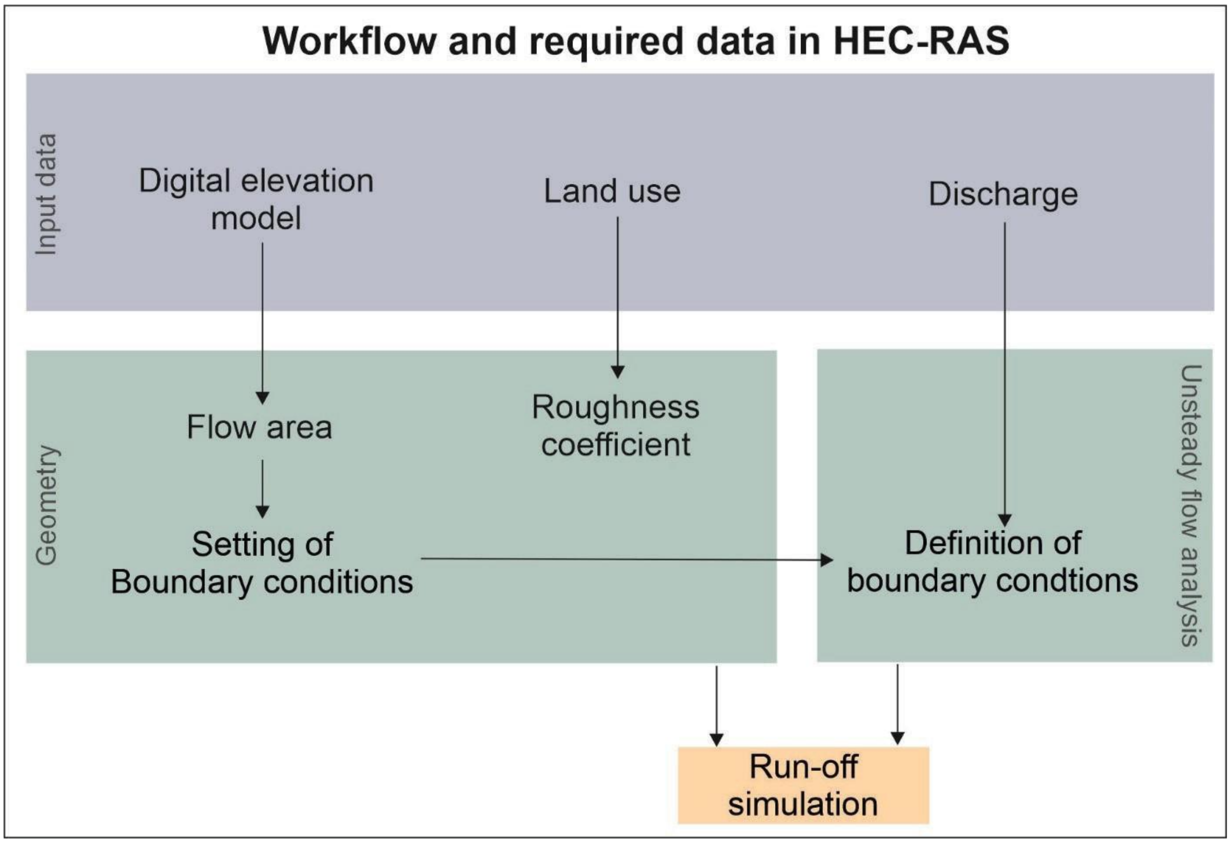


Figure 2. Schematic representation of the workflow in HEC-RAS.

and water depth for estimating the retention capacity, it is also possible to export runoff velocities and sediment transportation from the model.

3.2 MAES-DE-Indicator: Ecosystem service "Water regulation by floodplains"

The MAES-DE working group has a focus on floods caused by rivers and therefore developed the ES-indicator "water regulation by floodplains" for the national scale. It describes the capacity of floodplains to absorb surface water, using an simplified area-based retention approach (Grunewald et al. 2016).

The indicator "area for flood retention" (Ger.: "Fläche für Hochwasserretention" (FHR)) is calculated based on the inundation area, that is not protected from flooding by dikes or other measures (equation 1). Only non-artificial land areas (e.g. areas with pastures, forests, shrubs and wetlands) are taken into account, whereas settlements and other sealed surfaces are subtracted from the floodplain area (Grunewald et al. 2016; Albert et al. 2015):

$$FHR = \text{recent floodplain} - \text{settlements \& traffic area}$$

(Equation 1)

The delimitation of the floodplain area was carried out using the DEM and the dyke line from the land use dataset.

3.3 Database

A DEM, land use data and runoff data are needed for the methodological application. Table a in the annex gives a detailed overview of the used data for both approaches, including information about the type of data, spatial resolution and data sources. The modelling with HEC-RAS require a DEM and land use data. The land use data is used to derive the Manning n value as a roughness coefficient (see Table 1). In addition, the model needs a run-off dataset. For this study, the discharge data from the summer flood 2013 at the Wittenberge gauge, a few kilometres upstream of Schnackenburg, were used (Figure 3). The event lasted 57 days, from May 5th to July 20th, with the maximum discharge on July 10th (discharge: 4250 m^3/s; water level: 780 cm) (IKSE n.d.). For the future flood scenario, the summer flood event of 2013 was elevated by 10% to consider a potentially higher extreme event in future. With this adjustment, the maximum discharge on June 10th reaches

4700 m³/s. This value complies with the assumption of Alexy (2014), who used a climate change-caused-caused extreme scenario runoff value of 5000 m³/s for another study next to our research area. Other studies such as Nilson et al. (2014) used a projected bandwidth of an annual mean discharge in the Elbe between -20% and +5% until the end of the 21st century towards the reference period of 1961-1990. Regardless of land use changes and engineering measures in the upstream part of the Elbe catchment, which also have a high impact on the discharge behaviour, our approach represents a “potential future flood scenario”.

The indicator-based approach requires respective land use data and topography data to delimit the floodplain area.

3.4 Land use scenarios

To compare the effects of different types of land use and land use changes on retention capacity and river discharge, three scenarios were investigated (Figure 1, Table b). All scenarios can be classified as nature-based solutions (NBS) (WWAP 2018). NBS are nature- and ecosystem-based adaptation measures that are inspired or supported by the characteristics and processes of nature and/or copy, use or imitate these (European Commission 2015; WWAP 2018). The land use scenarios are abbreviated as NBS in the following.

Table 1. Land use in the case study area and their roughness coefficients by Manning (Brunner 2016c).

Land use	**Roughness coefficient by Manning n**	**Land use**	**Roughness coefficient by Manning n**
Settlement	0.016	Forest	0.1
Farmland	0.037	Grove	0.06
Pasture	0.03	Water	0.045

The current use of the floodplain is listed as NBS 0. The first land use scenario (NBS 1) is a floodplain forest. All areas within the floodplain except the water bodies are changed to forests. The second scenario (NBS 2) is a dike relocation on the southern site of the Elbe river. Detailed information and effects of the different scenarios can be found in Table b.

4 Results

4.1 HEC-RAS modelling

Water volume and water area as valuation parameters for the retention capacity

For the valuation of the surface retention capacity derived from the modelling, an area-based and volume-based assessment was made for the study area. Figure 4 shows the comparison of the flooded area (x-axis) and the water volume (y-axis), determined

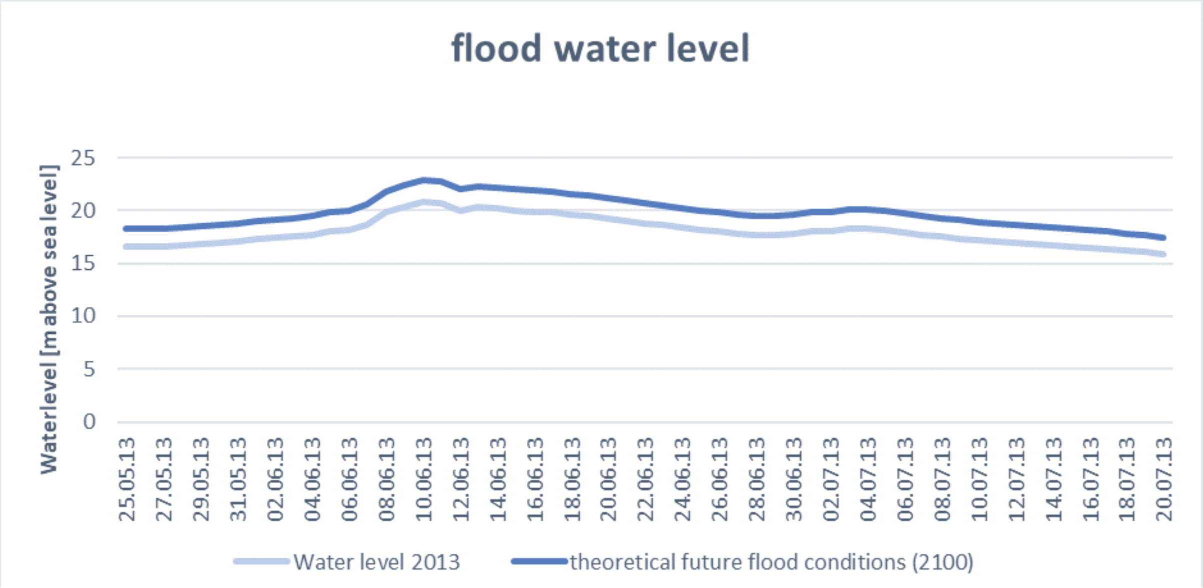


Figure 3. Water level of the summer flood 2013 at the Elbe river near Schnackenburg (IKSE n.d.) and theoretical future flood conditions for the year 2100 (IKSE n.d.; Nilson et al. 2014).

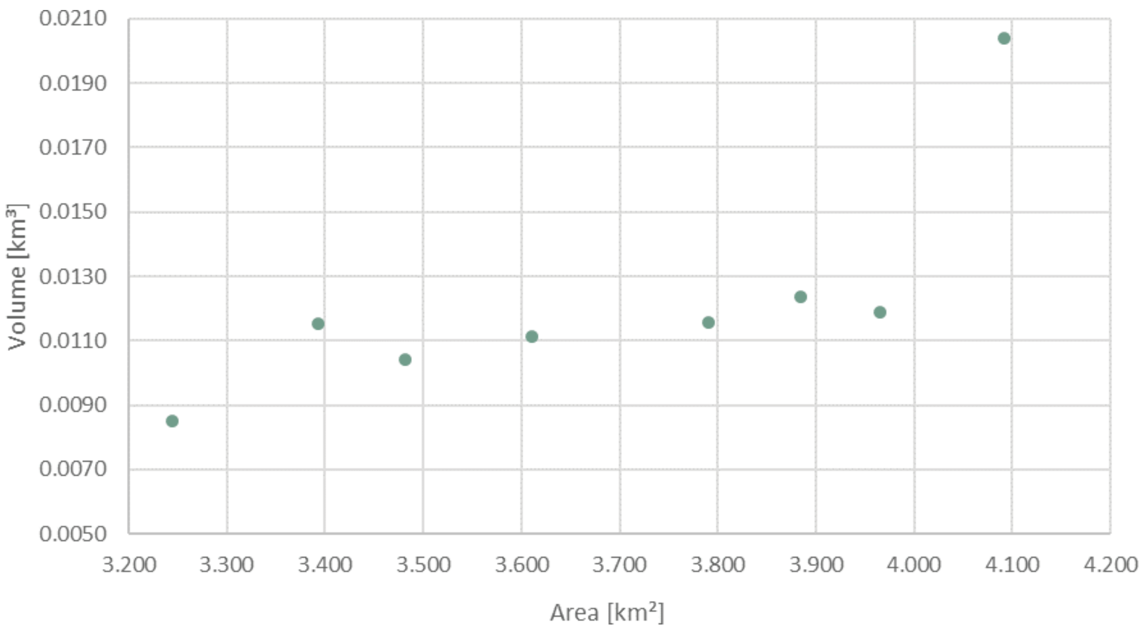
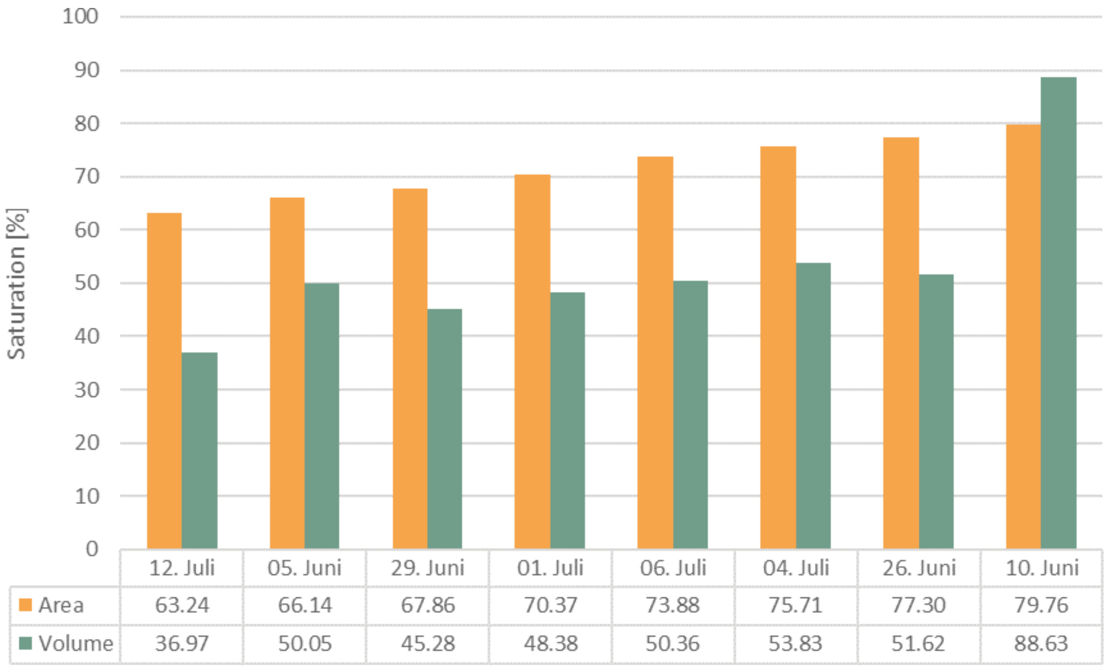


Figure 4. Comparison of the flooded area and the water retention volume for certain days of the simulated flood event in 2013.



	12. Juli	05. Juni	29. Juni	01. Juli	06. Juli	04. Juli	26. Juni	10. Juni
Area	63.24	66.14	67.86	70.37	73.88	75.71	77.30	79.76
Volume	36.97	50.05	45.28	48.38	50.36	53.83	51.62	88.63

Figure 5. Exploitation of the floodplain area and volume capacity for chosen days of the simulated flood event in 2013.

from the water depth and the area in the floodplain for selected days of the flood event. Three phases can be identified. After the area is filled with water and the volume increases, the water spreads more in area than in depth. A constant volume is reached. At a certain point, the water depth and also the volume increases. This means there is a non-linear relation between the flooding area and flooding volume.

The flooded area and the water volume vary in the extent of coverage of the potential floodplain retention capacity (Figure 5). The utilisation of the floodplain area for water retention ranges between 63 % and 80 %. In relation to that, the average exploitation of the floodplain volume is between 37 % and 54 % and is generally lower than the area exploitation. The volume exploitation is higher only on the peak day (June 10th) in comparison to the other days and it is only on this day that the volume exploitation is higher than the area one.

Effects of different land uses

In order to analyse the impact of different land uses on the flood regulation, the parameters of flood area and water depth are examined in Figure 6. The percentage of the simulated mean water depth towards the total water depth is given in green. The percentage of the extent of the flooded area towards the total flooded area for each land use in the floodplain on June 10th 2013 is given in orange. As expected, the highest water columns (6.31 m) and largest flooded area (2.5 m) occur over the land use type ‘water’, where the surface elevation is low (middle elevation of the riverbed is about 13.7 m above sea level). The second highest water columns (2.81 m) and second extensive flooded area (2.25 m) are above the pasture areas. After the land use type ‘water’, these areas account for the largest share of flooded areas and greatest water depths. Groves have a mean water depth (2.7 m) which is comparable to the pastures. Figure 6 shows, that the percentage of the flooded area is higher than the water depth above the land uses pasture and water. In contrast, the percentage of the flooded depth is higher above the land use types forest and groves.

Impact of extreme future flood scenarios

The effects of a possible future higher runoff, caused by changing climate patterns, was considered for the three land use scenarios with HEC-RAS. Again, both the inundation area and the volume were evaluated (Figure 7). The green points depict the volume, while the flooded area is mapped in orange triangles. The bright symbols display the present scenarios and the dark ones show the future scenario with a 10% higher discharge compared to 2013. The HEC-RAS model results indicate a decrease of the flooded area under current flood runoff conditions for the NBS1 and NBS2 compared to NBS0 (light orange triangles). However, an increase in forest areas result in a higher water volume at the current run off level (light green). In contrast, the dike relocation and thus the increased floodplain area not only reduces the flooded area, but also the volume.

A flood event with 10% higher amounts of discharge (dark coloured symbols) causes both increasing water volumes and higher flood area extensions. For all three scenarios, a flooded area of ~4.9 km² and a water volume of ~0.03 km³ is estimated. The differences of the water amount between the scenarios is very low compared to the current discharge. Only the dike relocation leads to a larger extension of flooded area. Furthermore, the animations indicate that in the assumed future discharge scenario, the water overflows the dikes.

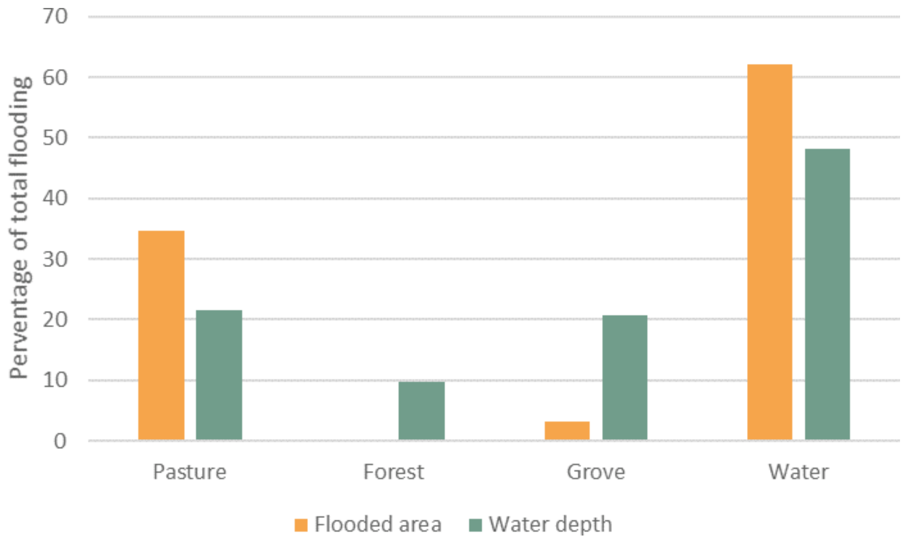


Figure 6. Water depth and flooded area by different land uses at the day with the highest water level during the simulated flood event in 2013.

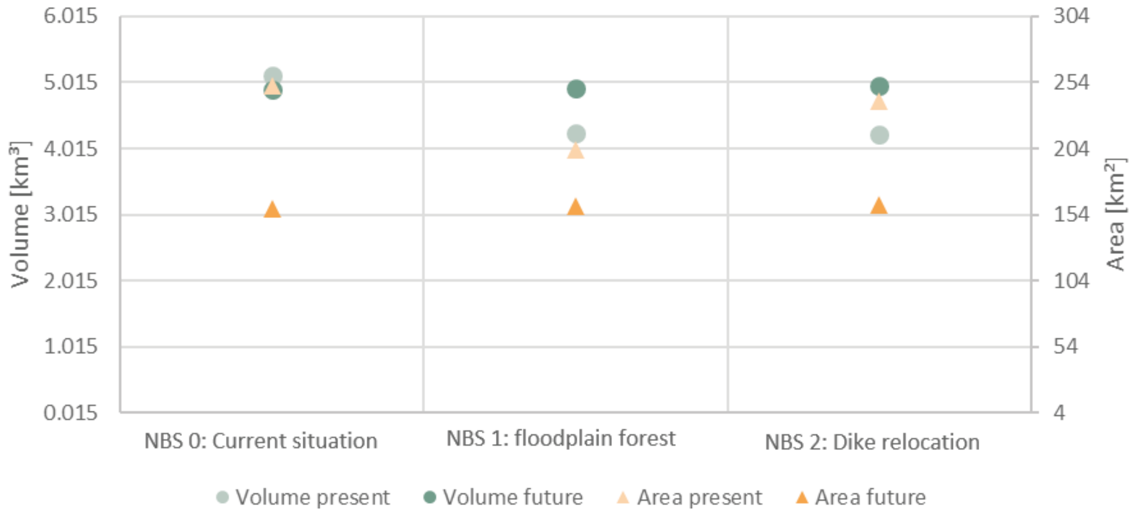


Figure 7. Flood volume and area for a high water level in 2013 and in the future with a 10 % higher water level.

4.2 FHR-Indicator

For each land use scenario, the FHR-Indicator of the German MAES-working group was calculated in order to classify and evaluate the model results and the method. Table 2 lists the results. Derived from land use, the current retention area of the floodplain is 2.54 km². According to the indicator values, a land use change from pasture to forest does not lead to a change of the flood retention area capacity compared to the current land use scenario. The indicator value remains at 2.54 km². Only the proportion of the land use shifts to more forests than pasture. However, this is not represented by a respective change in the indicator value. The selected scenario “dike relocation” increases the flood retention area by 0.62 km² to 3.16 km². This means, that the FHR-Indicator increases by 24% in this scenario compared to the other scenarios.

Table 2. Results of the FHR-indicator for the three scenarios..

Scenarios	**Current situation**	**Forest**	**Dike relocation**
Total [km²]	2.54	2.54	3.16
Changing to current situation [%]		+ 0	+ 24.4

5.2 Discussion

The comparison results of area and volume by the hydraulic model show that besides the consideration of processes that influence flood regulation, the selection of the evaluation parameter and dimension for flood retention service play an important role. The result of the HEC-RAS simulations show that water retention capacity cannot only be expressed by the flooding area, because the relation to the retained volume of water is not linear (Figure 4, Figure 5). With regard to the floodplain characteristics, the simulations confirm that at a certain point in time, the water level and with that, the water volume rises faster than the spread of water in an area. This means that there are different retention capacities between an area-based and a volume-based analyses approach (Figure 4), which is not considered by the approaches that use the FHR-indicator for example. In addition, the schematic representation in Figure 8 shows that the same area can store different amounts of water depending on the slope. de Groot et al. (2010) have already proposed a water volume based assessment that consider depressions and soil storage.

Land use is another aspect that is considered differently in both approaches. The model results support the findings of Karabulut et al. (2016) in which land cover has a high impact on flood formation. Above forest and groves the percentage of the water depth

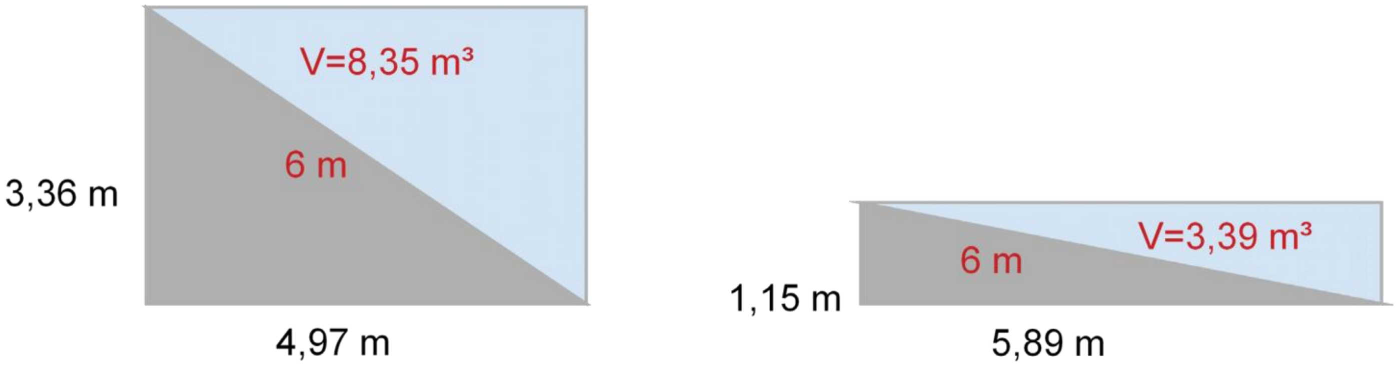


Figure 8. Schematic presentation of different volume capacities by the same area with a width of 1 m.

is higher than the percentage of flooded area (Figure 6). Higher surface roughness by forests or groves decrease the velocities of water runoff and consequently, retain water (Figure 6, Figure 7) (Promny et al. 2015; Karabulut et al. 2016; LFU-Bayern 2018). Simoultaniously they provide an important water retention capacity to mitigate flood risks by slowing down the velocities (de Groot et al. 2010; Vallecil-lo et al. 2019). In contrast, pasture areas usually reduce the water level while increasing surface runoff and spreading (Karabulut et al. 2016; Promny et al. 2015). The ratio of retention in water depth is lower than by the flooded area (Figure 6).

Future flood scenarios were tested with HEC-RAS. The results confirm that flood regulation is driven by climate information. Climate affects the water cycle and so the temporal and spatial course of the flood. In this study, a future potential extreme flood event was simulated based on literature review (Alexy 2014; Nilson et al. 2014). However, the bandwidth of possible discharge rates is large and the resulting outcomes are often not robust (Nilson et al. 2014; EEA 2017). Nevertheless, the historical observations from 1980 to 2010 show an increase of the number of severe floods in Europe (EEA 2017). Alexy (2014) assumes a maximum discharge of 5000 m³/s for future runoff simulations for a study in Lenzen flood plain of the Biosphere Reserve Lower Saxonia Elbe Valley, which is directly connected to our research area. Alexy's value is comparable to our flood event peak that is 10 % higher than the peak of 2013 (4700 m³/s). Projected changes of precipitation by EU- RO-CORDEX and ReKliEs-DE (Jacobet al. 2014) showan increasing number of days with precipitation more than 20 mm/day in the Biosphere Reserve Low- er Saxonia Elbe Valley. The annual change is expected to be between -1 and 2 days/year (RCP2.6), 0 and 2 days/year (RCP4.5) and 0 and 3 days/year (RCP8.5; significant) (Bowyer et al. 2020). This results altered surface runoff values and illuminate the necessity to consider climate information in flood regulation ES assessments. On the other hand, climate change brings greater and longer drought periods with it in contrast to extreme flood events (Bowyer et al. 2020). Their impact on ecosystem services must also be considered in the future (Gaglio et al. 2019).

When considering climate change impacts on the water cycle especially on higher flood peaks, the simulation of an intensified flood event shows a higher extension of the flooded area and higher water columns over parts of the flooded land (Figure 7). The current retention capacity in the research area is not sufficient to handle flood events in this dimension. Concerning the chosen NBS, both selected flood regulation measures fail if a limit water level is exceeded. As a result, areas and settlements behind the dikes would be flooded. In addition, the small variation in flooded area and volume with higher water levels between the different NBS also shows that the effect of the measurements, compared to the current landscape situation, is very small.

Besides the considered processes in the hydraulic modelling (surface water storage in depressions and regulation by the roughness of land use) other landscape functions and processes also play an important role for flood regulation. The interception capacity and imperviousness are land use characteristics that affect surface runoff (Burkhard and Maes 2017). Terrain and slope are essential landscape features that influence water flow paths and velocities (Nedkov and Burkhard 2012). The dike relocation demonstrates the change in flow conditions due to altered terrain conditions. Technical and morphological flow barriers (in this case dikes) are important flood regulating factors that influence water flow path, velocity and direction (Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN) 2017; NLWKN 2017). Terrain also influences infiltration capacities. Steeper slopes lead to a faster runoff by higher elevation differences and so to a smaller time period for infiltration (Burkhard and Maes 2017), while being able to absorb higher water columns in depressions (Figure 8). Another important limiting factor for flood regulation ES supply, which was not considered in this study, is the water holding capacity of soils (Liu et al. 2013). Infiltration and permeability are two of the main processes that influence the soil water storage capacity and retention function (Nedkov and Burkhard 2012). In addition, flood hazards and associated flood regulation ES supply depend on the type of rainfall, the intensity, the location, the duration as well as the spatial distribution (Nedkov and Burkhard 2012; Stürck et al. 2014).

Both methods have some limitations that should to be mentioned. Hydraulic modelling can simulate flood area and water volume retention and offers the possibility to test different scenarios and input data sets such as land use change or climate-induced change (Grizzetti et al. 2015; Grizzetti et al. 2016). Burkhard and Maes (2017, p.100) mention, “for regulating services, modelling is sometimes the only option in order to quantify actual ecosystem service flows”. Nedkov and Burkhard (2012, p.71) add to this “[…] hydrologic models can be used to quantify indicators that represent the flood prevention function of ecosystems”. However, due to limited data availability and the complexity of nature and physical processes, simplifications must be made in general and also for the specific research area.

For example, during the flood of 2013, areas behind the dike were also flooded. This may have been caused by high groundwater levels, exceeding the water absorption capacity, or by high precipitation rates (Rannow and Warner 2016; Mosbrugger et al. 2012). The applied hydraulic HEC-RAS model does not consider these processes and only indicates the surface runoff. With the assumption of a high groundwater level and a negligible unsaturated zone, which is typical for river flood plains, infiltration is of minor importance. In view of the research questions, a more complex approach is not useful. This requires a more comprehensive and not available data basis. Furthermore, the applied area based FHR-indicator of the MAES-DE working group refers also to the surface based retention performance. Therefore, the exclusive focus on surface runoff with the HEC-RAS simulation covers the main hydrau-lic effects of surface flood retention and allows the comparison with the FHR-indicator.

In contrast, the area based FHR-indicator provides an easy method to estimate the availability and development of floodplain areas on the national scale. Advantage are the low data requirements and the simple calculation process. However, the method misses some crucial flood retention functions as vegetation roughness and volume surface water storage capacity. Functionality and sufficient capacity under future climate conditions cannot be tested by this approach (Table c).

When comparing these two methods, it must be mentioned that both were developed for different scales and to answer different questions. While the modelling approach is best suited for local to regional scales and can generate detailed output, the FHR-indicator by the MAES-working group was designed for the national scale (Grunewald et al. 2016). However, we applied the indicator on the local level in our study. Flood retention is particularly relevant locally and serves to protect the population. The retention area of the floodplain can be calculated by the approach of the FHR-indicator and was used in this study to classify and evaluate the results by the hydraulic modelling approach.

The pressure climate change on flood regulation ES is used indirectly as a time variable input by runoff values. Changed precipitation patterns indicate a change in the local water cycle, which influences runoff. If a preceding hydrological model (e.g. HEC-HMS) is used, climate data are used as drivers to calculate discharge parameters as input for the hydraulic model. Changed climate conditions must be taken into account in the assessment of flood-regulation ES. The FHR-indicator represents the current flood area capacity. Climate as pressure of insufficient capacity can not be considered.

6 Conclusions and outlook

Flood regulation ES supply is complex and determined by many natural and anthropogenic drivers and processes. Land use, climate change, terrain and soil are some of the main influencing factors. With the hydraulic Model HEC-RAS, surface retention ES, can be determined for current and future discharge scenarios. In contrast, the FHR-indicator is merely based on the area regardless of other locally detailed factors and cannot provide estimations about future functionality of the floodplain.

This study focus on hydraulic surface retention functions and the water spreading in the area and volume. The application of hydrological models in a continuative research approach offers the possibility to consider infiltration and interception processes more effectively to estimate temporal and spatial variations of runoff. This is an interesting and important approach to increase the knowledge of flood regulation ES and to investigate the importance of soil and vegetation retention. Through this extended approach, regional climate information could also be directly included in the analysis.

The results of this study already show the impact of climate information via the water cycle. This information is necessary to estimate future flood regulation ES potentials and capacities, for example, to test land use scenarios for future suitability. With respect to climate change, the importance of ES that regulate the effects of flooding will increase in the future due to expected changes of all water cycle components. To cover as many future flood scenarios as possible and to test the functionality of the flood regulation ES, it is useful to consider a bandwidth of climate simulations.

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Appendix

Table a. Overview of the used dataset.

Data	Type and spatial resolution	Used for indicator	Used for HEC-RAS	Sources
Digital elevation model (DEM)	Raster; 1 m		x	Biosphere reserve management (2018)
Land use	Vector; ATKIS-Basis DLM (AdV 2018)	x	x	Biosphere reserve management (2018) (AdV 2018)
Run-off data	Historical measurements of a gauge nearby (57 days, daily resolution); future projections of the discharge behaviour		x	(IKSE n.d.; Nilson et al. 2014)
Roughness coefficients (Manning)	Look-up table (see Table 1)		x	(Chow 1959; Brunner 2016c)

Table b. Description of the land use scenarios.

Scenario	Description
Reference scenario: current situation (NBS 0)	Current situation with pastures and water bodies as main land uses within the floodplain.
NBS 1 – floodplain forest	A land use change from pastures to forest changes the roughness and so the velocity and water balance. It is a typical natural measure in run-off management (WWAP 2018; WWF 2016). The areal extension of the floodplain does not change by this measure.
NBS 2 – dike relocation	A dike relocation on the southern site of the Elbe river increases the recent floodplain from 5.13 km² to 7.32 km². The additional area is used as pastures. It is a common method to recover old floodplain areas (WWAP 2018; WWF 2016). This measure is supposed to improve natural processes and to increase the resilience against flooding of the surrounding areas.

Table c. Advantages and limitations of the methods (FHR-indicator and hydraulic modelling with HEC-RAS) to estimate flood regulation services.

	Ecosystem service FHR-indicator	Hydraulic modelling with HEC-RAS
Advantages	Easy-to-communicate values	Including crucial parameters and processes such as: terrain elevations, hydrographs (observation and future assumptions), land cover for roughness, dike location and other barriers with heights
	Simple and easy to calculate	Simulation of long time periods as well as single events
	Small data set required	Easy-to-use hydraulic model with little input data
Limitations	Misses some crucial factors such as soil conditions (infiltration), additional land cover characteristics (roughness and interception), terrain conditions, climate information	More complex in handling and in data requirements (in comparison to the FHR-indicator). Not all boundary conditions are available
	Based on used data, no conclusion is possible regarding to the limits of retention capacity	Comparison of results is more complex because more analysis and calculations are needed
		No input of soil and geology data (e.g. type, thickness of the unsaturated zone, groundwater levels) and so no modelling of infiltration

4

PUBLICATION 2

MODEL CALIBRATION AND THE CONTRIBUTION OF URBAN TREES TO MITIGATE PLUVIAL FLOODING

Based on the finding of the previous publication, a hydrological model that resolves the spatial resolution of single landscape elements and that considers vegetation-related processes such as interception was developed (Chapter 2.2.3.2 LEAFlood). Because urban hydrological modelling often lacks measurement data for calibration, the model was tested for its functionality in Vauban, where suffcient observation datasets exist. Thus, in this publication, the hydrological model LEAFlood is calibrated and validated by comparing the model results with observation data. The model overcomes some of the limitations for flood-regulating ES. The Chapter proves the applicability of the hydrological model for future research. In addition, the role of trees in flood mitigation is investigated, which provides insights into the performance of adaptation measures.

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Article

What Is the Contribution of Urban Trees to Mitigate Pluvial Flooding?

Karina Sinaí Medina Camarena [1,†], Thea Wübbelmann [2,3,*,†] and Kristian Förster [1]

[1] Institute of Hydrology and Water Resources Management, Leibniz Universität Hannover, 30167 Hannover, Germany; karina.sinai.medina.camarena@stud.uni-hannover.de (K.S.M.C.); foerster@iww.uni-hannover.de (K.F.)
[2] Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, 21502 Hamburg, Germany
[3] Institute of Physical Geography and Landscape Ecology, Leibniz Universität Hannover, 30167 Hannover, Germany
* Correspondence: thea.wuebbelmann@hereon.de
† These authors contributed equally to this work.

Abstract: Hydrological modeling is commonly used in urban areas for drainage design and to estimate pluvial flood hazards in order to mitigate flood risks and damages. In general, modelers choose well-known and proven models, which are tailored to represent the runoff generation of impervious areas and surface runoff. However, interception and other vegetation-related processes are usually simplified or neglected in models to predict pluvial flooding in urban areas. In this study, we test and calibrate the hydrological model LEAFlood (Landscape and vEgetAtion-dependent Flood model), which is based on the open source 'Catchment Modeling Framework' (CMF), tailored to represent hydrological processes related to vegetation and includes a 2D simulation of pluvial flooding in urban areas using landscape elements. The application of LEAFlood was carried out in Vauban, a district in Freiburg (Germany) with an area of ~31 hectares, where an extensive hydrological measurement network is available. Two events were used for calibration (max intensity 17 mm/h and 28 mm/h) and validation (max intensity 25 mm/h and 14 mm/h), respectively. Moreover, the ability of the model to represent interception, as well as the influence of urban trees on the runoff, was analyzed. The comparison of observed and modeled data shows that the model is well-suited to represent interception and runoff generation processes. The site-specific contribution of each single tree, approximately corresponding to retaining one cup of coffee per second (~0.14 L/s), is viewed as a tangible value that can be easily communicated to stakeholders. For the entire study area, all trees decrease the peak discharge by 17 to 27% for this magnitude of rainfall intensities. The model has the advantage that single landscape elements can be selected and evaluated regarding their natural contribution of soil and vegetation to flood regulating ecosystem services.

Keywords: LEAFlood (Landscape and vEgetAtion-dependent Flood model); Catchment Modeling Framework (CMF); hydrological modeling; heavy rainfall; Vauban; interception; model calibration; pluvial flooding; urban trees

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1. Introduction

Hydrological models are important tools in planning and for research and being increasingly used. Often, modelers choose well-known and proven rainfall-runoff models [1], which are tailored to represent the runoff generation of impervious areas and surface runoff. However, hydrological models that also adequately represent and include vegetation are rare, and more modeling studies on this topic are needed [2]. An overview of modeling tools that analyze the impact of trees on hydrology is presented by Coville et al. [3]. In sum- mary, the authors highlight the diverging range of complexity of models involved, ranging from tree-scale models to catchment-scale models [3].

The vast majority of models that predict the extent of pluvial flooding focus on 2D hydrology-hydrodynamics with a simplified representation of interactions with vegetation in predicting runoff generation [4–6]. Moreover, typical 'stormwater' models—rainfall-runoff models designed for urban areas—used to predict hydrological processes in urban areas also simplify hydrology-vegetation interactions and focus on surface runoff over impervious surfaces, thus suggesting further improvements of model components [7,8]. However, models that include a better representation of vegetation in hydrology mostly operate at the catchment scale [9–12]—a scale, which is too coarse to study the impact of single trees at a quarter scale. Hence, a better representation of both vegetation and 2D routing would be preferable to study the effect of different types of stormwater measures. For this very reason and in view of the fact that using an existing model based on earlier experience is not necessarily the best choice [13], a model is needed that fulfills the following characteristics:

- Simple 2D-hydrodynamics to predict the extent of pluvial flooding in urban areas,
- Detailed representation of hydrology–vegetation interactions (i.e., interception).

These research gaps bring up the following research questions: (i) Can we parameterize a hydrological model that is capable of predicting both interception processes and the spatio-temporal extent of pluvial flooding at the same time? (ii) What is the role of (single) trees in retaining heavy rainfall at the quarter scale? In order to bridge the gap between very detailed 2D hydrological-hydrodynamic models and catchment-scale hydrological models that are capable of predicting vegetation interactions, a model tailored to these requirements is used and tested in this study. Furthermore, in order to benefit from proven and existing model components, the model (LEAFlood—Landscape and vEgetAtion-dependent Flood model) we applied is based on the Catchment Model ling Framework (CMF) [14]. Among numerous other applications, this framework has already been used to study the storage of green roofs [15]. In the present study, LEAFlood allows us to combine the benefits of a detailed canopy and interception representation together with a 2D surface routing based on the kinematic wave approximation. For calibration of urban hydrological models, runoff measurements are needed, however, these data are rare in ungauged urban areas [16]. The urban district Vauban in Freiburg (Germany) provides a comprehensive measuring network of hydrological variables, i.e., runoff and canopy throughfall among others. In order to overcome the challenge of calibration and plausibility checks in urban areas, the datasets from Vauban are used to validate LEAFlood.

The objectives of this paper are to (i) test and calibrate a model that accounts for both detailed vegetation interactions with hydrology during heavy rainfall events and a 2D surface runoff simulation. After model set-up and calibration, we demonstrate the added value of the model and (ii) estimate the role of trees in runoff generation during pluvial flooding at the quarter scale.

After this introduction, the materials and methods are presented. These include the study area, the data, the model LEAFlood, the calibration set up and procedure for the model experiments with different tree coverage. The results and discussion follow ina combined chapter. It is divided into sub-chapters about the model performance for interception, the surface runoff calibration and the results of the model experiments with different tree coverage to study "the role of trees in pluvial flooding". The chapter ends with a section about limitations before going on to the conclusions and outlook.

2. Materials and Methods

2.1. Study Area

The research area is located in the Vauban district of Freiburg, Germany and has an area of 30.8 ha (Figure 1). It is a residential area with an estimated of 5500 inhabitants [17]. The area was chosen due to its detailed hydrological measuring network that is available within the urban area, installed to monitor the performance of its drainage system, which has already been used in various studies [18,19]. This measurement dataset is used to calibrate and validate the LEAFlood model.

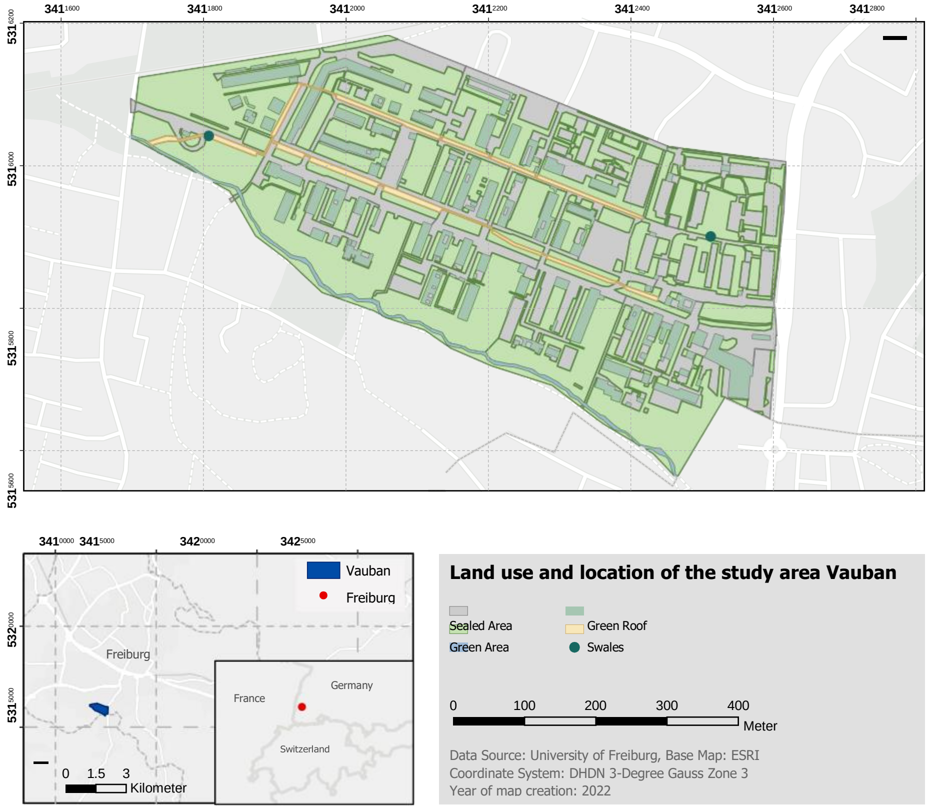

Figure 1. Land use and location of the study area Vauban.

The climate conditions in the region are maritime to semi-continental. The mean annual precipitation is 934 mm (1981–2010) at the DWD Freiburg station [20] (5.4 km from study area, which is used to analyze climate conditions, while local measurements are available for further analyses). The dominant land use type in the zone are green areas (65.3%), including vegetative swales and green roofs. The remaining area is covered by sealed urban areas (33.8%) and a water body (1%). Around 14% of the district is covered by tree canopies. The main soil types are loam and sandy loam [19,21,22] (data adopted fromthe UrbanRoGeR model).

The study site was developed on a former French military base from the 20th century. After an urban design competition, a maximization on Green Infrastructure (GI) (Notwithstanding the broad range of terms used similarly [23], such as, e.g., Low Impact Development (LID) [18], water smart cities etc. [24], the term GI is used here for simplicity) was achieved [25]. The winning urban plan included extensive green areas, making most of the roofs green, walking paths with permeable pavements, rainwater harvesting and incentives for intensive private gardening [17]. The generated runoff of the area is collected and redirected to a central Infiltration-Swale System (ISS). The ISS consists of individual swales connected as cascade by pipes under the streets, forming two parallel lines along the main streets (Nordgraben, Boulevardgraben). A downstream swale collects the dischargeof both lines, redirecting the overflow via an intake structure into the receiving watercourse. The downstream swale drains as a free overflow to the downstream part of the Dorfbach creek, located along the southern border of the district, which flows from southeast to west.

2.2. Data

Meteorological data and geodata are required for the application of the model. Table 1 shows a detailed overview of the used datasets, their resolution and sources. The Digital Elevation Model (DEM), tree coverage and soil class map are used to define the geometry and parameters of cells (a term adopted from CMF, i.e., a polygon) in LEAFlood. The climate data, such as precipitation and temperature, determine the meteorological conditions during the event, whereas the measured records (runoff and interception) are used for calibration and evaluation of the model performance. Rainfall has been recorded on-site with a heated tipping bucket rain gauge with 0.1 mm resolution [18]. Regarding the number of tree units, these allow us to quantify the contribution of individual urban trees to reduce runoff generation. Lime tree (*tilia*), plane tree (*platanus*) and, to a smaller degree, firs (*abies*) are the prevailing tree species for which interception—or more specifically throughfall—measurements exist in the study area. Throughfall is measured through a tipping bucket rain gauge, which is mounted under the tree's canopy.

Table 1. Overview of the input datasets for the LEAFlood model.

Data	Type	Resolution	Units	Geodata	Climate Data	Measured	Source
DEM	Raster	1 m	m	x			Freiburg University
Throughfall	Timeseries	1 min	mm/min			x	Freiburg University
Land use map	Shapefile	-	-	x			Freiburg University
Precipitation	Timeseries	1 min	mm/min		x		Freiburg University
Relative humidity	Timeseries	5 min	%		x		Freiburg station [26]
Runoff	Timeseries	5 min	L/s			x	Freiburg University
Soil class map	Shapefile	-	-	x			Freiburg University
Sunshine hours	Timeseries	5 min	h/h		x		Freiburg station [27]
Temperature	Timeseries	5 min	°C		x		Freiburg station [26]
Tree coverage	Shapefile	-	-	x			Freiburg University
Tree number	Aerial image	unit	trees	x			Google Earth
Wind speed	Timeseries	5 min	m/s		x		Freiburg station [28]

2.3. LEAFlood (Landscape and vEgetAtion-Dependent Flood Model)

The LEAFlood model [29] is based on existing model components of the Catchment Modelling Framework (CMF) [14,30]. CMF is not a ready-to-use model, but a programming library for hydrological modeling that allows for the development of models tailored to various research questions in hydrology. The modular structure of this open source Python package provides high flexibility and is adaptable to different research questions. It is written in C++ and uses the finite volume method [14]. It thus fills the gap needed for a modular and flexible hydrological model framework. This is especially important for hydrological modeling in urban areas and the reason why we chose this framework [8,31]. With CMF it is possible to create polygon cells out of a GIS shapefile in the required spatial resolution in order to overcome the aforementioned limitation: CMF allows to develop a model that accounts for both a detailed representation of interception and a lateral 2D surface runoff simulation. In addition, the hydrological processes can be selected from a range of different approaches depending on the research question, as demonstrated for physically-based hydrological modeling of green roofs based on CMF [15]. This makes the package very suitable for a spatially explicit analysis of flood regulating ecosystem services supply in urban areas.

LEAFlood considers the hydrological processes of canopy interception, throughfall, soil infiltration and surface runoff (Figure 2). Evaporation from the canopy is regarded in the model, while evapotranspiration and evaporation from the surface is neglected. This limitation is accepted in this study, as the model is designed to be utilized for single heavy rainfall events (e.g., [32]), during which canopy evaporation is expected to be the dominant evaporative loss among all evapotranspiration fluxes. The geometry is created on the basis of an irregular polygon shapefile.

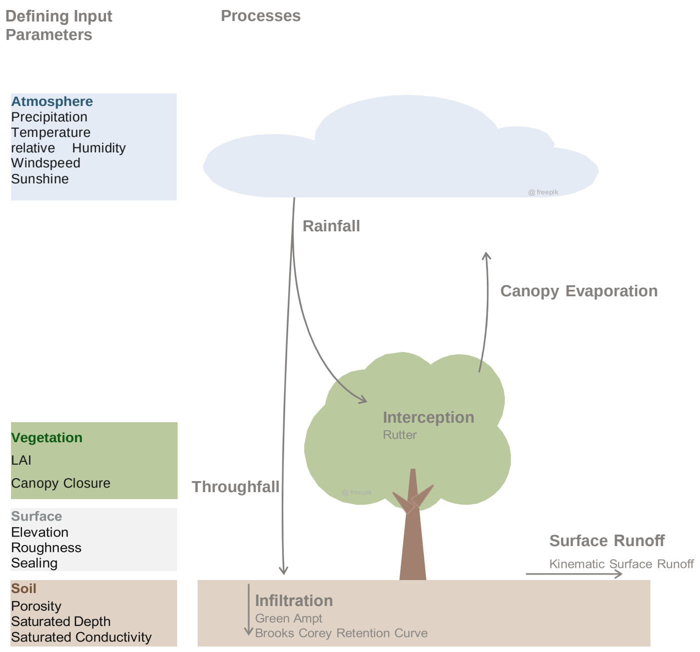

Figure 2. Used processes and defining parameters of storages in CMF.

The model is driven by meteorological data of rainfall, temperature, wind speed, relative humidity and solar radiation in a five-minute resolution. The interception utilises the Rutter approach [30,33]. Depending on the canopy closure, the precipitation can either be intercepted in the canopy or fall directly to the ground. A canopy closure of 1 means all rain is intercepted and 0 indicates throughfall [30]. To define the canopy closure of each cell, we used a polygon shapefile with the tree canopy in the area and intersect it with its corresponding cell's location. The quotient of the canopy area and cell area equals the canopy closure. Average LAI and interception capacity were defined representative for all trees.

The soil consists of one soil layer with the Green-Ampt infiltration method and the Brooks-Corey Retention Curve. It is assumed that during heavy precipitation events only the upper layer plays a role in infiltration and that percolation does not due to the time decay. Except for saturated conductivity (K_{sat}), all other parameters are the same throughout the study area (Table 2). The base value for Ksat is 0.3 m/d resulting from the soil property sandy loam and the dry bulk density 4 + 5 [34]. Depending on the degree of soil sealing, K_{sat} is reduced by the following function:

$$K_{sat,spec} = \left(1 - \frac{sealing}{100}\right) * K_{sat,gen} \tag{1}$$

A higher degree of sealing therefore results in a lower K_{sat} value. The porosity of sandy loam is 0.453 [34]. Because of soil compaction in urban areas the value is reduced to 0.3 [35]. The surface runoff follows the kinematic approach based on topography and surface roughness [30]. Manning's roughness coefficient is defined for each land use class (Table 3).

Table 2. Setting and processes in cmf.

Process/ Parameter	Setting
Interception	Rutter Interception
	Throughfall Canopy Overflow
Infiltration	Green Ampt
	Brooks Corey Retention curve
Layer depth	0.5 m
Saturated Conductivity (K_{sat})	0.3 m/d (base value)
Porosity	0.3
Surface Runoff	Kinematic

Table 3. The roughness coefficient Manning's n and the saturated conductivity (K_{sat}) defined for each land use class.

Land Use	Manning's n	Saturated Conductivity [m/Day]
Urban Sealed Area	0.013	0
Green Area	0.03	0.25
Green Roofs	0.03	0.72
Vegetative Swale	0.03	0.7
Water	0.03	0.015

With these components, LEAFlood entails a level of describing hydrological processes, which is in between a conceptual and physically-based, distributed, deterministic model description [36].

2.4. Calibration

In order to achieve a reasonable calibration of the model, two events are selected (Table 4) and a split-sample test is employed [37] to assess the model calibration through an independent validation with two further events. The selection of the events is based on the highest precipitation intensities observed over the 2 years of available data. The rainfall events for calibration reach a maximum intensity of 16.5 mm/h with a return period of less than one year (event 1) and 28 mm/h (return period ∼5 years) for event 2 (return periods refer to the study of Shehu et al. [38]). Similar intensities can be observed for event 3 and 4, which are used for validation. Event 3 has a maximum intensity of 25 mm/h (return period between 1–5 years) and event 4 has a maximum intensity of 14 mm/h (return period less than 1 year). Besides runoff, interception is also observed by throughfall measure- ments. The accuracy of interception measurements is checked before model calibration. As the throughfall is measured instead of interception storage S_i, a simple bucket model is employed to compute interception from observed rainfall P_i and throughfall $P_{T,i}$:

$$S_i = S_{i-1} + P_i - P_{T,i} - E_i \tag{2}$$

where i denotes the time step, S_{i-1} is the storage computed for the previous time step, and E_i the rate of evaporation losses from the canopy, which is neglected (i.e., $E_i = 0$). Since the interception model in CMF and LEAFlood has no adjustable parameters, the model performance of interception modelling is assessed before calibrating other hydrological processes similar to Förster et al. [39]. It is assumed that a reasonable representation of interception processes justifies calibrating only those model parameters of runoff generation that govern hydrological processes below the canopy.

Table 4. Overview of events with highest peak runoff in the runoff time series, covering the years 2011–2012. 'Saturated depth' is the initial condition guess used for each event, while the last column ('c/v') indicates whether the event is used for calibration (c) or validation (v).

Event	Start Date	Time	Duration [h]	Peak Intensity [mm/h]	Return Period [a]	Rainfall Total Event [mm]	−10 d [mm]	Peak Runoff [L/s]	Saturated Depth [m]	c/v
#1	17 June 2011	16:15	17	16.5	<1	23.4	41.6	361	0.50	c
#2	30 May 2012	13:40	15	27.9	~5	35.3	35.3	339	20.0	c
#3	13 June 2012	12:00	19	25.1	1–5	27.4	82.9	595	0.25	v
#4	9 October 2012	00:40	28	14.2	<1	32.7	15.4	291	7.00	v

Given a sufficient accuracy in interception modeling, processes related to runoff generation below the canopy are considered, mainly parameters governing infiltration. These are the parameter b of the Brooks–Corey retention curve and two scaling parameters that allowfor adjusting Manning's roughness n and saturated hydraulic conductivity K_{sat}, respectively. The latter two parameters are factors applied to the roughness and conductivity values foreach polygon.

In order to calibrate the model according to the split-sample test, an objective function is introduced first, which consists of two components. The first component is the Nash–Sutcliffe model efficiency E, which is computed for observed q and predicted $\hat{q}$ runoff [40], given that each time series consists of N time steps i:

$$E = 1 - \frac{\frac{1}{N}\sum_{i=1}^{N}(q_i - \hat{q}_i)^2}{\frac{1}{N}\sum_{i=1}^{N}(q_i - \bar{q}_i)} \tag{3}$$

A second component, the relative difference in peak discharge over n_e events, is introduced in order to give more emphasis on peak runoff in the calibration procedure:

$$d_{max} = \frac{1}{n_e}\sum_{i=1}^{n_e}\frac{|\max \hat{q}_i - \max q_i|}{\max q_i} \tag{4}$$

Finally, the objective function f to be minimized is computed considering Equations (3) and (4):

$$f = \frac{1}{2}(1 - E) + \frac{1}{2}d_{\max} \tag{5}$$

The objective function f (Equation (5)) is being minimized utilizing the SCE-UA algorithm [41] as implemented in spotpy [42].

2.5. Model Experiments with Different Tree Coverage

The quantification of the impact of trees on hydrological processes in the study area, mainly the impact on pluvial flooding, is performed utilizing two model experiments for each event. First, the calibrated model is used to study the hydrological response of the study area covered by trees 'as is'. Second, a similar run—but with a zero tree coverage—is performed to study the hydrological response of the same event without any trees. Since both runs only differ in terms of tree coverage, it is possible to quantify the role of trees through a comparison of both runs [39].

3. Results and Discussion

3.1. Interception

The first step in our model evaluation pertains to analyzing the model interception component. For three types of trees (lime tree (*tilia*), plane tree (*platanus*), and fir (*abies*)), throughfall was recorded in the study area. However, we focus on the lime tree only, since the plane tree is similar in terms of throughfall and firs with higher interception storage rarely occur in the study area, making them less representative.

The interception storage, computed utilizing Equation (2), for each time step during the first three events are compiled in Figure 3. Since evaporation is neglected, making Equation (2) valid for the rainfall event only, the dry period after each event is indicated as dashed lines, for which the comparison is subject to the aforementioned limitation. In general, the temporal evolution of intercepted load (intercepted water/storage) is represented well by the model. This holds true for both the timing of increments in interception storage and its absolute values over time. Only for event 2 is interception slightly underestimated by 5 mm at the end of the event, while for event 4, no interception measurements are available. However, given the overall high accuracy of predicting interception, the model is capable of representing interception during rainfall events.

Interception is subject to uncertainties related to the characteristics of individual trees, which influence the interception amount [2,43]. Here, the location and the coverage of the trees are known. However, we neither have detailed information about the spatial distribution of tree species nor about individual LAI and interception capacities. Therefore, we assume a mean LAI and interception capacity for all trees. Furthermore, the seasonalityof trees governs the annual course of LAI and interception capacity [44]. This seasonal dependence is not considered in this study, which is accepted, since all events considered in this study occurred in the vegetation time.

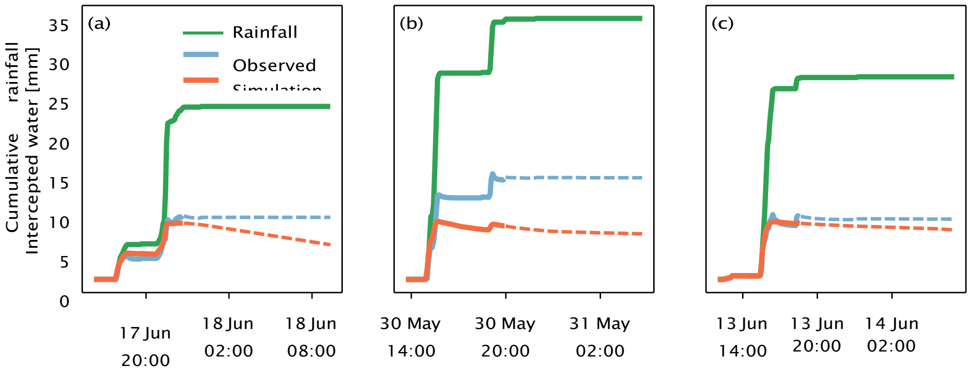

Figure 3. Comparison of observed and predicted interception load for (**a**) event #1 (June 2011), (b) event #2 (May 2012), and (**c**) event #3 (June 2012)).

3.2. Runoff

Having demonstrated the high predictive skill in interception modeling, Figure 4 shows the model results of the runoff calibration, which focus on runoff generation processes below the canopy (i.e., infiltration and surface runoff). The parameters found through minimizing the objective function f in Equation (5) using SCE-UA in spotpy yield the following parameters with convergence after 573 iterations:

- Parameter b of the Brooks-Corey retention curve: 13.1876;
- Scaling factor for Manning's n roughness: 3.57788;
- Scaling factor for saturated hydraulic conductivity K_{sat}: 0.0700464.

The scaling parameters found through calibration deviate from 1.0, suggesting that the assignment of land-use classes to roughness and conductivity values has been altered during calibration. The resulting values are still viewed meaningful. However, they are effective values that include sub-scale variability [45], like, e.g., unknown soil variability and local compaction or obstacles on the surface.

The range of Nash–Sutcliffe model efficiency E values obtained for all events extends from 0.63 to 0.92. In the process of model calibration, E amounts to 0.92 (event 1) and 0.70 (event 2), respectively. The goodness-of-fit achieved for event 1 (E = 0.92) is considered to be very good, while for event 2, E = 0.70 is still satisfactory. One possible reasonfor the lower model skill achieved for event 2 could be the fact that the event consists of two peaks. However, given the good match of peak flow values, the results of the calibration are acceptable.

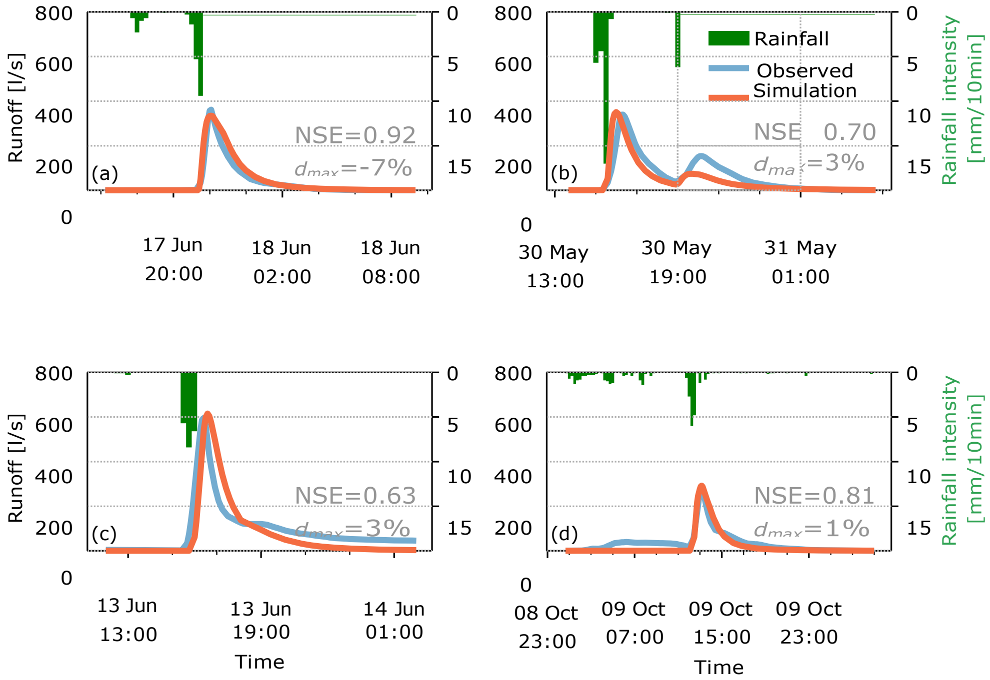

Figure 4. Results of calibration and validation for (**a**) event #1 (June 2011), (**b**) event #2 (May 2012), (c) event #3 (June 2012), and (**d**) event #4 (October 2012). Nash–Sutcliffe model efficiency *E* (NSE) and the difference between observed and predicted peak runoff $d_{\max}$ (as percentage) are indicated for each event.

The validation confirms that the model calibration is transferable to other events. Even though the Nash–Sutcliffe model efficiency found for event 3 (E = 0.63) is lower than the corresponding values found during calibration, it is still within an acceptable range of values higher than 0.5 [46] (it is worth mentioning that even a model with $E > 0$ has a higher predictive value than predicting just the average value, which is the benchmark value included in E). Event 4 even reflects a better model skill with E = 0.81. Similar to the calibration events, peak discharge is represented well even for the events considered for validating the model. For both types of events, i.e., calibration and validation, the differences in peak runoff are within the range ±3% (except for event 1, for which the difference amounts to 7%), which we view as a very good coincidence. Hence, we assume that the model is successfully calibrated and validated according to the split-sample test and that it has predictive skill for events not considered in the calibration procedure.

Figure 5 compiles a series of maps that show the spatio-temporal distribution of surface water in the study area. This visualization helps to analyze whether the model is also realistic in terms of runoff routing on the surface. In contrast to other models that utilize a unit-hydrograph or similar parametrizations to compute runoff concentration, explicit kinematic surface water routing is used instead. The temporal evolution of maps highlights how water is routed via the swales from east to west towards the intake structure (for which runoff measurements exist). Since no water level observations are available for the events,this figure is at least helpful for checking whether the model shows a realistic surface routing. The sequence of maps suggests that the model reflects a plausible surface routing.

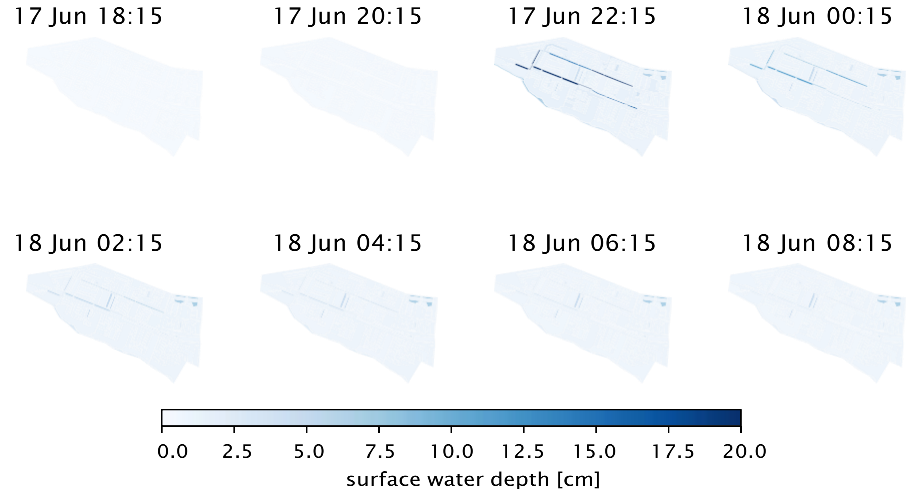

Figure 5. Spatial distribution of surface water depth for different time steps of event #1 (June 2011). Maximum runoff occurs around 22:15.

3.3. The Role of Trees in Pluvial Flooding

Finally, the role of trees in runoff generation is analyzed through comparing the runs from Figure 4 with corresponding runs, which have been conducted without trees. Table 5 compiles the most important characteristics for each of these event-based comparisons. For each event, the deactivation of trees is quantified in terms of (i) increase in maximum runoff, (ii) the increase in volume and (iii) its relative change, for both.

Table 5. Results of the model experiments considering runs with and without trees. The values indicate the increase in peak runoff and volume if trees are not included in the simulation.

Event	Quarter Scale				Tree Scale (Avg.)			
	Δ max $\bar{q}$ [L/s]	**Δ max $\bar{q}$ [%]**	**Δ Volume [L]**	**Δ Volume [%]**	**Δ max $\bar{q}$ [L/s]**	**Δ max $\bar{q}$ [%]**	**Δ Volume [L]**	**Δ Volume [%]**
#1	83	25%	368,550	15%	0.135	0.04%	603	0.02%
#2	96	27%	432,141	18%	0.156	0.04%	707	0.03%
#3	104	17%	409,373	11%	0.170	0.04%	670	0.02%
#4	57	19%	332,064	15%	0.093	0.03%	543	0.02%

The differences in peak discharge at the quarter scale range between 17% and 27% and, therefore, exceed the differences between observed and modeled peak runoff for all events. Predicted changes in peak runoff associated to changes in tree coverage therefore clearly exceed the inaccuracy in predicting model discharge by one order of magnitude. The values are highest for events 2 (27%) and 1 (25%), while they are lower but still in the order of 15–20% for events 3 and 4. Likewise, the changes in volume reach up to 18% for event 2 if trees are not included. Similar values are reached for event 1 and 4 (15%), and for event 3 (11%). These rates of change demonstrate that the coverage of trees, though no dominant land use fraction, is important to retain water during heavy rainfall events.

The average tree-scale values are remarkable: Peak runoff is reduced by 0.139 ± 0.033 L/s for all events. Even though the corresponding relative contribution in reducing peak runoff is small (~0.04%), the average value of 0.139 ± 0.033 L/s is still a tangible result. In terms of volume, the relative contribution for each tree is also small (~0.02%). However, the average difference in volume computed for each tree (631 ± 73 L) is higher than the value one might expect from just considering maximum interception capacity: the average projected area of an average tree amounts to 43.95 m^2. Given an interception capacity of 10 mm yields ~439.5 L of intercepted water for each tree (439.5 L · 611 = 268,535 L for all 611 trees). This volume is only ~70% of the volume differences achieved from comparison of the modeling experiments. A reason for this higher retention could be attributed to the non-linearity in the model. Intercepted water does not contribute to infiltration and surface runoff, respectively. However, in case of absent trees more water will turn into surface runoff that even affects areas downhill from the considered area without trees. More surface runoff in downstream areas, which are laterally connected, even potentially exceeds the infiltration capacity. This is especially true during peak rainfall intensities, which, in turn, highlights the relevance of trees.

Indeed, the percentage described here depends on the rainfall event in terms of magnitude. Hence, the relative contribution is lower for higher rainfall intensities. This is especially relevant, since it is expected that climate change might lead to increasing rainfall intensities. The return periods considered here do not represent extreme values, but they are typical values considered in urban drainage planning and associated guidelines (e.g., DIN EN 752 (DIN EN 752:2017-07 Drain and sewer systems outside buildings—Sewer system management)). Thus, our findings highlight that each tree contributes to reduce peak discharge in an quantifiable way, whilst being tangible for stakeholders.

3.4. Limitations

The accuracy of hydrological model outputs highly depends on the rainfall data. A major uncertainty in modeling hydrological response in urban areas is related to spatio-temporal rainfall variability [47]. Rainfall variability occurs below 1 km^2 and therefore can not be resolved by operational radar networks. For modeling fast responding catchments,a higher density of rain gauges is required [48,49]. Furthermore, no information about the initial soil saturation is available that can be taken into account. However, we can make assumptions based on the precipitation conditions of the previous days.

Urban soils are highly heterogeneous, due to compaction, sealing and other anthropogenic impacts, where there is a lack of data on their spatial distribution. Additionally, the used soil dataset in this study is limited on spatial variability, and therefore probably does not represent reality in accurate detail. Furthermore, we used a simple one layer approach, which might simplify the infiltration processes. Due to disturbed compacted soils and porosity reduction in urban areas, infiltration rates can be very low [50,51]. We reduced the given porosity according to literature (0.453 for sandy loam) [34] to 0.3. Even though we assume a porosity reduction due to urban soil compaction, we decided not to calibratethis parameter because of the availability of principle data from feasible literature. Other possible parameters that could be calibrated are further terms of the Brooks–Corey retention curve, such as the porosity decay or adjustments to the retention curve through the provision of value pairs of volumetric soil moisture and matrix potential, respectively [30]. Salvadore et al. [8] also suggest new techniques in calibration that are not only based on curve fitting at single locations, but also spatial distributed indices.

Likewise, uncertainties in the measurement should not be disregarded as a possible source of error since the urban hydrology system is highly complex with lots of uncertainties and not yet completely understood [8]. For instance, in Vauban the throughfall is measured with a tipping bucket rain gauge. Compared to standard rainfall measurements, throughfall measured this way is subject to higher maintenance (regular removal of leafs and needles), which needs to be considered as additional uncertainty in calculating interception with a simple bucket model. Errors in modeling and measurements are both possible. Especially for urban hydrology, data availability is limited and more measurements and open datasets (e.g., the Bellinge dataset [52]) are needed for calibrating models [8,53]. Besides level and runoff data, also more measurements of interception and infiltration should be collected to improve the urban hydrology system and thus modeling in this field.

4. Conclusions and Outlook

With respect to the two research questions raised in this paper, the major findings can be summarized as follows: The results suggest that our modeling approach is capableof representing both interception and surface runoff in a single model structure with a sufficient level of detail. This has been demonstrated by a good correspondence of modeled and measured runoff data and interception, respectively. Moreover, the model is able to quantify the contribution of single trees to mitigate effects of pluvial flooding at the quarter scale, at least on average.

The single contribution of each tree to reduce the flood peak (i.e., 0.139 ± 0.033 L/s) is site-specific, as it depends upon area size and tree coverage. Thus, the reduction in peak discharge cannot be transferred from one site to another. Whereas, the modeling approach can enable a transfer to other sites, since the comparison of observed and modeled interception and runoff, respectively, underlines a skillful representation runoff generation processes. At least, re-calibrating soil parameters is recommended if data is available. However, the site-specific single contribution of each tree is viewed as a tangible value, one that approximately corresponds to retaining a volume corresponding to one cup of coffee per second. This value could be computed likewise for arbitrary study areas with the approach described in this paper and communicated to stakeholders to make them aware of the role of trees in general and that every single tree is significant in flood mitigation at the quarter scale. Since the model is viewed scenario-capable, different levels of tree coverageor higher rainfall intensities could be studied likewise with LEAFlood. Furthermore, urban trees can store a greater amount of water in comparison to natural forest trees, since they tend to have a more circumference growth and thus a greater potential of water storage capacity [54]. With this outcome, new approaches in the assessment of flood regulating ecosystem services for heavy rainfall events in urban areas can be developed.

Unlike other hydrological models and studies that recommend a resolution of 3 to5 m for an adequate representation of the urban structure [55], the one used here is basedon irregular polygons. Comparisons with a raster approach have shown no improvementin the results, therefore a triangle or raster approach is not necessary. This significantly reduces the computation time and features the preparation of the modeling domain with standard GIS tools. The programming based structure of CMF provides the possibilityto couple the hydrological model with other models [56] to include dynamic interactions with surrounding environments of climate, land use, ecosystems and society. LEAFlood is ready to be adopted for other research questions. For instance, the evapotranspiration could be included for longer or intermittent rainfall events. This can be an important tool for informing decision makers and urban planners in the future, in order to understand and evaluate systems holistically.

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5

PUBLICATION 3

FLOOD-REGULATING ECOSYSTEM SERVICE MODELLING APPROACH FOR EXTREME EVENTS IN URBAN AREAS

This publication drafts a modelling approach for flood-regulating ES of heavy rainfall in urban areas. The outputs of the hydrological model LEAFlood were applied to quantify flood-regulating ES indicators. The model was applied because of the spatial resolution and the consideration of canopy interception and thus, it overcomes currently missing flood-regulating ES elements in urban areas. Ecosystem services supply and demand were estimated and compared in a mismatch analysis to identify unmet demand and supply surplus.

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Research Article

Urban ecosystems and heavy rainfall – A Flood Regulating Ecosystem Service modelling approach for extreme events on the local scale

Thea Wübbelmann[‡,§], Laurens M. Bouwer[‡], Kristian Förster[|], Steffen Bender[‡], Benjamin Burkhard[§,¶]

‡ Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, Hamburg, Germany
§ Leibniz Universität Hannover, Institute of Physical Geography and Landscape Ecology, Hannover, Germany
| Leibniz Universität Hannover, Institute of Hydrology and Water Resource Management, Hannover, Germany
¶ Leibniz Centre for Agricultural Landscape Research ZALF, Müncheberg, Germany

Corresponding author: Thea Wübbelmann (thea.wuebbelmann@hereon.de)

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Abstract

Increasing urbanisation in combination with a rise in the frequency and intensity of heavy rain events increase the risk of urban flooding. Flood Regulating Ecosystem Services (FRES) address the capacity of ecosystems to reduce the flood hazard and lower damage. FRES can be estimated by quantification of supply (provision of a service by an ecosystem) and demand (need for specific ES by society). However, FRES for pluvial floods in cities have rarely been studied and there is a gap in research and methods on FRES supply and demand quantification.

In this study, we assessed FRES of an urban district in the City of Rostock (Germany) for a one-hour heavy rainfall event using the hydrological model LEAFlood. The hydrological model delivered the FRES supply indicators of soil water retention and water retained by canopies (interception). An intersection of the potential demand (based on indicators of population density, land reference value, monuments and infrastructure) and the modelled surface water depth revealed the actual demand. Comparing the actual demand andsupply indicated the budget of FRES to identify unmet demand and supply surplus.

Results show highest mean FRES supply on greened areas of forests, woodlands and green areas, resulting in a supply surplus. Whereas, sealed areas (paved surface where water cannot infiltrate into the soil), such as settlements, urban dense areas, traffic areas and industry, have an unmet demand resulting from low supply and relatively high actual demand.

With the hydrological model LEAFlood, single landscape elements on the urban scale can be evaluated regarding their FRES and interception can be considered. Both are important for FRES assessment in urban areas. In contrast to flood risk maps, the study of FRES gives the opportunity to take into account the contribution of nature to flood regulation benefits for the socio-economic system. The visualisation of FRES supply and demand balance helps urban planners to identify hotspots and reduce potential impacts of urban pluvial flooding with ecosystem-based adaptations.

Keywords

supply and demand, unmet demand, mismatch, hydrological modelling, LEAFlood

Introduction

The sixth report of working group I of the Intergovernmental Panel on Climate Change (IPCC) (Arias et al. 2021) highlighted the past and future development of extreme weather events. This includes heavy precipitation events, which are projected to become more frequent and intense in the future. Urban areas in particular are vulnerable to these events because of the high degree of sealing, the presence of critical infrastructure and high population densities. Besides technical solutions, ecosystems and their structures, processes, resulting functions and services play an important role in urban flood regulation.The concept of Ecosystem Services (ES) can be used to quantify and map the links of the social and environmental systems to estimate benefits that people obtain from ecosystems (Millennium Ecosystem Assessment 2005). ES are the direct and indirect contributions of ecosystems to human well-being (TEEB 2010). Thereby, flood regulating ecosystem services (FRES) address the capacity to lower flood hazards by reducing water run-off (Stürck et al. 2014), reduce economic and social damage (Vallecillo et al. 2019) and protect property, houses, infrastructure and human life (Nedkov and Burkhard 2012).Relevant ecosystem processes, such as interception by vegetation, water storage in surface water bodies, infiltration in soil and percolation to the groundwater, contribute to flood regulation by storing water, distributing the run-off in time and reducing the peak discharge (Albert et al. 2015, Burkhard and Maes 2017).

To assess ES, the matrix method is a widely known and simple method that classifies ES, based on land-use classes from 0 to 5 (Burkhard et al. 2009, Burkhard et al. 2014, Goldenberg et al. 2017). Other, more quantitative, forward approaches are based on a purely spatial evaluation of data on land use, topography and soil to estimate FRES (Liyun et al. 2018, Vallecillo et al. 2020).

Additionally, the indicator framework developed by the German working group of "Mapping and Assessment of Ecosystem an their Servies" (MAES), in the context of the EU Biodiversity Strategy to 2020, included a FRES supply indicator to quantify water storage capacity, based on the area of floodplains (Albert et al. 2015).

Although a more comprehensive picture is given by quantitative models, which are increasingly being used in ES research (Syrbe and Walz 2012), the number of such studies is still comparatively small (Campagne et al. 2020). Quantitative modelling of ES helps to estimate supply and demand, to fill spatial and temporal data gaps and supports the extrapolation of measurements and observations. For regulating ES, such as FRES, modelling is often the best option to quantify the actual supply and demand of ES (Burkhard and Maes 2017). InVEST, for instance, is a dedicated model toolbox for the estimation of ES with the "Urban Flood Risk Mitigation model" (Natural Capital Project 2020), which is simple to use for FRES assessment (Gaglio et al. 2019).

The use of hydrological models, instead, is more complex, but more accurate in its depiction of reality. Depending on the research question, different hydrological models can be used (Nedkov and Burkhard 2012, Logsdon and Chaubey 2013, Stürck et al. 2014, Lüke and Hack 2018, Wübbelmann et al. 2021). The study by Nedkov and Burkhard (2012)is one of the first that exclusively focuses on FRES for river catchments using a combination of hydrological modelling and the matrix method (Burkhard et al. 2009) by classifying the results per land use and soil classes from 0 to 5.

The MAES-Indicators, as well as many methods based on models that determined FRES, focus on fluvial floods and on gauged catchment areas (Nedkov and Burkhard 2012, Boyanova et al. 2014, Stürck et al. 2014, Li et al. 2019). Although urban areas, in particular, are vulnerable to pluvial flood events caused by heavy precipitation and the prediction of FRES on the city scale is important for adaptation planning, pluvial FRES have so far been little investigated in urban areas (Shen et al. 2019, Wang et al. 2019). It isimportant to highlight that pluvial flooding – as addressed here – differs significantly from riverine flooding regarding the following aspects: (i) pluvial flooding can occur everywhere, even far away from rivers, (ii) its occurrence is local, mainly caused by convective events that can cause a very high hydrological response in terms of run-off (also referred to as flash flood). In this respect, the MAES-indicator and other indicators derived by land-use or catchment hydrological modelling with focus on fluvial flooding and floodplains have limitedsuitability for use in heterogenic urban areas (Kremer et al. 2016) and, in addition, disregard some crucial parameters (Wübbelmann et al. 2021), such as interception, infiltration, surface roughness and slope (Burkhard and Maes 2017). For pluvial FRES assessment in urban areas, other indicators and methods should be used, which consider the spatial heteorgenity and important hydrological retention processes, such as the interception or infiltration capacity.

Flood regulating supply only has a societal value and turns into an ES if there is an according demand (Stürck et al. 2015). However, most studies focus on the supply sideand there is a gap in research on ES demand (Campagne et al. 2020). Furthermore, qualitative differences exist for ES demand assessments, since they are mainly assessed by comparably simple statistical or literature data and the multidisciplinary complexity of the demand has rarely been mapped (Dworczyk and Burkhard 2021). For a simple estimation, the matrix approach can be chosen, based on land-use/land-cover data with urban areas, settlements or traffic areas classified as ES demand areas (Burkhard et al. 2009, Syrbe and Walz 2012). Vallecillo et al. (2019) presented a more quantitative approach using the area as the unit for defined demand land-use classes. This can be extended to a more comprehensive assessment using demographic, topographic, economic and statistical data (Nedkov and Burkhard 2012, Dworczyk and Burkhard 2021). Others define the demand for FRES by the flood risk as the function of hazard, exposure and vulnerability, while the flood hazard is defined by the extent and depth of inundation (Stürck et al. 2014, Shen et al. 2019). Dworczyk and Burkhard (2021) recommend to consider different methods and user groups to increase the knowledge and diversity of ES demand. For instance, the flood risk management plan of the European Union suggested different protection goods, such as the number of inhabitants or economy activities (European Parliament 2007).

After evaluating FRES supply and demand, a budget analysis can be applied to identify mismatches of ES supply and demand to discover unmet demand besides the benefiting areas with a supply surplus (Syrbe and Walz 2012, Lorilla et al. 2019, Dworczyk and Burkhard 2021).

Therefore, the main aim of this paper is to fill the research gap of a comprehensive FRES assessment of natural supply and demand and their mismatches at the urban scale with a focus on heavy precipitation events. Accordingly, we applied the methodological approach to an exemplary area and heavy precipitation event. We tested indicators of soil water storage and interception for FRES supply using the hydrological Model LEAFlood that is based on the Catchment Modelling Framework (CMF). After we identified FRES supply areas, we carried out a comprehensive FRES demand analysis that takes into account different demand types. Finally, we conducted an analysis at the urban scale to uncover the unmet demand.

We, therefore, address the following research questions:

- Which (eco)system elements and structures have high natural FRES supply in urban areas?
- Which areas have a high FRES demand and how can we identify the level of unmet demand?
- What are the strengths and weaknesses of the LEAFlood model for the assessment of FRES in urban areas for heavy rainfall events?

Material and Methods

The basis for the following analysis was the hydrological model LEAFlood. The model was designed by Wübbelmann and Förster (2022) for scales well below the catchment scale, which allows for resolving features of urban districts (such as parks, buildings, streets) in a distributed way, in order to predict urban flooding at the neighbourhood scale, scaled up to a few square kilometres. It considers vertical hydrological processes, incorporating rainfall interception by tree canopies, infiltration and surface run-off either from rainfall intensities that exceed the infiltration rates or soil saturation excess, respectively. The spatial resolution is flexible in order to represent spatial elements - such as landscape elements - of arbitrary size. Lateral connectivity of landscape elements is accomplished through a simplified representation of 2D hydrodynamics for surface run-off, which meets the objectives of the small-scale FRES analysis of pluvial flooding in urban areas.

In the following, the results of the model and other spatial data used in the FRES analysis were analysed with ArcGIS Pro 2.8 from ESRI and Python 3.7. For the FRES analysis, we partly followed the approaches of existing studies (Nedkov and Burkhard 2012, Biota 2014) and adapted these to our research question related to the analysis of unmet demand (Dworczyk and Burkhard 2021). A district in the City of Rostock, Germany served as the test area for the approach.

Study Area

The study area covers partially the city districts Hansaviertel, Reutershagen and Köpeliner-Tor-Vorstadt in Rostock (northeast Germany) at the estuary of the River Warnow at the Baltic Sea (Fig. 1). The city and its surroundings cover an area of 181.5 km². The elevation ranges from 0 m to a maximum height of 54.64 m a.s.l. (Landesamt Mecklenburg- Vorpommern n.Y.).

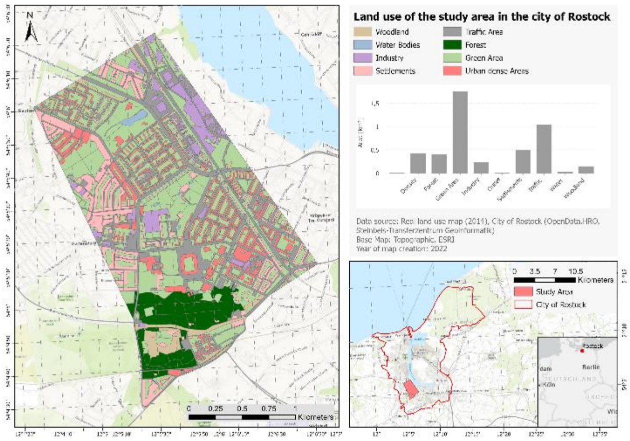

Figure 1.

Location and Land use of the research area in the City of Rostock.

Due to its proximity to the Baltic Sea, the climate in Rostock is mild-maritime. The annual mean temperature is 9.2°C (1981-2010). The annual precipitation sum is 730 mm with a maximum monthly precipitation of around 70 mm in July (DWD Climate Data Center 2022).

Several heavy precipitation events occurred in the past (Fig. 2). Especially, the summer of 2011 was very wet and floods occurred more frequently (Miegel et al. 2014).

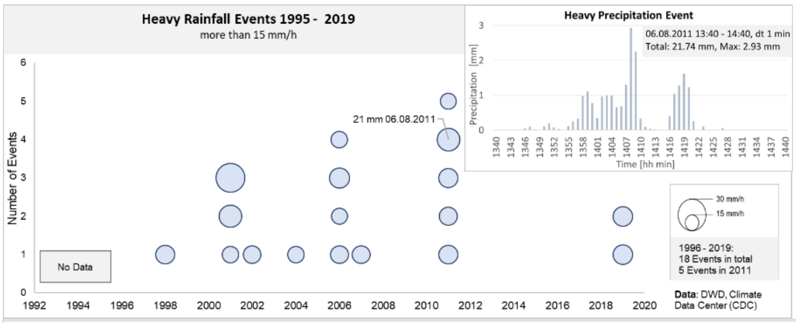

Figure 2.

Heavy Rainfall events from 1995 - 2019 with more than 15 mm/h and the chosen rainfall event on 06.08.2011 for the modelling in this study.

The study area with a size of 4.5 km² is located in the southwest of Rostock (Fig. 1). This area was chosen because of the variety of different land uses. Approx. 50% of the area comprises green areas (parks, forests and woodland), 23% consists of traffic areas and 25% contains sealed areas (settlements, urban dense areas and industry) (Steinbeis-Transferzentrum Geoinformatik 2017). The soil types in the study area are mainly luvisol-pseudogley and regosol. The texture of the substrate is sandy loam and loamy sand with wet characteristics (Hanse- und Universitätsstadt Rostock – Amt für Umwelt- und Klimaschutz 2019a, Hanse- und Universitätsstadt Rostock – Amt für Umwelt- und Klimaschutz 2019b).

Data

The hydrological model requires an appropriate dataset of meteorological, land use, soil and elevation information. The main meteorological input dataset is precipitation. We used the data of the DWD climate station Rostock-Warnemünde at one minute resolution (DWD Climate Data Center 2021a). The selected event (6.8.2011 13:40 – 14:40 h) covers a rain duration of one hour, with a total amount of 21.74 mm and a maximum intensity of 2.93 mm/min (see small figure in Figure 1).

Other required meteorological data that are used if (canopy) evaporation is activated, are the minimum and maximum temperature (DWD Climate Data Center 2019a), wind speed (DWD Climate Data Center 2019b), solar radiation (DWD Climate Data Center 2021b) and relative humidity (DWD Climate Data Center 2019c). These data are only provided in 10 minute resolution. To resample these data to the one minute interval, we keep the 10 minute value constantly for all one minute values of the intervals.

Spatial data of the land use includes soil-sealing information (Steinbeis-Transferzentrum Geoinformatik 2017) and, in addition, a point shapefile of the tree locations with information on the tree diameter and tree type was available (Hanse- und Universitätsstadt Rostock -

Amt für Stadtgrün Naturschutz und Friedhofswesen 2017). Spatial data on soil type (Hanse- und Universitätsstadt Rostock – Amt für Umwelt- und Klimaschutz 2019a) were used to set up the geometry. A digital elevation model was provided by the State of Mecklenburg-Vorpommern at one metre resolution (Landesamt Mecklenburg-Vorpommernn.Y.).

The FRES demand analysis also required a set of spatial data. In addition to the land-use data, which was used to identify the traffic infrastructure (Steinbeis-Transferzentrum Geoinformatik 2017), a map with land reference values (the average economic value for a majority of areas of mainly the same use and value characteristics (Lenzen 2014)) (Hanse- und Universitätsstadt Rostock – Kataster- Vermessungs- und Liegenschaftsamt 2021) and a map with the location of monuments (Hanse- und Universitätsstadt Rostock – Amt für Kultur Denkmalpflege und Museen 2017) were integrated. In addition, a collection of spatial data on critical infrastructure including hospitals (Hanse- und Universitätsstadt Rostock – Kataster- Vermessungs- und Liegenschaftsamt 2017), fire stations (Hanse- und Universitätsstadt Rostock – Brandschutz- und Rettungsamt 2017), schools (Hanse- und Universitätsstadt Rostock – Schulverwaltungsamt 2017), care facilities (Hanse- und Universitätsstadt Rostock – Amt für Jugend Soziales und Asyl 2017b) and institutions for the disabled (Hanse- und Universitätsstadt Rostock – Amt für Jugend Soziales und Asyl 2017a) were used in the analysis.

Hydrological Model LEAFlood

For the hydrological modelling, we used LEAFlood (Landscape vEgetAtion and Flood model) (Wübbelmann and Förster 2022), which is based on the Catchment Modelling Framework (CMF) (Kraft et al. 2011). CMF is an open source programming library for hydrological modelling. The modular structure of this Python package provides high flexibility and is adaptable to different research questions. Hydrological processes can be selected from a range of different approaches depending on the question, as demonstrated by Förster et al. (2021) for physically based hydrological modelling of green roofs.

LEAFlood adopts CMF features to create the geometry, based on polygon cells out of GIS shapefiles on the spatial resolution that is required for adequate hydrological modelling on the city scale. Most models designed for urban areas focus on urban drainage with a simplified representation of vegetation (Iffland et al. 2021). LEAFlood considers hydrological processes of canopy interception, through-fall, canopy evaporation, soil infiltration and surface run-off (see Fig. 3). It accounts for a detailed representation of interception and a lateral surface run-off simulation through a 2D kinematic wave approximation. The model was described and tested in detail by Camarena et al. (2022). They compared measured run-off data with LEAFlood model results and verified the good representation of both interception by tree canopies and run-off at the quarter scale. In the present study, neither run-off nor interception measurements were available for Rostock, but model comparison and on-site inspections confirm the plausibility of computed spatial inundation patterns. In general, models should be calibrated for new sites, whenever possible. Even though some parameters are site-specific, the results demonstrated by

Camarena et al. (2022) highlight that the model is capable of representing pluvial flooding for landscape elements, which is why we chose the model.

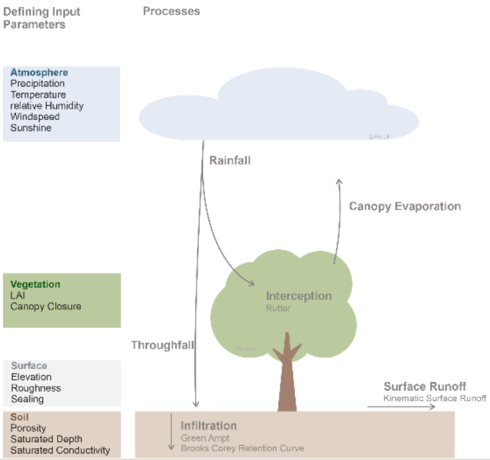

Figure 3.

The hydrological processes, defining parameters and storages in LEAFlood (Wübbelmann and Förster 2022).

The geometry for our study was created on the basis of an irregular polygon shapefile consisting of 4750 cells with an average size of approximately 1000 m², in order to best possibly resolve relevant urban landscape elements on the one hand side and numerical stability on the other. The canopy closure, which defines the amount of through-fall and canopy interception, was given by the quotient of the projected canopy area and cell area. Each tree was assigned a Leaf Area Index (LAI) value and an interception capacity, based on its species-specific attributes using the datasets of Breuer et al. (2003) and Iio and Ito (2014). After that, for each cell, a mean LAI and interception capacity was calculated from all trees included in that cell. For missing values, a mean of all existing values was used. Since literature values of interception capacity, like those compiled by Breuer et al. (2003), cover a broad range of precipitation events in terms of precipitation total and event duration, they do not necessarily represent the maximum retention governed by interception during heavy rainfall events, as demonstrated by Asadian and Weiler (2009) and Alves et al. (2018). Therefore, supported by the validated modelling experiments conducted by Camarena et al. (2022), a scaling factor of 5 was applied to the literature values to compensate the mismatch in temporal scale and to acknowledge the higher possible interception load of trees during heavy rainfall events.

LEAFlood uses a one soil layer approach, assuming that only the upper layer is relevant for infiltration and that percolation does not play a role due to the time delay. The used infiltration approach is Green-Ampt, which is an approximate theory adaptation of the Darcy equation (Rawls et al. 1993). Except for saturated conductivity (Ksat), all other parameters were the same throughout the study area (Table 1). The base value for Ksat was 0.3 m/d resulting from the soil property sandy loam (Sponagel et al. 2005). Depending on the degree of soil sealing, Ksat was reduced by the following function:

$$K_{sat,reduced} = (1 - \frac{sealing}{100}) * K_{sat}$$

Table 1.

Settings and processes in LEAFlood.

Process/ Parameter	**Setting**
Interception	Rutter Interception Through-fall Canopy Evaporation
Infiltration	Green-Ampt Brooks Cores Retention Curve
Layer depth	0.5 m
Saturated conductivity (Ksat)	0.3 m/d (base value)
Porosity	0.3 [-]
Theta_x	0.2 [-]
_b	8 [-]
Porosity decay	0.2 m^{-1}
Saturated depth	1 m
Surface Run-off	Kinematic wave

A higher degree of sealing, therefore, resulted in a lower Ksat value (Table 2). The porosity of sandy loams, given in literature (0.45) (Sponagel et al. 2005), was lowered to 0.3 due to urban compaction and resulting reduced infiltration rates (Gregory et al. 2006). The Manning roughness coefficient was assigned for each land-use class (Table 2).

Table 2.

The roughness coefficient Manning's n and the saturated conductivity (Ksat) defined for each land use class.

Land use	**Manning's n [s*$m^{-1/3}$]** (Brunner 2021)	**Saturated Conductivity [m/day]**
Urban dense areas	0.2	0
Settlements	0.12	0.015
Industry	0.12	0
Traffic area	0.03	0.006
Green area	0.05	0.29
Woodland	0.14	0.3
Forest	0.15	0.3
Water	0.03	0.015

Flood Regulating Ecosystem Services (FRES) analysis

The FRES analysis was undertaken with Python and ArcGIS Pro using an intersection of spatial information of population, economy, land use and hydrological model results. Fig. 4 gives an overview of the workflow and Table 3 shows the definitions of the used FRES terms and the used indicators. The potential demand was determined by a GIS analysis of various economic and social indicators. The output of LEAFlood was the water storage on the surface, the soil water and the intercepted canopy water. While the last two variables were used as indicators for the supply of FRES, the surface water, together with an intersection of the potential demand, indicated the actual demand. Finally, the FRESsupply and demand budget was calculated by the difference of the supply and actual demand.

Table 3.

Definitions of the terms used for FRES.

Term	Definition	Indicators	Other studies
Used Supply	ES supply indicates the provision of a service by an ecosystem (Burkhard and Maes 2017). The pluvial FRES supply indicators in this study are soil water content and intercepted water by vegetation.	Interception capacity [mm] + Soil water capacity [mm] *Difference between Maximum and initial depth (t0)* = Supply [mm] *converted into relative scale 0-1*	There is no synonym from other studies, such as the vulnerability and risk approach, since they do not consider flood regulating elements, but are focused on the flooding itself.
Potential demand	An ecosystem only provides ES if there is a demand by society or other stakeholder. Therefore, the demand is the need of an ES by society or other stakeholders (Burkhard and Maes 2017, Syrbe and Grunewald 2017, Syrbe and Walz 2012) and describes the values that need to be protected (European Parliament 2007, Biota 2014). For pluvial FRES, it refers to the need for risk reduction, prevention and security increase (Dworczyk and Burkhard 2021). This is always the existing general demand of areas that might get flooded.	Population Density [people/100 km^2] Monuments [-] Land reference value [€] Infrastructure [-] (for details see Table 4)	In other concepts or approaches, the terms of vulnerability and exposure (Oppenheimer et al. 2014) or damage potential (European Parliament 2007, Biota 2014) are used. While exposure is the spatial presence of, for instance, humans or infrastructure, the vulnerability refers to the characteristics of the human and socio-economic system (Oppenheimer et al. 2014).
Flood hazard	Flood hazard indicates the surface flooding. The indicator is the modelled surface water depth.	Surface water depth [mm] *converted into relative scale 0-1*	In vulnerability and flood risk assessments, flooding is referred to as hazard and is the potential occurrence of an event (Oppenheimer et al. 2014). While these concepts are referred to as statistical design events, we consider a specific event.

Term	Definition	Indicators	Other studies
Actual demand	The actual demand resulting from an intersection of the potential demand and flood hazard. It is the potential demand that was actually used for this single rainfall event (flood hazard). Therefore, the potential demand turns into a actual demand.	*Product of potential demand and flood hazard*	The actual demand can be understood as the risk and results of the function of vulnerability, exposure and hazard (Oppenheimer et al. 2014).
Budget	ES budget results from the difference of FRES actual demand and supply. It indicates the mismatches of supply and demand as benefiting areas with a supply surplus and unmet demand areas, where the FRES is not sufficient to balance the amount of precipitation (Nedkov and Burkhard 2012, Dworczyk and Burkhard 2021).	*Difference of supply and flood hazard*	Other concepts do not consider the used regulating storage capacities and balance to examine the sufficiency of FRES supply.

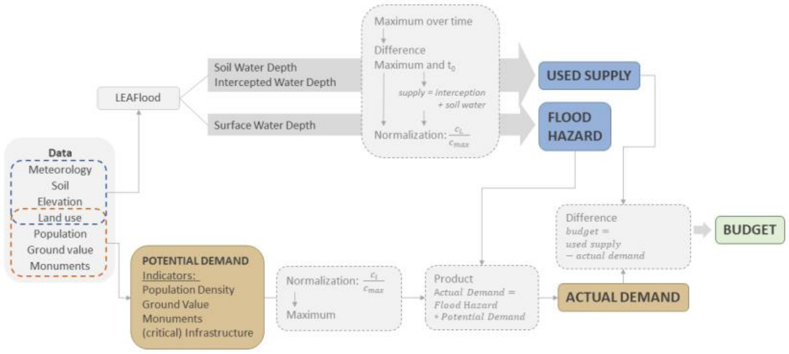

Figure 4.

Workflow of the FRES analysis.

t_0 is the starting time at the beginning of the rainfall event. c_i is the water depth of an individual polygon. c_{max} is the maximum water depth of all cells for the respective parameter or the 90% quantile for the surface water depth.

FRES supply

The FRES supply indicators were the soil water depth and the intercepted water depth on the canopies. They were defined by the difference of the maximum over the time and the initial water column at the first time step. The values were derived from the output of the hydrological model. The total supply resulted from the sum of both indicators (Fig. 4).

The supply and its indicators were individually classified into a relative scale from 0 to 1 by dividing the water depth of the cell by the maximum of all cells. Thereby, 0 to 0.2 indicates a very low supply, 0.2 to 0.4 a low supply, 0.4 to 0.6 a medium supply, 0.6 to 0.8 a high supply and 0.8 to 1.0 a very high supply with the 1.0 as maximum supply, according to the suggested 0 to 5 classification by Burkhard et al. (2009).

FRES demand

For the demand analysis, we used the proposed indicators of the INTEK project in Rostock (Biota 2014). This approach was based on the vulnerability for different protected assets, which we transferred to ES. Protected assets can be referred to as potential demand and the intersection with the flood hazard, as actual demand.

Five different indicators were selected, covering different potential demand types of population density [people/100 m^2], cultural heritage [-], economy by the land-reference value [€] and the infrastructure sectors [-] (see Table 4); (Biota 2014). Additionally, we added an indicator for critical infrastructure elements that includes, for instance, the presence of hospitals, fire stations and social institutions. The associated point shapefiles of these were buffered by a 100 m radius around the institutions. All indicators were classified into a relative scale from 0 to 1.0 (see Table 4). For the indicators with units (population density and land reference value), the cell value was divided by the maximum of all polygons. The indicators of cultural heritage and infrastructure were dimensionless asthey depict the occurrence of the elements and are referred to as an entire polygon. The occurrence of cultural heritage and critical infrastrucutre were indicated with 1.0, station, main streets and railway tracks with 0.6, streets with 0.4 and ways with 0.2. A very low potential demand ranges from 0 to 0.2 and a very high potential demand from 0.8 to 1.0. For the total potential demand, all indicators were intersected and the maximum for each polygon was taken out of all potential demand indicators in order to present the most vulnerable variable.

Table 4.

The potential demand indicators and the relative scale.

Sector	Population	Cultural Heritage	Economy	Infrastructure	
Indicator	Population density [people/100m^2]	Monuments [-]	Land reference value [€]	Critical Infrastructure [-]	Traffic [-]
Scaling	*converted into relative scale 0-1: Value of scale divided by maximum of all cells*	1.0: monuments	*converted into relative scale 0-1: Value of scale dividedby maximum of all cells*	1.0: hospitals, fire stations, schools, care facility, disabled institutions	0.6: station, main streets, railway tracks 0.4: streets 0.2:ways

The actual demand is understood to be the area that has a potential demand or need for flood protection (for instance, by population or economy) and that was actually flooded by the observed event, according to our hydrological simulation. This means that, if an area is flooded and has a potential demand, this turns into an actual demand. Accordingly, this indicator resulted from the intersection of potential demand and flood hazard (Fig. 4). The surface water depth, an output of the LEAFlood model, defined the flood hazard. Equally, for the supply indicators, the difference of the maximum water depth over the time and initial surface water at the beginning of the event was scaled from 0 to 1.0. Due to some single values with very high water depth in terrain depressions, the 90% quantile (31.4

mm) was chosen here instead of the maximum. This means that everything above the 90% quantile was indexed with 1. The product of the flood hazard and the potential demand yielded the magnitude of the actual demand (Biota 2014). Again, 0 to 0.2 indicates a very low actual demand, 0.2 to 0.4 a low actual demnad, 0.4 to 0.6 a medium actual demand, 0.6 to 0.8 a high actual demand and 0.8 to 1.0 a very high actual demand with the 1.0 as maximum actual demand.

FRES budget

In order to quantify, map and visualise the mismatches between actual demand and supply, a FRES budget map was created. The budget resulted from the spatial overlay and difference of the total supply and the actual demand of FRES (see Fig. 4) (Nedkov and Burkhard 2012). The scale ranged from -1.0 to 1.0, where 1.0 indicated a very high supply surplus, 0 showed a balance and -1.0 indicated a high unmet demand that was not covered by the supply. For instance, a polygon of high supply (0.8) and a low actual demand (0.2) has a supply surplus since the supply exceeds the actual demand. If supply and actual demand had the same score, they were in balance (0).

Results

The main results are analysis and maps for all three FRES-components – supply, demand and budget. The supply map includes the two indicators of soil water and interception, as well as the total supply (see chapter FRES supply). The demand map shows the potential and actual demand, as well as the flood hazard (see chapter FRES demand). The mismatch of supply and actual demand is displayed in the budget map and is analysed in the following chapter 'FRES budget'. It indicates the unmet demand and benefitting/ supplysurplus areas. In addition, the table in the Suppl. material 2 lists the relative scale values for all FRES parameters for each land use.

The mean stored water depth of soils was highest on forest, woodlands and green areas land uses with 2.5 mm (see Suppl. material 1), while the sealed areas did not store water by soil due to the low saturated conductivity. Whereas, the interception by canopies had higher water columns for the sealed areas with an average of ~ 1 to 2 mm for settlements, traffic areas and urban dense areas. Additionally, green areas, such as parks, only had a mean water depth of 1.3 mm on canopies and woodlands stored 2 mm. As expected, forests had the highest mean water depth by interception of 6.2 mm. In general, this resulted in a total mean supply (soil + interception) of 3.2 mm in the study area. Greened spaces had higher supply water depth with ~ 9 mm on forest areas, ~ 4 mm over green areas and 5 mm on woodlands. The sealed areas had a low total water depth of soil and interception with 0.3 mm (industry) to 2 mm (traffic areas).

Over the entire study area, the surface water depth was higher than the supply by interception and soil. The surface flooding reached from ~ 16 mm on settlements, forests and urban dense areas and up to 90 mm on terrain depressions of water land-uses. Traffic areas were flooded with an average water depth of 30 mm.

FRES supply

The indicators for the FRES supply were the water depth of interception and soil. Each indicator and the total supply, which resulted from the sum of interception and soil water depth, were converted into relative scales from 0 to 1, respectively. The maximum interception depth was 7 mm, soil water depth was 3 mm and the total supply in one cell reached a maximum of 10 mm. Fig. 5 displays the indicators and the total supply in maps and a chart diagram of the area weighted mean supply of the indicators and the total supply for each land use.

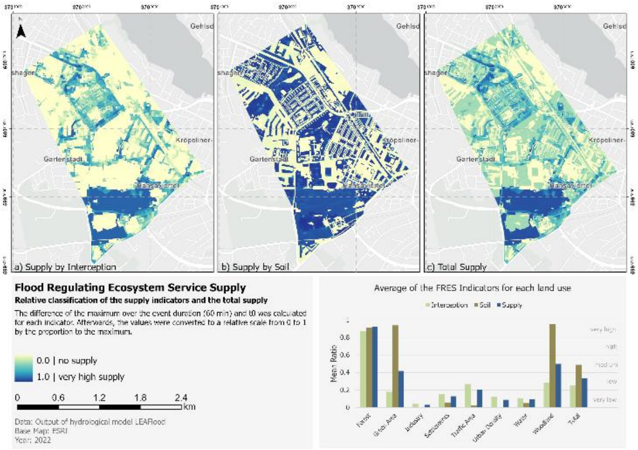

Figure 5.

FRES supply. a) Interception by canopies, b) Soil storage, c) Total supply.

In general, green areas, such as forests, parks and woodlands, had the highest supply. A very high supply was provided by forests with ~ 0.9. Both the supply through interception and through the soil were very high. The supply on green areas and woodland were mainly provided by soil (very high), while the supply by interception on this areas was low (0.2 to 0.3).

Traffic areas had a low supply, which resulted from a low supply by interception (0.3), while the supply by soil was very low. The other sealed areas had a very low supply, which was also due to the very low supply by interception (0.15).

Over the entire area, the interception supply was low (~ 0.3), the soil supply medium (~ 0.5) and the total supply low (~ 0.3) on a relative scale. However, the results also showed, if a canopy were present, the absolute amount of interception storage was higher than the soil storage.

FRES demand

The demand components of potential demand, flood hazard and actual demand are displayed in Fig. 6. While the maps show the spatial distribution of the relative scaled demand, the bar chart shows the area weighted mean demand over the entire study area grouped by land uses. The individual indicators for the FRES potential demand are mapped in the Suppl. material 3.

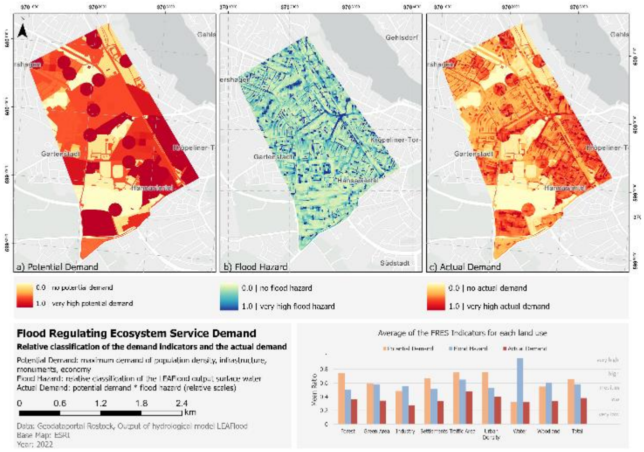

Figure 6.

ES components of FRES demand. a) potential demand, b) flood hazard, c) actual demand.

The potential demand (Fig. 6a), based on the indicators of population, reference land value, monuments and infrastructure, was relatively high (0.6) (see also Suppl. material 3), with maximum values on traffic areas and urban areas (~ 0.75). On green areas and settlements, the potential demand was high and, on industry and woodland, it was medium. Additionally, forest areas in the south were indicated with a high potential demanddue to the cultural heritage status of the area.

The flood hazard (Fig. 6b) resulted from the surface water from the LEAFlood model and was converted to a relative scale, based on the 90% Quantile of 31.4 mm, while the maximum reached up to 2047 mm in depressions. Therefore, a very high flood hazard was indicated on water bodies (0.95). Traffic areas had a high flood hazard, while the remaining land uses of forests, green areas, industry, settlements and urban density were exposed to a medium flood hazard.

The actual demand (Fig. 6c) resulted from the product of potential demand and flood hazard on each individual cell and can be a maximum of 1. On average, there was no high or very high actual demand for any land-use. The highest actual demand were on traffic areas (0.5) and urban density areas (0.4; medium), whereas, green areas, water, woodland, industry and settlements had a low actual demand on average.

FRES budget

The budget map (Fig. 7) shows the difference between the supply and actual demand with a relative scale from -1 (unmet demand) to 1 (supply surplus) and a balance of 0.

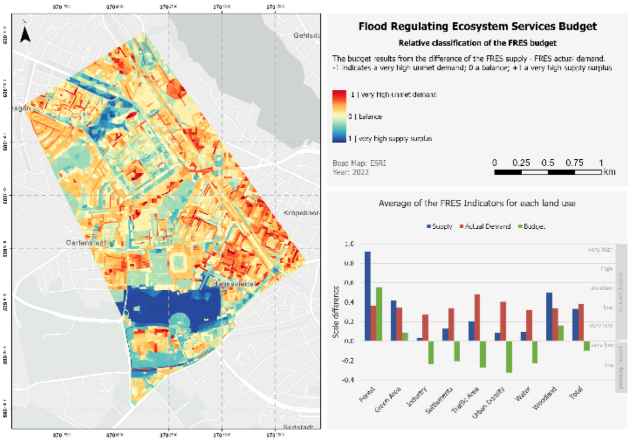

Figure 7.

Budget of the FRES supply and demand resulting in unmet demand and supply surplus.

Greened spaces, such as forests, green areas and woodlands, had an average supply surplus. Thereby, forests had a very high supply and low actual demand, which resulted in a medium supply surplus (~ 0.55). Green areas and woodlands were exposed to a medium supply (> 0.4) and a low actual demand. On average, there was a very low supply surplus on green areas (0.1) and a low supply surplus (~ 0.2) for woodlands.

On the contrary, sealed spaces were indicated with an unmet demand. While the supply was low on nearly all land-uses, the actual demand was low or medium (traffic areas, urban dense areas). This resulted in a very low unmet demand for settlements, industry, traffic areas and urban density areas.

In total, the study area had a low supply and low to medium actual demand. Therefore, the budget was calculated with a very low unmet demand of -0.1.

Discussion

The results showed local pluvial FRES supply and demand that were quantified and mapped in an exemplary urban area and heavy precipitation event. These results indicated that vegetation plays an important part in flood regulation, if the soils are saturated or sealed and, thus, should be considered in urban FRES assessments. The intercepted values of maximum 7 mm are comparable to the measurements and model results of otherstudies (Alves et al. 2018, Camarena et al. 2022). Therefore, green urban areas have, in general, a high FRES supply, while sealed areas are indicated with low to no supply. A mismatch of supply and actual demand could be identified. While parks and forest provideda high supply, the actual demand in this areas is relatively low and vice versa. Thus, the settlements in the east of the study area were indicated to have high unmet demand resulting from a high potential demand by critical infrastructure and land reference value and a low supply due to missing vegetation elements, such as trees or green spaces where water can be intercepted or infiltrate. Furthermore, lower lying areas, for instance, the Holbeinplatz, had a higher unmet demand, which resulted from a high flood hazard andhigh potential demand by traffic areas.

Over the entire study area, the surface water depth was found to be deeper than the water depth of the total supply. To counteract the high water levels on the surfaces, more storage by ecosystems can be provided (e.g. infiltration or interception). Since we investigated a single event, even changing intial conditions, such as a lower saturated depth, could leadto more supply capacity. Furthermore, we did not consider the sewerage system in the hydrological modelling, as the focus was on the possible contribution of natural ecosystems to the regulation of pluvial floods. Neglecting the drainage system is a limitation, which might overestimate the actual demand, but does not influence the FRES supply. At this point, we accept this limitation, since the study focuses on rare events of high intensities that potentially cause pluvial flooding that typically exceeds the capacity of urban drainage systems - as observed during the considered event in 2011 (Miegel et al. 2014).

Model uncertainties of LEAFlood for pluvial FRES Modeling

By using hydrological models for FRES-assessment, it is possible to take different rainfall events and initial conditions into account. Thus, the results of the actual FRES demand and budget analysis are only valid for a specific event. However, this also gives the opportunity to test different scenarios and replicate real events with different initial conditions to get a bandwith of possible impacts. Designed events and ideal (drier) soil conditions, for example, could lead to an improbably high supply and are far from reality. The total capacity would be determined rather than the actual used flood regulating capacity available to the population.

CMF fills the gap of flexible and modular hydrological modelling structure that the community is asking for (Elga et al. 2015). With this framework, it was possible to build up LEAFlood, which provides the opportunity to value single landscape structures and elements of ungauged urban areas including their lateral connectivity instead of entire catchments, while having a flexible choice of hydrological processes. This way, LEAFlood enables hydrological predictions below the scale of typical land use classifications as it allows for resolving single elements of urban districts in a distributed way such as parks, buildings, streets or even elements of green infrastructure (for instance swales or trees) (Camarena et al. 2022). It is capable of incorporating vegetation-related hydrological processes, which are an important FRES-supply element (Nedkov and Burkhard 2012, Burkhard and Maes 2017) and which is unaccounted in typical stormwater models used in urban hydrology. The use of point shapefiles for the trees, a land use dataset that resolves individual elements of a city and a 1 m DEM can, therefore, be considered as sufficient for the application in this model. However, modelling and programming experiences are required and, even if it is possible to take vegetation and individual landscape elements into account with LEAFlood, this hydrological model is - like all models - only a simplified representation of reality.

Besides the vegetation-related hydrological processes, we considered the infiltration with the Green-Ampt approach and the kinematic surface run-off. For infiltration, we only lookedat the upper soil layer and did not consider percolation (water flow from the unsaturated to the saturated soil zone), because of a time delay, most of the water infiltrates into the upper layer during an short rainfall event (Markovič et al. 2014). The same applies to interflow (horizontal water flow in the unsaturated soil zone), which is not considered in LEAFlood. These limitations are acceptable for event-based modelling in urban areas, as surface run-off is the most dominant process. Furthermore, evapotranspiration is neglected. This is based on the assumption that the rate of evapotranspiration losses is at least one order of magnitude lower than corresponding rainfall intensities during a heavy rainfall event (Elga et al. 2015).

The advantage of hydrological modelling, especially of LEAFlood, for valuing FRES, is its flexibility. Depending on the available data and the research question, the complexity of the model can be adapted and extended by the processes, input data or resolution. For instance, we used a simple soil approach with regard to the spatial distribution because detailed information about soil texture distribution was unavailable. Urban soils are highly heterogeneous, which is why a dense measurement network is necessary for detailed soil mapping. In addition to the enormous measurement effort, it is difficult to obtain according permissions. Therefore, the existing level of detail is sufficient for the research question and, even with the simpler approach, good conclusions can be drawn about FRES.

A calibration of the ungauged urban study area in Rostock is not possible because of missing field measurements, which is common for urban areas since these are not demarcated catchments on this scale (Krebs et al. 2014) and high measurement efforts arerequired. However, the functionality of LEAFlood has been proven in the study area of Vauban (Freiburg, Germany) by showing that the model is capable to model run-off and canopy interception (Camarena et al. 2022). Both study sites in Vauban and Rostock are smaller districts within a city with a soil texture of sandy loam. Information about trees is more detailed in Rostock; however, the mean characteristics of the trees and so the settings of LAI and interception capacities are similar. Therefore, the functionality of infiltration and interception processes can be assumed as transferable from one site to the other. Nevertheless, the set and calibrated model parameters in Vauban cannot be transferred directly to other areas for hydrological modelling, as they are site and event specific (e.g. saturated depth) and, thus, reflect uncertainties. However, the results can be considered as sufficient, since an on-site inspection showed comparable flooding of past pluvial flood events in Rostock (for instance, at the Holbeinplatz) (OZ 2014) and also other modelling studies in Rostock emphasise these areas, which were indicated as hotspots in our study (Biota 2013). Furthermore, Rostock provides a comprehensive dataset, which is sufficient for the mode setup of the qualitative analysis of FRES.

Spatial Analysis of pluvial Flood Regulating Ecosystem Service modellingresults

The results showed that the interception by vegetation has a large share of the total FRES supply, which is particularly true when the soil is highly saturated. This confirms the statement by Nedkov and Burkhard (2012) and Burkhard and Maes (2017) that interception plays an important role in FRES supply assessment. The importance of urban trees is further supported in other studies, which have found that urban trees have a larger canopy circumference than forest trees because they have more space to grow.Consequently, they have a greater interception capacity (Asadian and Weiler 2009, Carlyle-Moses et al. 2020). With LEAFlood, we can model the interception and the importance for FRES supply on the spatial resolution of individual landscape patterns and, therefore, perform a spatially-detailed FRES supply assessment for the indicator bymodelling, instead of working with general assumptions of interception classification based on literature (e.g. Nedkov and Burkhard 2012, Liyun et al. 2018). We avoided a weighting of the two supply indicators according to their importance and influence on flood regulation by summing up the absolute water depth values of both indicators and calculating therelative scale of the total supply afterwards. Furthermore, we did not incorporate the supplyby upstream areas as other studies did (Goldenberg et al. 2017, Shen et al. 2021). Since we investigated a short heavy rainfall event and the topograhy of the study area isrealtively flat, it can be initally assumed that the inflow or retention from the surroundingareas is low during this short time period. Rather, the present study is concerned with the direct regulating contribution of the areas in the study area.

In addition to the common processes of interception and infiltration, smaller landscape and green infrastructure elements, such as green roofs, have great potential to contribute to flood regulation (Zölch et al. 2017, Basu et al. 2022, Twohig et al. 2022). Camarena et al. (2022) considered green roofs in LEAFlood with a simple approach by increasing the saturated conductivity. However, for a comprehensive consideration of these elements in a FRES assessment, LEAFlood should and can be adapted accordingly (Förster et al. 2021).Since no spatial information on green roofs was available for the study area in Rostock and, in addition, satellite images did not show any green roofs, we have not taken this element into account as a regulation function.

Flood regulating demand should not only be roughly estimated by land-use or population density, as it is often used in other studies (Nedkov and Burkhard 2012, Goldenberg et al. 2017, Vallecillo et al. 2019), but is multidisciplinary and multiple data types and indicators from different disciplines, such as societal, economic, ecological and cultural demand should be analysed (European Parliament 2007, Milcu et al. 2013, Dworczyk and Burkhard2021). By taking into account economic and cultural values, a different demand resultsthan the estimation based on land use. Monuments are classified with a high demand, which is missing in an estimation based on land use, for example, if it is a park. While moststudies focus on a detailed analysis of the supply of ES, the demand is often neglected or considered by using comparably simple analysis approaches, for instance, based on land- use classifications (Campagne et al. 2020). Using different sectors and data types, including different levels of demand, increases the knowledge and details of the demand assessment (Dworczyk and Burkhard 2021). By considering various protected assets, such as population, economy, infrastructure and monuments, we are tackling this point. Nevertheless, not all aspects of demand could be taken into account and not all potential demand indicators could be quantified monetarily or biophysically. The existing data can be refined spatially and temporally by adding further information and including stakeholders. For instance, instead of the population density in 100 m grid resolution, the number of persons per building could be used. Another possibility is the intersection of the land-use with the land reference value for a more detailed damage potential built environment.

We defined the protected assets of population, economy, cultural and infrastructure as potential demand, by arguing that all vulnerable areas and activities have a demand for flood protection regardless of whether they are actually exposed to the hazard. The actual demand results from the areas of potential demand that would be flooded. Therefore, it must be noted that the actual demand calculated here is only valid for the selectedprecipitation event and its initial conditions. For a more comprehensive assessment, other possible extreme precipitation events and initial conditions need to be considered.

A mismatch analysis of FRES demand and supply is important to identify priority areas for adaptation with an unmet demand, which is necessary, for instance, for adaptation planning (Syrbe and Grunewald 2017). By comparing supply and demand through subtraction, areas with a balance, as well as unmet demand and areas with a supply surplus, can be identified. Such an analysis is an indication of various parameters, which visualisation with maps supports decision-makers for urban and adaptation planning (Lüke and Hack 2018). Since demand indicators are expressed in social or economic units (for instance people/100 m² or euro) and supply indicators on biophysical units (for instance mm or mm²), we transferred them to a relative scale from 0 to 1, in order to compare these different units of indicators. This means that a direct comparison of the biophysical values cannot be conducted (Czúcz et al. 2018), but it does make it possible to compare indicators from different units for the supply and actual demand mismatch analysis. Additionally, interpreting the relative scale of indicators with the same unit relies on: 1) different upper boundaries related to the maximum or 90% quantile of each parameter and
2) the fact that this value is site specific and can be computed for arbitrary sites. Therefore, the approach is an indication instead of absolute values, because they are not comparable due to different units and maxima, but still reflect the bandwith of supply or demand. Identifying mismatches or balances should, therefore, always be done with respect to scaling classification. Nevertheless, we additionally showed the imbalance between the biophysical values of supply and hazard by their quotients to draw attention to the unequal distribution of water in a cell and to illustrate the high run-off fractions over the surface.

Furthermore, the budget analysis can be strongly influenced by site-specific and short-term aspects. This is particularly true for this study, where event-based modelling was used. The results are valid for a one-hour event with a total amount of 22 mm with a saturated soil, as has already been observed in Rostock. A less saturated soil at the beginning couldincrease the FRES supply and consequently the supply surplus in green-related areas. However, no improvement is expected for areas with a high unmet demand since these areas are mainly highly sealed. Whereas, with a prolonged or more intense rainfall, the proportion of land with unmet demand is expected to increase.

We would like to emphasise here that the results of the mismatch analysis do not constitute a flood hazard map. Rather, it serves as an input dataset in the FRES analysis and as an indicator of hazard, which in turn, is the output of the modelling. Unlike the FloodFramework Directive (European Parliament 2007) or the IPCC's vulnerability and risk approach (Oppenheimer et al. 2014), a comprehensive FRES study, that considers and compares both supply and demand, captures the contribution of natural ecosystems to flood regulation. With this approach, missing biophysical FRES supply on demand areas can be identified. This information can help to identify adaptation areas in order to create a sustainable city by ecosystem and biophysical adaptation measures by increasing the FRES supply where the analysis highlights the need. In an area with high potential demandfor flood hazards, such as a city, biophysical structures and ecosystems thus have a social and economic contribution to protect the population and reduce damage costs. Long-term consequences of FRES loss might be high economic costs and increasing vulnerability anddecreasing resilience (Gómez-Baggethun and Barton 2013). Therefore, the mapping of scaled FRES demand and supply indicators and their mismatch delivers an easy-to-comunicate and important tool to identify the benefit and missing FRES supply for a sustainable urban planning.

Outlook

Since CMF is a modular python package, it is possible to connect it with other models, including models from other disciplines (Kraft et al. 2010). Against this background, it would be interesting to examine whether the hydrological model can be linked to regional climate model information. With this, the FRES assessment could be conducted for differentpossible future climate scenarios. An extensive spatial analysis of the soil would further improve the model. Run-off measurements are necessary for a local calibration of the model. Adding the effect of urban drainage system is an other outlook for future research. This would allow a FRES analysis with more emphasis on artificial elements (Vallecillo et al. 2019).

In terms of ES research, it is interesting to compare the results obtained in this study with the well-known and frequently used ES matrix method, based on land-use classifications (Burkhard et al. 2009). So far, only a few studies have compared the matrix method to quantitative estimations (Campagne et al. 2020). To counteract the issue of scaling and different units, all indicators must be aligned to one unit. For this, in a next step, the ecosystem value could be converted into economic values (Constanza et al. 1997, Constanza et al. 2014).

It has already been mentioned that demand is multidisciplinary (Dworczyk and Burkhard 2021) and often neglected in ES research (Campagne et al. 2020). Besides developing, adapting and extending the demand indicators, modelling of temporal changes (e.g. land- use changes and population development) could be conducted to improve ES research on the demand side. Furthermore, the damage costs could be calculated in monetary values to add another aspect of economic value. The temporal and time aspect should also be considered on the supply side, by analysing the development of the used supply capacity and the mismatch with demand during a heavy precipitation event.

So far, we did not consider future climate and land-use scenarios. For urban planning, the method would be an interesting approach to test adaptation measures in terms of their FRES supply functionality under changing climate conditions.

Conclusions

Cities are, in particular, vulnerable to pluvial flood events caused by heavy precipitation. The prediction of FRES on the city scale is an important tool for flood risk assessment to value the contribution of natural (or near-natural) structures and processes to flood regulation and the benefits for demanding factors, such as society, economy or culture. This study proposes an approach for the quantification of FRES supply, demand and their mismatches in urban areas for short-term heavy precipitation events.

FRES supply was estimated by the soil water and canopy interception, based on the LEAFlood model. It could be shown that interception has a high FRES supply in soil water saturated or sealed areas and is, therefore, an important indicator to be considered in FRES assessment on the urban scale. Green spaces, such as forests or parks, had high FRES supply, whereas sealed areas had a low FRES supply.

We argued that an area used in a certain way has a demand for protection against pluvial flooding, since pluvial flooding can happen everywhere. Therefore, the approach to investigate the flood regulating effects cannot be reduced only to single areas which are actually flooded. With the terminology of potential and actual demand, we could consider a general demand that is always asked by different sectors of society and economy and the demand for single flood events, when the potential demand turned into an actual demand. The potential demand was conducted by considering multiple actors of economy, population, infrastructure, critical infrastructure and monuments. In our analysis, monuments and critical infrastructure had a high impact on the total potential demand. Therefore, a demand analysis, solely based on land use classification, is not sufficient. Afterwards, the actual demand was defined by a function of the hazard and potential demand. The subsequent budget analysis of supply and actual demand indicated unmet demand for the entire study area. While greened areas had a supply surplus, sealed areas and, in particular, industry, urban dense areas and traffic areas had an unmet demand. Even the existing street trees could not compensate the unmet demand over traffic land- uses. In general, the water retained by the soil and interception, which represented the supply, was smaller over the entire study area than the surface water, which was the indicator for the hazard.

The visualisation of mismatches in maps with indicators is an essential tool for urban planning and flood risk management. Compared to the flood risk approach, the concept of ES for flood regulation has the advantage that also the supply side of flood risk reduction is considered. In the case of ecosystem-based adaptation, the ES concept can estimate the contributions of nature to flood regulation and their benefits to the socio-economic system. This can support city planners in making sustainable decisions in order to avoid long-term consequences of ecosystem loss.

For urban areas, a catchment area-based model is not sufficient, because of the spatial and temporal scale, as well as the involved considered processes. Instead of the catchment scale, it is more important to be able to identify the flood regulation supply capacities of single landscape elements and to include vegetation related hydrological processes, which are both considered by LEAFlood. In general, ungauged urban areas face the problem of lack of data for calibration and validation for hydrological models. However, previous studies could prove the model performance of LEAFlood in urban areasregarding run-off and interception. Therefore, it can be classified as a suitable hydrological model for quantifying and assessing FRES on urban scale for heavy precipitation events.

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Author contributions

Literature review: Wübbelmann

Study design: Wübbelmann, Bouwer, BurkhardModelling: Wübbelmann, Förster

Writing: Wübbelmann

Review: Bouwer, Förster, Bender, BurkhardSupervision: Bender, Burkhard

Conflicts of interest

The authors declare no conflict of interest.

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Supplementary materials

Suppl. material 1: Ratio of FRES supply and flood hazard doi

Authors: Wübbelmann, T., Bouwer, L.M., Förster, K., Bender, S., Burkhard, B.
Data type: Image Download file (1.09 MB)

Suppl. material 2: Table of the scaled Flood Regulating Ecosystem Services indicators and categories doi

Authors: Wübbelmann, T., Bouwer, L.M., Förster, K., Bender, S., Burkhard, B.
Data type: Table Download file (225.34 kb)

Suppl. material 3: Maps of the individual potential FRES demand indicators doi

Authors: Wübbelmann, T., Bouwer, L.M., Förster, K., Bender, S., Burkhard, B.
Data type: Image, MapDownload file (1.62 MB)

6

PUBLICATION 4

SCENARIO ANALYSIS: IMPACT OF PROJECTED CLIMATE CHANGE AND BENEFITS OF NATURE-BASED SOLUTIONS IN URBAN AREAS FOR HEAVY RAINFALL

In this publication, the previously developed flood-regulating ES modelling approach was applied in a scenario analysis to investigate the pressures and impacts of climate change and adaptation measures on flood-regulating ES. First, the flood-regulating ES supply, demand, and their mismatches for different heavy rainfall scenarios based on climate change were analysed. Second, the influence of adaptation measures, such as Nature-based Solutions, on supply and demand was examined for present and future heavy rainfall events. With that, the influence of climate change on flood-regulating ecosystem services and the benefits of adaptation measures to enhance these were studied.

Wübbelmann T., Förster K., Bouwer L.M., Dworczyk, C., Bender S., Burkhard B. (2022). Urban flood regulating ecosystem services under climate change – How can Nature-based Solutions contribute? Frontiers in Water (submitted).

Urban flood regulating ecosystem services under climate change – How can Nature-based Solutions contribute?

Thea Wübbelmann[1,2*], Kristian Förster[3,4], Laurens M. Bouwer[1], Claudia Dworczyk[2], Steffen Bender[1], Benjamin Burkhard[2,5]

[1]Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, Hamburg, Germany
[2]Institute of Physical Geography and Landscape Ecology, Leibniz University Hannover, Hannover, Germany
[3]Institute of Hydrology and Water Resource Management, Leibniz University Hannover, Hannover, Germany
[4]Institute of Ecology and Landscape, Weihenstephan-Triesdorf University of Applied Sciences, Freisingen, Germany
[5]Leibniz Centre for Agricultural Landscape Research ZALF, Müncheberg, Germany

*** Correspondence:**
Thea Wübbelmann
thea.wuebbelmann@hereon.de

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Abstract

Urban areas are mostly highly sealed spaces, which often leads to large proportions of surface runoff. At the same time, heavy rainfall events are projected to increase in frequency and intensity with anthropogenic climate change. Consequently, higher risks and damages from pluvial flooding are expected. The analysis of Flood Regulating Ecosystem Services (FRES) can help to determine the benefits from nature to people by reducing surface runoff and runoff peaks. However, urban FRES are rarely studied for heavy rainfall events under changing climate conditions. Therefore, we first estimate the functionality of current urban FRES-supply and demand under changing climate conditions. Secondly, we identify the effects of nature-based solutions (NbS) on FRES-supply and demand and their potential future functionality and benefits concerning more intensive rainfall events.

A district of the city of Rostock in northeastern Germany serves as the case study area. Besides the reference conditions based on the current land use, we investigate two potential NbS: 1) increasing the number of trees; and 2) unsealing and soil improvement. Both NbS and a combination of both are applied for three heavy rainfall scenarios. Besides a reference scenario, two future scenarios were developed to investigate the FRES functionality, based on 21% and 28% more intense rainfall. While the potential FRES-demand was held constant, we assessed the FRES-supply and actual demand for all scenario combinations, using the hydrological model LEAFlood. The comparison between the actual demand and supply indicates the changes in FRES-supply surplus and unmet demand increase.

Existing land use structures reached a FRES capacity and cannot buffer more intense rainfall events. Whereas, the NbS serve FRES benefits by increasing the supply and reducing the actual demand. Using FRES indicators, based on hydrological models to estimate future functionality under changing climate conditions and the benefits of NBS, can serve as an analysis and decision-support tool for decision-makers to reduce future urban flood risk.

1 Introduction

Heavy rainfall is projected to increase in frequency and intensity due to climate change (Jacob et al., 2014; Rajczak and Schär, 2017; Villaseñor, 2021). Consequently, rainfall changes will have a major impact on pluvial flooding in urban areas. Flood Regulating Ecosystem Services (FRES) can function as a measure to mitigate pluvial flooding. Ecosystem Services (ES) are defined as the linkage of ecosystems and society with direct or indirect contributions of ecosystem functions to human well-being (MEA, 2005; TEEB, 2010). FRES in particular are ecosystem processes and functions that store water and consequently decrease surface runoff, which benefits human well-being by protecting and securing livelihoods (Burkhard and Maes, 2017). FRES-supply comprises the contribution of the ecosystem to reduce the flood hazard and the ecosystem delivers a service when there is a societal demand or need for this flood reduction. Therefore, climate change must be urgently taken into account in the assessment of FRES to prove their future functionality (Maes et al., 2020).

Different studies already address the impact of climate change on the future functionality of FRES using hydrological modelling (Shen et al., 2021; Wübbelmann et al., 2021). In general, FRES assessments focus on fluvial floods in catchments on the regional or European scale (Nedkov and Burkhard, 2012; Stürck et al., 2014; Gaglio et al., 2019). However, cities are particularly affected by pluvial floods because of two reasons. First, they are vulnerable due to high population densities and the large potential for social and economic damage. Second, the high degree of sealing has modified the water cycle and contributes to higher surface runoff. So far, FRES has been less frequently applied at the local or urban scale (Shen et al., 2019; Wübbelmann et al., 2022).

Mismatch analyses of supply and demand can identify and visualise the benefits of FRES to society. The results can also reveal whether the demand for flood reduction can be met or not. In the case of heavy rain events, unmet demand may indicate flood risk to people and infrastructure. However, ES demand is less frequently spatially assessed and mapped (Campagne et al., 2020), causing research and knowledge gaps in mismatch analyses. For instance, Mori et al. (2022) mapped supply, demand and budget changes between 1990 and 2018 for a river basin using SWAT and Xiong and Wang (2022) conducted a mismatch analysis for an urban area. However, the future functionality of urban FRES under changing climate conditions for heavy rainfall events remains unclear in most of the existing studies.

To counteract flood risks and to adapt to climate change, different concepts of natural adaptation measures exist (Kabisch et al., 2017). One concept of adaptation measures are Nature-based Solutions (NbS). NbS are measures or actions, which are inspired or supported by nature and use or imitate its complex characteristics and processes (European Commission, 2015). They are “actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges […] effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016, xii). However, for a successful implementation, urban planners lack information on the performance and benefits of NbS (Zölch et al., 2017). With the concept of ES this knowledge gap can be closed by considering the supply of ecosystems and the contribution of green infrastructure on the flood regulation as benefits and contribution to human safety.

For sustainable development, the NbS must withstand the impacts of climate change and should also contribute services under future conditions. However, strong evidence on the performance of NbS for climate adaptation is missing (Kabisch et al., 2016). Zölch et al. (2017) tested different NbS regarding their capacity and functionality under higher precipitation amounts with hydrological models. With increasing rainfall intensity, runoff regulation potential of the NbS decreased. Other studies used system dynamic models to assess the long-term effectiveness of NbS under changing climate conditions in rural areas (Gómez Martín et al., 2021). Studies on water supply and regulation for the future functionality of NbS under changing climate conditions for a floodplain have been conducted using the InVEST model that analyses seasonal water yield (Gaglio et al., 2019; Natural Capital Project, 2020). However, a comprehensive ES analysis including supply and demand in the urban area is missing.

Most studies on FRES for reducing impacts from climate change and the usefulness of NbS are focused on floodplains and river catchments. The few existing studies on urban FRES are related to the current situation and lack the analysis of future scenarios. Therefore, the objectives of this study are 1) to estimate future functionality of urban FRES under more intense rainfall on the event-scale, and 2) to estimate the benefits of NbS on urban FRES under current and future climate conditions. For this, we determine the FRES-supply change, the change in actual demand, and finally, the change in the FRES budget. These objectives lead to the following research questions:

- How does more extreme precipitation affect urban FRES-supply and as a consequence the urban FRES-actual demand?
- Can ecosystem-based climate adaptation by NbS enhance the urban FRES-supply and reduce the actual demand and how significant is their benefit related to more intense rainfall events?
- Can the future functionality of urban FRES and mismatches between FRES-supply and demand be identified with the suggested approach?

2 Material and Methods

2.1 Study Area

The study area is located in the southwest of Rostock in northern Germany and has an area of 4.5 km² (see Figure 1). In the past, Rostock was affected by several heavy rainfall events. In particular, in the summer of 2011 several heavy rainfall events were observed (Miegel, 2011), which created awareness and resulted in research projects. The study area was chosen because of the present critical infrastructure, the diversity of urban land use structures and the flooding observed in the past in the area. In particular, the Holbeinplatz – an important transport hub - in the east of the study area, is located in a depression and is therefore regularly affected by flooding.

The dominant land-use types are green areas (parks, forests and woodland) covering 50 % of the area, 23 % consisting of traffic areas and 25 % containing sealed areas (settlements, urban dense areas, and industry) (Steinbeis-Transferzentrum Geoinformatik, 2017). The predominant soil types are luvisol-pseudogley and regosol and the substrate textures of the soil are wet sandy loam and loamy sand (Hanse- und Universitätsstadt Rostock – Amt für Umwelt- und Klimaschutz, 2019). The climate conditions in Rostock are mild-maritime due to the vicinity to the Baltic Sea. The mean annual temperature is 9.4 °C (1981-2010) (DWD Climate Data Center, 2022a) and the annual precipitation sum is 646.2 mm with a summer precipitation of around 202 mm (DWD Climate Data Center, 2022b) at the DWD station Rostock-Warnemünde (closest weather station in ~ 9.6 km distance).

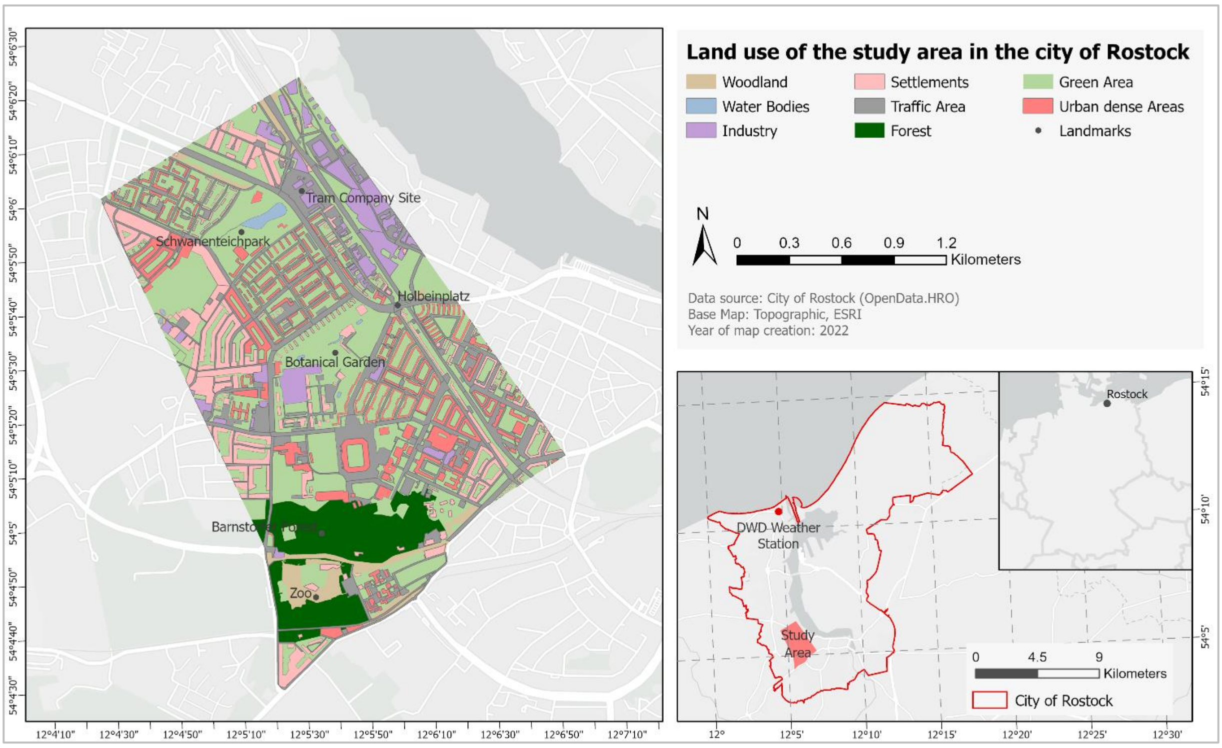


Figure 1: Location and land use of the research area in Rostock

2.2 Data

The hydrological modelling and FRES analysis require a number of datasets. Table 1 in the supplements shows a detailed overview of the data used.

The spatial geometry of the hydrological model is defined by the spatial data of land use, soil type, elevation, and tree coverage and characteristics. Temperature, relative humidity, solar radiation, wind speed and precipitation comprise the meteorological input data. For them, observation data were taken from the climate station Rostock-Warnemünde, operated by the national German Weather Service (DWD). The heavy precipitation event used for the present study was observed on August 6th, 2011 and lasted over one hour with a rainfall total of 21.7 mm. Further spatial data about infrastructure, population density, land reference value, and appearance of monuments were used for the FRES-demand analysis (see Table 1).

2.3 Hydrological Model LEAFlood

The hydrological model quantifies ES indicators for canopy interception and soil water for the supply, and the surface water depth for the actual demand. We used the hydrological model LEAFlood (Landscape vEgetAtion and Flood model) (Wübbelmann and Förster, 2022), which is based on the modular and open-source Python package "Catchment Modelling Framework" (CMF) (Kraft et al., 2011; Kraft, 2020). LEAFlood adopts and uses CMF functions to create a mesh out of a GIS shapefile. The model enables a detailed presentation of canopy interception, including through fall and canopy evaporation. Infiltration follows the Green-Ampt approach (Rawls et al., 1993) and the Brooks Corey Retention curve. The lateral surface runoff simulation uses a 2D kinematic wave approximation (Figure 2). The representation of canopy interception and runoff by LEAFlood was verified in detail by Camarena et al. (2022), who compared measured runoff and canopy interception observations with LEAFlood results in a calibration and validation analyses. Since hydrological and hydraulic measurements were not available for the present study area, the computed spatial inundation patterns were compared with on-site inspections and other hydraulic model simulations to confirm the plausibility of the model.

The geometry in this analysis is based on a polygon shapefile with cell sizes of approximately 1000m². For the boundary conditions, inflow from surrounding areas was not considered due to the short-term event and the flat study area, while an outflow at defined boundary conditions was detected. The canopy cover was calculated by a quotient of the canopy area and polygon area. Each tree species was assigned a Leaf Area Index (LAI) and an interception capacity (Breuer et al., 2003). Afterward, both a mean LAI and interception capacity were calculated for each individual polygon by an intersection of the tree point information. The literature values by Breuer et al. (2003) depict the mean interception capacity including a range of different rainfall events regarding amount and duration, but they do not provide information about the maximum interception during heavy rainfall events as investigated here. Therefore, based on the modelling results in a neighborhood in the city of Freiburg, Germany (Camarena et al., 2022), observation data on this site (Jackisch et al., 2013) and further interception measures from other studies (Asadian and Weiler, 2009; Alves et al., 2018) the interception values of all cells were increased by a factor of 5.

A constant soil layer depth of 0.5 m was assumed for the whole area based on available soil drill datasets. Due to the time lag of soil water flow, we assumed that during short heavy precipitation events, the dominant process is surface runoff, while infiltration processes only occur in the upper soil layer. The saturated conductivity (Ksat) varied over the area and depended on the state of sealing (see Table 5). Based on sandy loam, a baseline value of 0.3m/d was assumed and reduced for higher sealing degrees (Sponagel et al., 2005; Wübbelmann et al., 2022). Further soil parameters were regarded as constant in the area. In addition, each land use was assigned a surface roughness coefficient Manning (see Table 5). Since the objective of this study is to analyze the natural contribution of infiltration and interception to regulate floods caused by heavy rainfall events and the drainage system is assumed to be exhausted for heavy rainfall events of higher return periods, a drainage system was not considered.

The output of the model consists of surface water depth, soil water depth, intercepted water depth, and the outflow at the outlets. The outflow is detected as water that leaves the study area at the set boundary conditions (constant head). These results are generated per polygon and per time step.

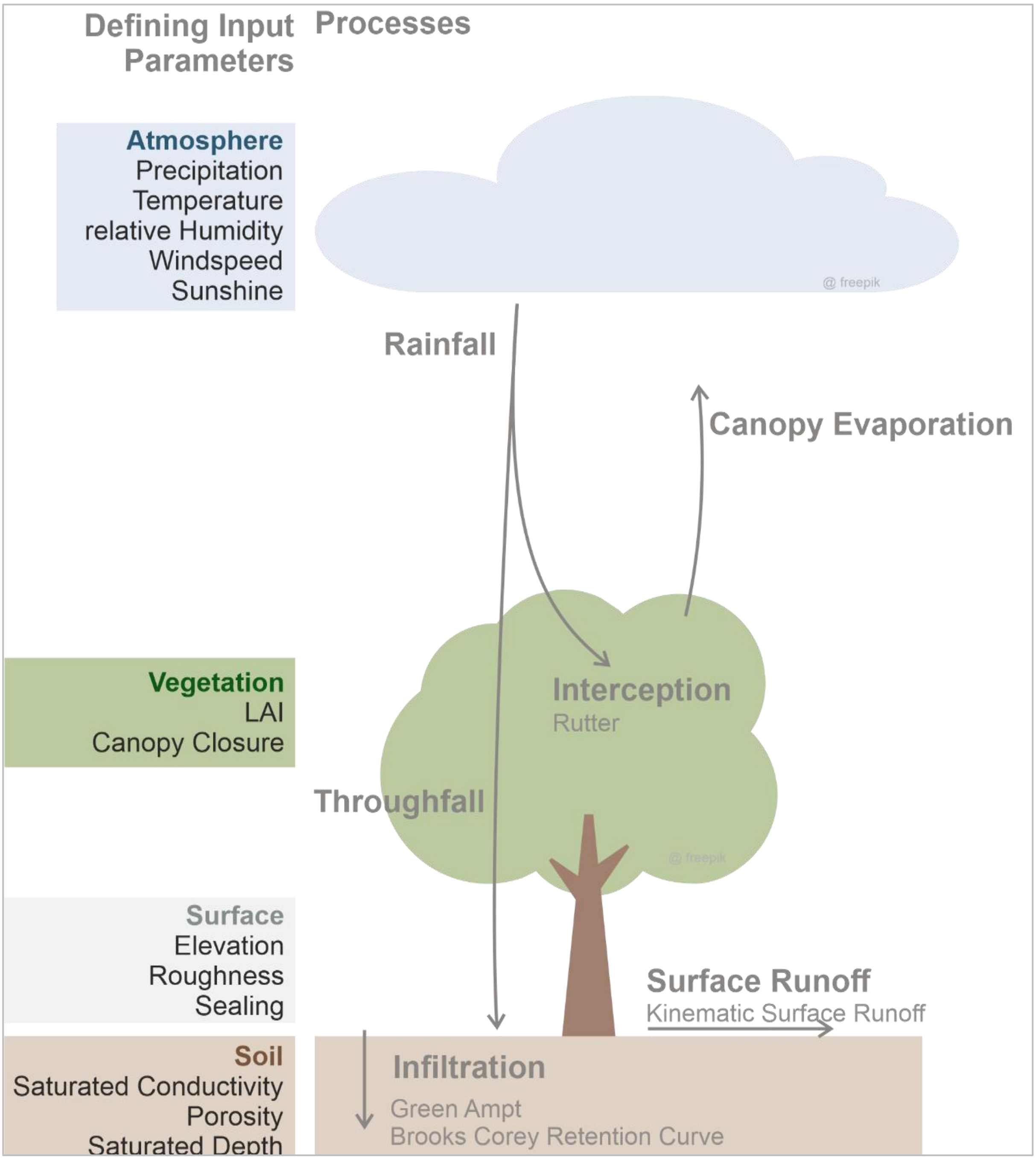


Figure 2: The hydrological processes of LEAFlood (Wübbelmann and Förster, 2022).

2.4 Flood regulating Ecosystem Services Analysis - Indicators and Quantification

The FRES analysis was conducted using ArcGIS Pro 2.8.0 by ESRI and statistical calculation with Python. The general method and indicators are based on Wübbelmann et al. (2022) and were adapted to a scenario analysis using the changes to a reference scenario as indicators on the event-scale. Figure 3 shows the methodological framework of the analysis. The different indicators for the supply and demand analysis are listed in Table 2 in the Supplements.

The hydrological modelling with LEAFlood delivered the supply indicators of soil water depth and intercepted water depth by the tree canopies in mm. Both storages can be important flood regulating elements in urban areas and therefore should be to be considered as indicators in urban FRES assessment. With LEAFlood, the interception can be considered on an appropriate resolution of single landscape elements of urban environments (such as parks or streets). For both storages (canopy interception and soil water storage), the difference between maximum water depth over the whole period and initial water depth was used to estimate the FRES-supply on the event-scale. Afterward, the difference to the reference scenario was calculated for each scenario. The results were finally normalized to a relative scale from -1 to 1 based on maximum supply change (here 5.9 mm). Thereby, -1 indicates a very high decrease in supply, 0 no change, and 1 a very high increase in supply.

The corresponding indicator for the flood hazard change is the surface water depth [mm] of the model output. As the supply, the difference to the reference scenario was normalized to a relative scale from -1 (decrease of surface water) to 1 (an increase of surface water). To ensure a comparable scale for the supply and flood hazard in order to conduct the subsequent budget analysis, we chose the maximum of both components for the normalization (maximum supply change: 5.9mm and 90% quantile of hazard change: 5.7mm), therefore 5.9 mm. The intersection of the changed flood hazard and the potential demand as a weighting factor gave the actual demand change with the same scale from -1 to 1. For a better estimation of the NbS effects and the impact of future rain events, we set the potential demand for all scenarios on a constant value. The potential demand in our approach consists of five indicators – population density, monuments, land reference value, critical infrastructure, and traffic areas (Biota, 2014; Wübbelmann et al. 2022).

Finally, the difference between the classified supply and actual demand change resulted in the budget change. The resulting scale can therefore take values on bandwidth from -2 to 2.

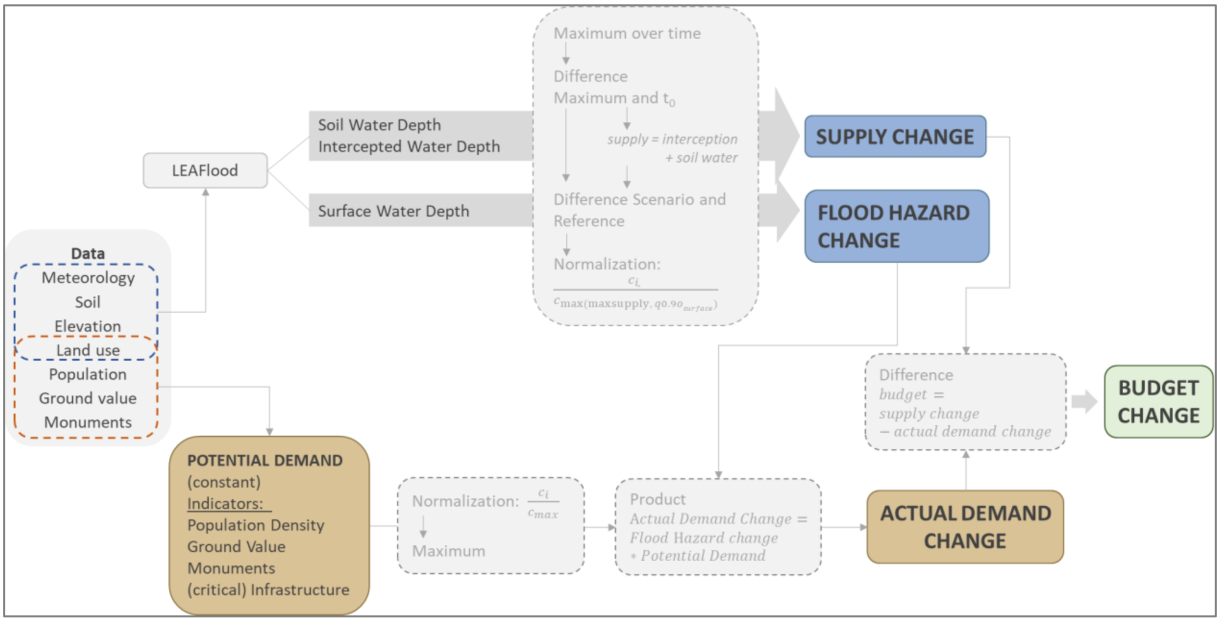


Figure 3: Workflow of the FRES analysis. t_0 is the first time step of the modelling, c_i represents the water depth in one cell and $c_{max\ or\ q0.9}$ is the maximum or 90% quantile water depth for this hydrological parameter over all cells.

2.5 Scenarios and adaptation measures

2.5.1 Rainfall scenarios

For the analysis of the current and future functionality of FRES in an urban area we used a reference scenario and two future scenarios (period 2050). They are based on an observed one-hour rainfall event in 2011 measured at the DWD station in Rostock-Warnemünde with a temporal resolution of one minute. The total rainfall amount in this hour was 21.74 mm with a maximum intensity of 2.93 mm/min after 29 minutes (see Table 3). The event can be assigned to a three-years return period (DWD Climate Data Center, 2020), which corresponds to the design standards in the planning of urban drainage systems in residential areas (DIN-EN, 2017).

For the definition of the future scenarios, we used the super Clausius-Clapeyron (sCC) relation between atmospheric water vapor content and temperature, to scale (increase) the rainfall intensity of the observed 2011 event with the expected temperature increase due to further global warming. Unlike the CC scaling approach, the sCC relation is more appropriate for sub-daily and convective events (Westra et al., 2014; Förster and Thiele, 2020). This sCC relation assumes an increase in precipitation intensity of up to 14 % per degree of temperature increase for short extreme events, at daily mean temperatures higher than 12 °C (Lenderink and van Meijgaard, 2008; Dahm et al., 2019; Förster and Thiele, 2020). We used scenarios of 1.5°C and 2°C warming compared to 2011. Therefore, with the sCC scaling factor of 14%, warming of 1.5°C and 2°C suggests an increase in precipitation intensity of 21% and 28% in 2011, respectively. Table 3 compiles major statistical characteristics for each scenario.

According to regional climate model projections by the Climate Service Center Germany (2019), the year 2011 was already around +0.8°C warmer than the annual mean temperature of the reference period 1971 – 2000. The earliest possible year (upper boundary of the projection bandwidth) in which climate projections for different RCP (Representative Concentration Pathways) scenarios reach an increase of 1.5°C or 2°C warming compared to 2011 is listed:

- 1.5°C warming for RCP 8.5 will be reached in 2032
- 1.5°C warming for RCP 4.5 will be reached in 2041
- 2°C warming for RCP 8.5 will be reached in 2046
- 2°C warming for RCP 4.5 will be reached in 2053

It must be mentioned that the results of the climate projections have a high bandwidth. The listed values represent the upper boundaries of the ensemble. In a low emission scenario (RCP2.6) these warming scenarios compared to 2011 will not be reached (Climate Service Center Germany, 2019).

Table 1: Names and statistical description of the rainfall scenarios. The return period was estimated utilizing the KOSTRA dataset (DWD Climate Data Center, 2020).

Scenario		Abbreviation	Sum [mm/h]	Return period [a]	Maximum [mm/min]
Reference	2011	F0	21.74	3	2.93
Future 1.5°	+21%	F1.5	26.31	5 - 10	3.55
Future 2°	+28%	F2	27.83	5 - 10	3.75

2.5.2 Adaptation measures

Besides the current land use and land cover conditions, we investigate the potential benefit of two adaptation measures – named as NbS in the following – of increasing canopy coverage and a reduction of sealed areas to improve infiltration (see Table 4). These two measures were first applied separately and additionally in combination. These NbS measures represent options for climate adaptation to reduce urban flood risk.

Table 2: Overview and description of the applied nature-based solutions

NBS measure	Abbreviation	Description
Reference land use	NbS_0	Aggregated and reclassified land use from the 'Realnutzungskartierung' from 2014 (Steinbeis-Transferzentrum Geoinformatik, 2017)
Additional trees	NbS_{tree}	Increased tree coverage by increasing the canopy cover over: - Forest land: minimum coverage of 90% - Green areas: minimum coverage of 30% - Traffic areas: minimum coverage of 30%
Unsealing	$NbS_{unsealing}$	Increased saturated conductivity (Ksat) for better infiltration (see table 3)
Combined	$NbS_{combined}$	A combination of both NbS. The increased tree coverage of NbS_{tree} and the enhanced saturated conductivity for better infiltration of $NbS_{unsealing}$ were applied

In a first step, we implemented a higher canopy cover in the study area. For this, we defined a minimum canopy cover of 90% above forest land use polygons, 30% for green areas, and 30% for traffic areas. This leads to an increase in average canopy coverage from 18% to 33% throughout the study area. This percentage can be considered as a realistic and feasible option compared to the canopy cover of other cities up to 30 % (e.g. Oslo or Singapore (MIT Senseable City Lab; The Guardian, 2019)). We set the LAI to 5 and the Interception Capacity to 1.4, reflecting the mean of all main tree species in the study area.

The second adaption measure entails an unsealing of traffic areas and a soil improvement for green areas. The idea behind the unsealing of traffic areas was an increased proportion of green stripes, such as swales, along the streets, reducing the sealing of this sections. To simplify the application in the model and to avoid small fragments of polygons in the shapefile causing possible numerical instability, we did not create smaller polygons for green space along the street. Instead, we adjusted the saturated conductivity - as the defining sealing parameter in the model - from 0.006 m/day to 0.1 m/day for all respective traffic area polygons. The saturated conductivity of the green areas was increased from 0.3 m/day to 0.4 m/day, respectively (see Table 5).

For the combination of both NbS, the canopy cover and saturated conductivity were adjusted as described above.

Table 3 Saturated conductivity (Ksat) for the Reference Scenario and the adaptation measure "Unsealing".

Land use	**Manning n** (Brunner, 2021)	**Saturated Conductivity [m/day]**	
		Reference	Unsealing
Urban dense areas	0.2	0	0
Settlements	0.12	0.015	0.015
Industry	0.12	0	0
Traffic area	0.03	0.006	0.1
Green area	0.05	0.29	0.4
Woodland	0.14	0.3	0.3
Forest	0.15	0.3	0.3
Water	0.03	0.015	0.015

3 Results

We analyzed flood regulation in two ways. In one part, we focused on the temporal evolution by aggregating all spatial elements by the median and 90%-quantile, to obtain the mean and maximum water storage excluding outliers. In another part, we focused on the spatial distribution of supply and demand change on the event-scale by computing the averaged values of demand and supply over time.

3.1 Timeline

The timeline for the supply (interception + soil water; upper plot), the surface water (middle plot), and the total outflow of the study area (lower plot) are shown in Figure 4. The solid line displays the median water depth and the dashed line the 90% quantile over all polygons. Orange indicates the reference land use (NbS_0), green the tree NbS (NbS_{tree}), blue the unsealing NbS ($NbS_{unsealing}$), and purple the combination of the NbS_{tree} and $NbS_{unsealing}$ ($NbS_{combined}$), while darker colors denote the 1.5 and 2°C warming rainfall scenario with 21 and 28% higher intensities (F1.5 and F2) and lighter colors for the reference scenario of 2011 (F0).

The median supply was not significantly increased for higher rainfall intensities for all NbS measures. However, both NbS have a higher supply than the NbS_0. While the supply increase by the $NbS_{unsealing}$ is relatively small, it is higher with the NbS_{tree} and highest with a combination of both NbS (for median and 90% quantile).

The NbS_{tree} leads to a higher decrease of the surface water than the $NbS_{unsealing}$ compared to the NbS_0. The decreasing effect is smaller for higher rainfall events (e.g. F2). The 90% quantile has greater differences between the NbS than the median. While the NbSunsealing reduces surface water only slightly, the influence of the trees is visible (for all precipitation scenarios). The highest reduction of surface water can be reached with the combination of both adaptation measures. The increase of surface water depth by higher rainfall intensities is high for the 90% quantile compared to the increase of the median. This indicates a further filling and retention in surface sinks by lateral runoff.

In addition, we investigated the total outflow of the area by summarizing the surface water depth at all outlets for each time step (Figure 4). The total outflow is computed through superposition of flux time series in all outlet cells, which have been defined as boundary conditions. The maximum value of the peak, the change of the peak to the reference scenario of NbS$_0$ and F0, and the reduction by the single NbS compared to the NbS$_0$ for the respective rainfall scenario are listed in Table 6. Higher rainfall amounts increased the amount of outflow and the peak discharge by 17.33 m^3/min for the F1.5 scenario and by 23.51 m^3/min for the F2 scenario. Whereas, the NbS decrease the peak outflow for the F0 scenario by -7.5 [m^3/min] for NbS$_{tree}$, -1.4 [m^3/min] for NbSunsealing, and -8.7[m^3/min] for NbS$_{combined}$. The NbS$_{tree}$ had a higher impact by reducing the outflow and the peak discharge than the NbS$_{unsealing}$ compared to the NbS$_0$ (-9.2[m^3/min] for F1.5 and -9.9[m^3/min] for F2). The outflow of NbS$_{tree}$ for scenario F2 is even lower than the amount for the NbS$_0$ and NbS$_{unsealing}$ for the climate scenario F1.5. The maximum outflow peak reduction for the NbS$_{unsealing}$ is 1.6 [m^3/min] for the F1.5 scenario. The combination of both NbS (NbS$_{combined}$) reduces the outflow by about 1.2 – 1.4 [m^3/min] more than the NbS$_{tree}$.

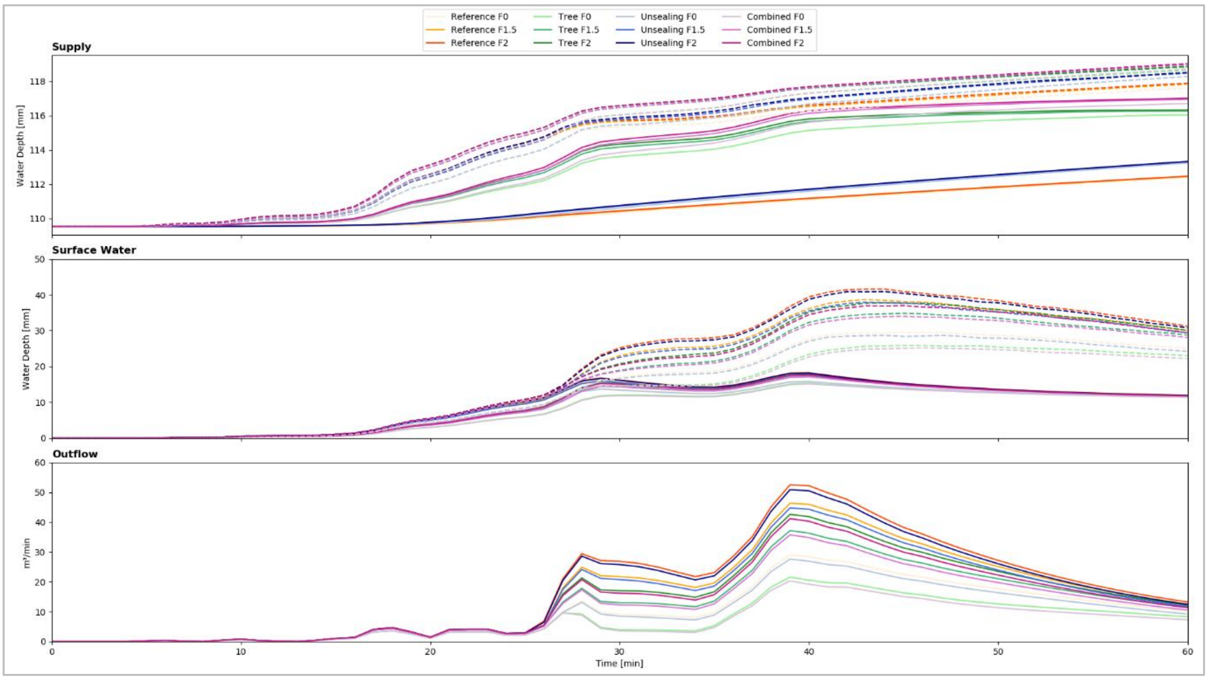


Figure 4: Above figure: Median (solid line) and 90% quantile (dashed line) FRES supply (interception + soil water) of all cells in the study area. Bottom figure: Median (solid line) and 90% quantile (dashed line) surface water depth of all cells in the study are

Table 4: Peak Runoff and the changes to the reference scenarios for all combinations of rainfall scenarios and NbS. The first column displays the peak runoff, the second column the peak increase/ reduction compared to the reference scenario NbS$_0$ /F0, and the third column the reduction to the NbS$_0$ of each rainfall scenario.

	F0			F1.5			F2		
	Peak Max [m^3/min]	Peak change to NbS$_0$/ F0 [m^3/min]	Reduction to NbS$_0$ [m^3/min]	Peak Max [m^3/min]	Peak change to NbS$_0$/ F0 [m^3/min]	Reduction to NbS$_0$ [m^3/min]	Peak Max [m^3/min]	Peak change to NbS$_0$/ F0 [m^3/min]	Reduction to NbS$_0$ [m^3/min]
NbS$_0$	29.03	-	-	46.35	17.33	-	52.54	23.51	-
NbS$_{\text{Tree}}$	21.57	-7.45	-7.45	37.17	8.15	-9.18	42.62	13.59	-9.92
NbS$_{\text{unsealing}}$	27.64	-1.38	-1.38	44.77	15.75	-1.58	50.89	21.86	-1.65

3.2 Supply Change

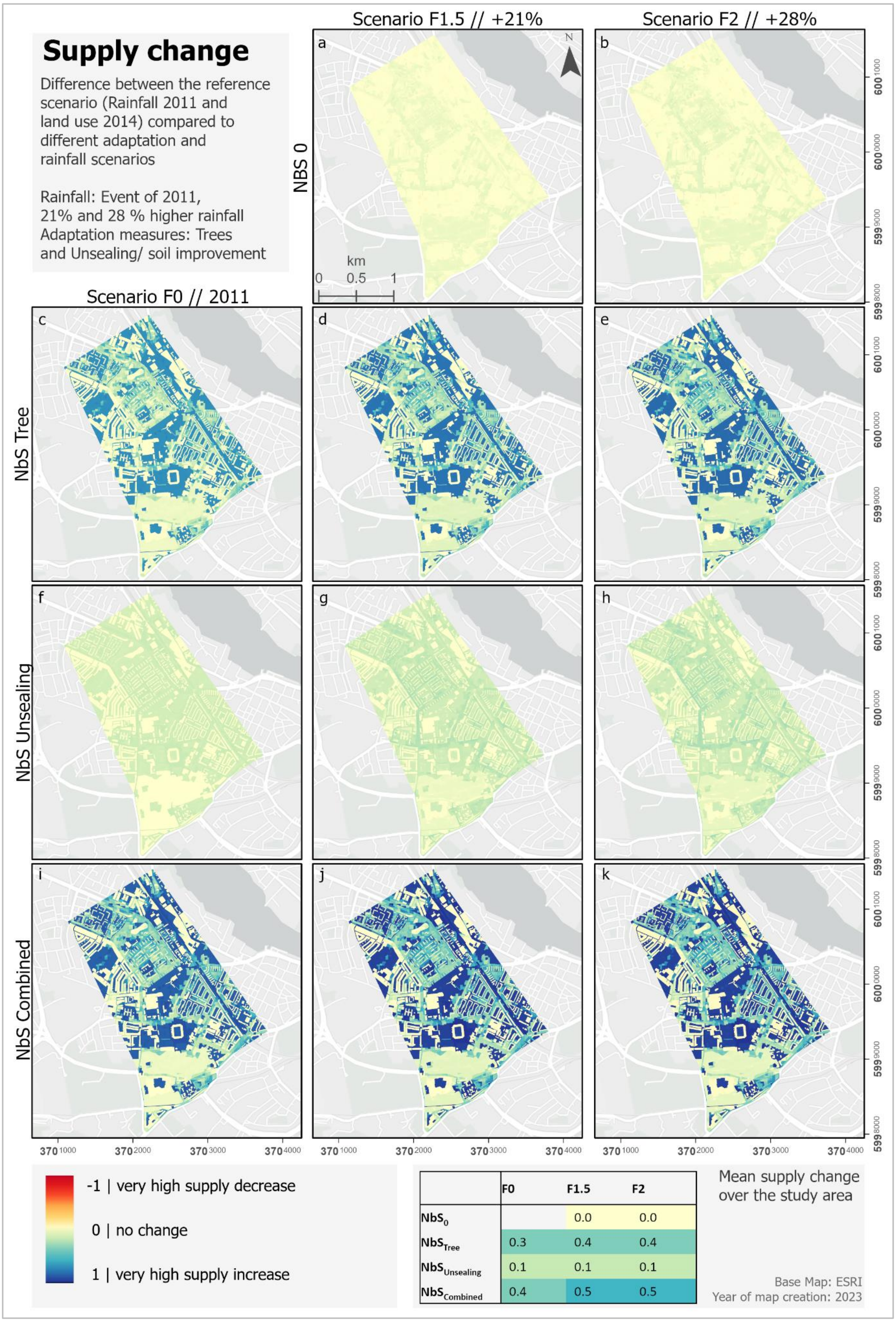
The supply change, as the comparison of the difference of the maximum and initial supply for the respective scenario and NbS combination compared to the reference scenario, is mapped in Figure 5. It also shows the mean change over the entire study area for each rainfall scenario and NbS combination. The maximum interception of all cells and time steps and all scenario combinations was 7.5mm, the soil water storage 3.9mm, and the total supply 1 mm. Figure 6 shows the change in the individual land use classes.

Without any NbS but with increasing rainfall intensities, the supply did not increase over the entire study area. Only some parts of the study area show a slight increase during heavier rainfall events, with highest values in forest areas (Figure 5).

With the NbS$_{\text{tree}}$ an average low supply increase in the total area was detected. The future rainfall scenario F1.5 and F2 increased the supply even more (medium). However, the difference between F1.5 and F2 is very small (Figure 5). In particular, traffic areas and green areas, over which the canopy closure has been significantly increased, were affected by the positive change in supply (Figure 6).

Overall, the increase in supply achieved through NbS$_{\text{unsealing}}$ was very low for all rainfall events. A positive supply change was mainly shown in green areas and traffic areas where the adaptation measure was implemented (Figure 6). The future rainfall scenarios led to a slight supply increase in these areas, but in total the supply in the area did not increase for F0.

The combination of both NbS (NbS$_{\text{combined}}$) enhanced the supply even more than the NbS$_{\text{tree}}$. For all scenarios, a medium supply increase could be observed compared to the reference scenario of NbS$_0$/F0. As for the NbStree and NbS$_{\text{unsealing}}$ the highest changes were detected on green areas and traffic areas.



	F0	F1.5	F2
NbS_0		0.0	0.0
NbS_{Tree}	0.3	0.4	0.4
$NbS_{Unsealing}$	0.1	0.1	0.1
$NbS_{Combined}$	0.4	0.5	0.5

Figure 5: Map of the total FRES supply change by interception and soil water.

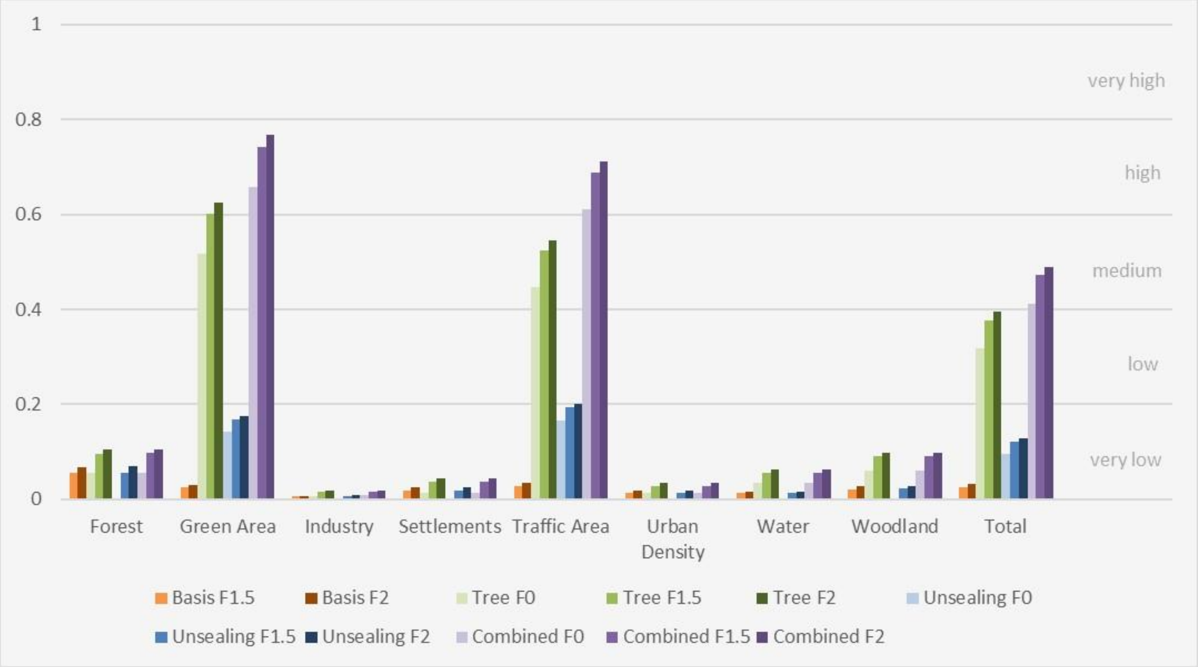


Figure 6: Area weighted FRES supply change by the NbS and rainfall scenarios over the different land uses.

3.3 Actual Demand Change

The spatial distribution of the actual demand change, as the difference for the respective rainfall scenarios and NbS combinations compared to the reference scenario, as well as the mean change over the study area is shown in Figure 7. Note that in this map, red colors indicate demand increases; contrary to Figure 5, where red indicates supply decreases. The maximum modelled surface water of all cells and time steps and all scenarios was 4682.3 mm with a 90%-quantile of 36.7 mm. Figure 8 displays the actual demand change over individual land use classes.

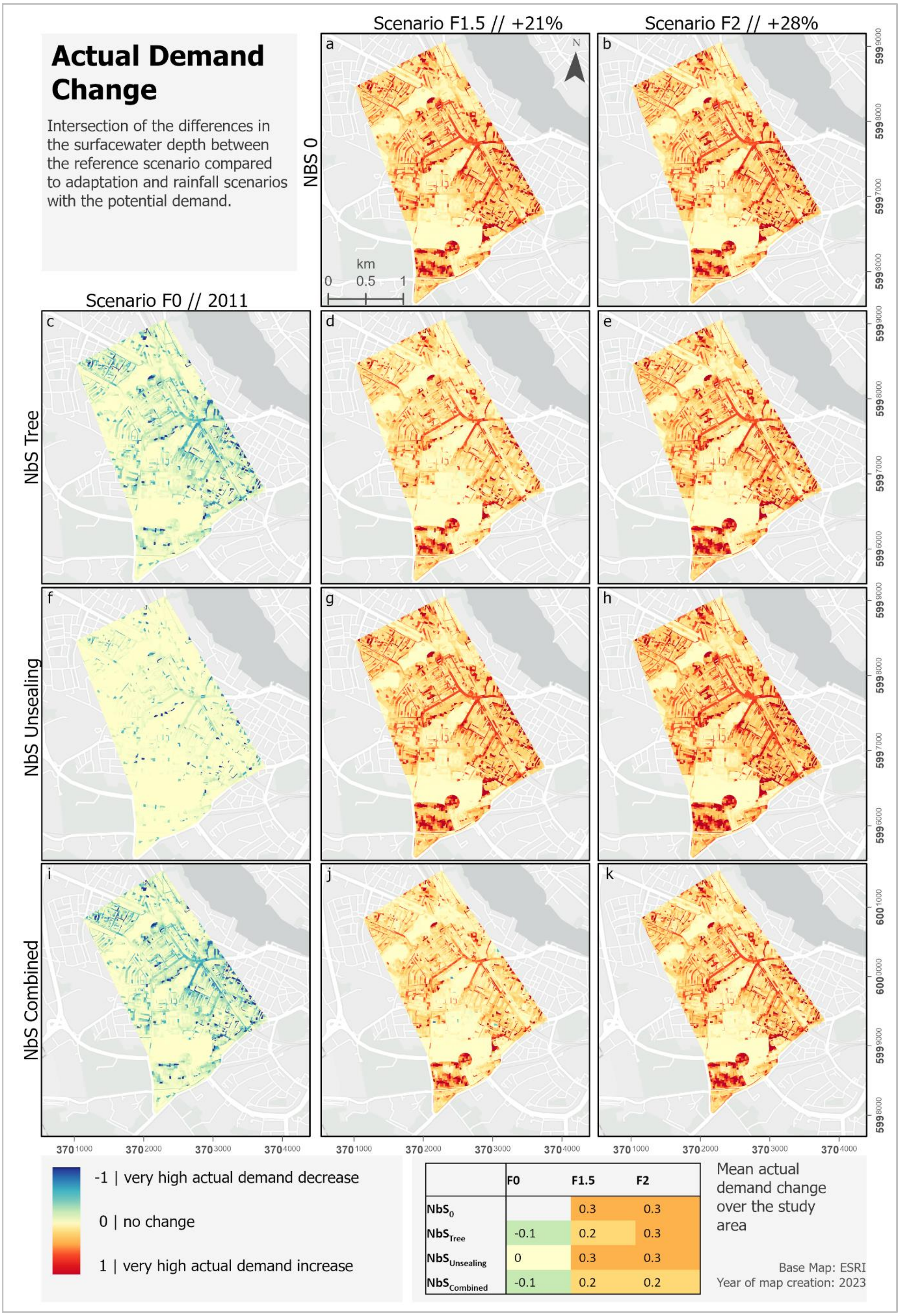
Without NbS (NbS_0) and with higher rainfall intensities, the actual demand showed partly a very high increase (Figure 7). The difference between the future rainfall scenarios F1.5 and F2 is very small, both in the spatial distribution and on average over the entire area. The highest increase in actual demand was computed over traffic areas (Figure 8).

The NbS_{tree} decreased the actual demand only slightly for F0 in the study area. The decrease is highest on water bodies and traffic areas (low). Whereas the actual demand was very low it increased for the F1.5 scenario. In contrast to the F0 scenario, where a low decrease was observed on traffic areas, a low increase was shown for the F1.5 and F2 scenarios. However, the change is smaller between F1.5 and F2, than between F0 and F1.5. The relations of spatial patterns are similar to the F1.5 scenario with a slight increase.

The $NbS_{unsealing}$ did not reduce the actual demand for the reference scenario F0. Only water land uses, traffic areas and green areas had a visible decrease in actual demand (Figure 8). For both future rainfall scenarios (F1.5 and F2) a medium increase of actual demand with the adaptation measure was computed. The highest actual demand change was again shown over traffic areas that was comparable to the NbS_0/F2 scenario.

The combination of trees and unsealing led to a very low decrease in actual demand for the reference rainfall scenario, a very low increase for F1.5, and a medium increase for F2. Thereby, the changes are similar to these of the NbS_{tree} (Figure 7).

All NbS indicated similar hotspots for the respective rain scenario (see Figure 8). In particular, the streets leading to the Holbeinplatz tended to have a high actual demand for future rainfall scenarios, probably resulting from lower elevations and high sealing around this area.



	F0	F1.5	F2
NbS_0		0.3	0.3
NbS_{Tree}	-0.1	0.2	0.3
$NbS_{Unsealing}$	0	0.3	0.3
$NbS_{Combined}$	-0.1	0.2	0.2

Figure 7: Map of the FRES actual demand change by interception and soil water.

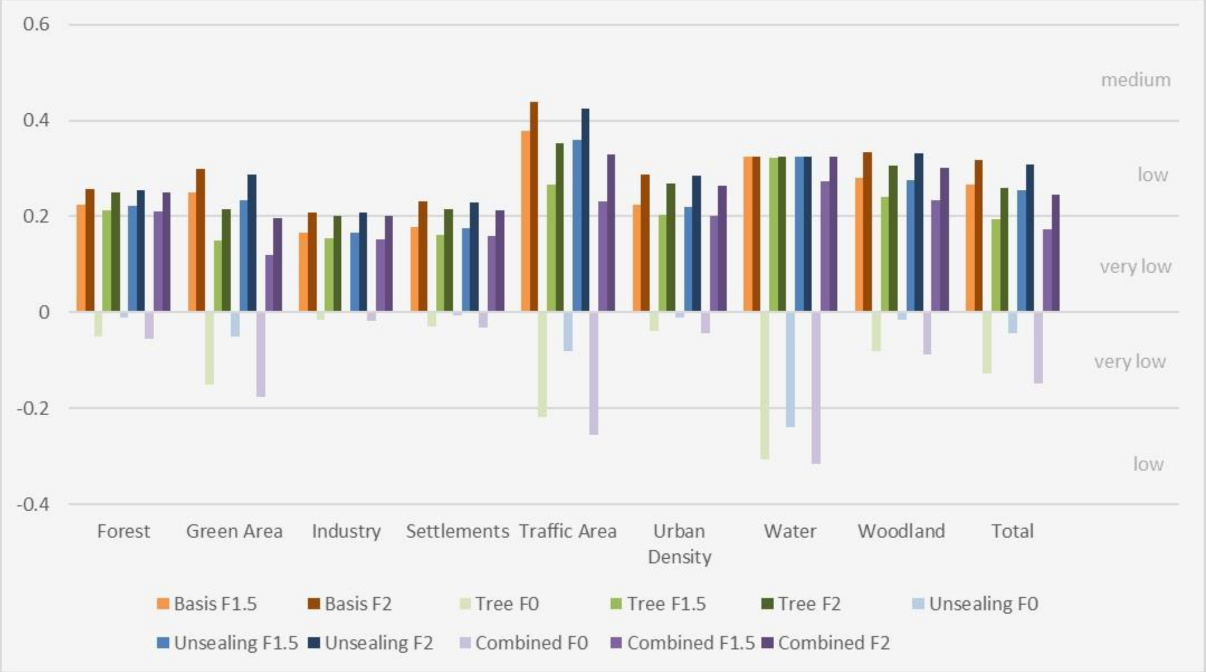


Figure 8: Area weighted FRES actual demand change by the NbS and rainfall scenarios over the different land uses.

3.4 Budget change

To determine the budget change, we calculated the difference between the supply change and the actual demand change (Figure 3). The results are mapped in Figure 9. Positive values indicate a higher supply change towards supply surplus (blue). Negative values indicate a higher actual demand change towards unmet demand (red). In Figure 10 the budget change over the individual land uses is displayed.

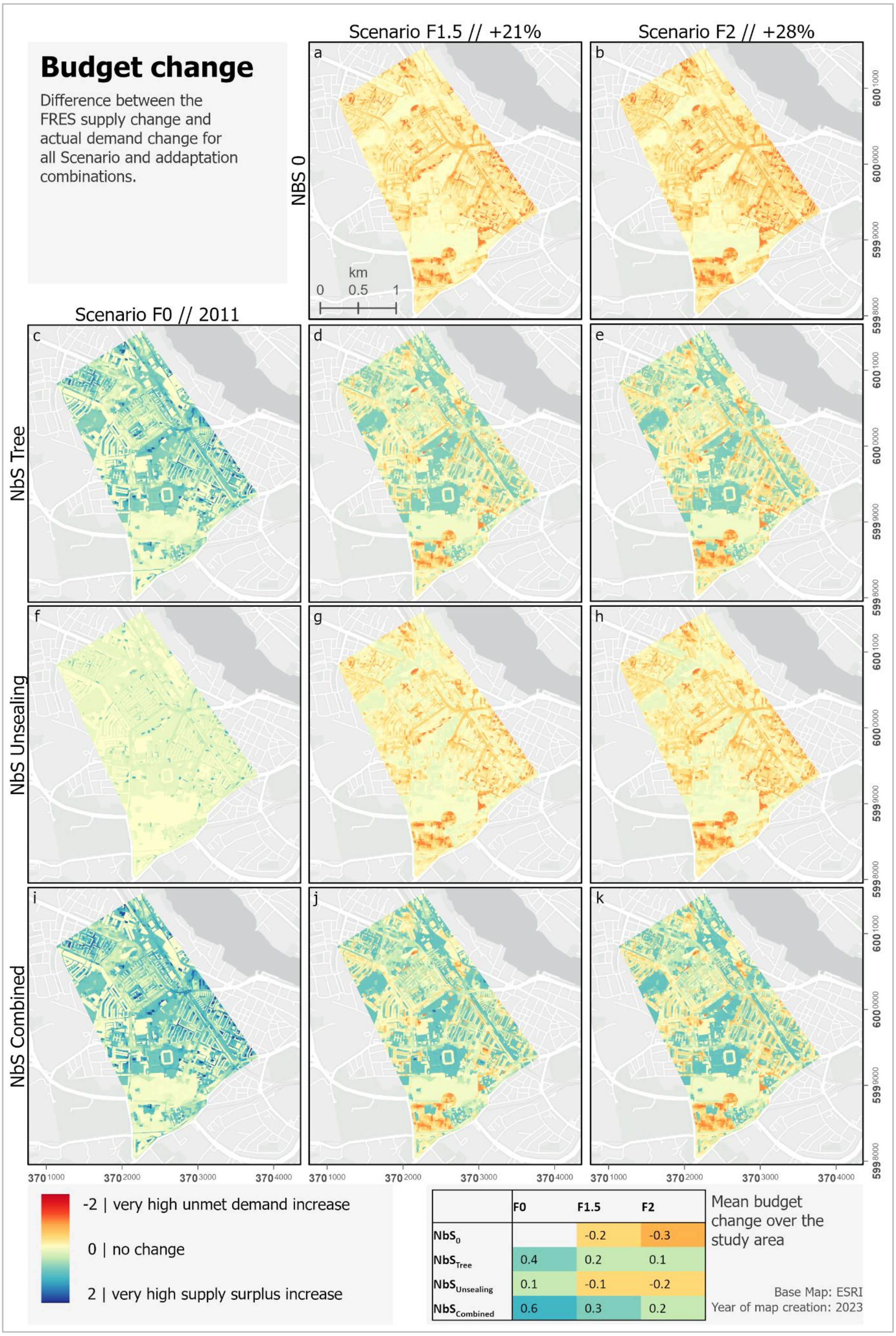
The budget analysis showed a low increase in actual demand for NbS_0 for both future scenarios. In general, traffic areas are most affected by a medium increase in unmet demand. In the entire area, no supply surplus increase can be observed.

The NbS_{tree} measure in contrast led to a medium supply increase in the reference scenario F0. While settlements and industrial areas had no or a very low increase in supply, green areas and traffic areas with higher tree coverage showed a high increase in supply surplus. This increase was lower for the future rainfall events F1.5 and F2 (very low), but it still exceeded the actual demand on average over the entire study area. In particular, green areas and traffic areas, where the NbS was implemented, benefitted from the measure (Figure 10). Some parts had a high or very high supply increase. Whereas settlements, urban dense areas, and industrial areas had a very low increase in unmet demand.

The $NbS_{unsealing}$ measure led to a very low increase of supply in the area average for the F0 scenario. On average, green and traffic areas showed a low supply increase, while built areas were not affected by a demand change (Figure 10). Under the future climate scenarios F1.5 and F2, the demand increase exceeded the supply. Still, the demand increase was lower than for the NbS_0. However, the land uses where no adaptation measure were implemented show similar demand increases as without adaptation measures.

The combination of both NbS highly increased the supply for the reference rainfall scenario F0, which also exceeded the effect of the NbS_{tree}. Higher rainfall amounts of the F1.5 scenario decreased the supply increase but it was still higher than the actual demand. Therefore, a medium supply surplus change was observed for F1.5 and a low supply exceed to the actual demand for the F2 scenario was shown. The spatial patterns were comparable to that of the NbS_{tree}, whereby the increase in supply exceeding the actual demand was more strongly over green and traffic areas for $NbS_{combined}$.

All rainfall scenarios and NbS combinations showed hotspots on the west of the Botanical garden and in the south of the study area at the Zoo. While the supply increase is slightly higher than the actual demand increase for the NbS_{tree} and $NbS_{combined}$ at the Holbeinplatz, the actual demand exceeded the supply with the NbS_0 and $NbS_{unsealing}$.



	F0	F1.5	F2
NbS_0		-0.2	-0.3
NbS_{Tree}	0.4	0.2	0.1
$NbS_{Unsealing}$	0.1	-0.1	-0.2
$NbS_{Combined}$	0.6	0.3	0.2

Figure 9: Map of the FRES budget of supply and actual demand change by interception and soil water.

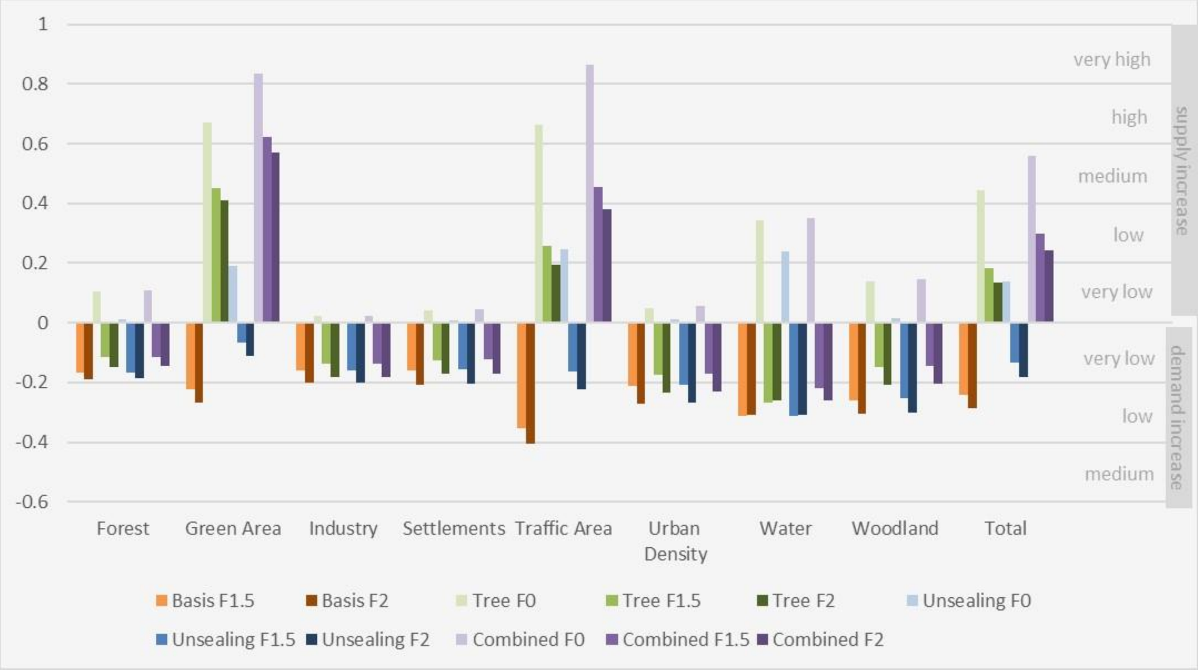


Figure 10: Area weighted FRES budget of supply and actual demand change by the NbS and rainfall scenarios over the different land uses.

4 Discussion

4.1 The benefit of NbS and the impact of heavier rainfalls

Based on the model results, there is no supply increase under more intense rainfall events for NbS_0. This allows the conclusion that retention by soil and canopy interception under the given model conditions has reached a capacity limit for the reference scenario F0 (Figure 4 and 5). This capacity is determined by some green areas. However, the large increase in actual demand on traffic areas indicates that adaptation measures are necessary.

Both NbS increased the supply, reduced the runoff, and decreased the actual demand. In the future scenarios, they were able to decrease the discharge and flooding impacts compared to the reference conditions (NbS_0) of the respective rainfall scenarios (Table 4). However, they do not increase the supply sufficiently to prevent flooding under higher rainfall events of scenarios F1.5 and F2 (Figure 7).

The expansion of tree canopies (NbS_{tree}), had a higher positive flood-reducing effect than unsealing. Trees increased the supply by interception and led to a low actual demand decrease. The mismatch analysis shows a higher increase of supply than actual demand for NbS_{tree}. It also showed the highest reduction of outflow and surface water depth over the 60 min time period (Figure 4), which also resulted in less water being available to flow into depressions of water bodies, thus reducing water levels and actual demand. Due to of the increasing supply during higher rainfall amounts such as for the F1.5 scenario, it can be assumed that the total supply capacity was not reached with the NbS_{tree} for the reference rainfall scenario. Despite the higher supply, the surface water increased here during higher rainfall events and consequently increased the actual demand. One possible consequence of higher surface water depth could be higher flow velocities and faster runoff. Still, some traffic areas (for instance around the Holbeinplatz) had a very high increased actual demand with a simultaneous increase of supply with higher rainfall events. This might be the result of the high sealing in combination with surrounding areas contributing to inundations of the depression at the Holbeinplatz.

Other studies had also proven the contribution of interception by trees to reduce the peak runoff (Camarena et al. 2022). Even if those results were site-specific, a single tree stored one cup of coffee per second, which may not have a major impact on the site at first, but contributed significantly to flood regulation for the entire area and reduces the runoff for downstream areas. Also Yarnvudhi et al. (2021) found that 60% catchment runoff can be avoided by trees per year. Although our case study shows a reduction of 28% only, it must be taken into account that we are looking at heavy rainfall in ungauged urban areas, while Yarnvudhi et al. (2021) focused on long-term balances of a catchment. Interception capacities therefore initially have a buffering effect, especially through an increase in tree cover (Zölch et al., 2017), but even their capacities are limited for extreme events (Smets et al., 2019). In summary, the NbS_{tree} can be seen as an effective adaptation measure for current and future extreme events to increase retention supply and reduce flood hazards.

In contrast, the benefits of the NbSunsealing measure were smaller. The supply increase could not reduce the actual demand. It is worth mentioning that unsealing in our study has only been applied to a small area, for which this measure was currently viewed as reasonable. Indeed, a supply increase was only visible in those areas where the measure was applied (green spaces and traffic areas), while the impact on the actual demand was very low (Figure 6). Local effects could still be observed and the timeline analysis showed a small reduction due to the unsealing for all rainfall scenarios compared to NbS0 (Figure 4). As a result of the lower surface water levels, the actual demand was lower at the depressions of water bodies, which are mainly located within green areas where the NbS was applied. Therefore, a positive effect on surrounding deeper areas can be noted. The application of the measure to a limited number of elements and the aggregation of spatial or temporal elements in the further analysis, resulted in a small positive flood regulating impact for the $\text{NbS}_{\text{unsealing}}$ and therefore the change signal is mostly determined by the climate changes (Strasser et al., 2019). Besides all NbS activities, it is important to mention that the used FRES-supply depends on the initial saturation. Thus, unsealing is still a very important flood prevention measure as it raises the potential infiltration capacity. In addition, it delivers further ES such as supporting groundwater recharge, improving biodiversity, and enhancing climate regulation.

The combination of both NbS partially improved the FRES compared to the individual measure NbS_{tree} and influenced the supply in particular. For the rainfall scenario F2 (+28%) both, the NBS_{tree} and $\text{NbS}_{\text{combined}}$, seem to reach their supply capacity, because no significant increase was detected (Figure 5 and 6) and also the supply timeline showed a similar level for both rainfall scenarios (Figure 4), while the actual demand increased (Figure 7 and 8).

Using extreme events to evaluate adaptation measures shows the limited effects of NbS due to exceeded retention capacities. Regardless of this fact, NbS still decrease the runoff and have a retention effect, but their relative contribution is smaller as the rainfall intensities increase. This is shown by the same mean FRES actual demand indication of F2 for NbS_0, NbS_{Tree}, and $\text{NbS}_{\text{unsealing}}$ (Figure 7). Single NbS are not able to prevent an acutal demand increase, only the combination of NbS have the potential to decrease the actual demand. However, the mismatch analysis (Figure 9) showed a higher supply increase for the NbS, which indicates a surplus of water on the ecosystems. This can support the sewer system and be used for other ecological processes such as cooling by evaporation. The model results show that the main impacts of the NbS are local where elements were implemented, such as on traffic and green areas. FRES improvement for settlements, urban areas, and industry without these elements was not determined. Consequently, it can be said that single localized adaptation measures with few elements are probably not sufficient (Smets et al., 2019). Trees will help to reduce flooding caused by heavy precipitation that may occur under an RCP 8.5 partly, but flooding cannot be avoided by one single ecosystem-based adaptation measure, only. Furthermore, the NbS have synergy effects and co-benefits on other ecosystem services and are not only positive for flood regulation, but also for instance biodiversity, urban climate regulation, pollination and recreation.

4.2 Uncertainties and limitations of the approach

We used the sCC relation to scale future possible extreme events. Although this is a simple qualitative approach, we consider it a valid approximation and indication of the future direction. It is an alternative to climate modelling, which currently do not provide reliable results on local and short-duration precipitation projections, but non-hydrostatic models are under development (Lenderink and van Meijgaard, 2008; Westra et al., 2014; Manola et al., 2018; Dahm et al., 2019). For a sensitivity analysis of ecosystem services the (super-) Clausius-Clapeyron scaling is an appropriate method and was also used by Lenderink and Attema (2015) for climate scenario analysis. Originally, the sCC is the scaling of precipitation using the dew point temperature following local convective atmospheric processes, which leads to more robust results than the temperature. However, since no detailed information was available, we used the temperature approach. Under the assumption of constant relative humidity 1°C temperature rising is linear to a 1°C dew point rising (Lenderink et al., 2011). Yet, it is unclear whether the scaling approach of sCC is transferable to regions with higher temperatures (above 24°C) (Westra et al., 2014; Lenderink et al., 2017).

We did not consider drier soil conditions in the future climate scenarios, in order to keep the model as simple as possible in this phase. However, projected longer and more intense dry periods in combination with higher temperatures will cause a decrease in soil moisture in some regions in the future (Holsten et al., 2009; Villaseñor, 2021). Parched soils can absorb less water and have a low infiltration rate, which reduces flood regulation by soils, lead to higher surface water levels, and will consequently cause higher actual demand (Liu et al., 2011). With the current set-up of LEAFlood, we cannot capture such an effect.

We have adopted a simplified methodological approach for the unsealing of the NbSunsealing. Entire road sections were unsealed instead of separating smaller areas, which in reality would be the case with green stripes. The applied NbS aim for maximized green infrastructure, neglecting the possible implementation. This could be investigated in detail in a next step. Furthermore, we did not consider soil improvement by the NbStree. Rooting loosens the soil and improves infiltration (Smets et al., 2019). Indeed, only small open areas are created along roads and the soils are very compact. Therefore, taking soil improvement at tree pits into account would probably not have much effect here. Moreover, the results of the unsealing measure and the combination of trees and unsealing already showed that the actions only have minor effects.

The used hydrological model LEAFlood quantified three indicators. Modelling is always only a simplification and reflection of reality and therefore input data are always event (e.g. saturated depth) and site-specific (e.g. Manning n, saturated conductivity, or vegetation parameters). In the absence of on-site measurements - which is common for most urban areas – we relied on plausibility checks based on on-site inspections from past events. Additionally, we refer to literature, modelling, and measurements from other areas. The comparative study by Camarena et al. (2022) showed a good match between modelled results with LEAFlood and observation data in terms of interception and surface runoff. Even though the Green-Ampt infiltration and kinematic wave surface flow are simplified physics-based approaches, they are common approaches in estimating flooding extent and their applicability in LEAFlood has been demonstrated in Camarena et al. (2022). LEAFlood is also capable of using the diffusive wave approach at the expense of higher computational costs and higher requirements of spatial resolution.

The demand might be overestimated because the urban drainage system was not taken into account. However, this does not influence the FRES-supply. Since this study 1) focuses on the contribution of the natural ecosystem to flood regulation and 2) investigates the high rainfall intensities that typically exceed the capacity of urban drainage systems, this limitation is acceptable.

Furthermore, the ES classification on the event-scale eliminates some effects and details regarding temporal resolution. The maximum or 90%-quantile over the event duration was considered, and hence features, in particular throughout the event, are aggregated through statistical summarization and classification. The concept is thus static and the temporal course, which is important in flood regulation for reducing and shifting peak discharges, is summarized in simple ES indicators. Therefore, it is also important to examine the model results and absolute values, which is why we have additionally consulted the time series.

The ES concept serves as a communication tool with simplified indicators. It highlights the supply of ecosystems, rather than focusing on flood hazards only (European Parliament, 2007; Oppenheimer et al., 2014). The mismatch analysis of FRES-supply and demand has the advantage of 1) quantifying the contribution of natural ecosystems to flood regulation, and 2) identifying missing FRES-supply on hotspots with high actual demand (Dworczyk and Burkhard, 2021).

Concerning the higher rainfall intensities due to climate change, the mismatch analysis helps to highlight areas where the actual demand increases more due to higher surface water than the provided water retention by natural ecosystems. By taking the FRES-supply into account, a value is attributed to the natural ecosystems and adaptation measures such as NbS can be tested regarding their sufficiency and long-term effectiveness to reduce flood hazards and consequently the actual demand. Therefore, the FRES framework provides a useful tool for testing the potential functionality of NbS under changing climate conditions. This study did not include feedback from stakeholder and decision-makers. However, involving stakeholders in future research approaches can improve the FRES framework will be beneficial for the identification of stakeholder needs, the science-praxis dialogue, and the practical application of NbS in urban planning (Grunewald et al., 2021).

4.3 Outlook

In this paper, we have shown the benefits and contributions of single NbS measures under increasing rainfall events due to climate change by examining indicators of canopy interception and soil water storage for the supply and surface water depth as a component of the actual demand. Another interesting additional indicator to estimate the effects of the NbS measures and the climate change projections would be the flow velocity. High velocities can cause high damage and are therefore interesting for the estimation of FRES- demand impacts.

To further improve the flood regulating ES, other NbS, like green roofs, or a combination of different adaptation measures should be tested and is probably needed in order to sustainably to deal with future extreme events (Zölch et al., 2017). Green roofs tend to have a large effect on annual stormwater runoff and peak runoffs (Bengtsson, 2005), while the retention for extreme events is small (Stovin et al., 2013). LEAFlood is able to consider green roofs either in a simple way as land use with appropriate soil settings (Camarena et al., 2022) or it can be further developed and connected with the detailed CMF model setup of green roofs by Förster et al. (2021). Additionally, a sensitivity analysis of the NbS could be conducted to improve the understanding of their performance and the impact of changing input on the model performance.

Before bringing these or other adaptation measures into practice, a feasibility study for practical application needs with stakeholders has to be carried out. The NbS how they are applied here, are theoretical concepts aiming for a maximized green infrastructure. For instance, a tree cover of 30 % cannot be realized over all traffic areas. Likewise, it is not necessarily possible to unseal all traffic areas by implementing green strips, nor to increase saturated conductivity by improving soil conditions.

We tested different rainfall scenarios and land use measures, while the potential demand was held constant. However, demographic change, urbanization and digitalization will change future demands and there is still a lack of analysis on the ES demand side (Campagne et al., 2020). For instance, Mori et al. (2022) analyzed the temporal dynamics of FRES-budget for a catchment basin by land use/ land cover changes from 1990 to 2018. Therefore, another future task would be to test different demand scenarios by adjusting the potential demand indicators and assess the increasing vulnerability to more intense rainfall events using the ecosystem services concept.

Lastly, policy and decision-makers need better guidance tools that apply comprehensive and holistic approaches and highlight the synergies and benefits of NbS or ecosystem-based adaptations to support sustainable urban development (Zölch et al., 2018).

5 Conclusion

FRES assessment focuses on fluvial floods in rural catchments under current hydrological conditions. We assessed the future functionality of urban FRES under more intense heavy rainfall events in urban areas. Additionally, we estimated the benefits and contribution of NbS to urban FRES under current and possible future rainfall events to improve the evidence on the performance of NbS for climate change adaptation. Therefore, we quantified FRES indicators based on outputs of a coupled 2D hydrological-hydrodynamic model LEAFlood.

Our results show that existing ecosystems have already reached a supply capacity. Higher extreme events led to an increase in actual demand, which exceeded the supply. The applied NbS - in particular trees and combined NbS – enhanced the FRES supply. They partly increased the FRES-supply and reduced the flood hazard and consequently the actual demand under today's rainfall events. Although they could not prevent an increasing actual demand for more intense rainfall events, the supply increase was still higher than the actual demand increase. Indeed, the actual demand increase was lower compared to scenarios without NbS. This confirms the positive contribution of NbS to future flood regulation, which is worth being acknowledged here. However, as both types of NbS were applied on the same land uses (mainly traffic areas and green areas), we suggest implementing a full set and combination of green infrastructure on different sites, such as settlements.

Our indicator-based approach, comparing each scenario to a reference scenario, appears to be appropriate to estimate the long-term change and development of ES functions. The identification of FRES-supply and demand changes due to climate change and the benefits of NbS is a useful visualization and quantification tool for urban planning to identify mismatches in changes. This is helpful to make decision-makers aware of areas where natural ecosystem services are missing. The outline method could lead to a more holistic view of the design of NbS in sustainable city planning.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Writing: TW; Study Design: TW, KF, LB, CD; Modelling: TW, KF; Reviewing: KF, LB, CD, BB; Supervision: SB, BB

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Supplements

Table 5: Used datasets

Data	Type	Application		Description	Source
		Model	ES		
Precipitation	Timeseries	x		1 min resolution	(DWD Climate Data Center, 2021b)
Temperature	Timeseries	x		10 min resolution Minimum and Maximum	(DWD Climate Data Center, 2019a)
Wind speed	Timeseries	x		10 min resolution	(DWD Climate Data Center, 2019a)
Solar radiation	Timeseries	x		10 min resolution	(DWD Climate Data Center, 2021)
Relative humidity	Timeseries	x		10 min resolution	(DWD Climate Data Center, 2019)
DEM	Geodata	x		1 m resolution	(Landesamt Mecklenburg-Vorpommern, -)
Tree	Geodata	x		Used Attributes: Type, Diameter	(Hanse- und Universitätsstadt Rostock - Amt für Stadtgrün, Naturschutz und Friedhofswesen, 2017)
Soil type	Geodata	x			(Hanse- und Universitätsstadt Rostock – Amt für Umwelt- und Klimaschutz, 2019a)
Land use	Geodata	x	x	Used Attributes: Land use types, Sealing	(Steinbeis-Transferzentrum Geoinformatik, 2017)
Population density	Geodata		x	Unit: People/ha	(Hanse- und Universitätsstadt Rostock – Kataster-, Vermessungs- und Liegenschaftsamt)
Land reference value	Geodata		x		(Hanse- und Universitätsstadt Rostock – Kataster-, Vermessungs- und

					Liegenschaftsamt, 2021)
Monuments	Geodata		x		(Hanse- und Universitätsstadt Rostock – Amt für Kultur, Denkmalpflege und Museen, 2017)
Hospitals	Geodata		x		(Hanse- und Universitätsstadt Rostock – Kataster-, Vermessungs- und Liegenschaftsamt, 2017)
Fire stations	Geodata		x		(Hanse- und Universitätsstadt Rostock – Brandschutz- und Rettungsamt, 2017)
Schools	Geodata		x		(Hanse- und Universitätsstadt Rostock – Schulverwaltungsamt, 2017)
Care facilities	Geodata		x		(Hanse- und Universitätsstadt Rostock – Amt für Jugend, Soziales und Asyl, 2017b)
Institutions for disabled	Geodata		x		(Hanse- und Universitätsstadt Rostock – Amt für Jugend, Soziales und Asyl, 2017)

Table 6: Indicators and explanation of used FRES terms. Further details and descriptions of supply, actual demand, and budget definitions can be found in Wübbelmann et al. (2022a).

Term	**Explanation**	**Indicator**
Supply Change	The FRES supply is the provision of a service by an ecosystem (Burkhard and Maes, 2017). In our study, FRES supply is provided by canopy interception and soil water storage.	Change of intercepted water depth [mm] Change of soil water depth [mm]

	Here, the FRES supply change in a particular ecosystem captures the supply increase or decrease through climatic (rainfall) or site-specific composition (NBS) changes.	
Hazard Change	The flood hazard is defined by the model output surface flooding. The flood hazard change indicates the increasing or decreasing of surface water due to adaptation measures (NBS) or higher rainfall amounts by the difference between the scenario and the reference scenario.	Change of surface water depth [mm] Reduction of peak runoff [m³/min]
Potential Demand	The potential demand describes the potential need for an ES by society or other stakeholders. The demand for FRES can be captured by the need for risk reduction, prevention and security increase. The potential demand is always existing irrespective of currently existing flooding and does not change in this study.	Population density [inhabitants/ha] Occurrence of monuments [-] Ground reference value [€] Occurrence of critical Infrastructure [-] (hospitals, fire brigade, schools, care facilities, disabled institutions) Occurrence of traffic infrastructure [-] (streets, railways, stations)
Actual Demand Change	The potential demand turns into an actual demand when it is actually flooded due to a rainfall event. It results from an intersection of potential demand and flood hazard. The actual demand change is therefore the increase or decrease of actual demand due to adaptation measures and rainfall scenarios compared to the reference scenario. Since the potential demand is static, it is based on the flood hazard change.	Change of potential demanding area that is flooded [-]
Budget Change	The budget change results from the mismatch analysis of supply change and actual demand change. It indicates whether the supply increase is higher than the actual demand, the actual demand	Supply – Demand Budget Index [-]

	increase is higher than the supply or if the change of both is in balance.	

7

SYNTHESIS

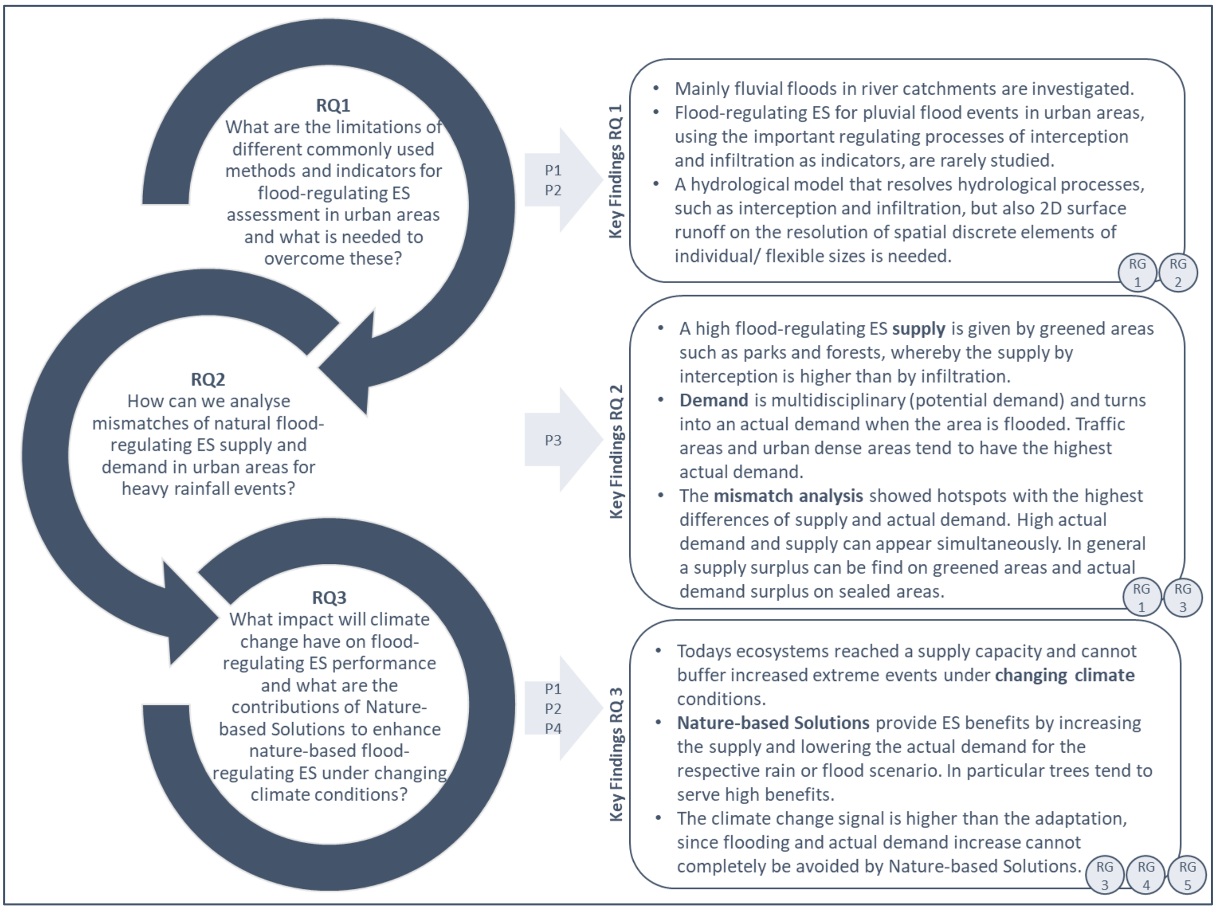
In this final Chapter, the overall research questions are answered. This is followed by a section on limitations and uncertainties. In addition, the contribution of this study to practical applications is highlighted. Based on the overall research process, an outlook and recommendations for future research are made. Finally, in the conclusions, the main findings are wrapped up and the novelty of the thesis is emphasized.

7.1 Main Results and answers to the Research Questions

This Chapter is structured along the outlined research questions. They will be answered based on the main findings of Chapters 3 to 6.

The limitations of the flood-regulating ES approaches for fluvial flooding as determined in Chapter 3 show that methods and indicators are not easily transferable to urban areas and heavy rainfall. Based on this and on the review of hydrological models, the LEAFlood model was developed. Its functionality was proven by calibration and validation with observation data, see Chapter 4. This allowed a further application of the model for the development of a framework to estimate urban flood-regulating ES for heavy rainfall as described in Chapter 5. This framework was then applied to an analysis of climate change scenarios and adaptation measures in Chapter 6.

Figure 9 summarises the key findings of each research question. They are discussed in detail in the following sections.



RQ1
What are the limitations of different commonly used methods and indicators for flood-regulating ES assessment in urban areas and what is needed to overcome these?

RQ2
How can we analyse mismatches of natural flood-regulating ES supply and demand in urban areas for heavy rainfall events?

RQ3
What impact will climate change have on flood-regulating ES performance and what are the contributions of Nature-based Solutions to enhance nature-based flood-regulating ES under changing climate conditions?

Key Findings RQ 1

- Mainly fluvial floods in river catchments are investigated.
- Flood-regulating ES for pluvial flood events in urban areas, using the important regulating processes of interception and infiltration as indicators, are rarely studied.
- A hydrological model that resolves hydrological processes, such as interception and infiltration, but also 2D surface runoff on the resolution of spatial discrete elements of individual/ flexible sizes is needed.

Key Findings RQ 2

- A high flood-regulating ES **supply** is given by greened areas such as parks and forests, whereby the supply by interception is higher than by infiltration.
- **Demand** is multidisciplinary (potential demand) and turns into an actual demand when the area is flooded. Traffic areas and urban dense areas tend to have the highest actual demand.
- The **mismatch analysis** showed hotspots with the highest differences of supply and actual demand. High actual demand and supply can appear simultaneously. In general a supply surplus can be find on greened areas and actual demand surplus on sealed areas.

Key Findings RQ 3

- Todays ecosystems reached a supply capacity and cannot buffer increased extreme events under **changing climate** conditions.
- **Nature-based Solutions** provide ES benefits by increasing the supply and lowering the actual demand for the respective rain or flood scenario. In particular trees tend to serve high benefits.
- The climate change signal is higher than the adaptation, since flooding and actual demand increase cannot completely be avoided by Nature-based Solutions.

Figure 9: Summary of the key findings for each Research Question (RQ) including the related Publication (P) and addressed Research Gaps (RG).

7.1.1 Limitations of existing methods and indicators for flood-regulating Ecosystem Services in urban areas and approaches to overcome these

Existing flood-regulating ES assessments mainly focus on fluvial floods in river catchments (Nedkov and Burkhard, 2012; Stürck et al., 2014). The critical discussion of two approaches of different complexity to derive indicators in Chapter 3 provided feasible information for fluvial flood-regulating ES assessments. Indicators for fluvial flood-regulating ES are usually based on the spatial extent of catchments in the floodplain (e.g. Chapter 3 and Albert et al., 2015; Shen et al., 2019; Wübbelmann et al., 2021) or runoff at catchment outlets (Nedkov and Burkhard, 2012; Stürck et al., 2014). More detailed spatial information on hydrological processes is neglected, e.g. infiltration depth, interception, or permeability. However, for urban flood-regulating ES of heavy rainfall, hydrological processes are crucial indicators (Burkhard and Maes, 2017). The comparison of two different approaches that assess flood-regulating ES-indicators (Chapter 3) showed the advantages of modelling over simplified methods based on spatial data analysis. For instance, modelling allows to simulate processes that are more complex and to consider more boundary conditions (e.g. roughness or slope). In addition, modelling can assess climate change impacts, land use scenarios, or NbS by adjusting input data, whose impacts on flood-regulating ES can be evaluated.

Although commonly used high spatial resolution models can be applied to investigate surface water flow for short-duration events, they are not capable of resolving all hydrological processes. In particular, they neglect the urban flood-regulating process of interception (Chapter 2.2.1). The hydraulic model HEC-RAS is one example that was applied in Chapter 3, where infiltration and interception processes were not included. It is important to mention that a newer version of HEC-RAS (6.0) was developed in the meantime that can consider simplified infiltration processes (Brunner, 2022b). Another example of a commonly used model for urban areas is SWMM, which was tested in the context of this dissertation in the Vauban area in the city of Freiburg, Germany (see Appendix 'Master Thesis Carina Sinaí Medina Camarena'; Medina Camarena, 2021). Despite the good results, the SWMM model was not used for the evaluation of flood-regulating ES, as vegetation is simplified by depression storages and does not represent interception by tree canopies (Iffland et al., 2021). Nevertheless, the application was helpful for plausibility checks of further results and modelling. In contrast, existing hydrological models that sufficiently portray such processes, are too coarse in their spatial resolution (e.g. catchment or sub-catchment level) and therefore cannot adequately represent the urban environment (e.g. SWAT) (Wang et al., 2019). In summary, the analysed approaches are not directly transferable to pluvial floods in urban areas due to different spatial scales and the flood-regulating processes that should be taken into account.

Consequently, to quantify flood-regulating ES in urban areas for heavy rainfall events and to answer the outlined research questions adequately, a hydrological model should fulfil the following three objectives. First, the model approach should be able to resolve single landscape elements adequately, such as streets, parks, and buildings. The consideration of individual landscape elements is especially important to display the heterogeneity of urban environments. Second, it should consider significant hydrological processes and elements that regulate flooding by heavy rainfall. In particular, detailed vegetation interaction with hydrology such as interception and throughfall were shown to be an essential flood-regulating element in urban environments that potentially lower peak discharge and surface water depth (Zölch et al., 2017; Medina Camarena et al., 2022). Third, in addition to the vertical processes, lateral hydrological processes are relevant to ensure surface water routing.

Based on these findings, the hydrological model LEAFlood was developed (Chapter 2.2.3.2, (Wübbelmann and Förster, 2022)). The calibration and validation of the model using runoff measurements in the Vauban area (city of Freiburg im Breisgau, Germany) and the additional focus on the representation of vegetation interception by the model could be confirmed in Chapter 4. The good match of peak flow values proved to be an acceptable calibration. The additional validation with other rainfall events showed that the model is transferable to other events. Furthermore, the model reflected a plausible surface routing. The comparison of modelled and measured interception values also showed that interception is in general well represented in timing and absolute values by the model. LEAFlood can deliver data to quantify ES indicators of canopy interception depth, soil water depth, surface water depth and outflow at the boundaries of the study area.

In summary, the consideration of a combined vertical-horizontal hydrological model and the spatial resolution based on landscape elements with an interface to Geographic Information Systems (GIS) led to the development of LEAFlood. Therefore, it is well suited to assess urban flood-regulating ES by landscape elements and structures. Due to its open accessibility and flexible structure, it can be adapted to other research questions and practical applications.

7.1.2 Mismatch analysis of flood-regulating Ecosystem Services supply and demand in urban areas for heavy rainfall events

Based on the gaps identified in Chapter 3 and the literature review, a framework to assess pluvial flood-regulating ES in urban areas was developed in Chapter 5. The objective of this framework was to overcome the research gap of missing flood-regulating ES assessment in urban areas for pluvial flooding and to conduct a comprehensive mismatch analysis of ES supply and demand. LEAFlood (Chapter 2.2.3.2) delivered data to quantify indicators for ES supply and flood hazard as an indicator for flood-regulating ES demand.

Canopy interception and soil water estimated by the model were used as flood-regulating ES supply indicators. High flood-regulating ES supply was given by green areas. Interception accounts for the major proportion of ES supply. Because of the high degree of soil sealing, canopy interception is a main water retention element in cities. This supports the outlined statement in the previous Chapter 7.1.1 that existing indicators and methods need to be adjusted for flood-regulating ES assessment in urban areas. Flood-regulating ES supply by soils showed to be smaller compared to ES supply by interception of canopies. However, the contribution of soils should not be neglected. The results obtained here are event-specific and site-specific and depend on the initial conditions of the hydrological model. Less compact soil, reduced soil sealing, and lower groundwater depth can increase the ES supply capacity and utilization of soils. Furthermore, unsealed soils have several of co-benefits, such as groundwater recharge, climate regulation and improved biodiversity (O'Riordan et al., 2021).

The demand for flood-regulating ES was assessed in two steps. First, a cluster of several socio-economic indicators identified the potential demand. Particularly in cities, the demand is multidimensional by multiple stakeholder groups (Geijzendorffer et al., 2015). For instance, besides the population density, the consideration of economic values and (critical) infrastructure is important. Architectural monuments (buildings and areas) were shown to be an important potential ES demand indicator. They increased the potential demand on greened areas, such as protected green areas with monument status. These areas simultaneously have a high supply provided by interception by forests and soil infiltration of green areas. Simultaneously high potential demand and supply would not have been indicated if the demand had been identified by a single indicator such as population, or by a simplified proxy indicator based on land cover classification. In the second step, an intersection of the flood hazard and potential demand was done to identify the actual demand. A potential demand turns into an actual demand when an area is flooded. Identifying the potential demand first is justified by the fact that non-affected people also have a demand for flood protection and therefore, should not be neglected. Therefore, an actual demand depends on a natural hazard but also on potential demand. It reflects a demand for a specific rainfall event. The highest actual demand was given in traffic areas and urban dense areas, resulting from a high potential demand and high flood hazard (Chapter 5).

The mismatch analysis of supply and actual demand identified areas of supply and actual demand surplus. It has been shown that areas could have high actual demand and supply simultaneously if different dimensions and user groups of potential demand were considered (e.g. monuments). In general, a supply surplus was given in greened areas, while an actual demand surplus was identified in sealed areas. In this context, it is worth mentioning that the absolute water depth of the supply storage (canopy interception and soil) was lower than the surface water depth. However, the mismatch analysis of supply and demand by relative values gives spatial indication and distribution to identify hotspots with the highest differences in supply and demand. Based on this information, adaptation measures can be conducted to increase supply in high actual demand areas. Furthermore, a mismatch analysis is necessary to prove the relevance of supply, since ecosystem functions only turn into an ES if there is a demand by society (Haines-Yong and Potschin, 2013; Geijzendorffer et al., 2015). This approach additionally emphasises that demand cannot be equated with ES-benefits since an unmet demand might remain and not all demanding areas benefit from ES supply (Dworczyk and Burkhard, 2021).

In contrast to the ‘Urban Flood Risk Mitigation model’ by InVEST (Natural Capital Project, 2020), the framework presented in this thesis offers a higher and more flexible spatial and temporal resolution. Single and individual landscape elements can be resolved depending on the resolution of the available input dataset. On the other hand, InVEST is based on sub-catchments, whereby different land uses are part of one catchment with limited spatial variability (Nedkov et al., 2022). Individual land use characteristics cannot be considered and thus, spatially explicit ES contributions cannot be identified due to the catchment resolution (see the appendix: ‘Bachelor Thesis Joshua Bockbreder’; Bockbreder, 2021). In addition, the previously mentioned important hydrological processes of interception and infiltration for urban flood regulation were considered in more detail in the LEAFlood model and consequently in the flood-regulating ES supply assessment. Instead, InVEST simplifies infiltration assessment and neglects interception. Furthermore, LEAFlood is based on a timeline of rainfall input data, which resolution is variable depending on the data and research question. Here, a one-minute resolution for a 1-hour event was chosen. InVEST, on the other hand, is based on a fixed value in mm.

7.1.3 The impact of climate change and contribution of Nature-based Solutions for flood-regulating ecosystem services

In Chapter 3, a dike relocation and afforestation of the floodplain were investigated as Nature-based Solutions (NbS) along a river for a flood event in 2013 and a potentially increased flood event by 10 %. While Chapter 4 only investigated the contribution of trees to mitigate pluvial flooding for past rainfall events, Chapter 6 analysed the benefits of NbS for past and future heavy rainfall events. NbS of trees, unsealing of soil, and a combined action of both on flood-regulating ES were simulated for a heavy rainfall event in 2011 and for a possible increase of 14 % and 21 %. The results demonstrate the effects of climate change, but also possible adaptation response effects.

Climate change has shown to seriously impact flood-regulating ES. Current ES reached a limit of ES supply and would not be able to buffer extreme events under changing climate conditions. For both, the supply capacity did not increase, while the actual demand (only assessed for the pluvial flooding in an urban environment) did increase. Based on the results of previous ES analysis and the climate scenarios, possible adaptation measures of NbS that can mitigate future increases in actual demand could be identified.

NbS change ecosystem structures and functions and consequently the flood-regulating ES. They enhance societal and ecosystems benefits and therefore, operate as a response to the socio-economic system pressures, contributing to human well-being. One objective is to increase the resilience against environmental risks and counteract pressures, such as climate change (Cohen-Shacham et al., 2016). Although Chapter 3 does not address the urban environment and pluvial flooding by heavy rainfall, predictions can be made about the impact of climate change on ES and the functionality and benefits of NbS under changing climate conditions. In this context, it should be noted that all adaptation actions along rivers are also applied to protect human well-being and thus indicating linkages to urban areas present near the river. For both, fluvial (Chapter 3) and pluvial flooding (Chapters 4 and 6), similar effects of NbS could be found. Analysis of NbS showed benefits by increasing the flood-regulating ES supply while reducing the surface water depth, extent or runoff and consequently the actual demand for flood-regulating ES. In particular, an increased number of trees or increased canopy coverage were found to have a positive impact on flood-regulating ES. For heavy rainfall, a comparison of literature (Asadian and Weiler, 2009; Alves et al., 2018) and site observation data (Jackisch et al., 2013) showed that interception capacities reached up to 10 mm. The model results of LEAFlood reached similar orders of magnitude (see Chapter 4). Interception is an important flood-regulating element in urban areas, but literature values differ widely due to a lack of distinctions in event characteristics. Mean values are often considered over a long period of time (Breuer et al., 2003), which is why deviations occur especially during heavy precipitation events. This additionally shows that flood regulation is event-specific and should be modelled accordingly (Burkhard and Maes, 2017). In addition to on-site effects of trees by reduced surface water depth, model simulations showed changed runoff at the outlets. Based on these results, downstream flood-regulating benefits for underlying areas can be assumed.

For climate change scenarios, NbS also reached a capacity limit for fluvial (Chapter 3) and pluvial floods (Chapter 6). However, NbS still increased the supply of interception and infiltration, lowered the flood hazard, and consequently, the demand, compared to the baseline without NbS. However, they could not completely avoid an increase in flood hazards and flood-regulating ES demand. Therefore, the climate change signal was higher than the effects of the NbS (Strasser et al., 2019). This shows the limited effectiveness of NbS and that one adaptation measure might not be sufficient to adapt to climate change of increased intensity (10 % for fluvial floods and +14 % / +21 % for heavy rainfalls). The combined NbS in Chapter 6 showed the largest positive effects by increasing the flood-regulating ES supply and lowering the ES demand. Therefore, a set of several combined adaptation measures is recommendable as in the case study area Vauban (Chapters 2.5.2 and 4) with swales along traffic areas or green roofs in settlements. Green roofs were not studied specifically, but are widely present in the Vauban area and were indirect considered by respective soil settings in the LEAFlood model. Green roofs have the advantage that they can be installed on a larger scale, while the space for trees is usually limited in urban areas (Zölch et al., 2017).

7.2 Limitations and Uncertainties of the Methods

This thesis focuses on modelling flood-regulating ES. Indicators from hydrological modelling were used to estimate ES supply and ES demand under present and possible future climate and land cover conditions. Understanding the functionality of flood-regulating ES under changing climate conditions and the benefits of NbS is crucial for sustainable urban planning and climate change adaptation. However, models are a simplified representation of reality, thus some processes, datasets, and boundary conditions are neglected or simplified. In particular, urban hydrological modelling is still challenging due to the heterogeneity and complexity of urban areas (Fletcher et al., 2013; Salvadore et al., 2015). The uncertainties in this study are associated to data availability, understanding of complex hydrological urban processes, and calibration of ungauged urban areas (Fletcher et al., 2013; Salvadore et al., 2015; Cristiano et al., 2017). In the discussion section below, the focus will be on the application of the hydrological model LEAFlood developed for this thesis and hydrological modelling in urban environments. Other models were also used, but since these were only used in individual sections of the work and have already been discussed in the respective chapters, they will no longer be discussed in detail (e.g. HEC-RAS Chapter 3). The modelling uncertainties and additional impacts further affect the ES assessment by indicators.

Data availability and accuracy

An uncertainty that is valid for all models is given by data accuracy and resolution. Although LEAFlood allows considering spatially distributed data of land use, vegetation, and soils, the application depends on data availability and accuracy. For instance, for the study area Rostock in Chapters 5 and 6, a very well-resolved and detailed point shapefile with individual tree information was available. It differentiates tree locations, tree genus, and the tree crown diameter, however, it cannot be overlooked that some trees were not mapped. For the study area Vauban in Chapter 4, an area shapefile with less information (e.g. missing tree genous information) was available. Consequently, spatially variable vegetation parameters such as the Leaf Area Index could not be considered as an input parameter in the hydrological modelling. The same applies to the spatial variability of soil. Although urban soils are very heterogeneous (Greinert, 2015; Wiesner et al., 2016), there is a lack of corresponding data with an appropriate representation of spatial variability. For comprehensive mapping, a high mapping effort with a dense measurement network would be needed. The accuracy of data directly or indirectly influences the assessment of ES (Schulp et al., 2014). While ES supply is mainly indirectly affected by outputs of the hydrological model and their uncertainties, ES-demand (Chapters 5 and 6) assessment is directly affected by data accuracy, since it is based on a spatial analysis of geodata. The applied approach is multidisciplinary because it includes different stakeholders of society, economy, and culture. However, a more detailed consideration would reduce uncertainties but would require appropriate and available data.

Incomplete understanding and representation of hydrological processes

The heterogeneity of urban areas is given by the small-scale spatial distribution of land uses and soils but also by microclimatic effects (Cristiano et al., 2017). Due to the complexity of urban hydrological systems, hydrological interactions and processes have still not been completely understood (Fletcher et al., 2013; Salvadore et al., 2015), which consequently biases ES assessments (Schulp et al., 2014). In addition, models are usually designed for one specific application, therefore processes, datasets, and boundary conditions remain neglected or simplified. For instance, LEAFlood does not consider sewage systems. This might cause higher flood water levels and consequently, an overestimation of actual demands, but does not affect the natural contribution of flood-regulating ES supply. Indeed, given the research questions, which focus on the natural contribution of ecosystems to flood reduction, this limitation is acceptable. Furthermore, the focus was on rare extreme events of high intensities that typically reach or exceed the required capacity of a two years return period of urban drainage systems in Germany (DIN-EN, 2017).

Calibration of hydrological models in ungauged urban areas

The calibration of ungauged urban areas remains a further challenge in urban hydrological modelling. Observation data and measurements for calibration and validation are limited in urban areas (Fletcher et al., 2013; Salvadore et al., 2015). Although LEAFlood can map the spatial heterogeneity if the according data are available, the problem of hydrological observation data for validation remains. Such measurements were available for the Vauban area (Chapter 4), so that unique calibration and validation of the model were possible in this study area. However, such data were not available for Rostock (Chapter 5 and 6). Plausibility checks through on-site inspections were therefore applied in the latter case, as is often done in hydrological modelling for urban areas. Even if parameters and boundary conditions are always site- and event-specific, the results from the Vauban area confirm the functional suitability of the model and its processes. This allowed a further application of the model for flood-regulating ES estimation.

ES-Indicators: inconsistent definitions and a section of the system

ES research is a complex and challenging field, since it includes and combines complex ecological systems with socio-economic environments. Definitions of ES, ES components, and indicators are still inconsistent (Schulp et al., 2014; Luederitz et al., 2015). In particular research on ES demand lingers behind ES supply studies (Campagne et al., 2020), and definitions also remain inconsistent (Dworczyk and Burkhard, 2021).

In this study, indicators quantified ES. In general, indicators only represent a part of the system, and not all system components are mapped. For example, the ES supply in Chapters 5 and 6 was reduced to two indicators of canopy interception and soil water storage. Other ES supply elements such as surface depression storage were not specifically mapped but only indirectly considered in the modelling. The same applies to ES demand, where various aspects have already been taken into account. However, the approach can be expanded to include further relevant elements and related indicators (e.g. natural protection areas).

The simulations presented in this thesis are event-specific, since only single extreme events at 3 years or higher return periods were investigated. Furthermore, uncertainties of temporal dynamics on two levels should be mentioned. First, the aggregation to the maximum ES supply over the event time (e.g. Chapter 5) neglected the performance and development of flood regulation during the event. Second, the analysis of climate change scenarios in Chapters 3 and 6 were minimized to one and two scenarios, respectively. To cover all possible developments, bandwidths of different scenarios can be considered.

It should also be taken into account that there are spatial differences in the relationship between ES demand and supply. This means that the location of both components differs and is not always *in-situ*, as it was analysed in this thesis (Syrbe and Walz, 2012; Syrbe and Grunewald, 2017; Dworczyk and Burkhard, 2021). The analysis of runoff at the outlets in Chapters 4 and 6 showed that upstream or downstream effects could be important. Since the focus of this study is on short-duration extreme events in non-catchment urban areas, this fact might be less relevant. However, for fluvial flooding in catchments (Chapter 3) and flash-floods, the water flow from upstream areas (as ES supply) to downstream areas (as ES demand) are important flood-regulating ES indicators (Goldenberg et al., 2017; Shen et al., 2021).

7.3 Contribution to Practical Applications

Modelling flood-regulating ES helps to better understand the contributions of ecosystems to human safety. This thesis shows that the modelling approach and the framework of ES indicator-based assessments can help to identify unmet flood-regulating ES demand and shortages in ES supply. It is particularly important for urban planning to understand the contributions of ecosystems concerning flood risk reduction. Based on this information, practitioners can assess the current and future performance of a system, and react and adapt measures to manage future conditions. Scenario modelling can assess the impacts of climate change and the benefits of NbS on flood-regulating ES and help to ensure long-term sustainability and effectiveness (Dwarakish and Ganasri, 2015). Therefore, scenario analysis by modelling is highly asked by policymakers to better inform decision-makers (IPBES, 2016). In this context, this thesis first highlights significant flood-regulating elements related to heavy precipitation that should be considered in urban planning (e.g. canopy interception). Furthermore, the methodological framework and the suggested indicators represent a first approach that can be used in urban planning to assess current and future flood-regulating ES.

The relevance of NbS was emphasized in the EU Biodiversity Strategy for 2030 (European Commission, 2020). This strategy aims to increase the implementation of NbS, urban greening, and biodiversity in urban planning. In this context, the results of this thesis provide theoretical insights into the benefits and performance of selected NbS, particularly urban trees and reduction of soil sealing, on flood-regulation, upon which urban planning can build (Kabisch et al., 2017; Zölch et al., 2017).

The visualization of flood-regulating ES modelling results with maps based on the methodological framework allocates a communication tool to support urban planning to adapt to climate change. Communicating the impact of climate change on ecosystems and their services, and the performance of planned measures such as NbS to decision-makers emphasizes the state, contribution and importance of ecosystems for human well-being and supports humans to adapt to current and projected future climate change (IPCC, 2021).

7.4 Outlook for future research

Flood-regulating ES assessments involve different disciplines and systems, which is why further research can be made at various levels. Figure 10 depicts the main contributing systems to flood-regulating ES including an overview of future research possibilities. The outlook emphasizes two options: hydrological modelling and flood-regulating ES assessment.

The hydrological model LEAFlood already offers a detailed spatial variability and considers canopy interception. For further development of the model, groundwater interactions and evaporation could be included. This would enable an analysis of the impact of high groundwater levels on surface water flooding and consequently the flood-regulating ES actual demand. By including evaporation, longer meteorological periods with lighter rainfall events (e.g. hours or days) could be investigated or the regulation by evaporation after a heavy rainfall event could be assessed. A further element to be considered in the LEAFlood model is the sewer system. This could be used, for instance, to compare the contribution of natural and grey infrastructure in flood-regulating ES performances (Kabisch et al., 2016).

Heavy rainfall often occurs locally on a very small scale. The current hydrological model was based on a time series that has the same effect over the entire area. For the present study, this is feasible due to the small study area. The implementation of spatially distributed precipitation based on radar data could be conceivably improve the model (Kreklow et al., 2019). This is particularly important for larger study areas and cities with higher buildings, where luv and lee effects of precipitation exist (Schlünzen et al., 2010).

So far, the most projections of changes in extreme precipitation events from regional climate models exhibit large uncertainties, as the rainfall convective processes are parameterised, and the results are still relatively unreliable. However, the ongoing development of so-called non-hydrostatic models that explicitly simulate convective precipitation is making substantial progress (Fosser et al., 2020; Fowler et al., 2021), and such projections could be used in future studies. With a further look at the temporal long-term dynamics, it must be noted that climate change influences beyond increased heavy precipitation or runoff were not taken into account. For instance, climate models project an increase in frequency and intensity of drought periods (IPCC, 2021). This dries out soils and can reduce their water absorption capacity. The consequences are reduced infiltration while the surface runoff increases (Liu et al., 2011). In addition, the vegetation cover can change due to climate change (IPCC, 2019).

Besides the presented adaptation measures of trees and unsealing, green roofs play an important flood-regulating role since they can be applied on a large scale in the city

(Bengtsson, 2005; Zölch et al., 2017). In Chapter 4, a simplified approach was utilised via the land use classification of the polygons. A more detailed consideration of green roofs and their specific hydrological performance of interception and reducing runoff is possible through further development of the existing model or, for instance, through a coupling with another existing model based on CMF by Förster et al. (2021).

The challenge of calibrating ungauged areas was already mentioned. While this was possible for Vauban in Chapter 4, there was a lack of data for Rostock in Chapters 5 and 6. Implementation of sensors at hotspots, that were more frequently affected by flooding during heavy rainfall events in the past, could partially reduce the data gap of observation measures and additionally increase the understanding of the complex hydrological system (Salvadore et al., 2015). Another possibility would be to use radar measurements or remote sensing.

The flood-regulating ES scenario analysis in this study focused on climate change scenarios in combination with NbS. In the next step, socio-economic scenarios that influence the potential demand and consequently the actual demand can be conducted. Models already exist for this (Mikovits et al., 2018; González-Méndez et al., 2021). Alternatively, assumptions can be made based on literature data, such as changes in population density or land use changes.

Building upon this, the ecosystem service values of biophysical or relative scales can, if necessary, be converted into economic values. For example, Yarnvudhi et al. (2021) found that around 700 trees in a park could yearly reduce 60 % of runoff, which makes a monetary benefit of approximately 100,000 USD. Monetary valuation is another indication to communicate the manifold value and benefits of nature and ecosystems to humans (Costanza et al., 1997).

Up to now, programming, hydrological modelling and GIS skills are needed to apply the framework. Hydrological background knowledge will be indispensable and GIS skills are useful to conduct a flood-regulating ES assessment based on model results. However, the required python programming know-how can be reduced by creating a toolbox, ideally with a user-friendly interface (Bach et al., 2014). This can be directly implemented into any geoinformatic system such as ArcGIS or QGIS (to make it open source). The product would be comparable to the existing flood-regulating ES model in InVEST (Sharp et al., 2020), but on a smaller and more flexible spatial scale based on single landscape elements, with a time series of meteorological input data and considering hydrological processes, such as infiltration and canopy interception.

Transforming the framework into a GIS-toolbox is one possibility to improve the practical application potential of this model study in urban planning. For practical application of the framework, stakeholders of urban planning should be involved to design the product according to user’s needs (Bach et al., 2014; Haase et al., 2014). Furthermore, stakeholders should be involved to define the mentioned ES demand scenarios but also the ES demand indicators (Wolff et al., 2015). Based on this decision, they can rank indicators that are not based on units (e.g. critical infrastructure or monuments) according to their protection value (Luederitz et al., 2015). For example, so far, all monuments were ranked the same with the highest demand. For future research, a classification of all monuments by their protection status can be conducted together with local stakeholders. Moreover, the current study only provides an overview of the influence of theoretical NbS. In future studies, their practical application should be investigated and discussed with stakeholders. Lastly, the involvement of stakeholders is particularly important to raise awareness regarding the impact of urban floods and also the potential benefits of NbS and flood-regulating ES as strategy for climate adaptation (Haase et al., 2014; Kabisch et al., 2016; Groth et al., 2020).

Besides improved flood-regulating ES, adaptation measures (e.g. NbS) in urban areas also have co-benefits with other ES. For instance, an increasing number of trees provides important climate regulation by shadow and transpiration, while unsealing increases evaporation and consequently contributes to cooling. Green spaces also contribute to recreation and mental health (Callaghan et al., 2021). Other ES are for example biodiversity, carbon sequestration, and air quality. However, NbS can bring disservices to ecology, economy, health, or psychology that need also to be investigated. For instance, trees can cause damage to people or infrastructure by roots or falling fruits and pollen can cause allergies (Döhren and Haase, 2015, 2019). Therefore, analysing NbS regarding co-benefits and trade-offs is an important future task, in order to better reveal the full range of direct and indirect effects of the implemented measures.

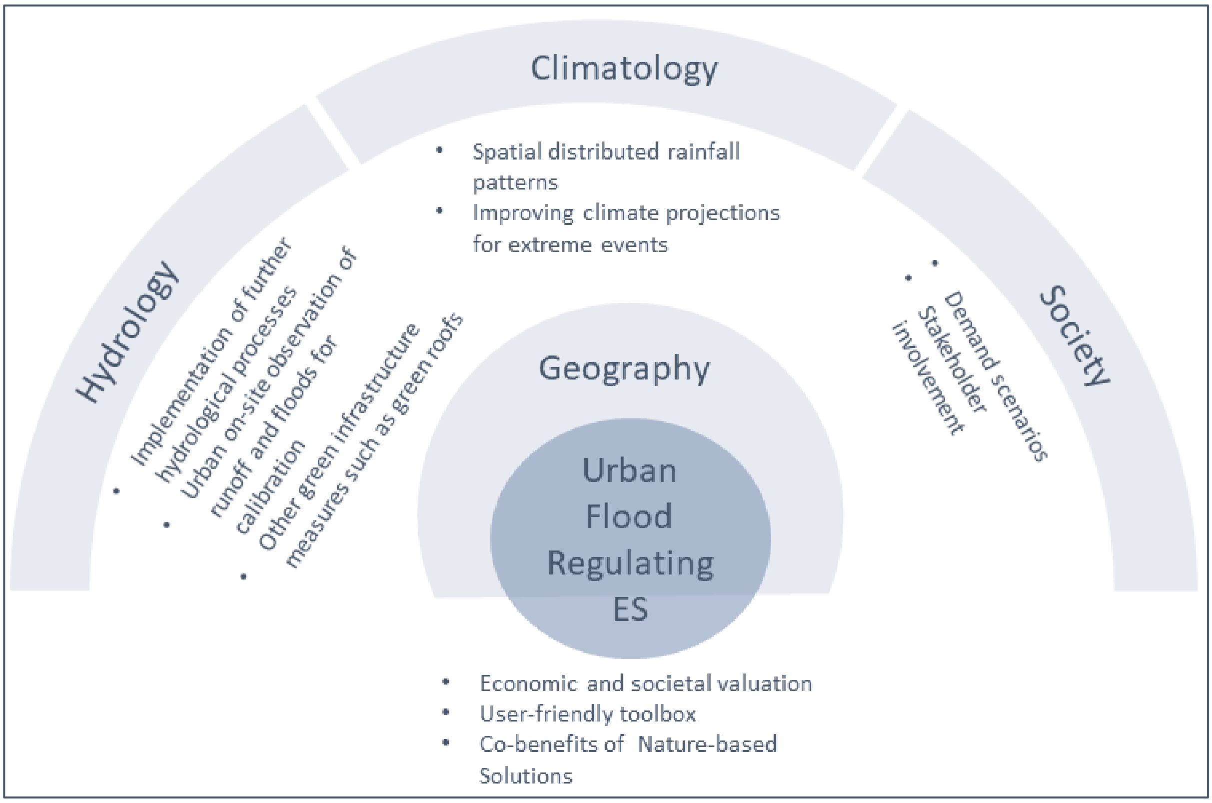


Figure 10: Schematical presentation of the future research options on pluvial flood-regulating ES for pluvial flooding divided by the main contributing systems.

7.5 Conclusions

The concept of ES links natural systems and socio-economic systems by highlighting the manifold contributions of ecosystems to human well-being. Systematic perspectives support the integration of various disciplines to analyse and evaluate human and environmental relationships. They translate biophysical results into ES as benefits for the social-economic system. Flood-regulating ES in particular focus on hydro-meteorological systems combined with landscape structures and their contribution to society. This goes beyond the risk assessment approach, as it emphasizes ES supply and ES demand by society simultaneously. The contribution of nature and ecosystems is valued to ensure sustainable urban development. This study provides empirical and theoretical insight into the dynamics of flood-regulating ES on three levels and with that, the study helps to fill relevant research gaps in flood-regulating ES studies.

Firstly, dynamics as a shift of scale and context from fluvial flood-regulating ES by rivers and catchments towards pluvial flood-regulating ES in urban environments was emphasized. Urban areas are particularly vulnerable and affected by pluvial floods. Mismatch analysis of ES supply and demand can reveal unmet demand and the need for adaptation. To achieve appropriate results at an urban scale, hydrological modelling at an adequate spatial resolution is necessary to represent the relevant hydrological processes, which play a key role in the regulation of heavy precipitation in cities.

Secondly, temporal dynamics were considered concerning the influence of climate change on flood-regulating ES. ES can provide solutions for adapting to climate change while their capacity and functionality are simultaneously affected by it. Climate change has a major impact on flood-regulating ES. For the investigated study areas, the results showed that the ES supply limit of the current ecosystems structures has been reached for current extreme hydro-meteorological events. Therefore, flood-regulating ES should be tested in regard to their future functionality and contribution to human well-being under changing climate conditions. Information about the impact of climate change on flood-regulating ES and related consequences for the social-economic system support urban planning to initiate possible adaptation measures to counteract climate change consequences.

Thirdly, NbS as a response by society to reduce negative impacts incorporates spatial dynamics of ES through land cover changes. NbS such as green and blue infrastructure can enhance ecosystems and their services. However, to ensure the sustainability and long-term contribution of ES and their enhancement by NbS, future performances under changing climate conditions must be properly assessed. Therefore, NbS should be tested in combination with climate change, as pressure and response on ecosystems and their flood-regulating ES. By mapping ES supply and demand changes due to climate change and NbS implementations, the effect of adaptation can be better understood and adjusted if necessary.

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Zölch, T., Henze, L., Keilholz, P., and Pauleit, S. 2017. Regulating urban surface runoff through nature-based solutions - An assessment at the micro-scale. Environmental research, vol 157, p 135–144. doi: 10.1016/j.envres.2017.05.023

APPENDIX

Summary of Master and Bachelor Thesis

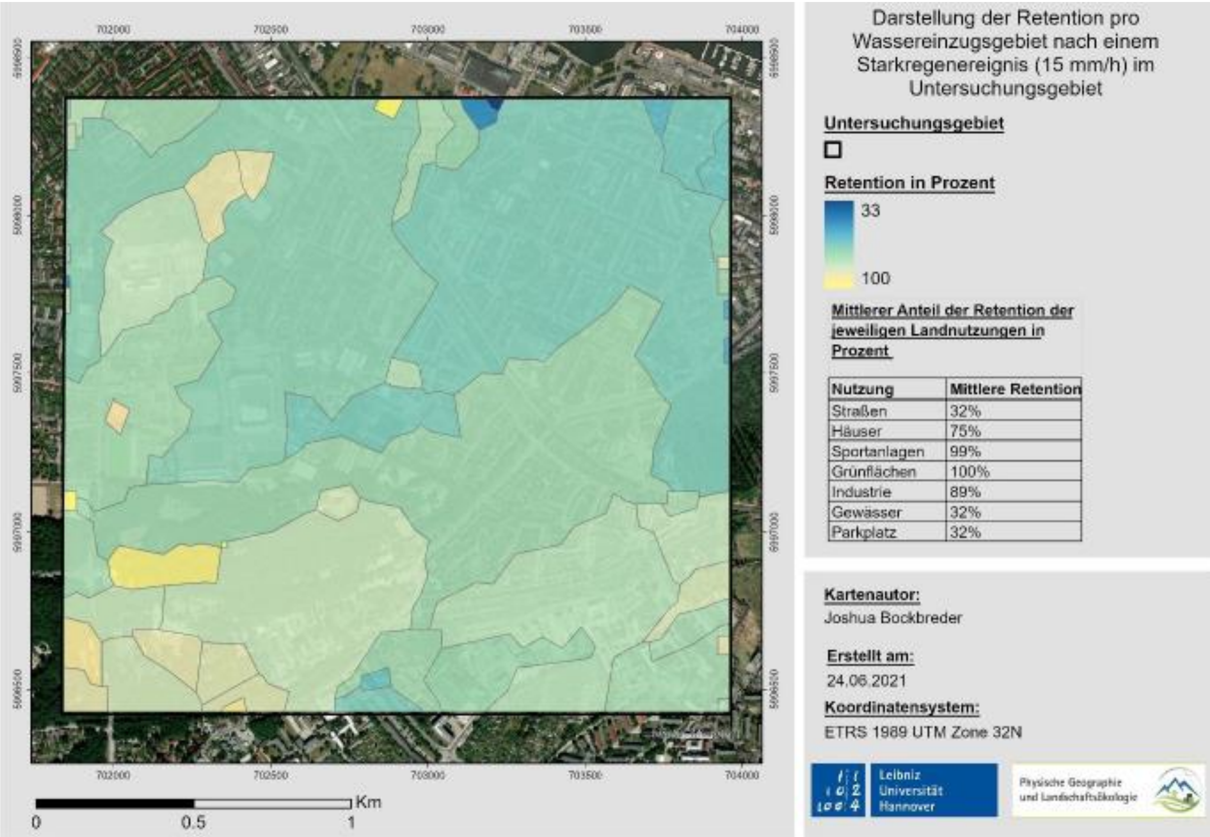
This Chapter gives an overview of Bachelor and Master theses that were written by students in Geography (Bachelor of Science level) and in Water Resources and Environmental Management (Master of Science level) in the context of this dissertation. They are cited in this dissertation and the most important results are summarized in the following.

Bachelor Thesis by Joshua Bockbreder

Joshua Charles Bockbreder (2021). Modellierung von Überschwemmungsrisiken im Rostocker Hansaviertel mit InVEST – Untersuchung der Auswirkungen von Landnutzungsänderungen. Leibniz University Hannover, 43 p. *Unpublished Bachelor Thesis.*

This bachelor thesis applied the Urban Flood Risk Mitigation Model from InVEST in a district of Rostock. Parts of this study area overlap with the study area in Rostock in this dissertation (chapter 2.5.3). Two rainfall events of 15 mm/h and 40 mm/h were analysed. In addition to the existing land use, the effect of two adaptation measures were tested: 1) Changing parking areas to green areas, 2) Implementation of green roofs. Since 15 mm/h corresponds more to the precipitation amounts selected in this dissertation, the following summary of the bachelor thesis focusses on this value. The figure below shows the runoff retention (no unit, relative to precipitation volume) of the existing land use for each watershed for a 15mm/h rainfall event.

The mean retention in the study area was 78% for a 15mm/h rainfall event. The results showed lowest retention in the northeast of the district where dense urban areas are present. Green areas had a retention up to 100%. Urban sealed areas, such as settlements and industry had a retention percentage of 70 to 90 % and streets 30%. The transformation of parking areas to green areas led to a retention change up to 17.8%. Small catchments at the outer had the highest changes. The second scenario of green roofs increased the retention up to 17% in some areas.



Nutzung	Mittlere Retention
Straßen	32%
Häuser	75%
Sportanlagen	99%
Grünflächen	100%
Industrie	89%
Gewässer	32%
Parkplatz	32%

Runoff retention for each watershed for a rainfall event of 15 mm/h modelled with the 'Urban Flood Risk Mitigation Model' of InVEST in the Hansaviertel a district of Rostock. Bachelor Thesis by Joshua Bockbreder.

Master Thesis by Karina Sinaí Medina Camarena

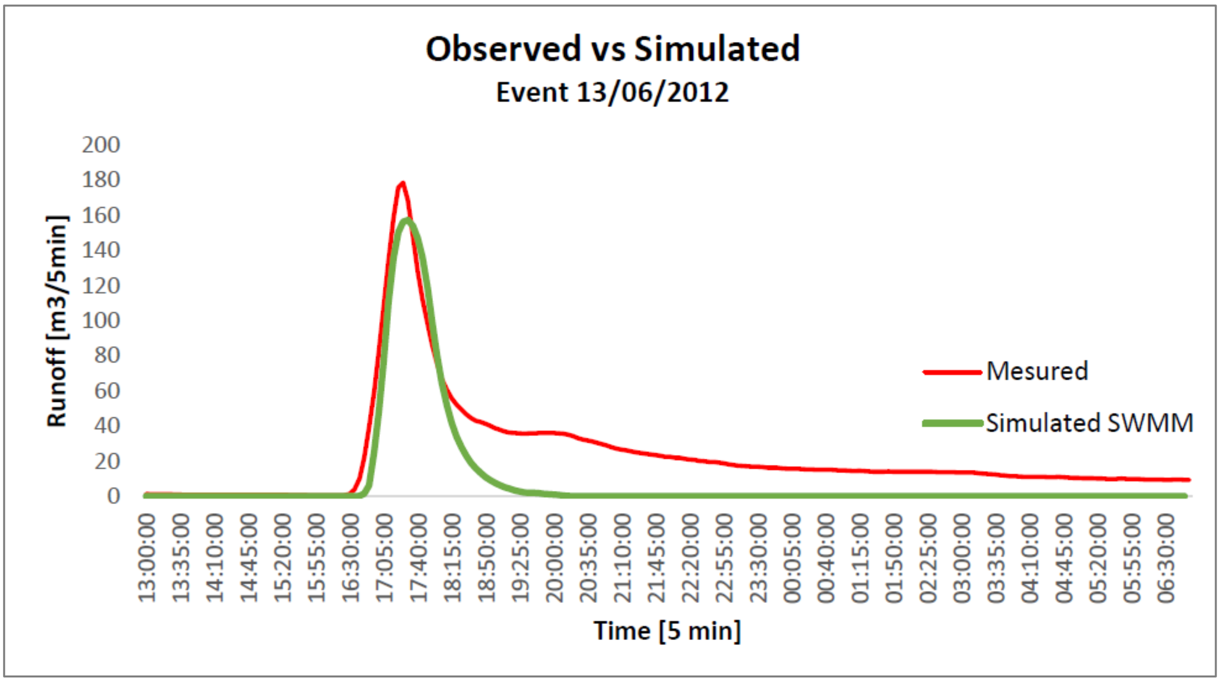
Medina Camarena, Karina Sinaí (2021): Quantification of stormwater runoff using two different models. Leibniz University Hannover, 94 p. *Unpublished Master Thesis.*

In this master thesis, the hydrological model SWMM (Storm Water Management Model) and the LEAFlood model were compared and calibrated about their performance to quantify runoff. Vauban, a district of Freiburg (Germany), served as a study area with a comprehensive measurement network of hydrological variables (presented in chapter 2.5.2). Three events were chosen for the calibration and two for validation. In addition, a sensitivity analysis of the most important parameters was carried out. Since LEAFlood was programmed within this dissertation (chapter 2.2.3.2) and the results were adjusted, published and presented in chapter 4, the focus of this summary is on the results of the EPA SWMM model.

SWMM is an open source software of the Environmental Protection Agency (EPA). The model offers hydraulic modelling, accounting for hydrological processes, pollutant load estimation and inclusion of GI and LID. In this work, the model was set-up based on 405 polygons considered as independent sub-catchment (see first figure). For infiltration, the Green-Ampt method was used according to the LEAFlood settings. Input parameters are the initial soil moisture deficit, the hydraulic conductivity, and the suction head at the wetting front. For surface routing, the kinematic wave was selected.

EPA SWMM model set-up for the study area Vauban. The colours represent land uses. Light green: Green Areas, Dark green: Green roofs, Grey: Sealed Areas, Yellow: Swales, Red: Outlets, Blue: Waterbodies. Master Thesis by Karina Sinaí Medina Camarena.

Based on the sensitivity analysis, a manual calibration was performed for three events. One represented event is shown in the following figure. For all three rainfall events, the calibration of the model showed an improvement of the runoff peak and timing. First, the model underestimated the peak runoff. With the calibration, an increase to the observed peak was achieved. The validation with two other rainfall events showed that the model overestimates the peak runoff and a time shift can be observed.



Comparison of calibrated EPA SWMM model results and observed runoff for a rainfall event (13.June 2012). Master Thesis by Karina Sinaí Medina Camarena.

Author contribution statements

Name	Thea Maria Wübbelmann
Subject	Geography
Topic of Dissertation	**Dynamics of Flood Regulating Ecosystem Services in Urban Areas** Modelling Heavy Rainfall, Climate Change impacts and benefits of Nature-based Solutions

Publication 1

Title	Modelling flood regulation ecosystem services dynamics based on climate and land use information
Authors	**Thea Wübbelmann**, Steffen Bender, Benjamin Burkhard
Year of publication	2021
Journal	Landscape Online, Vol 88
Own Contribution	Study Design, Data management and preparation, Modelling, Visualisations, Analysis, Writing, Revisions

Publication 2

Title	Modelling flood regulation ecosystem services dynamics based on climate and land use information
Authors	Karina Sinaí Medina Camarena, **Thea Wübbelmann**, Kristian Förster
Year of publication	2022
Journal	Hydrology
Own Contribution	Study Design, Model development, Visualisations, Writing, Revisions

Publication 3

Title	Urban ecosystems and heavy rainfall – A Flood Regulating Ecosystem Service modelling approach for extreme events on the local scale
Authors	**Thea Wübbelmann**, Laurens Menno Bouwer, Kristian Förster, Steffen Bender, Benjamin Burkhard
Year of publication	2022
Journal	One Ecosystem
Own Contribution	Study Design, Data management and preparation, Modelling, Visualisations, Analysis, Writing, Revisions

Publication 4

Title	Urban ecosystems and heavy rainfall – A Flood Regulating Ecosystem Service modelling approach for extreme events on the local scale
Authors	**Thea Wübbelmann**, Kristian Förster, Laurens Menno Bouwer, Claudia Dworczyk, Steffen Bender, Benjamin Burkhard
Year of publication	2022 (submitted)
Journal	Frontiers in Water
Own Contribution	Study Design, Data management and preparation, Modelling, Visualizations, Analysis, Writing

Curriculum Vitae

Thea Maria Wübbelmann

05. October 1993, Hannover (Germany)

Education

Since 10/2019	**PhD Candidate in Geography** Institute for Physical Geography and Landscape Ecology, Leibniz University Hannover Topic: Flood Regulation Ecosystem Services in urban areas under climate change Supervisors: Prof. Dr. Benjamin Burkhard and Apl.-Prof. Dr. Steffen Bender
10/2016 – 03/2019	**M.Sc. Landscape Sciences** Leibniz University of Hannover Focus: Climatology, Hydrology, GIS Master thesis: Assessment of runoff-enhancing nature-based solutions based on selected flood plain ecosystem services. Case study Schnackenburg under climate change conditions Research project: Modelling surface runoff after extreme events in the biosphere reserve Lower Saxonian Elbtalaue near Schnackenburg
10/2013 – 09/2016	**B.Sc. Geography** Leibniz University of Hannover Focus: Climatology, Hydrology Bachlor thesis: Comparison of meteorological data with results of the numerical simulation model FITNAH for selected locations in Hanover Study project: City climate Hannover
10/2012 – 09/2013	**B.Sc. Geodesy and Geoinformatics** Leibniz University of Hannover
2004 - 2012	Abitur, Graf-Anton-Günther Gymnasium Oldenburg

Professional Experiences

Since 06/2019	**Researcher and Doctoral Student** Climate Service Centre Germany (GERICS), Helmholtz-Centre Hereon
Since 09/2019	**Visiting Lecturer** Institute for Physical Geography and Landscape Ecology, Leibniz University Hannover
07/2018 – 03/2019	**Master student** Climate Service Centre Germany (GERICS), Helmholtz-Centre Hereon
04/2018 – 06/2018	**Internship** Climate Service Centre Germany (GERICS), Helmholtz-Centre Hereon
06/2017 – 08/2018	**Student assistant** Institute for Physical Geography and Landscape Ecology, Leibniz University Hannover
02/2017 – 03/2017	**Internship** University of Adelaide, Australia
09/2015 – 03/2018	**Student assistant** Umweltconsulting GEO-NET GmbH, Hannover
02/2015	**Internship** Niedersächsischen Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz, Hildesheim

List of Publications

List of Publication in the context of the PhD

Publication 1

Wübbelmann, T., Bender, S., Burkhard, B. (2021). Modelling flood regulation ecosystem services dynamics based on climate and land use information. In: Landscape Online, Vol 88, p 1-16, DOI 10.3097/LO.202188

Publication 2

Camarena, K., **Wübbelmann, T.**, Förster K. (2022). What Is the Contribution of Urban Trees to Mitigate Pluvial Flooding? In: Hydrology, 2022, 9, 108. https://doi.org/10.3390/hydrology9060108

Publication 3

Wübbelmann T., Bouwer L.M., Förster K., Bender S., Burkhard B. (2022). Urban ecosystems and heavy rainfall – A Flood Regulating Ecosystem Service modelling approach for extreme events on the local scale. In: One Ecosystem 7. https://doi.org/10.3897/oneeco.7.e87458

Publication 4

Wübbelmann T., Förster K., Bouwer L.M., Dworczyk, C., Bender S., Burkhard B. (2022). Urban flood regulating ecosystem services under climate change – How can Nature-based Solutions contribute? In: Frontiers in Water (submitted).

Python Code

Wübbelmann, T., Förster, K. (2022). LEAFlood - Landscape and vEgetAtion-dependent Flood model (Version 1). Zenodo. https://doi.org/10.5281/zenodo.6594181

List of Presentations in the context of the PhD

Wübbelmann, T., Burkhard, B., Bender, S. (2019). Comparison of two methods to calculate flood regulating ecosystem services. Indicator “flood retention capacity” and hydraulic modelling with HEC-RAS. 10th ESP World Conference in Hannover, Germany 21-25 Oct 2019. Poster presentation.

Wübbelmann, T., Burkhard, B., Bender, S. (2020). The relevance of Climate Information in the assessment of flood regulating ecosystem services. EGU, Vienna, Austria 04-08 May 2020. Poster presentation, online.

Wübbelmann, T., Bender, S., Burkhard, B. (2021). Wie können zukünftige Flutregulations-Ökosystemleistungen in urbanen Räumen erfasst und bewertet werden? DKT, Hamburg, Germany 15-18 Mar 2021. Poster presentation, online.

Wübbelmann, T., Förster, K., Burkhard, B., Bender, S. (2021). Urban flood regulation ecosystem services under climate change. A modelling approach for heavy precipitation events. 3rd ESP Europe Conference, Tartu, Estonia, 7-10 Jun 2021. Oral presentation, online.

Wübbelmann, T., Förster, K., Dworczyk C., Bouwer, L.M., Burkhard, B., Bender, S. (2022). Urban Ecosystems and heavy rainfall. Estimating the benefits of Nature-Based Solutions under changing climate conditions. 4th ESP Europe Conference, Heraklion, Greece, 10-14 Oct 2022. Oral presentation.

Other Publications and Presentations

Groth, M., Bender, S., **Wübbelmann, T.** (2020). Starkregen und Sturzfluten – Anwendung des GERICS-Stadtbaukasten in Bleckede – Report 34, Climate Service Center Germany, Hamburg.

Bender, S., Groth, M., **Wübbelmann, T.,** Bockbreder, J. (2022). Eine Starkregenmodellierung für zentrale Bereiche des Stadtgebiets Geesthacht unter Nutzung des Modells HEC-RAS. In preparation.

Atienza, S., Calicis, C., Candiago, S., Dendoncker, N., Desair, J., Fickel, T., Finne, E., Frison, C., Haensel, M., Hinsch, M., Kulfan, T., Kumagai, J., Mialyk, O., Nawrath, M., Nevzati, F., Washbourne, C., **Wübbelmann, T.** (2022). Transdisciplinary education: A leverage point to foster transformative change for biodiversity conservation. Insights from a Summer School. 4th ESP Europe Conference, Heraklion, Greece, 10-14 Oct 2022. Poster presentation.

Atienza, S., Calicis, C., Candiago, S., Dendoncker, N., Desair J., Espinosa, F., Fickel, T., Finne, E., Frison, C., Haensel, M., Hinsch, M., Kulfan, T., Kumagai, J., Mialyk, O., Muñoz, R., Nawrath, M., Nevzati, F., Ohlsson, M., Tsering, L., Washbourne, C., **Wübbelmann, T.** (2023). Head in the clouds, feet on the ground: How transdisciplinary learning can foster transformative change – insights from a summer school. In: Biodiversity and Conservation.