Urban Planning

Open Access Journal | ISSN: 2183-7635

Volume 6, Issue 3 (2021)

Smart Urban Governance for Climate Change Adaptation

Editors

Thomas Thaler, Patrick Witte, Thomas Hartmann
and Stan Geertman

COGITATIO

Urban Planning, 2021, Volume 6, Issue 3
Smart Urban Governance for Climate Change Adaptation

Published by Cogitatio Press
Rua Fialho de Almeida 14, 2º Esq.,
1070-129 Lisbon
Portugal

Academic Editors
Thomas Thaler (University of Natural Resources and Life Sciences, Austria)
Patrick Witte (Utrecht University, The Netherlands)
Thomas Hartmann (TU Dortmund University, Germany)
Stan Geertman (Utrecht University, The Netherlands)

Available online at: www.cogitatiopress.com/urbanplanning

Table of Contents

COGITATIO

Urban Planning (ISSN: 2183–7635)
2021, Volume 6, Issue 3, Pages 223–226
https://doi.org/10.17645/up.v6i3.4613

Editorial

Smart Urban Governance for Climate Change Adaptation

Thomas Thaler [1,]*, Patrick A. Witte [2], Thomas Hartmann [3] and Stan C. M. Geertman [2]

[1] Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences, Austria;
E-Mail: thomas.thaler@boku.ac.at
[2] Department of Human Geography and Planning, Utrecht University, The Netherlands; E-Mails: p.a.witte@uu.nl (P.A.W.), s.c.m.geertman@uu.nl (S.C.M.G.)
[3] School of Spatial Planning, TU Dortmund University, Germany; E-Mail: thomas.hartmann@tu-dortmund.de

* Corresponding author

Submitted: 18 June 2021 | Published: 19 August 2021

Abstract
Climate change will affect the way cities work substantially. Flooding and urban heating are among the most tangible consequences in cities around the globe. Extreme hydro-meteorological events will likely increase in the future due to climate change. Making cities climate-resilient is therefore an urgent challenge to sustain urban living. To adapt cities to the consequences of climate change, new ideas and concepts need to be adopted. This oftentimes requires action from different stakeholder groups and citizens. In other words, climate adaptation of cities needs governance. Facilitating such urban governance for climate adaptation is thus a big and increasing challenge of urban planning. Smart tools and its embedding in smart urban governance is promising to help in this respect. To what extent can the use of digital knowledge technologies in a collaborative planning setting be instrumental in facilitating climate adaptation? This question entails visualising effects of climate adaptation interventions and facilitating dialogue between governments, businesses such as engineering companies, and citizens. The aim of this thematic issue is to explore how the application of technologies in urban planning, embedded in smart urban governance, can contribute to provide climate change adaptation. We understand smart urban governance in this context both in terms of disclosing technical expert information to the wider public, and in terms of supporting with the help of technologies the wider governance debates between the stakeholders involved. The contributions reflect this dual focus on socio-technical innovations and planning support, and therefore include various dimensions, from modelling and interacting to new modes of urban governance and political dimensions of using technologies in climate change adaptation in urban areas.

Keywords
climate change; planning; resilience; risk management; smart technologies; smart urban governance; vulnerability

Issue
This editorial is part of the issue “Smart Urban Governance for Climate Change Adaptation” edited by Thomas Thaler (University of Natural Resources and Life Sciences, Austria), Patrick Witte (Utrecht University, The Netherlands), Thomas Hartmann (TU Dortmund University, Germany) and Stan Geertman (Utrecht University, The Netherlands).

1. Introduction

Extreme weather events, such as floods, droughts, water scarcity, or heat waves demand new responses and concepts to enable climate scientists and governments to address negative impacts of climate change on people and the environment. Extreme weather events are likely to increase in frequency and severity (Intergovernmental Panel on Climate Change, 2018). Urban areas are likely to be affected, as they are especially vulnerable to the impacts of a warmer climate because of urbanisation pressure and aging infrastructures (Feagan et al., 2019). Therefore, urban areas need innovative ideas and answers to current and future climate-related challenges (Andersson et al., 2021; Elmqvist et al., 2019; Ürge-Vorsatz et al., 2018). This makes climate adaptation an important task of urban planning.

Urban resilience has become already a goal for many policy makers at different levels (Meerow & Newell, 2019). Urban resilience to extreme weather events integrates social, ecological, and technological systems to provide adequate infrastructures to withstand a warmer climate (Tempels & Hartmann, 2014). This has implications for current modes of governance, decision-making processes, and a change of the current social practices of urban planning (Feagan et al., 2019). Urban planning plays a central role in attaining the goal of urban resilience (Bush & Doyon, 2019). For example, spatial planning can strengthen urban resilience in terms of influencing the urban structure.

A critical and yet understudied element in reaching the goal of urban resilience—in particular related to climate change—involves the use of technologies in planning, communication, and decision-making processes. In that, one can think of diverse technologies, ranging from websites collecting and/or providing relevant planning information (e.g., Maptionnaire) to instruments that support communication processes (e.g., Maptables) all the way to complex instruments for supporting design, modelling, and analysing activities (e.g., UrbanSim). The use of digital knowledge technologies in a collaborative governance setting promises to be instrumental in visualising effects of climate adaptation interventions and facilitating dialogue between governments, businesses such as engineering companies, and citizens. Hitherto, however, smart planning approaches have been mostly understood from a predominantly technocratic perspective (see, e.g., Hollands, 2008). In contrast, we advocate a more transformative and sociotechnical orientation, where the focus is on developing an interconnected and complex understanding of planning, which requires the use of technologies in planning processes to reach effective and efficient decisions (Jiang et al., 2020). We refer to this orientation as ‘smart urban governance.’ There are already numerous practical examples of smart urban governance that offer promising new modes of governance and methods of collaboration between decision-makers, stakeholders, and citizens. This thematic issue focuses especially on the contribution of smart urban governance for climate change adaptation. We understand this both in terms of disclosing technical expert information to the wider public, and in terms of supporting with the help of technologies the wider governance debates between the stakeholders involved.

The aim of this thematic issue is to present contributions across different disciplines that explore how technologies in urban planning (i.e., smart urban governance) can contribute to provide a robust response to extreme weather events caused by a warmer climate. The contributions reflect this dual focus on socio-technical innovations and planning support, and therefore cover various dimensions, from modelling and interacting to new modes of urban governance and the political dimensions of using technologies to effect climate change adaptation in urban areas.

2. Overview of the Thematic Issue

The articles in this thematic issue approach the connection between smart urban governance and climate change adaptation from different thematic, conceptual, methodological, and empirical orientations. When put in the light of the understanding of smart urban governance as presented before, we can structure the articles in two groups: more technology-dominant approaches on the one hand, and more governance-dominant approaches on the other.

Looking at the technology-dominant approaches, the article by Cai et al. (2021) focuses on the question of how geographic information and communication technology, in the case of LEAM (land-use evolution and impact assessment model), can assist planning processes in urban areas to reach urban resilience in the city, using the example of Nanjing (China). The article by Maiullari et al. (2021) uses a quantitative morphological method to map local climate typo-morphologies with the aim of understanding and assessing the different impacts of climate, such as temperature, wind, and humidity during a hot summer period, highlighting the risk of overheating, and showing how spatial planning might implement effective adaptation strategies to reduce the risk of overheating in Rotterdam (the Netherlands). The contribution by Brandt et al. (2021) focuses on the question of how uncertainties in flood risk management might support urban planning in terms of reaching urban resilience. Uncertainty zones play a critical role for spatial planners as these zones vary around different modeled flood boundaries. The article provides an idea of how to map uncertainties and their influence on actual decision-making processes.

How are smart tools embedded in urban governance? Davids and Thaler (2021) demonstrate how tailored advice communication strategies might encourage adaptive behaviour of private homeowners in the example of flood risk management in Flanders (Belgium) and Vorarlberg (Austria). The contribution shows that the role of smart technologies in flood risk management is highly influenced by co-evolutionary interaction between impact of climate change, actors, and the institutional framework. The article by Witte et al. (2021) evaluates the technical aspects and user experiences of technologies in flood risk management in the Netherlands. The article shows how different technical, analytical, and communicative qualities need to be addressed by smart flood risk assessment tools. Nevertheless, Witte et al. (2021) underline that smart governance approaches need more than a one-size-fits-all approach as residents assess flood risks not in a homogeneous way. The article by Sas-Bojarska (2021) takes a landscape perspective on climate change and looks into the added value of combining different governance tools and procedures in the case of urban planning in Poland. The article argues that a better understanding of the relation between environmental effects and the landscape can contribute to a better use of tools supporting spatial planning processes, which could positively influence the reduction of climate change. The article by Wright et al. (2021) shows how climate impact assessment influences regional planning processes. The article compares two regional climate change adaptation planning processes in Germany and the Netherlands showing the similarities and differences in terms of used methodologies, availability of data, and produced information in maps and how these assessment tools are used for visualisation and communication.

3. Conclusion

The selected articles within this thematic issue highlight the importance of using technologies in urban planning—smart urban governance—to provide adequate responses to the immediate climate challenges facing urban areas. The articles suggest that the introduction of technologies requires an urgent re-thinking of how decisions are made in urban regions. Consequently, the use of technologies offers and encourages an alternative understanding of governance; smart urban governance has become a crucial concept and an important alternative method to the current technocratic (top-down) governance of urban areas (Jiang et al., 2020).

The contributions show that technologies require new forms of urban governance arrangements and interactions between decision-makers and citizens. Nevertheless, the precise nature and scope of smart urban governance will depend on the needs and possibilities of the people in the different urban areas, as the articles in this thematic issue show. Smart urban governance includes a wide range of options and ideas, such as using different technologies like IoTs and AI, new administrative practices based on e-government, or new communication and collaboration tools with citizens (Jiang et al., 2020; Ruhlandt, 2018; Webster & Leleux, 2018).

The thematic issue provides evidence that technologies can be embedded into an urban system, thereby including different actors and stakeholders in the planning and decision-making process. The implementation of technologies allows urban areas not only to act more efficiently and effectively, but also encourages innovations, providing positive co-benefits, such as improved life satisfaction and biodiversity in cities. The use of technologies provides various advantages, but the planning and decision-making process should also address further complex questions, such as the issue of social equity. These issues are easily neglected but remain critical in terms of ensuring fairness and equality.

Acknowledgments

We gratefully acknowledge the help and support of the Urban Planning editorial staff in preparing this thematic issue. Further, we would like to thank the JPI-Urban Europe project FLOODLABEL for starting to question of the role of smart urban governance in climate change adaptation.

Conflict of Interests

The authors declare no conflict of interests.

References

Andersson, E., Haase, D., Anderson, P., Cortinovis, C., Goodness, J., Kendal, D., Lausch, A., McPhearson, T., Sikorska, D., & Wellmann, T. (2021). What are the traits of a social-ecological system: Towards a framework in support of urban sustainability. *npj Urban Sustainability*, *1*(1), 1–8.

Brandt, S. A., Lim, N. J., Colding, J., & Barthel, S. (2021). Mapping flood risk uncertainty zones in support of urban resilience planning. *Urban Planning*, *6*(3), 258–271.

Bush, J., & Doyon, A. (2019). Building urban resilience with nature-based solutions: How can urban planning contribute? *Cities*, *95*, Article 102483.

Cai, Z., Page, J., & Cvetkovic, V. (2021). Urban ecosystem vulnerability assessment of support climate-resilient city development. *Urban Planning*, *6*(3), 227–239.

Davids, P. R., & Thaler, T. (2021). Resilience communities: How we can encourage adaptive behaviour through smart tools in private-public interaction. *Urban Planning*, *6*(3), 272–282.

Elmqvist, T., Andersson, E., Frantzeskaki, N., McPhearson, T., Olsson, P., Gaffney, O., Takeuchi, K., & Folke, C. (2019). Sustainability and resilience for transformation in the urban century. *Nature Sustainability*, *2*, 267–273.

Feagan, M., Matsler, M., Meerow, S., Munoz-Erickson, T. A., Hobbins, R., Gim, C., & Miller, C. A. (2019). Redesigning knowledge systems for urban resilience. *Environmental Science & Policy*, *101*, 358–363.

Hollands, R. G. (2008). Will the real smart city please stand up? Intelligent, progressive or entrepreneurial? *City Analysis of Urban Change, Theory, Action*, *12*(3), 303–320.

Intergovernmental Panel on Climate Change. (2018). *Global warming of 1.5 ºC*. https://www.ipcc.ch/sr15

Jiang, H., Geertman, S., & Witte, P. (2020). Smart urban governance: An alternative to technocratic "smartness." *GeoJournal*.

Maiullari, D., Pijpers-van Esch, M., & van Timmeren, A. (2021). A quantitative morphological method for mapping local climate typo-morphologies. *Urban Planning*, *6*(3), 240–257.

Meerow, S., & Newell, J. P. (2019). Urban resilience for whom, what, when, where, and why? *Urban Geography*, *40*(3), 309–329.

Ruhlandt, R. W. S. (2018). The governance of smart cities: A systematic literature review. *Cities*, *81*, 1–23.

Sas-Bojarska, A. (2021). Landscape as a potential key concept in urban planning for the environment–the case of Poland. *Urban Planning*, *6*(3), 295–305.

Tempels, B., & Hartmann, T. (2014). A co-evolving frontier between land and water: Dilemmas of flexibility versus robustness in flood risk management. *Water International*, *39*(6), 872–883.

Ürge-Vorsatz, D., Rosenzweig, C., Dawson, R. J., Sanchez Rodriguez, R., Bai, X., Salisu Barau, A., Seto, K. C., & Dhakal, S. (2018). Locking in positive climate responses in cities. *Nature Climate Change*, *8*, 174–176.

Webster, C. W. R., & Leleux, C. (2018). Smart governance: Opportunities for technologically mediated citizen co-production. Information *Polity*, *23*(1), 1–16.

Witte, P. A., Snel, K. A. W., & Geertman, S. C. M. (2021). Less is more? Evaluating technical aspects and user experiences of smart flood risk assessment tools. *Urban Planning*, *6*(3), 283–294.

Wright, J., Flacke, J., Schmitt, J.-P., Schultze, J., & Greiving, S. (2021). Comparing climate impact assessments for rural adaptation planning in Germany and the Netherlands. *Urban Planning*, *6*(3), 306–320.

About the Authors

Thomas Thaler holds a PhD in Environmental Science and is currently working as a Post-Doc Researcher at the Institute of Mountain Risk Engineering at the University of Natural Resources and Life Sciences. His research and teaching activities focus on social justice, risk governance, and flood risk management.

Patrick A. Witte is Assistant Professor in Spatial Planning at Utrecht University. He is specialized in the interconnection of land use and transportation planning, with a particular focus on integrated corridor development and inland port development. He was the project coordinator of the JPI Urban Europe ENSUF project FLOODLABEL. His research interests are integrated spatial planning, transport infrastructure systems, transformations of cities, land use planning, and economic effects assessment.

Thomas Hartmann is Professor at the School of Spatial Planning at TU Dortmund University, Germany. He is also affiliated with Jan-Evangelista-Purkyně University Ústí nad Labem, Faculty of Social and Economic Studies. He conducts research on the relationship between land policy and its instruments, and flood risk management and retention. Additionally, he is President of the International Academic Association on Planning, Law, and Property Rights.

Stan C. M. Geertman is Professor of Planning Support Science and Chair of Spatial Planning at Utrecht University. He has published widely in both national and international journals and has published a range of (editorial) books. He is Editor of the international peer-reviewed journal *ASAP* and member of the editorial board of several other scientific journals. He has been member of several international conference organisations. He was principal investigator of the JPI Urban Europe ENSUF project FLOODLABEL.

Urban Planning (ISSN: 2183–7635)
2021, Volume 6, Issue 3, Pages 227–239
https://doi.org/10.17645/up.v6i3.4208

Article

Urban Ecosystem Vulnerability Assessment of Support Climate-Resilient City Development

Zipan Cai [1], Jessica Page [2,]* and Vladimir Cvetkovic [1]

[1] Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, Sweden; E-Mails: zipan@kth.se (Z.C.), vdc@kth.se (V.C.)
[2] Department of Physical Geography, Stockholm University, Sweden; E-Mail: jessica.page@natgeo.su.se

* Corresponding author

Submitted: 19 February 2021 | Accepted: 28 April 2021 | Published: 19 August 2021

Abstract

Climate change poses a threat to cities. Geospatial information and communication technology (Geo-ICT) assisted planning is increasingly being utilised to foster urban sustainability and adaptability to climate change. To fill the theoretical and practical gaps of urban adaptive planning and Geo-ICT implementation, this article presents an urban ecosystem vulnerability assessment approach using integrated socio-ecological modelling. The application of the Geo-ICT method is demonstrated in a specific case study of climate-resilient city development in Nanjing (China), aiming at helping city decision-makers understand the general geographic data processing and policy revision processes in response to hypothetical future disruptions and pressures on urban social, economic, and environmental systems. Ideally, the conceptual framework of the climate-resilient city transition proposed in this study effectively integrates the geographic data analysis, policy modification, and participatory planning. In the process of model building, we put forward the index system of urban ecosystem vulnerability assessment and use the assessment result as input data for the socio-ecological model. As a result, the model reveals the interaction processes of local land use, economy, and environment, further generating an evolving state of future land use in the studied city. The findings of this study demonstrate that socio-ecological modelling can provide guidance in adjusting the human-land interaction and climate-resilient city development from the perspective of macro policy. The decision support using urban ecosystem vulnerability assessment and quantitative system modelling can be useful for urban development under a variety of environmental change scenarios.

Keywords

climate change; climate-resilient city; ecosystem vulnerability; Geo-ICT; socio-ecological model

Issue

This article is part of the issue “Smart Urban Governance for Climate Change Adaptation” edited by Thomas Thaler (University of Natural Resources and Life Sciences, Austria), Patrick Witte (Utrecht University, The Netherlands), Thomas Hartmann (TU Dortmund University, Germany) and Stan Geertman (Utrecht University, The Netherlands).

1. Introduction

Climate change places increasing stress on the built environments of cities in the new era, bringing challenges to urban planning and development as well as urban services and management systems (Carter et al., 2015; Wamsler et al., 2013). Climate change impacts on cities, some of which are already being seen, include more frequent droughts, flooding, and other extreme weather events, flooding due to rising sea levels, and increasing temperatures and heat waves (worsened in cities due to urban heat island effects; Abiodun et al., 2017; Deilami et al., 2018; Fu et al., 2017). As socio-economic and ecological integrated systems, cities are likely to be subject to increasing disruptions due to climate change (Jabareen, 2013). The main reason is that the system integration is vulnerable and its self-regulation capacity is relatively weak and easily affected by the changes of external factors (Carmin et al., 2009). The challenge then is to better focus on human activities to cope with and minimise urban climate and environmental change impacts.

Because there are no international protocols on climate adaptation planning at the local level, and most national governments do not work together to address potential threats, some cities are developing independent goals and actions to jumpstart adaptive city development (Carmin et al., 2012; Roberts et al., 2011). Developing cities to be more climate-resilient is an increasing and pioneering effort jointly with actions to mitigate climate change (Dolman, 2021; Hofstad & Torfing, 2017). With the means of geospatial information and communication technology (Geo-ICT), some climate-resilient labelled cities have made progress in implementing timely responses to climate disasters, risk assessment of infrastructure, and coordination of urban planning and management (Aina, 2017; Mejri et al., 2017). Geo-ICT generally combines geographic information and ICT as a planning support system that facilitates efficient and effective governance, for example, through improving master planning, coordination, and cooperation (Meera et al., 2012). It includes the geographic information system (GIS), the spatial database management system, spatial information infrastructures, spatial decision support systems, and other geospatial technologies.

Verweij et al. (2020) presented a participatory method—QUICKScan—which promotes participatory use and transformation of geographic data to help stakeholders and decision-makers understand the human-land causality. Navarra and Bianchi (2013) proposed a cadastral system in which the operating process consists of a land management paradigm, Geo-ICT, and spatially enabled government to reduce greenhouse gas emissions (GHG), and further create sustainable urban governance dynamics. Pan et al. (2020) used a planning support system to model future land-use change and the related GHG to suggest spatial planning and policy changes that could significantly reduce the increase in GHG emissions associated with urban expansion to accommodate a growing population. Aina (2017) suggested a visual geographic information data platform to monitor the sustainability of cities' green facilities and the corresponding policy effects, aiming to create smart city development in Saudi Arabia. Hay et al. (2010) used the heat map overlay method to assess regional energy consumption and efficiency, allowing city planners and decision-makers to coordinate energy allocation and facility planning. The methods mentioned in all these and many other similar studies can be summarised into three groups of methods: tool-based planning regulation, risk reduction, and problem retreatment. Although one or more of these methods have similar principles and mechanisms and apply to solving the problems of local human settlements, the degree to which they are integrated into the overall urban planning is disparate and limited. Typical studies put forward the systematic problem-oriented approach based on Geo-ICT for the existing environmental problems but generally fail to translate the value of geographical data of various public sectors into feasible and specific planning schemes.

What can motivate city policymakers to plan for environment adaptation? Can intervention and effective incentives enhance stakeholders' participation in urban planning and policy? In this article, we describe a Geo-ICT-based socio-ecological model to enhance our understanding of the dynamic assessment of urban ecological vulnerability and the development possibilities of climate-resilient cities. To tackle specific local environmental and developmental issues, we used a city case study to quantitatively consider the prerequisites of environmentally adaptive planning and assess the feasibility of future urban growth. In the following sections, we discuss a dynamic socio-ecological model with a comprehensive assessment mechanism for urban ecosystem vulnerability and present a case study of the city of Nanjing (China) to support climate adaptation planning and the development of climate-resilient cities.

2. Methods

2.1. Geo-ICT for Climate-Resilient City Transition

Policy constraints and guidance for urban transformation and planning are complex, and policymakers need to take into account the impact of economic, social, natural, and spatial factors (Wardekker et al., 2020). The commitment to building a climate-resilient city requires a holistic operational approach (Lomba-Fernández et al., 2019). Therefore, we established a conceptual framework to answer major urban planning questions in a forward-looking way. Inspired by Jabareen (2009), and combined with the proposed technical processing means, we divided the Geo-ICT-assisted city transition into four steps and extracted the main concepts of the four parts, illustrated in the conceptual framework shown in Figure 1. According to our understanding, these four parts are related to each other and have a sequential relationship. The conceptual elements in each part are not only the interpretation and collection of the concepts of their respective parts but also the sub-concepts of the climate-resilient city transition.

The framework starts with urban governance and planning, as it is the primary element of city transition and a way to help meet the vision of a sustainable future. Early planning decisions can involve participation, open dialogue, and collaboration between actors, including government personnel, social groups, community and civil society organisations, and other local stakeholders. Discussions on the thematic planning scheme will be conducted in the direction of climate adaptation and future sustainability. The concrete implementation of these two objectives requires a deep understanding of the existing urban environmental and ecological problems. Therefore, in the second step, we use the method

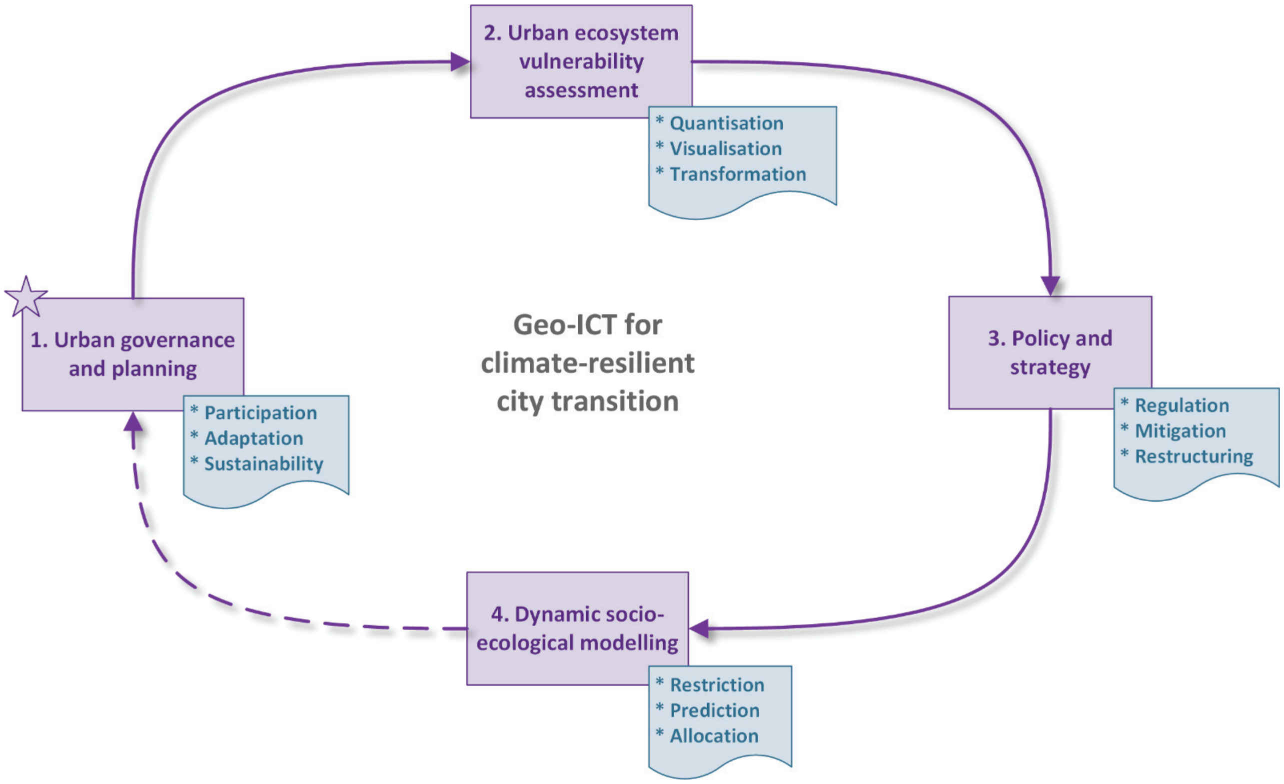


Figure 1. Conceptual framework of Geo-ICT for climate-resilient city transition.

of urban ecosystem vulnerability assessment to quantify and visualise the status quo of existing problems. We transform the results of the research data on urban ecosystem vulnerability into policy and strategic guidance information, aiming to make more integrated, deliberative, and balanced urban planning in terms of socio-economic and ecological development. In the third step, urban decision-makers can formulate binding policies on development for areas with fragile urban ecosystems, which can be through development regulation, environmental problem mitigation, or the restructuring of existing policy and strategy. To be more specific, according to the assessment results of urban ecosystem vulnerability, policy responses can be made to set up mandatory restricted construction areas or areas with high development priority, which can pave the way for the urban expansion simulation in the next step. In the fourth and the most critical step, we use the dynamic socio-ecological model to predict the future size, scale, and shape of cities to aid smart city planning. The detailed restriction policies of location development in the previous step will act as a decisive factor that shapes development possibilities and affects urban land allocation for future urban development and expansion. The dynamic socio-ecological model converts the assessment results of urban ecosystem vulnerability assessment into input data and combines a series of land-use change factors to generate future urban planning schemes. As a result, simulation outputs will be provided to urban decision-makers and all stakeholders for further discussion and guidance that connects back to the first step. Compared with the traditional urban planning guided by static ecological environment data analysis, this Geo-ICT planning support model with dynamic prediction and cyclic progressive optimisation provides decision-makers with more accurate assessment information.

2.2. Study Area and Data

Nanjing has the highest population density and is one of the largest (6598 km^2) and fastest urbanising cities on the southeast coast of China (see Figure 2). Studies show that the annual average temperature and precipitation in Nanjing have been continuously increasing while sunshine duration has been decreasing in the past 50 years (Li et al., 2018). The contradiction between human and land has gradually exposed the urban system to serious environmental problems in the region, including the urban heat island effect, flood disasters, water pollution, and so on (Gu et al., 2011). In response to the "Man and the Biosphere" program initiated by UNESCO, the city proposed to build a climate-resilient city to solve these ecological and environmental problems in the face of climate change (Ji et al., 2007). This strategic thinking was also reflected in the latest round of Nanjing's master planning schemes, in which urban planners try to adjust the land use planning to seek a more scientific and reasonable land development mode to adapt to climate change. Among them, the core planning programs, such as controlling the spread of construction land, ensuring the security of ecological patterns, and resisting the risk of natural disasters, are all carried out in the key analysis directions of urban environmental carrying capacity, ecological environmental sensitivity, and spatial development suitability (Qi & Gu, 2011). Taking Nanjing city as the focus area, this study not only caters to the local planning strategies guided by local policies but also further explores the feasibility and applicability of the Geo-ICT assisted planning model established.

The research data for this study includes local socio-economic data and ecological-environmental data of Nanjing city. Taking the dynamic socio-ecological model input as the standard, we also prepared the land use and land cover data of Nanjing in 2015 as the base year. We retrieved these geographical data from the Yangtze River Delta Science Data Centre (2019), the National Earth System Science Data Infrastructure and the National Science and Technology Infrastructure of China (2020), and the National Bureau of Statistics of China (2020). The detailed format and description of all the data are attached in Table 1 in the Supplementary File. Related data pre-processing including image editing, format conversion, coordinate system unification, and other operations are completed in the preliminary work of this study.

2.3. Urban Ecosystem Vulnerability Assessment

As for the assessment system of ecosystem vulnerability, different scholars and researchers have different professional experience, research priorities, and perspectives, thus no consensus has yet been reached. However, the index system in academic research can be roughly divided into a single type of regional index and a comprehensive index. From the perspective of general definition, urban ecosystem vulnerability corresponds to the stability of the ecological environment, which is the variation of ecological environment in a specific spatial region driven by natural or human activities; such change is often detrimental to human survival and development (Song et al., 2010; X. Zhang et al., 2017). Therefore, when dealing with the urban ecosystem vulnerability assessment, we need to not only consider the internal function and environmental structure but also the connection between the environment and the socio-economic dimension, which requires a relatively comprehensive index system. Considering the ecological environment characteristics, the regional scale of the study area, and the local geographic data availability while referring to the existing correlation study results of the natural ecosystem and urban system, we adopted the "Sensitivity-Pressure-Elasticity" index system (Qiao et al., 2008). Among them, ecological sensitivity refers to the degree of sensitivity of the ecological environment to external natural factors and disturbances caused by perceived factors, reflecting the ability of the urban ecosystem to resist external disturbances. Ecological pressure refers to the pressure brought by natural disasters, human needs, and social and economic development to the ecological environment. Ecological elasticity refers to the ability of the ecosystem to self-adjust and recover to its original state under the premise that external disturbance or pressure does not exceed the elastic limit. Given the above, we constructed the following ecosystem vulnerability index (EVI) structure (see Table 1).

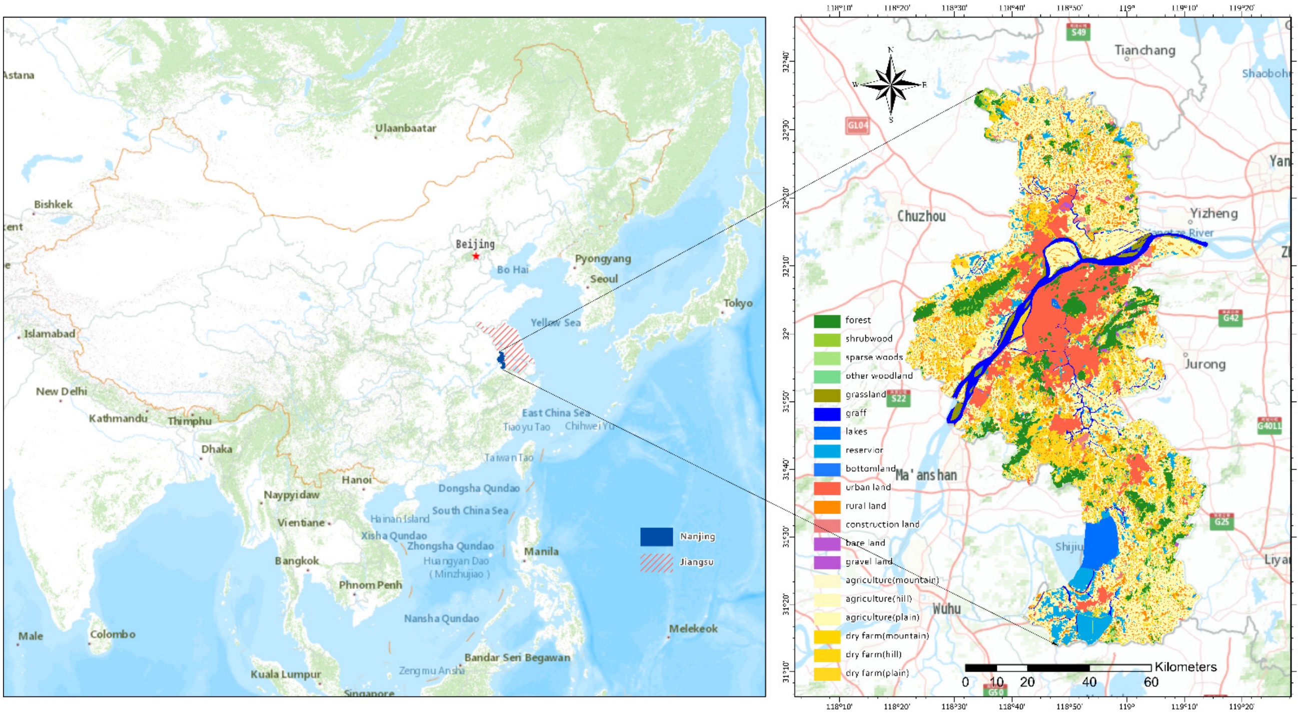


Figure 2. Location and map of Nanjing (China).

Table 1. Index system for urban ecosystem vulnerability assessment in Nanjing.

Primary index	Secondary index	Tertiary index	Calculation method description of the tertiary index
Ecosystem vulnerability index (EVI)	Ecological sensitivity index (ESI)	X1: Degree of soil erosion	Calculated by the equation of soil and water loss (Wan et al., 2006)
		X2: Terrain factor	Calculated by the digital elevation model index conversion
		X3: Landscape sensitivity	Degree of landscape convergence and richness (Fu et al., 2017)
	Ecological pressure index (EPI)	X4: Construction pressure	Ratio of construction land per square kilometre (Han et al., 2016)
		X5: Population pressure	Standardised population density
		X6: Economic pressure	Standardised volume level of GDP
	Ecological elasticity index (EEI)	X7: Vegetation productivity	Normalised difference vegetation index
		X8: Nature protection factor	Standardised importance level value of nature reserves
		X9: Regional environmental suitability	Principle multi-criteria assessment on the data of annual average precipitation, temperature, and water distribution (Jafari & Zaredar, 2010)

Note: The importance level of nature reserves is retrieved from "Regulations of the People's Republic of China on Nature Reserves" (National Earth System Science Data Infrastructure & National Science and Technology Infrastructure of China, 2020), and it includes national and regional protection areas.

To synthesise the calculation of the urban EVI, we suggest the three-helix assessment model, which is a comprehensive evaluation suitable for the compromised relationship among ecological sensitivity, pressure, and elasticity of the "society-nature" coupled system. The calculation formula is as follows (Hong et al., 2016):

$$EVI = f(ESI, EPI, EEI) = \sum_{x=1}^{n} \left(ESI_x \times w_s\right) + \sum_{x=1}^{n} \left(EPI_x \times w_P\right) + \sum_{x=1}^{n} \left(EEI_x \times w_E\right) \quad (1)$$

where ESI_x, EPI_x, EEI_x are respectively the ESI, EPI, and EEI of each cell in raster data while w_s, w_P, w_E are the weights of the three indexes respectively. Since each calculated space vector needs to be weighted to carry out multivariate statistics, we use the spatial principal component analysis method in the GIS spatial analysis module (Rahman et al., 2015). This geoprocessing method calculates the principal component of space and its contribution rate, using the formula:

$$F = \sum_{i=1}^{m} F_i \times \frac{\gamma_i}{\sum_{i=1}^{m} \gamma_i} \quad (2)$$

$$w_j = \sum_{i=1}^{m} \left(\frac{b_{ij}}{\sqrt{x_j}} \times \frac{\sqrt{\gamma_i}}{\sum_{i=1}^{m} \gamma_i} \right) \Big/ \sum_{j=1}^{n} \sum_{i=1}^{m} \left(\frac{b_{ij}}{\sqrt{x_j}} \times \frac{\sqrt{\gamma_i}}{\sum_{i=1}^{m} \gamma_i} \right) \quad (3)$$

where F is the overall (global) index, F_i is the i^{th} principal component for spatial principal component analysis, m is the number of components, γ_i is the characteristic vector value of the i^{th} principal component, w_j is the weight of the j^{th} index, n is the number of indices, $\sqrt{x_j}$ is the standard deviation of the j^{th} index, and b_{ij} is the load coefficient of the i^{th} principal component on the j^{th} index. Thus, the secondary index in equation (1) and their weights can be calculated using equations (2) and (3).

In addition, we also need to consider the positive and negative correlation between the secondary index and the primary index. Therefore, we conduct data standardisation processing before calculation:

$$\text{For positive index: } P_f = (P - P_{\min}) / (P_{\max} - P_{\min}) \quad (4)$$

$$\text{For negative index: } P_f = (P_{\max} - P) / (P_{\max} - P_{\min}) \quad (5)$$

where P_f is the index standardisation value, P is the original value, and $P_{\max}$ is the maximum index value while $P_{\min}$ is the minimum index value. In the proposed index system, ESI and EPI are positive correlation indices while EEI is a negative correlation index.

2.4. Dynamic Socio-Ecological Modelling

In order to generate results of a phased policy that relates to dynamic urban development, we established a LEAM-based socio-ecological model, which supports the input of urban ecosystem vulnerability as a constraint for future land development. LEAM stands for the land-use evolution and impact assessment model, which is a smart planning support tool for urban dynamic spatial simulation. LEAM is a spatial model which predicts the future development locations in a study area with fine-scale (30 × 30m) gridded output maps (Deal et al., 2013; Deal & Pallathucheril, 2008; Pan et al., 2018).

This modelling tool was originally developed for use in Illinois, USA, and has been adapted in this work for use in Nanjing. Some of the latest studies with the LEAM model indicate that the model is suitable for visualisation, quantitative, and data transformation support (Cai et al., 2020; Pan et al., 2019; L. Zhang et al., 2021). Similar to the operational theory of cellular automata, LEAM consists of a simulation environment in a grid space where the cell properties would be transformed according to defined transformation rules and vicinities. Before the establishment of cell transformation rules, a set of initial drivers and projections will be imported as referenced factors for the land-use change simulation. The drivers cover both physical geographical (water, soil, slope, and other landforms) and socio-economic aspects (residence, employment, road network, administrative boundaries, and other planning areas). The urban land-use change drivers indicate the complex interaction between the urban system and the surrounding environment. All of the factors combine and interact in a variety of ways in the model to assign probabilities of potential land-use changes to each 30 × 30m cell in the studied grid space. The distribution of these urban built-up land change probability values is the result of the general superposition of local and global effects. It includes causal change mechanisms, such as the accessibility of cells to city attractors, the constraints of the ecological environment, the social-economic impact, and the stochastic disturbance. Among them, we extract the urban ecosystem vulnerability assessment result as the constraints on growth and consider zoning effects on urban land expansion. The change possibility of each land-use cell from urban unbuilt-up area to built-up area is defined as:

$$P_{i,\,t} = \alpha(A_{i,t} + N(\theta_{i,\,t-1}))ʃ(R_{i,t}) \tag{6}$$

where $P_{i,\,t}$ is the land-use change probability for land-use cell i at time step t, α is a stochastic disturbance parameter that facilitates the generated patterns to be closer to reality, $ʃ(R_{i,t})$ is the function of multiple growth restrictions and planning zoning effects on land-use types for land-use cell i at time step t, and $A_{i,t}$ is the accessibility value for land-use cell i at time step t, and is defined as:

$$A_{i,t} = \frac{\sum_{j=1}^{n} a_{i,j} w_{i,j}}{n} \tag{7}$$

where $a_{i,j}$ is the attraction power of land-use cell i to urban attractor cell j while $w_{i,j}$ is the corresponding weight and n is the total number of the attractors.

We aim to quantify how urban built-up areas are shaped by location-choice factors including population and employment centres, highways and major streets, forest and water resources, and compare the agglomeration and dispersion of developed lands in different urban areas. The location-choice factors are defined as attractors in this study under the assumption that they determine the surrounding development in a gravity-type function in which the attraction power decays with increased distances. This gravity function can be determined through the shortest distance algorithm and data value from various sources. This study uses Pan et al.'s (2018) parallel stochastic greedy algorithm to find the shortest distance and the inverse distance model to determine the attraction value for population, employment, and transportation attractors. In this inverse model, for each attractor j, its attraction to land-use cell i is noted as $a_{i,j}$ and is calculated as:

$$a_{i,j} = \sum_{k\in S_j} \frac{p_k}{d_{ij}} \tag{8}$$

where S_k is the set of attractors of type j, p_k is the attraction value of the k_{th} attractor in S_k, d_{ij} is the distance between the k_{th} attractor in S_k, and land-use cell i is calculated by stochastic greedy algorithm.

In addition, $N(\theta_{i,\,t-1})$ in formula (1) is the function that converts the nearest neighbouring effects to a probability value and is defined as:

$$N(\theta_{i,\,t-1}) = \frac{\sum_{1}^{k} (N_{pr,t-1} + \sigma_i)}{k} \tag{9}$$

where $N_{pr,t-1}$ is the development possibility for neighbourhood cells in time step $t-1$ while σ_i is a spread coefficient over all surrounding cells ($k \leq 8$).

In the LEAM model, land-use transformation potential cells are assessed by explicit quantification drivers which contribute to the urban land-use change. The causal mechanisms involved in knowledge change provide local decision-makers with the opportunity to test policy and investment decisions that are key components of the scenario planning exercise and are different from the traditional static geographic data analysis led by the specific planning. The accessibility approach based on formula (7) is used to measure the current land-use cells of cities and population centres to help identify areas where re-development of existing developed land is highly likely. The probability mapping of future urban land-use development (calculated by formula 6) is based on model calibration and scenario setting. The details on model calibration, validation, and parameter tuning can be found in Appendix B in the Supplementary File.

3. Results and Discussions

3.1. Urban Ecosystem Vulnerability Assessment Results

According to the defined equation of the urban EVI (in Section 2.3), we used the raster calculator and the band arithmetic tool in ArcGIS Pro to generate the evaluation result for Nanjing (see Figure 3). The standardised data results of three sub-indexes ESI, EPI, and EEI are also attached in Figure 4. Based on the distribution of EVI results, we assigned five evaluation grades based on the index range (equal interval) and calculated the area proportion of each index grade as shown in Table 2. By summarising the information in the figure and table, we can see that the spatial heterogeneity of ESI, EPI, and

EEI in the study area is high, and the ecological sensitivity, pressure, and elasticity of each region are different. Among them, the area of very low sensitivity ESI in the study area accounted for the largest proportion—78.6%—which is mainly distributed in the north and south along the river plain. On the contrary, the EPI result shows the characteristics of urban agglomeration and distribution because it is related to human social activities. It occupies the highest proportion in areas with very high-pressure—62.5%—while the main land use in these areas is urban built-up land and farmland area. From the EEI result, areas with the highest area ratios are moderate and high—36.4% and 35.2% respectively. The areas involved are mostly urban built-up land, and the junction and boundary of urban built-up land, farmland, and grassland. When the results of the three sub-indices were added into the range method and weighted, we obtained the EVI with a completely different evaluation grading and distribution result. The EVI values of moderate-, low-, and high-grade areas were basically the same, and accounted for the highest proportion. These areas are mainly distributed along the urban development boundaries. Also, some highly ecosystem-sensitive areas are distributed in the special terrain and landforms. For example, steep mountain areas are prone to ecological risks of soil and water loss while water sources and wetlands near the Yangtze River are susceptible to flood disasters. In general, the distribution of low ecosystem vulnerability areas presents an increasing “circle-layer” distribution from the urban centre to the areas where green space is more concentrated. The existing urban land is mostly distributed in plain regions, where the intensity of land development is high and the vegetation is scarce. The ecosystem vulnerability of urban land represented by the central urban area and the adjacent suburban areas is high. However, the areas with moderate EVI have a relatively better ecological environment, stronger ecological anti-disturbance ability, and better

Figure 3. Urban EVI in Nanjing.

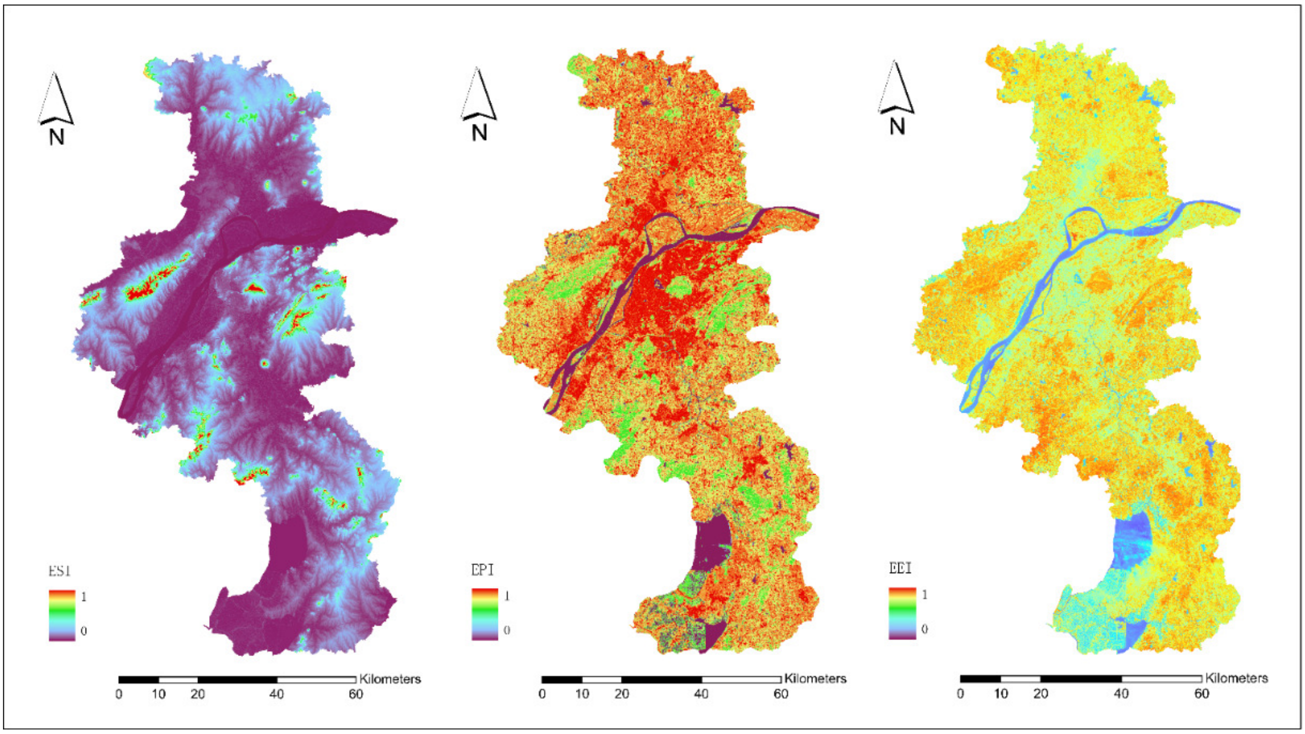


Figure 4. Standardised data results of three sub-indexes of ecosystem vulnerability in Nanjing.

disaster recovery ability. Ideally, these areas with low urban ecosystem vulnerability would be the preferred areas for future urban land development, regardless of other economic and social factors.

There is a close relationship between land use and land cover patterns and urban ecosystem vulnerability. The dominant factor of urban ecosystem vulnerability is the change of land use and land cover during urbanisation, that is, the transformation of natural vegetation to arable land or from arable land to urban construction land. Apart from rivers, lakes, and steep mountain landforms, urban construction land is the most vulnerable type of land use. The northern and southern suburban areas are mainly faced with the risk of cultivated land loss and landscape fragmentation and are also the main distribution areas of medium and high vulnerability. The ecosystem vulnerability of grassland forest areas in the plain is low, but it has a certain risk of soil erosion.

3.2. Dynamic Socio-Ecological Modelling Results

Although the results of the urban ecosystem vulnerability assessment guide the direction of future urban development in a certain sense, the specific development still needs to follow the basic driving mechanism of urban land-use change (Chen et al., 2016). Therefore, in the socio-ecological model, we set EVI values between 0 and 1 in advance and regard it as an important part of the possibility of urban land-use change (see Equation 6). The area with an EVI of 1 was defined as the restricted construction area to keep the most vulnerable areas from further development. As a result, we obtained the final simulated urban built-up land in 2040 in Nanjing through the established dynamic socio-ecological model (see Figure 5). It can be noted that the future urban built-up land area in 2040 mainly expands outward from the existing urban land agglomeration areas and are

Table 2. The area proportion of the primary and secondary index of urban ecosystem vulnerability in each evaluation grade of Nanjing city.

		Area proportion (%)			
Evaluation grade	Range of index	EVI	ESI	EPI	EEI
Very low	0–0.2	13.4	78.6	4.8	6.2
Low	0.2–0.4	26.2	6.1	5.5	16.3
Moderate	0.4–0.6	26.4	3.2	12.3	36.4
High	0.6–0.8	22.7	6.8	14.9	35.2
Very high	0.8–1	11.3	5.3	62.5	5.9

Note: The result of area proportion is derived from the proportion of the number of pixel cells in the total number of cells in each index range by ArcGIS.

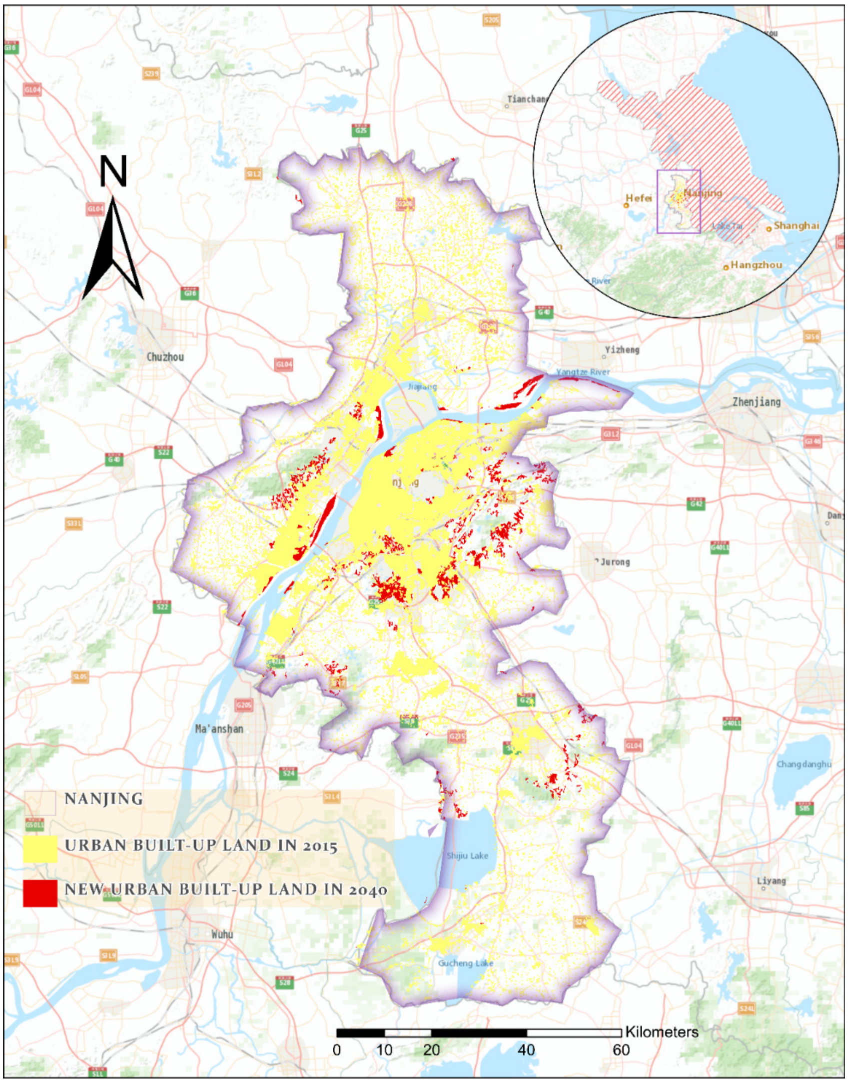


Figure 5. Prediction map of new urban built-up land in 2040 in Nanjing.

scattered and orderly around the urban built-up land in 2015. In addition to the central city area, some future urban areas are distributed in the new urban area on the north bank of the Yangtze River while a small number of areas are distributed in the suburban area in the south of the city. The predicted development results are broadly consistent with Nanjing's comprehensive plan for 2040 in the direction, area, scale, and other aspects of the growth plot. However, in terms of development details, the intensity of development in areas with fragile urban ecosystems is more emphasised in our modelling result.

3.3. Analysis of Results to Inform Planning and Policy

If we incorporate the periodic results of urban ecosystem vulnerability assessment and urban land growth simulation into the conceptual framework of Geo-ICT assisted climate-resilient city transition described above, we find that this is beneficial to both climate adaptation in urban planning and the future sustainable development of the city. Firstly, it is suggested to adopt different protection and restrictive development strategies according to the results of urban ecosystem vulnerability assessment in Nanjing. For example, for the fragile mountainous areas in the northern part of the city dominated by ecological sensitivity, a conservation strategy should be adopted, such as closing mountains for forest cultivation, returning farmland to natural grasslands, and gradually restoring the damaged natural forest and grassland ecosystems. For the regions with low ecological elasticity, rational utilisation of resources should be carried out to increase the area of artificial forest, to avoid human economic activities exceeding the scope of regional ecological carrying capacity. For the urban core areas with high ecological pressure, the future development intensity needs to be limited, and ecological corridors should be further improved to increase the urban green space area. Secondly, the predicted growth urban area can be used as the recommended priority area for future planning and development, as well as the reference basis for realising and adjusting development expectations. To be more specific, it can be the rational adjustment of the vision of urban social and economic future development, including the distribution of population growth, employed population growth, road planning, economic growth, and so on. Lastly, the simulation results can be generated repeatedly after the development vision is updated and changed; it can even lead to secondary and in-depth participatory deliberations leading to a more socially and ecologically sound viable development scheme.

Supporting policy exploration and implementation demonstrates the applicability of the Geo-ICT assisted modelling approach. Although future urban development is faced with uncertainties, a visualisation and data-based prediction of urban growth results increases the possibility of the vision development direction to meet the multiple demands from many actors in the city. Theoretically, urban planners can adopt advanced layout and rational planning to protect the urban natural system, the built environment, and the human living environment to minimise the impact of disruptive climate change on cities and their inhabitants. In practice, the implementation of such planning is difficult and often highly dependent on local and regional conditions. However, we can always set up different EVI systems based on the local geographical characteristics to adapt to different cities and regions. Whether to adjust the model parameters and forecast time to get the simulation results expected in accordance with planning needs to be determined according to the planning scale and policy standards of different regions. Different development scenarios can even be formulated in the policy and strategy phase according to the development needs to reveal the process trends and influencing factors of urban evolution in the future.

4. Conclusions

This article presents a Geo-ICT approach for climate-resilient city transition, which also answers the key questions about what, when, and how to guide urban policymakers in planning towards a more sustainable and climate-resilient urban development. This approach not only accounts for the imperfection of the support system in the conceptual framework of city planning but also proposes a scientific methodological guidance scheme using existing Geo-ICT-related technologies. Through a case study of Nanjing, we argue for specific types of incentives that promote institutional change and urban adaptation planning to respond to the call for climate-resilient city development. Our research results provide decision support for the subjective urban development, as well as ideas for the process of universal urban adaptive planning in a broad sense.

The main findings of this study are that: i) the transformation of the periodic geographical data results of urban ecosystem vulnerability assessment into policies and strategies for sustainable development provides a methodology for the continuous revision of urban governance and planning; ii) the interaction and causality between the local environmental ecosystem and the socio-economic system simplified and summarised by the socio-ecological modelling method, can help policymakers understand the specific impacts of proactive policy interventions; and iii) the simulated future urban growth can provide a reference for urban development goals and planning schemes because it intuitively and effectively shows to what extent urban land can be developed and the priority of the development in the region at a future time. These findings not only confirm the value of Geo-ICT-assisted planning through the socio-ecological model construction, but also expose new possibilities for city adaptive planning and the policy-making process. Ideally, the generated information from the comprehensive modelling process is an added value of detailed planning support, which can help planners effectively collaborate, communicate, and reach consensus. Through the city-based case study, we find that as a supplement to planning experience knowledge, the Geo-ICT approach integrated multi-planning policy-making and complex model simulation methods through progressive thinking and provided a circular way of exploring potential urban development possibilities.

In practice, the transformation from the Geo-ICT modelling results into concrete implementation measures still requires a means of adapting to local conditions. We must pay attention to the results of a planning scheme that relies entirely on the Geo-ICT approach to respond quickly to ecological priority development scenarios and whether they ignore the reality of capital dominance. The extent to which economic development benefits are limited by the specific development distribution advocated, how much ecological vulnerability risks caused by climate change are avoided, and how to balance the advantages and disadvantages of multiple planning schemes need to be further explored in future studies. Furthermore, we need to explore the influence and feasibility of urban development beliefs and goals on the modelling of scientific urban development because it may lead decision-makers into a dilemma between maintaining the status quo and acting more aggressively. Therefore, in future studies, one must analyse more accurately the relationship between urban ecosystem vulnerability and the possibility of future urban development, explore the geomorphological categories of existing land plots occupied by urban growth land, and calculate the possible loss of urban ecosystem service value. In this manner, we can more strongly link practical measures to on-going activities and thereby better support planning and implementation that is adapted to specific development expectations and goals.

Acknowledgments

The authors would like to express appreciation to Prof. Deal Brian and Prof. Huang Xianjin for their valuable opinions on the initial ideas of the article. The authors also highly appreciate the four anonymous reviewers for providing helpful and constructive comments and suggestions.

Conflict of Interests

The authors declare no conflict of interests.

Supplementary Material

Supplementary material for this article is available online in the format provided by the authors (unedited).

References

Abiodun, B. J., Adegoke, J., Abatan, A. A., Ibe, C. A., Egbebiyi, T. S., Engelbrecht, F., & Pinto, I. (2017). Potential impacts of climate change on extreme precipitation over four African coastal cities. *Climatic Change*, *143*(3), 399–413.

Aina, Y. A. (2017). Achieving smart sustainable cities with GeoICT support: The Saudi evolving smart cities. *Cities*, *71*, 49–58.

Cai, Z., Wang, B., Cong, C., & Cvetkovic, V. (2020). Spatial dynamic modelling for urban scenario planning: A case study of Nanjing, China. *Environment and Planning B: Urban Analytics and City Science*, *47*(8), 1380–1396.

Carmin, J., Anguelovski, I., & Roberts, D. (2012). Urban climate adaptation in the Global South: Planning in an emerging policy domain. *Journal of Planning Education and Research*, *32*(1), 18–32.

Carmin, J., Roberts, D., & Anguelovski, I. (2009). Planning climate resilient cities: Early lessons from early adapters. In *Proceedings of the World Bank Fifth Urban Research Symposium on Cities and Climate Change: Responding to an Urgent Agenda* (pp. 5–8). World Bank.

Carter, J. G., Cavan, G., Connelly, A., Guy, S., Handley, J., & Kazmierczak, A. (2015). Climate change and the city: Building capacity for urban adaptation. *Progress in Planning*, *95*, 1–66.

Chen, J., Gao, J., & Chen, W. (2016). Urban land expansion and the transitional mechanisms in Nanjing, China. *Habitat International*, *53*, 274–283.

Deal, B., Hewings, G., Kim, J., & Kim, Y. (2013). Complex urban systems integration: The LEAM experiences in coupling economic, land use, and transportation models in Chicago, IL. In M. Fischer, J. Thill, J. van Dijk, & H. Westlund (Eds.), *Advances in spatial science* (Vol. 74; pp. 107–131). Springer.

Deal, B., & Pallathucheril, V. (2008). Simulating regional futures: The Land-Use Evolution and impact Assessment Model (LEAM). In R. Brail (Ed.), *Planning support systems for cities and regions* (pp. 61–84). Lincoln Institute of Land Policy.

Deilami, K., Kamruzzaman, M., & Liu, Y. (2018). Urban heat island effect: A systematic review of spatio-temporal factors, data, methods, and mitigation measures. *International Journal of Applied Earth Observation and Geoinformation*, *67*, 30–42.

Dolman, N. (2021). Integration of water management and urban design for climate resilient cities. In R. de Graaf (Ed.), *Climate resilient urban areas: Governance, design and development in coastal delta cities* (pp. 21–43). Palgrave Macmillan.

Fu, X., Gomaa, M., Deng, Y., & Peng, Z.-R. (2017). Adaptation planning for sea level rise: A study of US coastal cities. *Journal of Environmental Planning and Management*, *60*(2), 249–265.

Gu, C., Hu, L., Zhang, X., Wang, X., & Guo, J. (2011). Climate change and urbanization in the Yangtze River Delta. *Habitat International*, *35*(4), 544–552.

Han, G., Yuang, J., & Li, K. (2016). Research on the urban vulnerability in Lanzhou. *Journal of Arid Land Resources and Environment*, *30*(11), 70–76.

Hay, G. J., Hemachandran, B., Chen, G., & Kyle, C. D. (2010). HEAT—Home energy assessment technologies: A web 2.0 residential waste heat analysis using geobia and airborne thermal imagery. *GIM International*, *24*(3), 1–3.

Hofstad, H., & Torfing, J. (2017). Towards a climate-resilient city: Collaborative innovation for a ‘green shift’ in Oslo. In R. Álvarez Fernández, S. Zubelzu, & R. Martínez (Eds.), *Carbon footprint and the industrial life cycle* (pp. 221–242). Springer.

Hong, W., Jiang, R., Yang, C., Zhang, F., Su, M., & Liao, Q. (2016). Establishing an ecological vulnerability assessment indicator system for spatial recognition and management of ecologically vulnerable areas in highly urbanized regions: A case study of Shenzhen, China. *Ecological Indicators*, *69*, 540–547.

Jabareen, Y. (2009). Building conceptual framework: Philosophy, definitions and procedure. *International Journal of Qualitative Methods*, *8*(4), 49–62.

Jabareen, Y. (2013). Planning the resilient city: Concepts and strategies for coping with climate change and environmental risk. *Cities*, *31*, 220–229.

Jafari, S., & Zaredar, N. (2010). Land suitability analysis using multi-attribute decision making approach. *International Journal of Environmental Science and Development*, *1*(5), 441–445.

Ji, B., Kong, J., & Kong, S. Y. (2007). Main eco-environmental problems in the course of urbanization and ecological city construction in Nanjing. *Journal of Modern Urban Research*, *2007*(5), 38–41.

Li, G., Cai, L., Chen, L., Chen, T., Zhang, X., & Pan, Y. (2018). Relations of total electricity consumption to climate change in Nanjing. *Energy Procedia*, *152*, 756–761.

Lomba-Fernández, C., Hernantes, J., & Labaka, L. (2019). Guide for climate-resilient cities: An urban critical infrastructures approach. *Sustainability*, *11*(17), Article 4727.

Meera, S. N., Balaji, V., Muthuraman, P., Sailaja, B., & Dixit, S. (2012). Changing roles of agricultural extension: Harnessing information and communication technology (ICT) for adapting to stresses envisaged under climate change. In B. Venkateswarlu, A. Shanker, C. Shanker, & M. Maheswari (Eds.), *Crop stress and its management: Perspectives and strategies* (pp. 585–605). Springer.

Mejri, O., Menoni, S., Matias, K., & Aminoltaheri, N. (2017). Crisis information to support spatial planning in post disaster recovery. *International Journal of Disaster Risk Reduction*, *22*, 46–61.

National Bureau of Statistics of China. (2020). *Zhongguo zhuyao chengshi niandu zhibiao shuju* [Annual index data of major cities in China]. https://data.stats.gov.cn/easyquery.htm?cn=E0105

National Earth System Science Data Infrastructure, & National Science and Technology Infrastructure of China. (2020). *Nanjing* shi 1: 25 wan ziyuan huanjing baohu shuju [Nanjing 1: 250.000 resource and environmental protection data]. http://nnu.geodata.cn:8008/data/datadetails.html?dataguid=122473169935001&docid=171

Navarra, D., & Bianchi, C. (2013). Territorial governance, e-government and sustainable development policy: A system dynamics approach. In M. A. Wimmer, M. Janssen, & H. J. Scholl (Eds.), *Electronic Government. EGOV 2013. Lecture Notes in Computer Science* (Vol. 8074, pp. 14–25). Springer.

Pan, H., Deal, B., Destouni, G., Zhang, Y., & Kalantari, Z. (2018). Sociohydrology modeling for complex urban environments in support of integrated land and water resource management practices. *Land Degradation & Development*, *29*(10), 3639–3652.

Pan, H., Page, J., Zhang, L., Chen, S., Cong, C., Destouni, G., Kalantari, Z., & Deal, B. (2019). Using comparative socio-ecological modeling to support climate action planning (CAP). *Journal of Cleaner Production*, *232*, 30–42.

Pan, H., Page, J., Zhang, L., Cong, C., & Kalantari, Z. (2020). Understanding interactions between urban development policies and GHG emissions: A case study in Stockholm Region. *Ambio*, *49*, 1313–1327.

Qi, Y., & Gu, C. (2011). Discussion on urban planning for responding to climate change in rapidly urbanizing areas: Taking Nanjing as an example. *Human Geography*, *26*(5), 54–59.

Qiao, Q., Gao, J., Wang, W., Tian, M., & Lu, S. (2008). Method and application of ecological frangibility assessment. *Research of Environmental Sciences*, *21*(5), 117–123.

Rahman, M. R., Shi, Z. H., Chongfa, C., & Dun, Z. (2015). Assessing soil erosion hazard—A raster based GIS approach with spatial principal component analysis (SPCA). *Earth Science Informatics*, *8*, 853–865.

Roberts, D., Boon, R., Diederichs, N., Douwes, E., Govender, N., Mcinnes, A., Mclean, C., O'Donoghue, S., & Spires, M. (2011). Exploring ecosystem-based adaptation in Durban, South Africa: "Learning-by-doing" at the local government coal face. *Environment and Urbanization*, *24*(1), 167–195.

Song, G., Chen, Y., Tian, M., Lv, S., Zhang, S., & Liu, S. (2010). The ecological vulnerability evaluation in Southwestern Mountain Region of China based on GIS and AHP method. *Procedia Environmental Sciences*, *2*, 465–475.

Verweij, P., Cormont, A., Eupen, M., Winograd, M., & Hardoy, J. (2020). Participatory modeling with QUICKScan to shape sustainable urban development. *Frontiers in Environmental Science*, *8*, 266.

Wamsler, C., Brink, E., & Rivera, C. (2013). Planning for climate change in urban areas: From theory to practice. *Journal of Cleaner Production*, *50*(1), 68–81.

Wan, Z., Wang, Z., Dong, L., Wang, Y., Chen, D., Li, X., & Xu, S. (2006). Ecosystem sensitivity assessment of Liaoning Province. *Chinese Journal of Ecology*, *25*(6), 677–681.

Wardekker, A., Wilk, B., Brown, V., Uittenbroek, C., Mees, H., Driessen, P., Wassen, M., Molenaar, A., Walda, J., & Runhaar, H. (2020). A diagnostic tool for supporting policymaking on urban resilience. *Cities*, *101*, Article 102691.

Yangtze River Delta Science Data Centre. (2019). *Nanjing shi tudi liyong ji chengzhen yongdi jiegou fenbu shuju* [Data of land use and urban land use structure distribution in Nanjing]. http://www.geodata.cn/data/datadetails.html?dataguid=238990791979153&docid=9126

Zhang, L., Cong, C., Pan, H., Cai, Z., Cvetkovic, V., & Deal, B. (2021). Socioecological informed comparative modeling to promote sustainable urban policy transitions: Case study in Chicago and Stockholm. *Journal of Cleaner Production*, *281*, Article 125050.

Zhang, X., Wang, L., Fu, X., Li, H., & Xu, C. (2017). Ecological vulnerability assessment based on PSSR in Yellow River Delta. *Journal of Cleaner Production*, *167*, 1106–1111.

About the Authors

Zipan Cai is a PhD student in the Department of Sustainable Development, Environmental Science and Engineering (SEED) at the KTH Royal Institute of Technology, Sweden. His research interests include urban spatial planning, spatial dynamic modelling, planning support system, and smart city studies. He has over 10 years of experience in the field of GIS and related professional skills. His current research focuses on decision support for urban planning.

Jessica Page is a PhD student at the Department of Physical Geography, Stockholm University, Sweden. Her focus is on urban and regional planning, in particular on using technology and planning support systems to further sustainability goals in cities through the study and modelling of the interactions between urban and sub-urban social systems with various ecological systems, ecosystem services, and water-climate interactions.

Vladimir Cvetkovic (PhD) is a Full Professor in Water System Engineering at the Department of Sustainable Development, Environmental Science and Engineering (SEED) at the KTH Royal Institute of Technology, Sweden. His research has been mostly focused on water resources involving theoretical and experimental studies. Since 2015, he has been coordinating and working on projects related to urban systems, particularly the socio-technical development toward sustainable smart cities.

COGITATIO

Urban Planning (ISSN: 2183–7635)
2021, Volume 6, Issue 3, Pages 240–257
https://doi.org/10.17645/up.v6i3.4223

Article

A Quantitative Morphological Method for Mapping Local Climate Types

Daniela Maiullari *, Marjolein Pijpers-van Esch and Arjan van Timmeren

Department of Urbanism, Delft University of Technology, The Netherlands; E-Mails: d.maiullari@tudelft.nl (D.M.), m.m.e.pijpers-vanesch@tudelft.nl (M.P.-v.E.), a.vantimmeren@tudelft.nl (A.v.T.)

* Corresponding author

Submitted: 26 February 2021 | Accepted: 6 May 2021 | Published: 19 August 2021

Abstract

Morphological characteristics of cities significantly influence urban heat island intensities and thermal responses to heat waves. Form attributes such as density, compactness, and vegetation cover are commonly used to analyse the impact of urban morphology on overheating processes. However, the use of abstract large-scale classifications hinders a full understanding of the thermal trade-off between single buildings and their immediate surrounding microclimate. Without analytical tools able to capture the complexity of cities with a high resolution, the microspatial dimension of urban climate phenomena cannot be properly addressed. Therefore, this study develops a new method for numerical identification of types, based on geometrical characteristics of buildings and climate-related form attributes of their surroundings in a 25m and 50m radius. The method, applied to the city of Rotterdam, combines quantitative descriptors of urban form, mapping GIS procedures, and clustering techniques. The resulting typo-morphological classification is assessed by modelling temperature, wind, and humidity during a hot summer period, in ENVI-met. Significant correlations are found between the morphotypes' characteristics and local climate phenomena, highlighting the differences in performative potential between the classified urban patterns. The study suggests that the method can be used to provide insight into the systemic relations between buildings, their context, and the risk of overheating in different urban settings. Finally, the study highlights the relevance of advanced mapping and modelling tools to inform spatial planning and mitigation strategies to reduce the risk of urban overheating.

Keywords

data-driven classification; microclimate; typologies; urban morphology

Issue

This article is part of the issue “Smart Urban Governance for Climate Change Adaptation” edited by Thomas Thaler (University of Natural Resources and Life Sciences, Austria), Patrick Witte (Utrecht University, The Netherlands), Thomas Hartmann (TU Dortmund University, Germany) and Stan Geertman (Utrecht University, The Netherlands).

1. Introduction

Urban planning research and practice are increasingly called to confront climate-related challenges of cities. While extreme events like heatwaves are becoming more frequent (Founda et al., 2019; Smid et al., 2019), climate scenarios also prognose an overall increase in temperatures in the coming decades (Guerreiro et al., 2018; Hoegh-Guldberg et al., 2018). Furthermore, climate change is expected to exacerbate warming mechanisms in urban environments already characterised by urban heat island (UHI) phenomena (Ward et al., 2016). At the same time, a growing number of European cities have active policies of urban (re-)densification (Næss et al., 2020; Westerink et al., 2013). Following the well-known paradigm of compact and dense sustainable urban development (European Commission, 1991), this approach seems to mark a transition from a zoning-oriented planning to an infill-planning that looks at local conditions for re-development (Amer et al., 2017; Wolff et al., 2017), increasing the morphological heterogeneity of the urban fabric (Marique & Reiter, 2014) and giving rise to the so-called compact city paradox (Bibri et al., 2020). From a climate perspective, in fact, higher building densities generally increase the magnitude of UHI effects and overheating of cities (Oke, 1987).

Climate change and urban densification thus pose great challenges as well as opportunities for urban planning and design, with respect to developing new frameworks and strategies for the construction of climate-resilient cities (Terrin, 2015). Although it is demonstrated that urban form characteristics significantly influence thermal and turbulent processes in cities, contributing to the formation of UHI effect (Oke et al., 1991), a deeper understanding of these processes in increasingly complex and heterogeneous built environments appears to be needed, in order to characterise the overheating risk at a finer scale-level and to facilitate the implementation of mitigation measures more sensitive to the local spatial conditions.

In the last decades, the field of urban climatology has been studying the role of urban form in urban climate phenomena, attempting to broaden the understanding of which spatial conditions exacerbate and reduce the risk of overheating (Zinzi & Santamouris, 2019). Two distinct morphological approaches can be recognised. The first has mainly been employed in parametric and comparative studies, focusing on the investigation of single form attributes (Ali-Toudert & Mayer, 2006; Morganti et al., 2017; Perini & Magliocco, 2014). However, methods to quantitatively identify representative samples of existing urban tissues are largely lacking. This results in the common practice of qualitative selection of homogeneous or generic form patterns (Toparlar et al., 2017) that limits its use to guide design and planning in existing cities. The second morphological approach employs qualitative and quantitative descriptions of form attributes and supervised classification techniques in order to identify zones with similar climate characteristics. A well-known representative of this approach is the local climate zone classification method (Stewart & Oke, 2012) that supports the identification of regions of uniform land cover, material, structure, and anthropogenic activities, defining characteristic temperature regimes for 17 standard local climate zones. The "urban climate maps" resulting from these classifications have, until now, been considered a crucial basis to inform design and planning decisions (Lenzholzer, 2015) and are based on the concept that different types of urban areas have typical thermal behaviours. However, while these methods cover district to city scale, their large aggregative units result in a rather coarse classification unable to describe the level of heterogeneity of the urban fabric.

Advancements in the field of mathematical urban morphology (D'Acci, 2019) over the last 50 years may help overcome the limitations of the approaches in urban climatology discussed above. This branch of urban form studies focuses on the understanding of spatial structures and characteristics of urban areas through an empirical and quantitative approach. In particular, the typo-morphology body of research—traditionally interested in identifying qualitative comparable physical characteristics (Vernez Moudon, 1997)—is increasingly showing applications of quantitative methods for measuring (Berghauser Pont & Haupt, 2010) and classifying urban forms (Serra et al., 2017). This recent typology-driven approach aims to overcome the use of traditional administrative units in the description of cities' physical context through morphological indicators (Serra et al., 2018), to support the application of typo-morphology to planning practice (Gil et al., 2012) and to facilitate the description of contemporary types that do not fall into standard classifications (Berghauser Pont et al., 2019).

Numerically defined typo-morphologies have been proposed in studies that have developed geo-computation methods for classifying forms of urban fabric and their basic physical elements: streets (Barthelemy, 2017), plots (Bobkova et al., 2019; Demetriou et al., 2013), buildings (Hecht et al., 2015; Perez et al., 2018), blocks (Peponis et al., 2007), and structural units (Haggag & Ayad, 2002). Particularly relevant are the contributions of authors that have integrated geometrical multi-variables and inter-scalar descriptions of urban form (Bobkova, 2019; Hausleitner & Berghauser Pont, 2017; Serra et al., 2018) and have developed methodological strategies to identify potential links between contextual factors and other variables, generating context-informed samples of urban areas. A part of these multi-variables and inter-scalar studies has a strong focus on defining typologies to investigate the geographical distribution of types of urban fabric (Araldi & Fusco, 2019) and to allow comparisons between cities (Berghauser Pont et al., 2019).

Despite the high potential of applying a typo-morphology approach in climate-oriented studies, it nevertheless is still relatively unexplored. Thus, the aim of this article is to address the potentials of morpho-based classification systems as a complementary approach to those existing in urban climatology. In order to facilitate the understanding of how space at the microscale influences urban climate phenomena, this study proposes a data-driven morphological classification approach. This approach allows to address heterogeneous urban fabric by characterising buildings and their contextual conditions separately. In addition, it supports a better understanding of the impacts of form characteristics on patterns of thermal and aerodynamic behaviours.

This study focuses on the development of the approach and its application in the city of Rotterdam (the Netherlands). Section 2 of the article introduces the methodological framework (see Figure 1) to obtain and assess numerically defined typo-morphologies based on climate-related form attributes. In Section 3, the detailed methods to characterise urban form types are described and deployed in the Rotterdam case study. Section 4 presents the microclimate performance of the identified form types, modelled in ENVI-met. Finally, a comparison is carried out to analyse the variations in

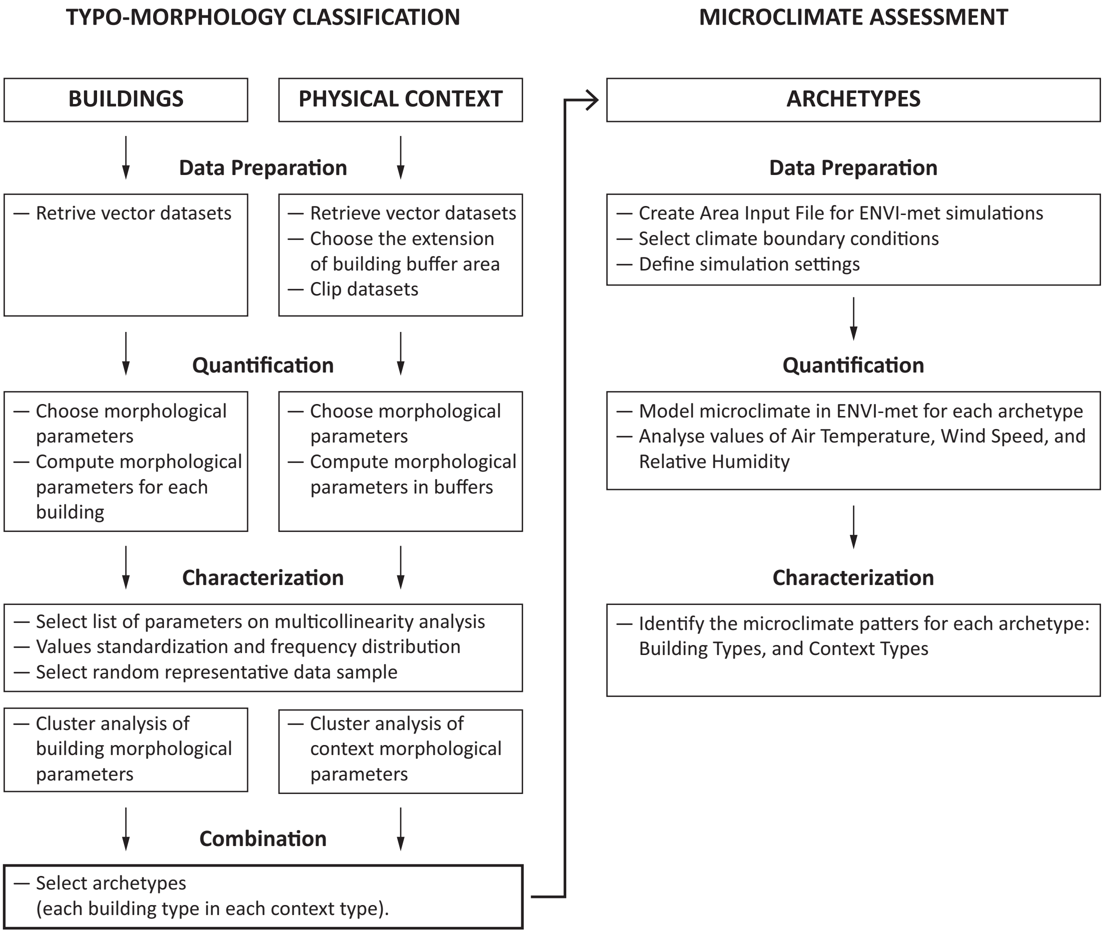


Figure 1. Methodological framework.

microclimate performance, dependent upon form characteristics of building types and context types, and conclusions are presented.

2. Methodological Framework

The proposed methodological framework builds on previous studies that integrate multi-variable geometrical descriptions with inter-scalar relational descriptions of urban form. To test the application of data-driven morphological classifications in the field of urban climatology, this study carries out a performance assessment on the identified typo-morphologies, by employing microclimate modelling. The methodological framework is therefore divided in two main parts: (1) typo-morphology classification, and (2) microclimate assessment, both organised in steps of data preparation, quantification, characterisation, and linked by a step named combination.

The methodology for the typo-morphology classification follows two parallel paths to identify building types and context types. Climate-related form attributes and measuring parameters are derived from literature and computed for buildings and context areas. The latter are defined by buffer areas from the buildings' envelopes, drawn with different radii. After combined statistical analyses on the calculated parameters, an unsupervised hierarchical clustering method is employed to identify and group similar objects (buildings) and similar surrounding conditions (contexts). After evaluating the optimal number of clusters, archetypical buildings for each context type are selected for the microclimate assessment phase.

This assessment is carried out through microclimate simulations in ENVI-met, a well-established urban climate model (Tsoka et al., 2018; Yang et al., 2013). Spatial vector-data of the domains under study is translated into 3D digital models and enriched with material attributes. Two hot summer days are selected as climate boundary conditions. After running the simulations, results for the selected archetypes are analysed by comparing air temperature, wind speed, and relative humidity values near building façades. Finally, microclimate patterns for the typo-morphologies and relations between building and context types are analysed.

2.1. Case Study Description

The methodological approach to identify and assess microclimate typo-morphologies is applied on the urban agglomeration of Rotterdam, the second largest city in the Netherlands, situated along the Nieuwe Maas river. The selection of this city allows for an analysis of the thermal performance of heterogeneous building and land cover configurations. Additionally, due to its densely built environment, Rotterdam has a significant UHI effect, as shown in previous studies (Roodenburg, 1983; Steeneveld et al., 2011). This urban climate phenomenon has a high intensity in the inner city and varies largely among urban districts. According to van Hove et al. (2015), atmospheric UHI_{max} values in Rotterdam vary from 4.3°C to 8°C depending on local urban characteristics of different areas, while surface UHI values show a daytime magnitude of 10°C, with a maximum variation in surface temperatures between warmest and coolest districts in a range of 12°C (Klok et al., 2012).

3. Classification of Building and Context Types

The overall goal of this classification is to identify typo-morphologies through clustering of climate-related urban form parameters for the city of Rotterdam. Usually, in both planning research and practice, urban form parameters are measured at large predefined units (administrative or dependent upon land ownership) that are biased by a high level of aggregation (Serra et al., 2018). The proposed framework overcomes this bias by allowing for the separate identification of building and context types. This approach is expected to allow for a distinction between microclimate behaviour that depends on a building's surroundings, from that which depends on the building's own geometrical characteristics.

3.1. Data Preparation for Morphological Quantification

The spatial datasets used in this study were made available by the Municipality of Rotterdam, and contain information regarding buildings, street network, vegetation cover, and trees at their status in December 2018. For the building dataset, data processing was necessary to extract basic geometrical characteristics from a 3D city model. Building footprints and heights were derived from the available 3D digital model in CityGML format (Gemeente Rotterdam, 2018). The term "building" here indicates a basic unit characterised by a singular height, that can also correspond to building parts in the case of complex geometries. Regarding the context data, two extra steps of refinement were required. First, buffer areas around each building were defined, with 25 and 50m radius, calculated from the building envelope. These radii have proven adequate to observe variations in microclimate processes (Jin et al., 2018; Takebayashi, 2017) as in these areas around the building the form characteristics of the tangent street canyons (25m) and the surrounding district structure (50m) are captured. Second, the datasets for each buffer were clipped to facilitate the computation of morphological parameters within these areas in the next phase.

3.2. Quantification of Morphological Attributes

In order to quantitatively describe the geometry of buildings and the form of the urban fabric, a set of eight climate-related morphological parameters was selected. The parameters chosen, based on literature, are quantitative and morphological by nature. The selection followed four main criteria; the parameters (1) describe attributes that influence the thermal behaviour of buildings and microclimate processes in their surroundings, (2) have minimal redundancy, (3) can be easily understood by planners and designers, and (4) are easily calculated.

For the building characterisation, three parameters were considered: height, footprint, and surface-to-volume ratio. Building height (B_Height) expresses the vertical dimension of a building object. From a microclimate perspective, wind speed and turbulence exponentially increase with increasing B_Height, while air temperature tends to decrease further from the ground. Building footprint (B_Footprint) describes the horizontal occupation of the buildings at the ground. The size of the footprint correlates with potential solar accessibility. Surface-to-volume ratio (B_StoV) measures the proportion between the exposed building envelope and its volume. The larger the value of B_StoV, the lower the compactness level. From a climate design perspective this parameter captures radiation accessibility and ventilation potential, mediated by the interface between outdoor and indoor environments (Vartholomaios, 2017).

In addition, five variables were used to measure urban fabric attributes of roughness, density, and green coverage, describing the morphological characteristics of the buildings' context. Mean building height (MeanH) is a primary descriptor of roughness. The roughness of the urban surface defines the friction capacity of the built environment to aerodynamic processes (Grimmond & Oke, 1999). MeanH identifies the average height of the context in a buffer of 50m radius. Floor space index (FSI) and ground space index (GSI; Berghauser Pont & Haupt, 2010) are two of the most known density indicators that describe the intensity of built space and building coverage, influencing the magnitude of overheating (Zhao et al., 2016) and solar irradiance (Morganti et al., 2017). FSI is defined as the ratio of the gross floor area to the overall site surface, which is calculated in the larger buffer area to describe the level of fabric compactness around a building. GSI is calculated as the ratio of buildings' footprint to the overall site surface. In this study, GSI (calculated in a 25m radius buffer) is used to intercept the closeness of buildings in the immediate surrounding. Vegetation cover affects microclimate in urban environments, by influencing air temperatures through shading and evapotranspiration, and by modifying wind velocity (Duarte et al., 2015; Perini & Magliocco, 2014). Two parameters are chosen to measure greenery characteristics. Green area (GArea) measures the total green coverage of grass surfaces in the larger buffer area (50m), while tree area (TArea) measures the sum of tree crown area in the smaller buffer area (25m). The list of morphological parameters used to describe building and context form is shown in Table 1. The eight variables deployed were computed for over 150,000 buildings and related buffer areas through the QGIS programme.

3.3. Urban Form Characterisation

All calculated morphological variables were standardised as z-scores in order to have similar scales. Since multi-collinearity should be avoided for unsupervised classification (Tan et al., 2005), a screening was performed to detect potential collinearity, confirming that the selected eight variables were not correlated.

In order to classify building and context characteristics a hierarchical cluster analysis was used. The hierarchical cluster analysis is an unsupervised classification method that groups data into homogeneous classes by proceeding stages. Beginning by defining each observation as a cluster, clusters get incrementally paired based on the minimum distance between them, until the merging of all values results in a single cluster. Although k-mean clustering has a stronger applicability to large datasets, the explorative character of the study required a certain degree of flexibility. From this perspective, hierarchical clustering would allow for the identification of the hierarchical relation between classes and provide the possibility to read the microclimate assessment results at different cutting levels of the dendrogram. Thus, to allow the applicability of a hierarchical cluster analysis despite computational restrictions, a representative 20% sample of the full data population was selected. A Kolmogorov-Smirnov test verified that the sample was statistically significant and preserved the same probability distribution of the full dataset.

The three building and five context variables calculated for the 21,047 features of the sample were

Table 1. Summary of the selected morphological parameters.

Categories	Unit	Parameter/Variable	Description	Sources
Building Geometry	Building parts	B_Height (m)	Measure of the B_Height	Godoy-Shimizu et al., 2018; Jurelionis & Bouris, 2016; Mangan et al., 2021; Saroglou et al., 2017; Yunhao Chen et al., 2020
		B_Footprint (m^2)	Area of the B_Footprint	Allen-Dumas et al., 2020; Hecht et al., 2015; Mavrogianni et al., 2012; Yixing Chen et al., 2019
		B_StoV (m^2/m^3)	Building envelope to volume ratio	Bourdic et al., 2012; Caldera et al., 2008; Mashhoodi et al., 2020; Ratti et al., 2005; Salat, 2009
Context Morphology	Buffer 25m radius	GSI	GSI	Jin et al., 2018; Lan & Zhan, 2017; Morganti et al., 2017; Salvati et al., 2019
		TArea (m^2)	Tree crown area in buffer	Kong et al., 2017; Rafiee et al., 2016; Rui et al., 2018
	Buffer 50m radius	FSI	FSI	Lan & Zhan, 2017; Rodríguez-Álvarez, 2016; Wang et al., 2017; Wei et al., 2016
		MeanH (m^2)	Average B_Height in buffer	Salvati et al., 2020; Touchaei & Wang, 2015; Wang et al., 2017
		GArea (m^2)	Total grass coverage area in buffer	Kong et al., 2016; Lobaccaro & Acero, 2015; Skelhorn et al., 2014; Vaz Monteiro et al., 2016; Wu et al., 2019

separately processed using a hierarchical cluster analysis with application of Ward's minimum variance method. To select the optimal number of clusters, the resulting dendrograms for the building classification and context classification were analysed (Figure 2). The cutting level was selected where the linking vertical lines are long(est) and the smallest number of clusters distinguishes sufficient differences among the groups. Thus, for both building and context variables, the optimal division is a five-cluster solution. Plotting the parameter values per cluster and a visual inspection of the cluster-centroids confirmed clear differences between the five building types, as well as between the five context types.

3.3.1. Description of the Building and Context Types

The combination of the selected morphological characteristics produced consistent typo-morphologies. The plotting and numeric profiling of the building and context types is shown in Figure 3. Building types identified through clustering of B_Height, B_Footprint, and B_StoV parameters can be described based on Figure 4.

B_Type1 and B_Type3 are low-rise buildings with a very small B_Footprint. The main difference between them is the level of compactness. Buildings of type 1 have a low compactness level (high StoV ratio), while buildings of type 3 have a high compactness level (low StoV ratio). These types predominately comprise of single houses, rowhouses, and small building parts. B_Type2 and B_Type5 consist of highly compact mid-rise buildings (low StoV). The discriminant between the two groups is the ground coverage size. While buildings in type 2 are characterised by small footprints (slabs, apartment buildings), in type 5 the B_Footprints are the largest, comprising of public facilities and industrial/commercial objects with a horizontal volume distribution. B_Type4 is composed of high-rise buildings with a medium size footprint and a high level of compactness (low StoV ratio). Towers and tall building parts on plinths belong to this group.

Context types emerged from the clustering analysis of GSI and TArea (25m buffer), and FSI, MeanH, and GArea (50m buffer). According to Figures 3 and 4, the types can be described as follows:

- C_Type1 consists mainly of low and mid-rise urban fabrics, with low density characteristics (low GSI and FSI). The main defining characteristic is the very large tree crown area and the medium level of grass coverage. This type of context tissue shows the ample presence of trees mainly located along street canyons.
- C_Type2 is characterised by mid-rise buildings, and medium density in terms of building coverage (GSI) and built-up intensity (FSI). The type has low values of grass and tree coverage.
- C_Type3 and C_Type4 are urban tissues both defined by low-rise buildings and low density. The main difference between the two types is the quantity of grass surfaces, which is very low in type 3 and medium in type 4.
- Finally, C_Type5 can be described by highly compact conditions of the urban fabric, characterised by high-rise, high building intensity, and building coverage. In this context type, greenery level (TArea, GArea) is low.

3.4. Archetype Selection

Once building types and context types were characterised and semantically described, 25 "archetypes" were selected to analyse the microclimate profile of the five building types in the five context conditions. Usually, the archetype is defined as the case that is closer to the cluster's centroid. Therefore, five cases were selected close to the cluster's centroid for each building type, one case for each context type (Figure 5).

4. Microclimate Assessment

Microclimate simulations of the 25 archetypes were performed with ENVI-met 4.4. ENVI-met is a three-dimensional prognostic model able to simulate the interaction between air, vegetation, and surfaces within an urban environment (Bruse & Fleer, 1998). This holistic microclimate modelling tool is widely used to compute air and surface temperatures, turbulence, radiation fluxes, humidity, and evaporation fluxes (Tsoka et al.,

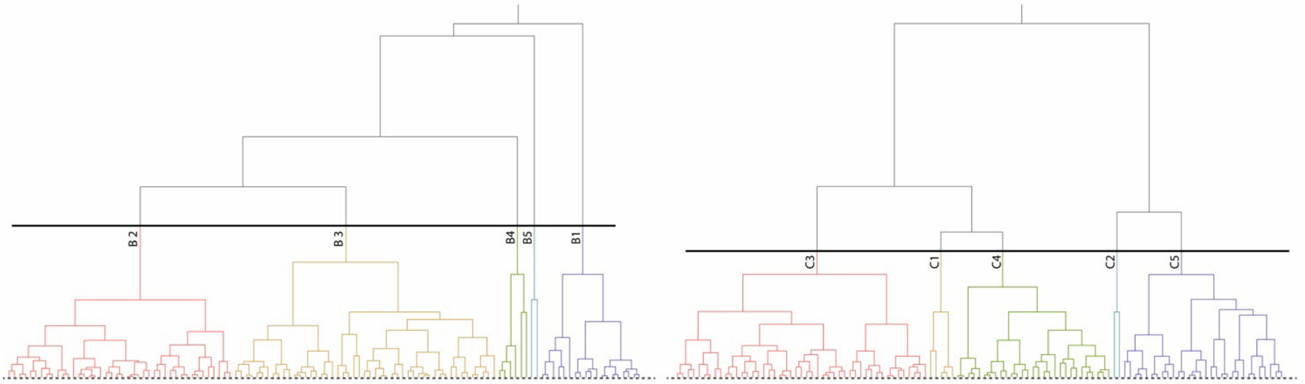


Figure 2. Hierarchical classification. Results: Building types (left) and context types (right).

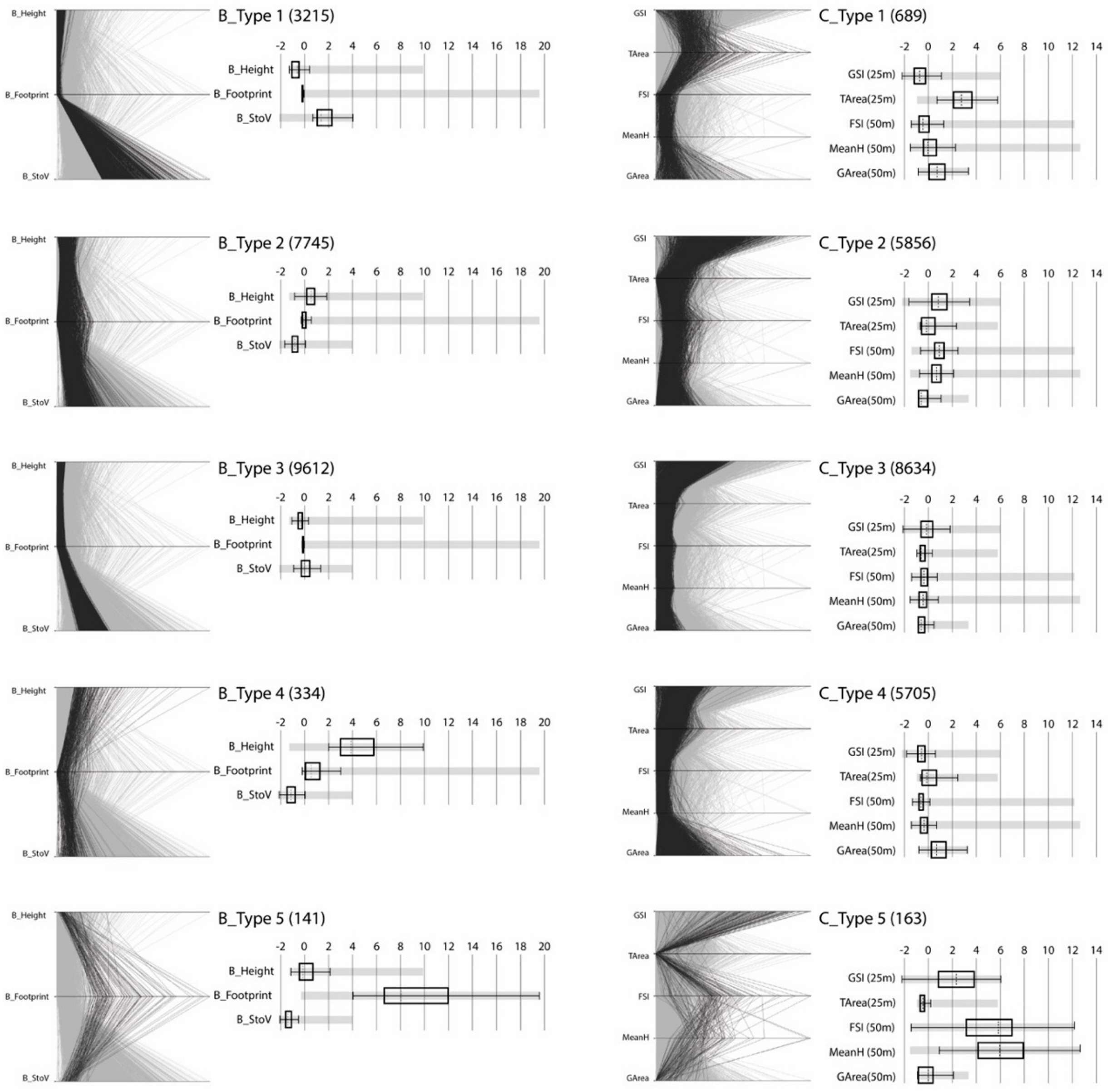


Figure 3. Standardised (z-score) numerical profiles of the building types (left column) and context types (right column).

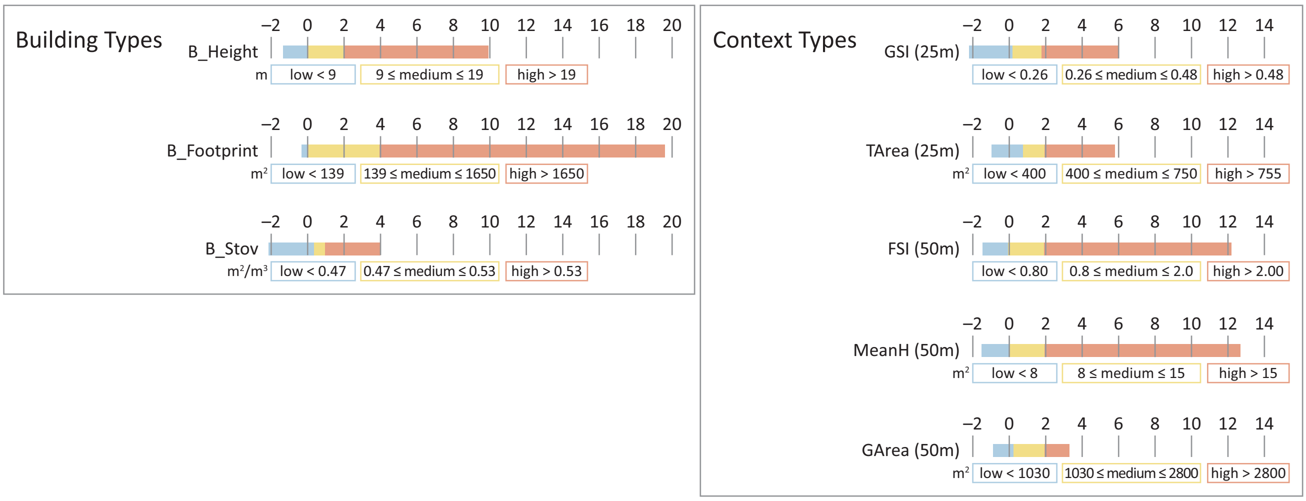


Figure 4. Numerical thresholds for the description of the building types (left) and context types (right).

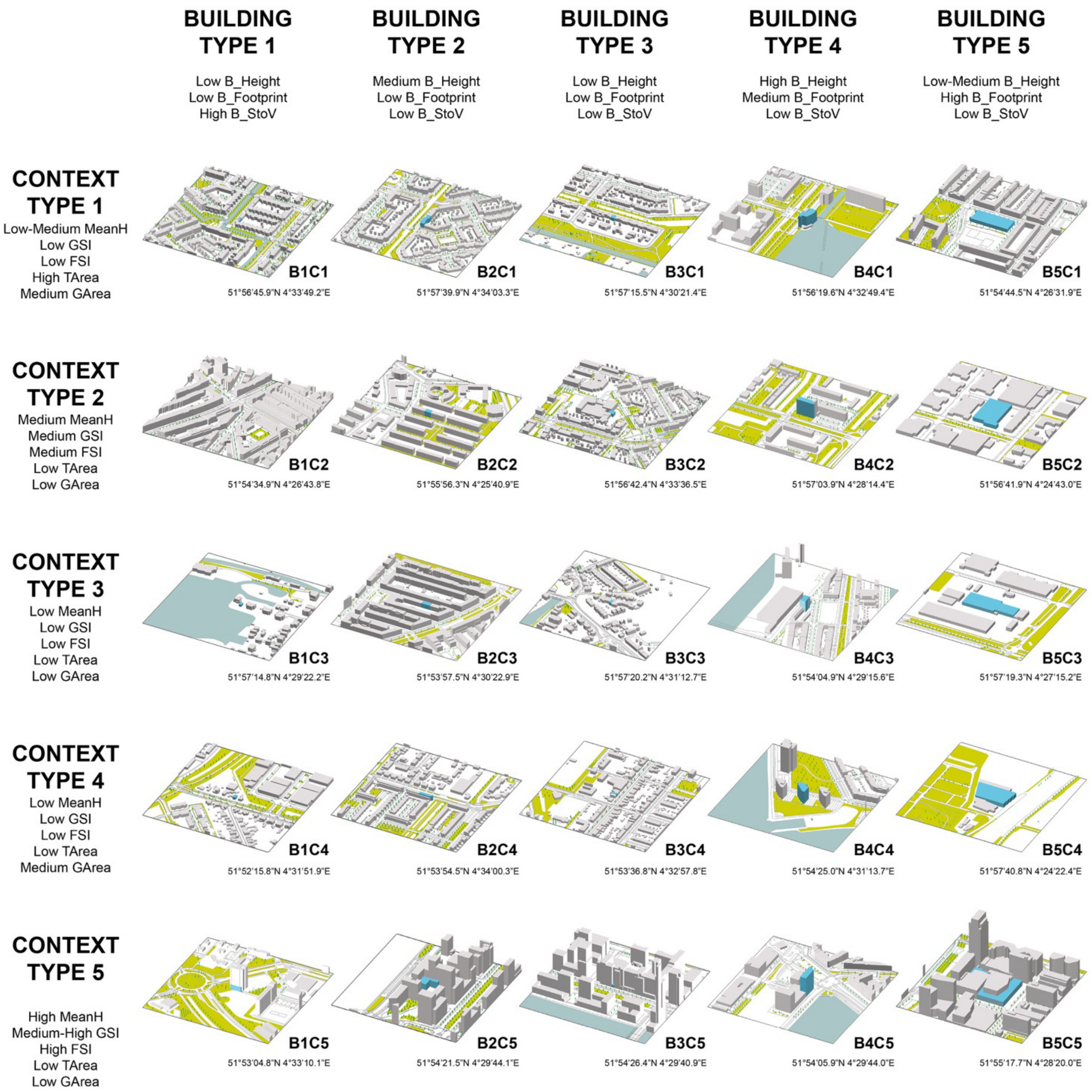


Figure 5. Visualisation of the building archetypes in the five context types.

2018). Validation studies have confirmed its high level of accuracy in modelling microclimate processes in urban conditions (Crank et al., 2018; Salata et al., 2016), and a high sensitivity to morphological characteristics of the built environment (Forouzandeh, 2018).

4.1. Data Preparation for Microclimate Modelling

To perform an ENVI-met simulation three types of input are required:

1) Digital spatial model: In the area input files, the model domains were created using a grid cell unit of 3m (x) by 3m (y) by 3m (z). In these domains, the 3D models were built using the Rotterdam dataset in shape format through the ENVI-met submodule Monde. To be able to isolate the microclimate impact of morphological factors, material characteristics were kept constant in all 25 models.
2) Material database: Three surface materials (asphalt for roads, concrete bricks for other paved surfaces, and grass for unpaved areas) were derived from ENVI-met default database, and a fourth—a theoretical building wall with medium insulation properties—was created in the user database. Additionally, based on height and crown diameter, trees were classified into three categories (small, medium, large).

3) Simulation settings: ENVI-met simulations used the full forcing method, by employing KNMI data from the weather station at Rotterdam Airport. After analysing the measured data of the past 10 years, two consecutive hot days ($T_{max} > 24°C$) were selected by filtering out days with clouds and rain. The two days identified therefore meet the required conditions for microclimate simulations. The first day (29 June 2018), a maximum air temperature of 25°C was reached, while on the second day (30 June 2018), it reached up to 28°C.

Before performing the simulations for the different archetypes a validation procedure was carried out. The existing urban areas around the urban weather stations of Delfshaven and Ommoord in Rotterdam were modelled with the material and meteorological settings described above. The ENVI-met spatial models of these two areas were built including the 50m buffer area around the building on which the sensors are positioned, in other words, with a domain size defined as for the archetypes. The comparison between model results and measured temperature values (TU Delft, 2018) showed an index of agreement (Willmott, 1982) of 0.98, confirming the good accuracy of ENVI-met and the reliability of the input data.

4.2. Microclimate Quantification Results and Discussions

The cumulative microclimate performance of the Rotterdam cases was analysed by comparing the rural climate conditions to the simulation results (Figure 6). Air temperature, wind speed and relative humidity values were retrieved in the air layer near the façades. Values were averaged for each building archetype. The comparison between simulated air temperatures and measured data at the rural KNMI weather station shows a clear UHI effect, in particular during daytime, for both days. The 25 simulated areas are generally warmer than the rural environment with an average maximum UHI effect of 1.1°C. The maximum UHI effect occurs between 12:00 and 15:00, and ranges between 0.5°C (B4C5) and 3°C (B1C4 and B3C2). The nocturnal UHI shows a smaller magnitude, reaching up to a maximum effect of 0.5°C.

Another clear effect is the decrease in wind speed. During the two days under study, wind velocity at the rural station reached 6m/s during daytime, with a significant drop during night-time. Compared to the rural hinterland conditions, the modelling results show that the overall urban wind velocity decreases strongly, down to 1m/s on average.

Relative humidity values, plotted in Figure 6, illustrate that during night-hours, humidity values reach a RH of 95% while during day-hours it drops below 30% for the second hot day. Compared to the values at the rural weather station, the humidity values in the urban samples from Rotterdam decrease within a maximum of 7%, which is consistent with observations in other studies (Ackerman, 1987; Liu et al., 2009). During daytime, the RH in the city is lower than in the rural hinterland, which can be correlated to the occurrence of the UHI effect.

This analysis of the simulation results also highlights the magnitude of microclimate variations for the Rotterdam sample of 25 archetypes. Since materials and settings were kept constant in the modelling process, it could be argued that the microclimate variations analysed are mainly dependent on morphological characteristics. The observed maximum differences in air

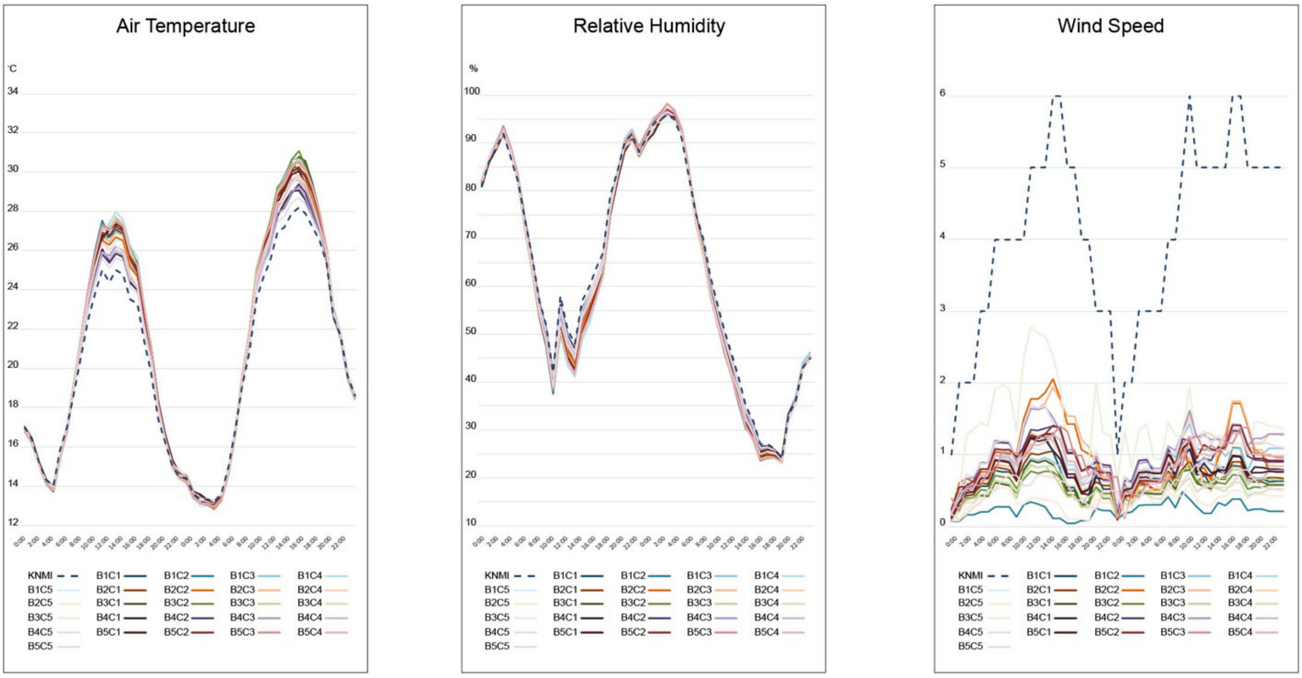


Figure 6. Building average air temperature (left), relative humidity (centre), and wind speed (right) near façade.

temperature, humidity, and wind among the 25 cases suggest that building geometry and urban form of the context account for up to 2.5°C change in air temperature, up to 3m/s change in wind speed, and up to 5% change in relative humidity.

As stated, the models' results indicate that, during the two days under study, the UHI intensity reaches 3°C. However, previous studies have found stronger magnitudes (between 2.3 and 8.0°C) during day- and especially night-time in Rotterdam (Steeneveld et al., 2011; van Hove et al., 2015). These studies are based on field measurements, and therefore also include anthropogenic heat and its contribution to the energy balance; ENVI-met does not. As it was the objective of this study to assess the impact of solely morphology on UHI, the omission of anthropogenic heat is justified, but is expected to lead to an underestimation of the UHI effect. Furthermore, for the same reason of isolating morphological effects, the 25 models in this study had greatly simplified building and paving material characteristics, which may also have influenced the magnitude of the modelled UHI.

4.3. Characterisation of Microclimate Patterns in Types

In order to understand if the typo-morphologies have typical thermal and aerodynamic behaviour, climate patterns are analysed for each building and context type. Furthermore, the overall capability of the data-driven classification in identifying common climate conditions based on morphological characteristics is assessed. Simulation results are retrieved for indoor air temperature as well as outdoor air temperature and wind speed near the façade and averaged for each building.

4.3.1. Indoor Temperature Patterns for the Different Building Types

The analysis of indoor temperatures highlights common behaviour for the different building types (Figure 7). In particular, low-rise buildings (B_Type 1 and 3) demonstrate a larger sensitivity to the influence of context. Low rise buildings in high-rise contexts (B1C5 and B3C5) yield the lowest indoor temperature among the 25 cases, due to reduced solar access at the façade. Except for these two "outliers," the cases representing each building type show similar thermal patterns. Therefore, each type can be described by the characteristic variation range between its five cases and the maximum temperature.

As shown in Table 2, B_Type4 has the lowest temperature variation among its cases, followed by B_Type3, 5, and 1. The highest variation is registered among B_Type2 cases. The similar behaviour among cases belonging to the same building type indicates that the context has a limited effect on the indoor temperature: The smaller the variation among cases, the lower the sensitivity of the building type to the context. Thus, high-rise buildings are the least affected by the surrounding conditions, while mid-rise buildings with low coverage are most influenced by their context.

T_{max} is higher in B_Type1 than in B_Type2, 5, and 3. High-rise buildings (B_Type4) consistently yield cooler indoor thermal conditions than the other building types. This is due to the lower contribution of radiation to the total thermal budget of the building due to the higher volumetric size, the higher exposure to cooling wind flows, and the fact that outdoor air temperatures tend to be lower when further away from the ground level.

4.3.2. Wind Speed Patterns for the Different Building Types

Wind velocity regulates heat dispersion from built surfaces and is strongly influenced by individual buildings and the roughness of their surroundings. As shown in Figure 7, the five cases of each building type experience similar wind speed behaviour near the façades. However, some exceptions can be observed for buildings in medium and highly dense contexts (B1C2, B3C5, and B5C5), which according to the size of the surrounding street canyon have very high or very low wind speed values.

All B_Type3, except for B3C5, show the lowest values of wind velocity (Table 3), with U_{max} below 0.8m/s and a limited maximum variation among context types (0.3 m/s). It is followed by B_Type1 (except B1C2) and B_Type 5 (except B5C5), which have a medium wind velocity near the façade (reaching an U_{max} of 1.4 m/s). The variation among cases accounts for 0.5m/s. B_Type4 is the building type that shows higher values of wind speed (U_{max} = 1.75 m/s), with a slightly higher interval among cases (0.6m/s). B_Type 2 shows quite different characteristics, as a clear pattern could not be identified. The latter type is characterised by medium height and a small footprint area and seems to be more sensitive to the size and predominant direction of the street canyons in the immediate surroundings.

Table 2. Patterns of indoor temperatures per building type.

Indoor Temperature	B_Type1	B_Type2	B_Type3	B_Type4	B_Type5
Variation among cases	1°C (B1C1–B1C4)	1.3°C	0.4°C (B1C1–B1C4)	0.2°C	0.6°C
Maximum temperature	25.2°C (B1C1–B1C4)	24.6°C	24.8°C (B1C1–B1C4)	23.2°C	24.6°C
Outliers	B1C5		B3C5		

Table 3. Patterns of wind speed per building type.

Wind Speed	B_Type1	B_Type2	B_Type3	B_Type4	B_Type5
Variation among cases	0.5m/s (B1C1–C3–C4–C5)	1.5m/s	0.3m/s (B1C1–B1C4)	0.6m/s	0.5m/s
Maximum speed	1.4m/s	2m/s	0.8m/s	1.75m/s	1.4m/s
Outliers	B1C2		B3C5		B5C5

4.3.3. Air Temperature Patterns for Different Context Types

In Figure 7, hourly values of the five cases per context type are plotted. Data clearly show that, independently of the context, temperatures are always the lowest around high-rise buildings (B_Type4). Inversely, the other four building types all together respond in a similar way to the context conditions (Figure7).

In group C_Type1, C_Type3, and C_Type4, having a low level of built-up intensity (FSI) and coverage (GSI) in common, but differing in grass and tree coverage, T_{max} values are similar, ranging from 29.8°C to 30.6°C, the second day. T_{max} variation among cases accounts for a 0.8°C (Table 4). The results suggest that at the microscale, vegetation has a minor effect on heat mitigation in contexts of low building density.

In C_Type2, characterised by a mid-rise context at medium density, high air temperatures and overall larger variations are observed. The fact that more variation exists among buildings in this context indicates a stronger trade-off between building geometry and mid-rise context at medium density. This can be explained by the fact that shading caused by the surroundings increases with the incline of height and compactness. Moreover, the influence of shading from the same context has a bigger impact on low-rise buildings than on higher ones. C_Type5 is the context with the most evident influence pattern on air temperatures. The high-density and high-rise characteristics that define this context type contribute to keeping daytime temperature for all the building types below 30°C on the second day. Compared to the other contexts, here air temperatures are the lowest during daytime hours and the highest during night-time hours.

The very similar behaviours of C_Type1, 3, and 4 suggest that while the three types characterise different urban fabric conditions, from a climatic perspective they correspond to similar temperature patterns. Observing the dendrogram (Figure 2) and the hierarchical relations between types, it can be noted that these three groups merge at the upper level in one type.

5. Limitations

As shown in this study, data-driven classifications offer a novel methodological approach in urban climatological mapping, able to address the complexity and heterogeneity of urban environments. The characterisation of types and microclimate assessment carried out in this study are subject to several limitations.

For the types' characterisation, climate-related morphological parameters were derived from literature. These well-established parameters describe attributes of size and compactness for single buildings, and density, roughness, and green coverage for urban fabrics. However, a more extensive list of parameters can be found in literature. Among others, characteristics of building orientation, window-to-wall ratio, sky view factor, fabric porosity, and water coverage have shown to influence thermal and aerodynamic processes. Despite the undeniable benefits of enlarging the number of variables to better characterise the types, this would result in an exponential increase of data preprocessing and multidimensional clustering computation. Therefore, the authors have chosen the parameters most relevant for the method and case study at hand.

Regarding microclimate modelling, although the heat produced by anthropogenic activities (mobility, space heating and cooling, industry) is an important component in the energy balance of urban environments, ENVI-met is not able to model the thermal contribution of these activities. Additionally, in the modelling of the archetypes, material of buildings and street surfaces are assumed to have similar characteristics for all 25 cases. Even though ENVI-met allows to define individual surface

Table 4. Patterns of outdoor air temperature per context type.

Air Temperature	C_Type1	C_Type2	C_Type3	C_Type4	C_Type5
Variation among cases	0.8 (B1C1–C2–C3–C5)	1 (B1C1–C2–C3–C5)	0.8 (B1C1–C2–C3–C5)	0.8 (B1C1–C2–C3–C5)	0.8 (B1C1–C2–C3–C5)
Maximum temperature	30.8	31.1	30.7	30.8	29.9
Outliers	B1C4	B2C4	B3C4	B4C4	B5C4

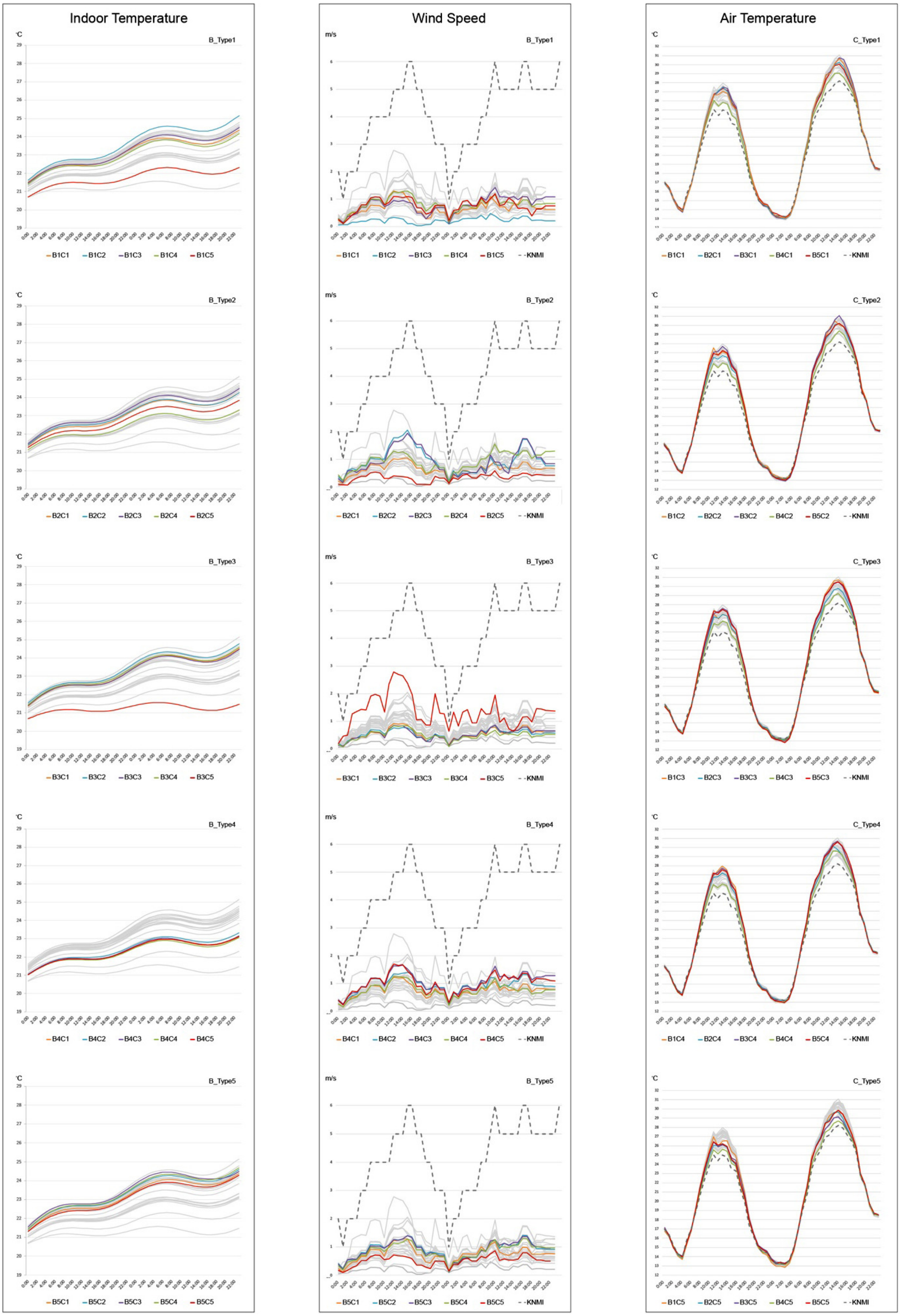


Figure 7. Indoor temperature values (left) and wind speed values (centre) for each building type; air temperature values for each context type (right).

characteristics, since the study has the goal of isolating the microclimate impacts of morphological factors, all other modelling inputs—including material properties—were kept constant. In order to limit the influence of this simplification on the results, in particular for buildings, a theoretical façade and roof material was created to represent average characteristics of absorption, reflection, and insulation capacity in the context. Windows were not included, therewith also limiting indoor heating due to incoming solar radiation. Finally, due to the computational limitations of the microclimatic model, simulations for an entire summer period were not possible. Instead, two consecutive days were selected as representative of a typical hot Dutch summer day without clouds.

6. Conclusions

Using a novel methodological approach for a data-driven classification of local climate typo-morphologies, a characterisation of five building types and five context types were defined for the Dutch case of the city of Rotterdam. The microclimate simulations carried out in ENVI-met for the resulting 25 combined archetypes showed that the identified types are able to describe a wide range of microclimate characteristics. The overall variations in air temperature, humidity, and wind for the 25 cases suggest that the morphological characteristics considered account for up to 2.5°C change in air temperature, up to 3m/s change in wind speed, and up to 5% change in relative humidity. Among all types, high-rise buildings (B_Type4) and high-density contexts (C_Type5) provide, respectively, the lowest indoor and outdoor temperatures during the days under study, showing the ability to mitigate the overheating process during the daytime in particular.

In addition, the analysis of climate patterns has confirmed similar behaviour among the cases representing each building type. The building type classification well represents patterns of indoor temperatures and wind velocities near façades. High-rise buildings (B_Type4) are characterised by the lowest indoor temperatures, while low-compact low-rise buildings (B_Type1) reach the highest indoor temperatures.

The analysis also highlights that some building types are more (or less) sensitive to the surrounding conditions than others. Due to different context conditions, mid-rise buildings with smaller footprint area (B_Type2) show large wind speed variations near the façade and probably as a consequence larger indoor temperature variation.

Regarding the context classification, no evident relation was found between context types and climate patterns within the groups. However, the flexibility granted by the clustering method allowed for a reading of microclimate patterns based on the hierarchical relations between groups. Two distinctive thermal patterns for medium (C_Type2) and high-density contexts (C_Type5) were found. However, very similar temperatures were observed in the three context types characterised by low building intensity and low building coverage (C_Type 1,3, and 4). Here, the use of the hierarchical clustering method showed that these three types are combined at a higher aggregation level in the dendrogram scheme. Therefore, it can be concluded that three types are enough to describe the morphological configurations of the context in relation to thermal behaviour.

The framework has allowed the authors to identify and climatically characterise building and context types in a Dutch case study. The application of the methodology in other geographical regions—or even other Dutch cities—might result in different morphological types and microclimate responses. Moreover, even if similar buildings and context types to the ones identified in Rotterdam would be found, the response of microclimate patterns and the intensity of UHI would likely change according to the meso-scale climate zone of the analysed city. Ultimately, the scope of the study is not to identify types that are present worldwide, but to offer an approach able to acknowledge the climate performance in conditions of spatial heterogeneity. The method proposed, when applied to other climate and spatial contexts, will contribute to the characterisation of local climate types, by recalling the concept of "locus" with its geographical, cultural, and atmospheric significance.

In the development of climate action plans, where tools are necessary to support the implementation of guidelines and climate adaptive interventions, this approach has the potential of supporting the understanding of the local spatial conditions that increase the risk of urban overheating. In the Netherlands, for example, national policy urged all local governments to perform such a risk assessment ("stress-test") and to formulate an implementation plan for climate adaptive measures before 2021 (National Delta Programme, 2015). However, currently, only 10% of the municipalities have set such an agenda for heat (National Delta Programme, 2021), indicating that local governments struggle to formulate appropriate measures. This is partly due to the fact that the existing infrastructure, urban fabric, and buildings limit the number of possible solutions and that there is a high variability of temperatures and related problems within the city (Albers et al., 2015). The identification of "archetypes" in each urban context can facilitate the planning of local, yet structural adaptation measures. For instance, in both new and existing urban developments, planners can regulate building type characteristics, being informed on the microclimatic trade-off that the existing context is likely going to create; and define the urgency of interventions based on the patterns of outdoor and indoor temperatures of types. Moreover, the result of this study has the potential to inform designers in integrating mitigation measures in existing contexts. In fact, the morphological characteristics of the types facilitate the understanding of the starting conditions and space availability on which designers are going to operate (for example, open and green space available, compactness of the urban fabric, etc.).

Although the present approach is generally intended to support local governments in heat risk management, the conceptual instrument of climate types and the methodology presented for their definition is expected to facilitate the interaction between spatial, institutional, and technological components in a broader vision of smart sociotechnical governance (Jiang et al., 2020). From a technological perspective this approach supports the analysis of local climate phenomena, as well as the communication of complex climate mechanisms through the use of visually and semantically explained types. Such an approach is expected to facilitate a deeper understanding of climate change challenges in urban transformation processes and constitute a common base for the elaboration of innovative strategies and novel modes of governance. In this direction, the separate identification of building types and context types can support a more targeted identification of roles and responsibilities in heat risk management, helping the collaboration between private and public actors to increase the mitigative and adaptive capacity of local communities. Additionally, from a spatial perspective, the specificity of neighbourhoods and cities inherent in the method offers a framework on which communities can elaborate the integration of other pressing social, economic and environmental needs related to sustainability goals. However, the use of such an approach in transformation processes requires testing in real life settings. Additionally, the application of a microscale typological classification needs to be further explored, in combination with a meso-scale classification, to assess its potential in informing the implementation of mitigation and adaptation measures, more attuned to the specific location and configuration of the urban fabric. Moreover, supplementary studies are necessary to explore the influence of other climate-related parameters such as surface water cover, building materials and orientation, and to further validate and assess this approach by measurements.

Acknowledgments

The authors would like to thank A. A. A. Aldakheelallah, L. M. de Carvalho Filho, and Dr. D. Cannatella (Delft University of Technology) for their support during the data processing and visualisation. Finally, the authors would like to express their gratitude to the city of Rotterdam and the researchers in the “Klimaatmonitoring in de stad” project for providing spatial and measured climate data.

Conflict of Interests

The authors declare no conflict of interests.

Supplementary Material

Supplementary material for this article is available online in the format provided by the authors (unedited).

References

Ackerman, B. (1987). Climatology of Chicago area urban-rural differences in humidity. *Journal of Applied Meteorology and Climatology*, *26*(3), 427-430. https://doi.org/10.1175/1520-0450(1987)026<0427:COCAUR>2.0.CO;2

Albers, R. A. W., Bosch, P. R., Blocken, B., van den Dobbelsteen, A. A. J. F., van Hove, L. W. A., Spit, T. J. M., van de Ven, F., van Hooff, T., & Rovers, V. (2015). Overview of challenges and achievements in the climate adaptation of cities and in the Climate Proof Cities program. *Building and Environment*, *83*, 1–10. https://doi.org/10.1016/j.buildenv.2014.09.006

Ali-Toudert, F., & Mayer, H. (2006). Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and Environment*, *41*(2), 94–108. https://doi.org/10.1016/j.buildenv.2005.01.013

Allen-Dumas, M. R., Rose, A. N., New, J. R., Omitaomu, O. A., Yuan, J., Branstetter, M. L., Sylvester, L. M., Seals, M. B., Carvalhaes, T. M., Adams, M. B., Bhandari, M. S., Shrestha, S. S., Sanyal, J., Berres, A. S., Kolosna, C. P., Fu, K. S., & Kahl, A. C. (2020). Impacts of the morphology of new neighborhoods on microclimate and building energy. *Renewable and Sustainable Energy Reviews*, *133*, Article 110030. https://doi.org/10.1016/j.rser.2020.110030

Amer, M., Mustafa, A., Teller, J., Attia, S., & Reiter, S. (2017). A methodology to determine the potential of urban densification through roof stacking. *Sustainable Cities and Society*, *35*, 677–691. https://doi.org/10.1016/j.scs.2017.09.021

Araldi, A., & Fusco, G. (2019). From the street to the metropolitan region: Pedestrian perspective in urban fabric analysis. *Environment and Planning B: Urban Analytics and City Science*, *46*(7), 1243–1263. https://doi.org/10.1177/2399808319832612

Barthelemy, M. (2017). From paths to blocks: New measures for street patterns. *Environment and Planning B: Urban Analytics and City Science*, *44*(2), 256–271. https://doi.org/10.1177/0265813515599982

Berghauser Pont, M., & Haupt, P. (2010). *Spacematrix: Space, density and urban form*. NAi Publishers.

Berghauser Pont, M., Stavroulaki, G., Bobkova, E., Gil, J., Marcus, L., Olsson, J., & Legeby, A. (2019). The spatial distribution and frequency of street, plot and building types across five European cities. *Environment and Planning B: Urban Analytics and City Science*, *46*(7), 1226–1242. https://doi.org/10.1177/2399808319857450

Bibri, S. E., Krogstie, J., & Kärrholm, M. (2020). Compact city planning and development: Emerging practices and strategies for achieving the goals of sustainability. *Developments in the Built Environment*, *4*, Article 100021. https://doi.org/10.1016/j.dibe.2020.100021

Bobkova, E. (2019). *Towards a theory of natural occu-*

pation: Developing theoretical, methodological and empirical support for the relation between plot systems and urban processes [Doctoral dissertation, Chalmers University of Technology]. Chalmers University of Technology Repository. https://research.chalmers.se/en/publication/513622

Bobkova, E., Berghauser Pont, M., & Marcus, L. (2021). Towards analytical typologies of plot systems: Quantitative profile of five European cities. *Environment and Planning B: Urban Analytics and City Science*, 48(4), 604–620. https://doi.org/10.1177/2399808319880902

Bourdic, L., Salat, S., & Nowacki, C. (2012). Assessing cities: A new system of cross-scale spatial indicators. *Building Research and Information*, *40*(5), 592–605. https://doi.org/10.1080/09613218.2012.703488

Bruse, M., & Fleer, H. (1998). With a three dimensional numerical model. *Environmental Modelling & Software*, *13*(3/4), 373–384.

Caldera, M., Corgnati, S. P., & Filippi, M. (2008). Energy demand for space heating through a statistical approach: Application to residential buildings. *Energy and Buildings*, *40*(10), 1972–1983. https://doi.org/10.1016/j.enbuild.2008.05.005

Chen, Yixing, Hong, T., Luo, X., & Hooper, B. (2019). Development of city buildings dataset for urban building energy modeling. *Energy and Buildings*, *183*, 252–265. https://doi.org/10.1016/j.enbuild.2018.11.008

Chen, Yunhao, Wu, J., Yu, K., & Wang, D. (2020). Evaluating the impact of the building density and height on the block surface temperature. *Building and Environment*, *168*(19), Article 106493. https://doi.org/10.1016/j.buildenv.2019.106493

Crank, P. J., Sailor, D. J., Ban-Weiss, G., & Taleghani, M. (2018). Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies. *Urban Climate*, *26*, 188–197. https://doi.org/10.1016/j.uclim.2018.09.002

D'Acci, L. (2019). On urban morphology and mathematics. In L. D'Acci (Ed.), *The mathematics of urban morphology* (pp. 1–18). Birkhäuser.

Demetriou, D., See, L., & Stillwell, J. (2013). A parcel shape index for use in land consolidation planning. *Transactions in GIS*, *17*(6), 861–882. https://doi.org/10.1111/j.1467-9671.2012.01371.x

Duarte, D. H. S., Shinzato, P., dos Santos Gusson, C., & Alves, C. A. (2015). The impact of vegetation on urban microclimate to counterbalance built density in a subtropical changing climate. *Urban Climate*, *14*, 224–239. https://doi.org/10.1016/j.uclim.2015.09.006

European Commission. (1991). *Green paper on the urban environment—Communication from the Commission to the Council and the Parliament*.

Forouzandeh, A. (2018). Numerical modeling validation for the microclimate thermal condition of semi-closed courtyard spaces between buildings. *Sustainable Cities and Society*, *36*, 327–345. https://doi.org/10.1016/j.scs.2017.07.025

Founda, D., Pierros, F., Katavoutas, G., & Keramitsoglou, I. (2019). Observed trends in thermal stress at European cities with different background climates. *Atmosphere*, *10*(8), Article 436. https://doi.org/10.3390/atmos10080436

Gemeente Rotterdam. (2018). *Rotterdam in 3D*. https://www.rotterdam.nl/werken-leren/3d

Gil, J., Beirão, J. N., Montenegro, N., & Duarte, J. P. (2012). On the discovery of urban typologies: Data mining the many dimansions of urban form. *Urban Morphology*, *16*(1), 27–40. https://www.researchgate.net/publication/256895610_On_the_discovery_of_urban_typologies_Data_mining_the_many_dimensions_of_urban_form

Godoy-Shimizu, D., Steadman, P., Hamilton, I., Donn, M., Evans, S., Moreno, G., & Shayesteh, H. (2018). Energy use and height in office buildings. *Building Research and Information*, *46*(8), 845–863. https://doi.org/10.1080/09613218.2018.1479927

Grimmond, C. S. B., & Oke, T. R. (1999). Aerodynamic properties of urban areas derived from analysis of surface form. *Journal of Applied Meteorology*, *38*(9), 1262–1292.

Guerreiro, S. B., Dawson, R. J., Kilsby, C., Lewis, E., & Ford, A. (2018). Future heat-waves, droughts and floods in 571 European cities. *Environmental Research Letters*, *13*(3), Article 034009. https://doi.org/10.1088/1748-9326/aaaad3

Haggag, M. A., & Ayad, H. M. (2002). The urban structural units method: A basis for evaluating environmental prospects for sustainable development. *Urban Design International*, *7*(2), 97–108. https://doi.org/10.1057/palgrave.udi.9000071

Hausleitner, B., & Berghauser Pont, M. (2017). Development of a configurational typology for micro-businesses integrating geometric and configurational variables. In *Proceedings of the 11th International Space Syntax Symposium*, (pp. 66.1–66.14). Instituto Superior Técnico.

Hecht, R., Meinel, G., & Buchroithner, M. (2015). Automatic identification of building types based on topographic databases: A comparison of different data sources. *International Journal of Cartography*, *1*(1), 18–31. https://doi.org/10.1080/23729333.2015.1055644

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K. L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S. I., Thomas, A., Warren, R., & Zhou, G. (2018). Impacts of 1.5°C global warming on natural and human systems. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (Eds.), *Global warming of 1.5°C. An*

IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (pp. 175–311).The Intergovernmental Panel on Climate Change.

Jiang, H., Geertman, S., & Witte, P. (2020). Smart urban governance: An alternative to technocratic "smartness." *GeoJournal*. https://doi.org/10.1007/s10708-020-10326-w

Jin, H., Cui, P., Wong, N., & Ignatius, M. (2018). Assessing the effects of urban morphology parameters on microclimate in Singapore to control the urban heat island effect. *Sustainability*, *10*(1), Article 206. https://doi.org/10.3390/su10010206

Jurelionis, A., & Bouris, D. G. (2016). Impact of urban morphology on infiltration-induced building energy consumption. *Energies*, *9*(3), 1–13. https://doi.org/10.3390/en9030177

Klok, L., Zwart, S., Verhagen, H., & Mauri, E. (2012). The surface heat island of Rotterdam and its relationship with urban surface characteristics. *Resources, Conservation and Recycling*, *64*, 23–29. https://doi.org/10.1016/j.resconrec.2012.01.009

Kong, F., Sun, C., Liu, F., Yin, H., Jiang, F., Pu, Y., Cavan, G., Skelhorn, C., Middel, A., & Dronova, I. (2016). Energy saving potential of fragmented green spaces due to their temperature regulating ecosystem services in the summer. *Applied Energy*, *183*, 1428–1440. https://doi.org/10.1016/j.apenergy.2016.09.070

Kong, L., Lau, K. K. L., Yuan, C., Chen, Y., Xu, Y., Ren, C., & Ng, E. (2017). Regulation of outdoor thermal comfort by trees in Hong Kong. *Sustainable Cities and Society*, *31*, 12–25. https://doi.org/10.1016/j.scs.2017.01.018

Lan, Y., & Zhan, Q. (2017). How do urban buildings impact summer air temperature? The effects of building configurations in space and time. *Building and Environment*, *125*, 88–98. https://doi.org/10.1016/j.buildenv.2017.08.046

Lenzholzer, S. (2015). *Weather in the city: How design shapes urban climate*. nai010.

Liu, W., You, H., & Dou, J. (2009). Urban-rural humidity and temperature differences in the Beijing area. *Theoretical and Applied Climatology*, *96*(3), 201–207. https://doi.org/10.1007/s00704-008-0024-6

Lobaccaro, G., & Acero, J. A. (2015). Comparative analysis of green actions to improve outdoor thermal comfort inside typical urban street canyons. *Urban Climate*, *14*, 251–267. https://doi.org/10.1016/j.uclim.2015.10.002

Mangan, S. D., Koclar Oral, G., Erdemir Kocagil, I., & Sozen, I. (2021). The impact of urban form on building energy and cost efficiency in temperate–humid zones. *Journal of Building Engineering*, *33*, Article 101626. https://doi.org/10.1016/j.jobe.2020.101626

Marique, A.-F., & Reiter, S. (2014). Retrofitting the suburbs: Insulation, density, urban form and location. *Environmental Management and Sustainable Development*, *3*(2), 138–153. https://doi.org/10.5296/emsd.v3i2.6589

Mashhoodi, B., Stead, D., & van Timmeren, A. (2020). Land surface temperature and households' energy consumption: Who is affected and where? *Applied Geography*, *114*, Article 102125. https://doi.org/10.1016/j.apgeog.2019.102125

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P., & Oikonomou, E. (2012). Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings. *Building and Environment*, *55*, 117–130. https://doi.org/10.1016/j.buildenv.2011.12.003

Morganti, M., Salvati, A., Coch, H., & Cecere, C. (2017). Urban morphology indicators for solar energy analysis. *Energy Procedia*, *134*, 807–814. https://doi.org/10.1016/j.egypro.2017.09.533

Næss, P., Saglie, I. L., & Richardson, T. (2020). Urban sustainability: Is densification sufficient? *European Planning Studies*, *28*(1), 146–165. https://doi.org/10.1080/09654313.2019.1604633

National Delta Programme. (2015). *Delta Programme 2015—Working on the delta: The decisions to keep the Netherlands safe and liveable*. https://english.deltacommissaris.nl/delta-programme/documents/publications/2014/09/16/delta-programme-2015

National Delta Programme. (2021). *Delta Programme 2021. Staying on track in climate-proofing the Netherlands* (English version). https://english.deltaprogramma.nl

Oke, T. R. (1987). *Boundary layer climates*. Routledge.

Oke, T. R., Johnson, G. T., Steyn, D. G., & Watson, I. D. (1991). Simulation of surface urban heat islands under "ideal" conditions at night part 2: Diagnosis of causation. *Boundary-Layer Meteorology*, *56*(4), 339–358. https://doi.org/10.1007/BF00119211

Peponis, J., Allen, D., French, S., Scoppa, M., & Brown, J. (2007). Street connectivity and urban density: Spatial measures and their correlation. In *Proceedings of the 6th International Space Syntax Symposium* (pp. 4.01–4.12). Istanbul Technical University.

Perez, J., Fusco, G., Araldi, A., & Fuse, T. (2018). *Building typologies for urban fabric classification: Osaka and Marseille case studies* [Conference paper]. International Conference on Spatial Analysis and Modeling, Tokyo, Japan.

Perini, K., & Magliocco, A. (2014). Effects of vegetation, urban density, building height, and atmospheric conditions on local temperatures and thermal comfort. *Urban Forestry and Urban Greening*, *13*(3), 495–506. https://doi.org/10.1016/j.ufug.2014.03.003

Rafiee, A., Dias, E., & Koomen, E. (2016). Local impact of tree volume on nocturnal urban heat island: A case study in Amsterdam. *Urban Forestry and Urban Greening*, *16*, 50–61. https://doi.org/10.1016/j.ufug.

2016.01.008

Ratti, C., Baker, N., & Steemers, K. (2005). Energy consumption and urban texture. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2004.10.010

Rodríguez-Álvarez, J. (2016). Urban energy index for buildings (UEIB): A new method to evaluate the effect of urban form on buildings' energy demand. *Landscape and Urban Planning*, *148*, 170–187. https://doi.org/10.1016/j.landurbplan.2016.01.001

Roodenburg, J. (1983). Adaptation of rural minimum temperature forecasts to an urban environment. *Archives for Meteorology, Geophysics, and Bioclimatology, Series B*, *32*(4), 395–401. https://doi.org/10.1007/BF02324659

Rui, L., Buccolieri, R., Gao, Z., Gatto, E., Rui, L., & Ding, W. (2018). Study of the effect of green quantity and structure on thermal comfort and air quality in an urban-like residential district by ENVI-met modelling. *Building Simulation*, *12*, 183–194. https://doi.org/10.1007/s12273-018-0498-9

Salat, S. (2009). Energy loads, CO_2 emissions and building stocks: Morphologies, typologies, energy systems and behaviour. *Building Research and Information*, *37*(5/6), 598–609. https://doi.org/10.1080/09613210903162126

Salata, F., Golasi, I., de Lieto Vollaro, R., & de Lieto Vollaro, A. (2016). Urban microclimate and outdoor thermal comfort: A proper procedure to fit ENVI-met simulation outputs to experimental data. *Sustainable Cities and Society*, *26*, 318–343. https://doi.org/10.1016/j.scs.2016.07.005

Salvati, A., Monti, P., Coch Roura, H., & Cecere, C. (2019). Climatic performance of urban textures: Analysis tools for a Mediterranean urban context. *Energy and Buildings*, *185*, 162–179. https://doi.org/10.1016/J.ENBUILD.2018.12.024

Salvati, A., Palme, M., Chiesa, G., & Kolokotroni, M. (2020). Built form, urban climate and building energy modelling: Case-studies in Rome and Antofagasta. *Journal of Building Performance Simulation*, *13*(2), 209–225. https://doi.org/10.1080/19401493.2019.1707876

Saroglou, T., Meir, I. A., Theodosiou, T., & Givoni, B. (2017). Towards energy efficient skyscrapers. *Energy and Buildings*, *149*, 437–449. https://doi.org/10.1016/j.enbuild.2017.05.057

Serra, M., Gil, J., & Pinho, P. (2017). Towards an understanding of morphogenesis in metropolitan streetnetworks. *Environment and Planning B: Urban Analytics and City Science*, *44*(2), 272–293. https://doi.org/10.1177/0265813516684136

Serra, M., Psarra, S., & O'Brien, J. (2018). Social and physical characterization of urban contexts: Techniques and methods for quantification, classification and purposive sampling. *Urban Planning*, *3*(1), 58–74. https://doi.org/10.17645/up.v3i1.1269

Skelhorn, C., Lindley, S., & Levermore, G. (2014). The impact of vegetation types on air and surface temperatures in a temperate city: A fine scale assessment in Manchester, UK. *Landscape and Urban Planning*, *121*, 129–140. https://doi.org/10.1016/j.landurbplan.2013.09.012

Smid, M., Russo, S., Costa, A. C., Granell, C., & Pebesma, E. (2019). Ranking European capitals by exposure to heat waves and cold waves. *Urban Climate*, *27*, 388–402. https://doi.org/10.1016/j.uclim.2018.12.010

Steeneveld, G. J., Koopmans, S., Heusinkveld, B. G., van Hove, L. W. A., & Holtslag, A. A. M. (2011). Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands. *Journal of Geophysical Research Atmospheres*, *116*(20), 1–14. https://doi.org/10.1029/2011JD015988

Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society*, *93*(12), 1879–1900. https://doi.org/10.1175/bams-d-11-00019.1

Takebayashi, H. (2017). Influence of urban green area on air temperature of surrounding built-up area. *Climate*, *5*(3), Article 60. https://doi.org/10.3390/cli5030060

Tan, P.-N., Steinbach, M., & Kumar, V. (2005). *Introduction to data mining*. Wesley Longman.

Terrin, J.-J. (2015). *Villes et changement climatique. Ilots de chaleur urbains* [Cities and climate change. Urban heat island]. Parentheses.

Toparlar, Y., Blocken, B., Maiheu, B., & van Heijst, G. J. F. (2017). A review on the CFD analysis of urban microclimate. *Renewable and Sustainable Energy Reviews*, *80*, 1613–1640. https://doi.org/10.1016/j.rser.2017.05.248

Touchaei, A. G., & Wang, Y. (2015). Characterizing urban heat island in Montreal (Canada)—Effect of urban morphology. *Sustainable Cities and Society*, *19*, 395–402. https://doi.org/10.1016/j.scs.2015.03.005

Tsoka, S., Tsikaloudaki, A., & Theodosiou, T. (2018). Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications–A review. *Sustainable Cities and Society*, *43*, 55–76. https://doi.org/10.1016/j.scs.2018.08.009

TU Delft. (2018). *Plots weather stations Rotterdam*. http://weather.tudelft.nl/plots/

van Hove, L. W. A., Jacobs, C. M. J., Heusinkveld, B. G., Elbers, J. A., Van Driel, B. L., & Holtslag, A. A. M. (2015). Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. *Building and Environment*, *83*, 91–103. https://doi.org/10.1016/j.buildenv.2014.08.029

Vartholomaios, A. (2017). A parametric sensitivity analysis of the influence of urban form on domestic energy consumption for heating and cooling in a Mediterranean city. *Sustainable Cities and Society*, *28*, 135–145. https://doi.org/10.1016/j.scs.2016.09.006

Vaz Monteiro, M., Doick, K. J., Handley, P., & Peace, A. (2016). The impact of greenspace size on the extent of local nocturnal air temperature cooling in London. *Urban Forestry and Urban Greening*, *16*, 160–169. https://doi.org/10.1016/j.ufug.2016.02.008

Vernez Moudon, A. (1997). Urban morphology as an emerging interdisciplinary field. *Urban Morphology*, *1*(1), 3–10. https://doi.org/1027-4278

Wang, B., Cot, L. D., Adolphe, L., Geoffroy, S., & Sun, S. (2017). Cross indicator analysis between wind energy potential and urban morphology. *Renewable Energy*, *113*, 989–1006. https://doi.org/10.1016/j.renene.2017.06.057

Ward, K., Lauf, S., Kleinschmit, B., & Endlicher, W. (2016). Heat waves and urban heat islands in Europe: A review of relevant drivers. *Science of the Total Environment*, *569*/*570*, 527–539. https://doi.org/10.1016/j.scitotenv.2016.06.119

Wei, R., Song, D., Wong, N. H., & Martin, M. (2016). Impact of urban morphology parameters on microclimate. *Procedia Engineering*, *169*, 142–149. https://doi.org/10.1016/j.proeng.2016.10.017

Westerink, J., Haase, D., Bauer, A., Ravetz, J., Jarrige, F., & Aalbers, C. B. E. M. (2013). Dealing with sustainability trade-offs of the compact city in periurban planning across European city regions. *European Planning Studies*, *21*(4), 473–497. https://doi.org/10.1080/09654313.2012.722927

Willmott, C. J. (1982). Some comments on the evaluation of model performance. *Bulletin of the American Meteorological Society*, *63*(11), 1309–1313. https://doi.org/10.1175/1520-0477(1982)063%3c1309:SCOTEO%3e2.0.CO;2

Wolff, M., Haase, A., Haase, D., & Kabisch, N. (2017). The impact of urban regrowth on the built environment. *Urban Studies*, *54*(12), 2683–2700. https://doi.org/10.1177/0042098016658231

Wu, Z., Dou, P., & Chen, L. (2019). Comparative and combinative cooling effects of different spatial arrangements of buildings and trees on microclimate. *Sustainable Cities and Society*, *51*, Article 101711. https://doi.org/10.1016/j.scs.2019.101711

Yang, X., Zhao, L., Bruse, M., & Meng, Q. (2013). Evaluation of a microclimate model for predicting the thermal behavior of different ground surfaces. *Building and Environment*, *60*, 93–104. https://doi.org/10.1016/j.buildenv.2012.11.008

Zhao, M., Cai, H., Qiao, Z., & Xu, X. (2016). Influence of urban expansion on the urban heat island effect in Shanghai. *International Journal of Geographical Information Science*, *30*(12), 2421–2441. https://doi.org/10.1080/13658816.2016.1178389

Zinzi, M., & Santamouris, M. (2019). Introducing urban overheating: Progress on mitigation science and engineering applications. *Climate*, *7*(1), Article 15. https://doi.org/10.3390/cli7010015

About the Authors

Daniela Maiullari is a PhD Candidate at the Faculty of Architecture and Built Environment at Delft University of Technology. Her research interest lies in investigating the energy and climate performative dimensions of urban morphological factors. By focusing on the interactions between the design of urban space and microclimate conditions, she addresses the challenges that the transition towards low-carbon cities pose in scenarios of climate change adaptation and mitigation.

Marjolein Pijpers-van Esch is an Assistant Professor at the Department of Urbanism, Environmental Technology & Design of the Faculty of Architecture and Built Environment at Delft University of Technology. She specialises in the impact of urban design on the urban microclimate on the scale levels of the street and neighbourhood. The foci of her research and teaching are design measures for climate adaptation, urban heat island (UHI) effect and outdoor thermal comfort, as well as the influence of the urban climate on the energy use of buildings.

Arjan van Timmeren is a Full Professor at the Department of Urbanism, Environmental Technology & Design of the Faculty of Architecture and the Built Environment at Delft University of Technology, and Principal Investigator at the AMS Institute in Amsterdam. His work focuses on sustainable development in the built environment, with emphasis on environmental technology, urban climate, urban metabolism, circular and biobased economy, and environmental behaviour. He leads several (inter)national projects and has seats in (inter)national steering groups, quality teams, and scientific boards.

COGITATIO

Urban Planning (ISSN: 2183–7635)
2021, Volume 6, Issue 3, Pages 258–271
https://doi.org/10.17645/up.v6i3.4073

Article

Mapping Flood Risk Uncertainty Zones in Support of Urban Resilience Planning

Sven Anders Brandt [1,*], Nancy Joy Lim [1], Johan Colding [2,3] and Stephan Barthel [2,4]

[1] Department of Computer and Geospatial Sciences, University of Gävle, Sweden; E-Mails: sab@hig.se (S.A.B.), naylim@hig.se (N.J.L.)
[2] Department of Building Engineering, Energy Systems and Sustainability Science, University of Gävle, Sweden; E-Mails: joncog@hig.se (J.C.), stnbal@hig.se (S.B.)
[3] The Beijer Institute of Ecological Economics, Royal Swedish Academy of Sciences, Sweden
[4] Stockholm Resilience Centre, Stockholm University, Sweden

* Corresponding author

Submitted: 30 January 2021 | Accepted: 21 April 2021 | Published: 19 August 2021

Abstract
River flooding and urbanization are processes of different character that take place worldwide. As the latter tends to make the consequences of the former worse, together with the uncertainties related to future climate change and flood-risk modeling, there is a need to both use existing tools and develop new ones that help the management and planning of urban environments. In this article a prototype tool, based on estimated maximum land cover roughness variation, the slope of the ground, and the quality of the used digital elevation models, and that can produce flood ‘uncertainty zones’ of varying width around modeled flood boundaries, is presented. The concept of uncertainty, which urban planners often fail to consider in the spatial planning process, changes from something very difficult into an advantage in this way. Not only may these uncertainties be easier to understand by the urban planners, but the uncertainties may also function as a communication tool between the planners and other stakeholders. Because flood risk is something that urban planners always need to consider, these uncertainty zones can function both as buffer areas against floods, and as blue-green designs of significant importance for a variety of ecosystem services. As the Earth is warming and the world is urbanizing at rates and scales unprecedented in history, we believe that new tools for urban resilience planning are not only urgently needed, but also will have a positive impact on urban planning.

Keywords
digital elevation models; ecosystem services; flood map uncertainties; GIS tool; river floods; urban resilience

Issue
This article is part of the issue “Smart Urban Governance for Climate Change Adaptation” edited by Thomas Thaler (University of Natural Resources and Life Sciences, Austria), Patrick Witte (Utrecht University, The Netherlands), Thomas Hartmann (TU Dortmund University, Germany) and Stan Geertman (Utrecht University, The Netherlands).

1. Introduction

Flooding is the natural hazard that historically has had the highest costs in terms of both economic impact and human deaths (Berz et al., 2001). Using the Emergency Events Database (http://www.emdat.be), de Brito and Evers (2016) concluded that between 2000 and 2014, floods were the most frequent natural disaster worldwide causing at least 85,000 fatalities, which had an impact on the wellbeing of about 1.4 billion people, and were associated with a total cost equivalent to USD 400 billion in damage.

Among the different types of floods, e.g., coastal sea and pluvial floods, this article will focus on urban river floods, as rivers are key features of many urban areas around the world. This is a major problem especially in coastal lowlands (Eldho et al., 2018). Cities and mega urban agglomerations that occupy delta landscapes typically become increasingly flood prone due to the multiple processes of climate-change driven flow-frequency changes, sea-level rise, and subsidence of land when upstream dams are hindering sediment transport and wetlands are converted to urban land (Bren d'Amour et al., 2017; Syvitski et al., 2009). While urban flooding cannot be entirely prevented, the losses that have occurred could be dealt with by planning authorities applying different flood risk management strategies such as flood risk prevention, flood defense, flood risk mitigation, flood preparation, and flood recovery (Hegger et al., 2016).

The vicinity of rivers has historically been attractive for urban development (Montz, 2000), as they provide transport possibilities, food, water for drinking and for irrigation, as well as numerous kinds of cultural ecosystem services, among other benefits. Between 1960 and 2017, global urbanization increased the number of urbanites from 1 to 4 billion (Ritchie & Roser, 2018), where a large part of the increase has taken place on river floodplains (Du et al., 2018). Besides changes as precipitation patterns and development practices, over time this has led to a greater share of the global population becoming increasingly exposed to floods (Głosińska, 2014). As the effects of river floods are well known and a variety of solutions of both technical and strategic nature are available, solving the river flood problem may sound like an easy task. However, history has shown that the human practice of building in low-lying floodplains or close to rivers is not easy to change. Although previous research does discuss how the risk of flooding can be better tackled, researchers have demonstrated that in many parts of the world material damage and death tolls caused by river floods continue to be high (Kundzewicz et al., 2018).

Human-induced global warming has taken place during the last 50 years (Intergovernmental Panel on Climate Change [IPCC], 2018). This climate change is often thought to equal warmer weather and greater risks of forest fires or increased sea levels due to glacier melting and thermal expansion of sea water. However, due to changing patterns of the weather systems or changes in the snow–melt cycles, the effects may as well bring increased rates of rainfall and surface runoff. Predicted future climate change will lead to changed river flow frequencies, which means that the 100-year flood will be smaller in some rivers, but larger in others, for instance (Arheimer & Lindström, 2015). Hence, there is great underlying uncertainty of what the future will bring in terms of magnitude of flood flows, as well as an uncertainty inherent in numerical flood risk modeling and mapping procedures (e.g., Merwade et al., 2008).

Previously, much of the urban research has focused on the sustainability of urban development. Around the turn of the last millennium, parts of this research began focusing on resilience (cf. Meerow et al., 2016). An early treatise of urban resilience and hazards in general was written by Godschalk (2003) with the aim to start resilient cities initiatives. Since then, attention has been paid particularly to flood hazards resilience. Liao (2012) puts forward how the resilience concept can be used to overcome the conventional view that cities need flood control as the only flood management tool, and instead adhere to flood adaptation strategies. Similar reasoning is found in Wenger (2017), who found evidence of a shift from structural mitigation and levee dependency to support for alternatives such as ecosystem-based measures and development relocation. Bergsma (2017) further argues that the traditional hard engineering kind of solutions should be complemented with local-oriented spatial planning expertise. Although the hydraulic models have proved very valuable in many cases, there is plenty of evidence that they and their related flood risk maps are uncertain; from model input, over model structure and parameterization, to model output (Di Baldassarre & Montanari, 2009; Lim & Brandt, 2019a). Similarly, Meerow et al. (2016) found evidence of an increase in academic resilience research, especially with respect to climate change, that *uncertainty* and risk were acknowledged as potential *drivers for creating urban resilience*. Therefore, drawing on Bertilsson et al. (2019), who point out that an intelligent urban drainage design used together with emerging resilience approaches may be an interesting way forward, we conclude that there may be new approaches that can go beyond and increase the benefits of these hydraulic models in relation to spatial planning and resilience. As it is obvious that urban planners cannot any longer ignore risks associated with urban floods, neither should they ignore the uncertainties related to flooding.

Most of today's urban areas have been developed in a climate different than what is expected in a near future, with only relatively limited considerations that climate change will impact both the magnitudes and the frequencies of river floods. We therefore argue herein that to benefit resilience thinking, current practices in urban planning need to be expanded, for example by developing new software tools. Our present and future urban management and development plans need not only to consider the uncertainty related to the wider effects of climate change, but also the uncertainty related to potential local impacts (Meerow & Woodruff, 2020). However, in practice, uncertainty is often seen as something difficult to deal with and often leads to maladaptive planning (Moroni & Chiffi, in press; Pappenberger & Beven, 2006). Hence, in this article an attempt will be made to propose a tool that can help using uncertainty as a leverage, or as a management opportunity, which together with resilience thinking may increase the chances of creating not only flood-resilient urban environments, but also resilient cities in a more general sense.

The aim of this article is therefore to increase the opportunities of reducing flood risks by using uncertainty as an argument and a tool to create more resilient urban areas. If this takes place, a number of other positive effects are then also possible, such as higher quality of urban ecosystem services for human wellbeing. In pursuit of this aim, the objectives of the article are: 1) to present a prototype flood-inundation mapping tool that creates a buffer zone of varying width around a river based on uncertainties associated with the digital elevation model (DEM) and land cover roughness; and 2) to discuss how this tool can benefit resilience thinking in urban planning.

2. Previous Research on Urban Resilience With Respect to Floods

2.1. Urban Resilience

The concept of resilience can be traced back to Holling's (1973, 1986) works. He defined resilience as "the ability of a system to maintain its structure and patterns of behavior in the face of disturbance"; something that is connected to, but different from, stability, which "emphasizes equilibrium, low variability, and resistance to and absorption of change" (Holling, 1986, pp. 296–297; cf. Folke et al., 2003, and Marchese et al., 2018, for a thorough treatise on the sustainability and resilience concepts). Meerow et al. (2016, p. 45) further add that urban resilience needs the ability "to adapt to change, and to quickly transform systems that limit current or future adaptive capacity." From there, one definition has emerged that particularly focuses on resilience to natural disasters, viz. "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (National Research Council, 2012, p. 1), which is particularly relevant for the topic of this article. Resilience thinking has therefore become a fundamental framework for understanding complex adaptive systems, from ecosystems to cities and cells and to economic systems (Levin, 1999). In ecology, the concept of resilience describes the capacity of an ecosystem to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks (Holling, 1973). Central for an understanding of resilience thinking is an understanding of what role disturbance plays for system renewal over space and time (Colding et al., 2003). Disturbances such as fires, heavy storms, and floods are considered to be a natural part of the development of many ecosystems, and the renewal capacity of ecosystems depends on natural perturbations (Holling, 1986); the trick is to make sure that the intensity, duration, and periodicity of a particular disturbance are not too high, long-lasting, and too frequent in order to avoid making them unmanageable (Connell, 1978).

Many human communities adapt to and even depend on flooding for their survival, such as for irrigation and fertilization of food cultivars and crops (Colding et al., 2003). The knowledge gained of flood management practices that promote resilience have enabled some communities to adapt to floods and their consequences and even taking advantage of this process. This is indicative of that the perception of *disturbance as a risk* also can be seen as a cultural phenomenon, where frequent natural disturbances force local-level management practices into action (Colding et al., 2003). This is in line with Zevenbergen et al. (2020), who argue that resilience in flood risk management entails that societies should learn to live with floods and not seek to entirely avoid them. However, flooding is commonly perceived as a nuisance in many societies, and decision makers often seek to command and control it in an attempt to entirely prevent the disturbance. Therefore, flood defense provides a key resilience strategy with the aim to reduce the probability of flooded areas through infrastructural measures such as through dikes, dams, and different kinds of embankments (Hegger et al., 2016). Such design and operation flood-control measures of flood resilient technologies have proven valuable (Zevenbergen et al., 2020), but engineering resilience measures risk altering natural disturbance regimes in such a way that pulse events are transformed into persistent disturbance or even chronic stresses (Nyström et al., 2000). Engineering resilience also presumes that the system remains constant over time, disregarding the fact that extreme disturbance events may have profound impacts on the system's functioning (Zevenbergen et al., 2020).

Social-ecological resilience involves the interaction between human societies and natural systems. Such resilience in a flood risk management context calls for an adaptive approach in recognition of that conditions change over space and time. Adaptability refers to human actions for sustaining critical functions on which humans depend and is a process of deliberate change in anticipation to external stresses (Folke, 2016). The adaptability concept in resilience thinking therefore captures "the capacity of people in a social-ecological system to learn, combine experience and knowledge, innovate, and adjust responses and institutions to changing external drivers and internal processes" (Folke, 2016, p. 44). By virtue of technological sophistication and the opportunity of advanced nations to invest in costly exogenous inputs, flood risk management in urban areas may be imperiled by focusing too narrowly on flood control by way of the construction of levees. It risks neglecting aspects such as coordinated investment in flood retaining activities and allowing seasonal flooding of catchment by, for example, providing compensation to land use that may dampen flood peaks (Johannessen, 2015). Abandoning building schemes entirely in flood-prone land may therefore be a sensible urban planning strategy. Findings by Lewis et al. (2017) in relation to resilience management following the catastrophic flooding during Hurricane Katrina in 2005 indicate that resettlement and landscape management policies such as flood risk prevention are important resilience measures. For boosting the adaptive capacity in social-ecological systems, Folke et al. (2003) therefore proposed four key features of social-ecological resilience-building; these include: learning to live with change and uncertainty, nurturing diversity for reorganization and renewal, combining different types of knowledge for learning, and creating opportunity for self-organization toward social-ecological sustainability.

Knowledge building is integral to strengthening resilience among people by informing them of the risks involved in flooding through a risk communication process. The imparted information during risk communication forms an important component of the knowledge base when dealing with hazards and risks, as it allows the general public, communities, organizations, and decision-makers to better comprehend risk, and to plan and take actions that can reduce costly consequences of flood disasters (cf. Lewis & Ernstson, 2019).

2.2. Natural Hazard Risk Communication

Risk communication is a significant part of the risk management process to cope with natural hazards, mitigate risks and impacts of disasters, as well as to reduce vulnerabilities. At the same time, it helps planners and decision-makers generate strategies that can be adopted to make communities sustainable and resilient (Pine, 2015). One of the important roles of risk communication in disaster mitigation is raising people's awareness about their exposure and vulnerability to a certain hazard, and informing them of how they can protect themselves in case the risks materializes into a disaster (Dransch et al., 2010).

Flood hazard and risk maps are the most common tools used in flood risk communication processes. Mapping as a whole provides a framework for examining, determining, and visualizing areas that are under potential threats of a natural hazard (Pine, 2015). Within the flood risk management context, risk communication aims to prepare people for the possibility of floods, so as to reduce the possible flood impacts to them (Rollason et al., 2018), thereby promoting resilient behaviors in terms of preparedness. Hazard maps visualize the geographical extents, depths, or velocities of floods at a given risk probability, while risk maps combine the former with the possible economic, social, environmental, or cultural consequences of flooding (van Alphen et al., 2009), i.e., taking into account the hazard and vulnerabilities as it visualizes the scale of the risk.

Recently, the focus on flood risk communication through maps has shifted to flood uncertainty mapping and visualization, as it is recognized by several researchers that there will always be associated uncertainties in flood maps. According to Pang et al. (1997), the main purpose of visualizing uncertainties is to mediate information inaccuracies, so as to increase understanding of the information and its limitations, as well as to facilitate decisions. In flood modeling, there are different approaches in quantifying uncertainties (cf. Section 2.3) and showing them on maps. Monte Carlo simulation results, for instance, where model inputs are varied to produce different outputs, are often weighted and aggregated into a single map, visualized as fuzzy information indicating the probability of the flood (Di Baldassarre et al., 2010) or the degree of uncertainty present in the flood map (Horritt, 2006). Results from fewer simulations are shown by overlaying different results to see how the flooding extents vary as effect of, for example, the resolution, Manning's roughness, or the model used (Lim & Brandt, 2019b). Using a multiple map display to show the various flood maps generated for each modeling is an alternative visualization method if visual overlay is impossible (Horritt, 2006; Lim & Brandt, 2019b; Saksena & Merwade, 2015). Hence, flood uncertainty communication through maps can help improve knowledge of the possible miscalculations of risks associated with flooding, by being able to recognize the limitations of the presented information. Such acknowledgement of the inevitability of uncertainty in flood maps due to the unpredictability of the flood event allows an adaptive way of dealing with the unknowns, which is an important concept in resilience, and in increasing adaptive capacity (Restemeyer et al., 2018). Furthermore, as Thorne et al. (2018) highlight, to really increase the implementation of blue-green infrastructure and sustainable flood risk management, not only biophysical but also social dimensions and political values need to be identified and managed in the communication process.

2.3. River Flood Modeling and Inherent Uncertainties

All models include weaknesses and flaws to different degrees, hydraulic models being no exceptions. Even though new research findings and more powerful computers have improved the models over the years, their results are still uncertain. Those uncertainties may arise from a variety of sources. Input data uncertainties depend on the raw-data acquisition instrument's accuracy and the processing methods that precedes the hydraulic modeling. Hydraulic models require topographic data, in the forms of DEMs or cross sections (CS), to derive the elevation values used in the models' equations. Uncertainties in model results as effect of topographic data are often caused by the DEM's quality (Lim & Brandt, 2019b; Saksena & Merwade, 2015), the geometric configuration of the CS (Cook & Merwade, 2009), and the inclusion of buildings and other structures in the DEM (Koivumäki et al., 2010) or unforeseen events such as dike and levee breaks (Apel et al., 2008; Ranzi et al., 2013). Hydrologic data are used for deriving rating curves, hydrographs, water stages, and depths that are used as input boundary conditions in the model. Errors in these can cause errors in the initial discharges/depths, which in turn cause uncertainties in flow calculations in the modeling (Di Baldassarre & Montanari, 2009). Uncertainties in the model are for example affected by approximations made in the equations applied to reduce computational complexities. Thus, different models can produce different results (Hunter et al., 2008). Finally, there is parameter uncertainty, of which the roughness coefficient is the most important and to which hydraulic models are highly sensitive (Lim & Brandt, 2019b). It is often expressed by the Manning's *n*-value, which is a measure of the frictional resistance the water experiences when it flows over channel bed and land. The resistance varies according to bed material grain sizes, type and amount of vegetation, presence of bedforms, sinuosity of the river, and so forth. It is usually assigned based on land cover type and recommended values in literature. However, its true value is never known, unless tested at the specific study site. Furthermore, the roughness also interacts with the DEM resolution, the boundary conditions and the discharge used, making its value difficult to determine.

All sources of uncertainties affect the calculated flow and hence also the extent of the inundation. How these uncertainties are dealt with varies. There are both deterministic and probabilistic approaches available (Beven, 2009; Di Baldassarre et al., 2010), where a common way to understand, estimate, or even reduce the degree of uncertainty is by performing a sensitivity analysis (Pappenberger et al., 2008). With respect to impact on the positional quality of the modeled flood boundary, the estimation of channel bed and floodplain roughness together with the quality of the DEM stand out as crucial for successful modeling (Lim & Brandt, 2019a, 2019b; Saksena & Merwade, 2015). Roughness estimation is usually handled through calibration, so that modeled flood boundaries match field observations as close as possible, and by varying the roughness, uncertainty estimates can be derived. The quality of the DEM, on the other hand, is not that easy to vary. There is consensus that high-resolution DEMs provide the best input for hydraulic modeling, and that if lower resolution DEMs are used, the uncertainty of the flood predictions correspondingly increases. However, besides resolution, the terrain slope also affects the uncertainty, as flat areas produce more uncertain results than steeper ones. But the slope depends not only on the DEM's cell distance; it is also related to the quality of each measured elevation point in the input data. This quality and estimated uncertainty heavily depends on land cover type, the sensor quality, and the distance between the sensor and the ground. Hence, simulating different quality of DEMs makes modeling significantly more difficult and time consuming compared with simulating roughness variation, where the roughness value can be changed easily for large geographical areas. Klang and Klang's (2009) study, simulating different airplane altitudes of Lidar data gathering, clearly shows the complexity of producing such DEMs. The next stage in uncertainty estimation would then involve using each DEM in the hydraulic modeling process to add further uncertainties. Due to the amount of work required to produce DEMs of truly different qualities, the normal approach to handle DEM uncertainty is to equate it with cell resolution. To overcome this uncertainty estimation problem, Brandt (2016) used Klang and Klang's (2009) DEMs and developed an empirical equation for one-dimensional (1D) flood models, where the disparity distance between modeled and true flood boundary is a function of the perpendicular terrain slope, the DEM resolution, and the percentile of interest (i.e., confidence level). Using this approach, it is then possible to produce uncertainty zones on both sides of the originally modeled crisp flood boundary line without needing to first create several DEMs of different qualities.

3. Development of a GIS Tool to Create Uncertainty Zones Around Modeled Flood Boundaries

3.1. Disparity Distance $\left(D_d\right)$ Algorithm

Brandt's (2016) algorithm (cf. Brandt & Lim, 2016; Lim, 2018) creates uncertainty zones around predicted flood boundaries from 1D hydraulic simulations. Whereas uncertainty zones usually are produced by probabilistic models (Merwade et al., 2008), disregarding the terrain slopes, the uncertainty zones here are based on the characteristics and quality of the used DEM. The algorithm's main assumptions are: 1) the disparity between model and reference data increases as the slope values decreases (and vice versa); and 2) lowering the DEM's resolution further increases this disparity. Thus, the disparity becomes a function of the slope perpendicular to the flow (*S*), DEM resolution (*δ*), and the level of confidence used for the uncertainty assessment (*P*; Equation 1).

$$D_d = \left[\delta^{0.970} 0.000792 P^{1.303}\right] S^{[0.1124 \ln(\delta) + 0.0709 \ln(P) - 1.0064]} \qquad \text{(Eq. 1)}$$

Data needed for the algorithm are the modeled flooded area, a DEM in Triangular Irregular Network (TIN) format, and CS. The TIN and CS are used to generate sampling nodes, while CS and flood boundary produce water surface elevation (WSE) points (Figure 1).

The algorithm proceeds iteratively, node-by-node, for every CS and part (left or right) of the channel. It starts by computing the slope and distance between a given sampled node and the WSE point (i.e., where the CS intersects the flood boundary). D_d is then calculated and evaluated if it exceeds the actual distance. When exceeded, the computation stops at this node. The node's elevation information is recorded as the inner or outer (i.e., on the channel or land side of the modeled flood boundary, respectively) *uncertain* height value for that CS and channel part, and these are assigned to the sampled nodes. These uncertain elevation values are afterwards used to generate one inner and one outer uncertain elevation TIN, which are compared with the original DEM to identify flooded, uncertain, and non-flooded areas (Figure 2).

3.2. Tool Development

The geographical information system (GIS) tool for delineating uncertainty zones around a modeled flood boundary was created with ArcGIS model builder and Python scripting language. The tool consists of two parts: 1)

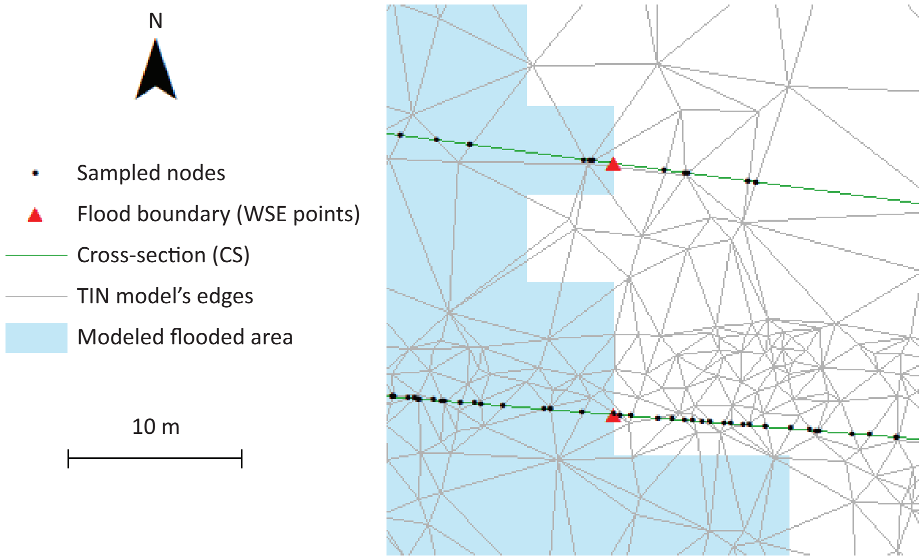


Figure 1. Sampled nodes (black points) are derived by intersecting the TIN model's edges and the CS. WSE points (red triangles) are derived where the flood boundary intersects the CS.

preparation of the data to be used for the algorithm (Figure 3); and 2) implementation of the uncertainty algorithm and mapping (Figure 4). In the preparation part, the flood boundary result from a previous 1D hydraulic simulation, the CS data with the WSE information, stream centerline, flowpaths, and a TIN elevation model are preprocessed. These are used to derive points at the flood boundaries intersecting each CS (i.e., *WSE points*), and sampling *nodes* from the CS intersecting the TIN model's edges (Figure 1). Each node is identified with the CS number, its part location (left or right) in the main channel, as well as if it is inside or outside the flood boundary, using the stream centerline and flowpaths datasets. The x, y coordinates and the height (H) information derived from both datasets are used to compute the distance (D, Eq. 1 in Figure 3), slope (S, Eq. 2), coefficient c and exponent z (Eqs. 3 and 4, derived from the resolution [δ] and percentile [P]), and the disparity distance (D_d, Eq. 5) between the given *node* and *WSE point*. The status of each node is evaluated whether it is flooded, dry, or uncertain. Afterwards, all nodes are grouped per CS, part and side, and sorted according to

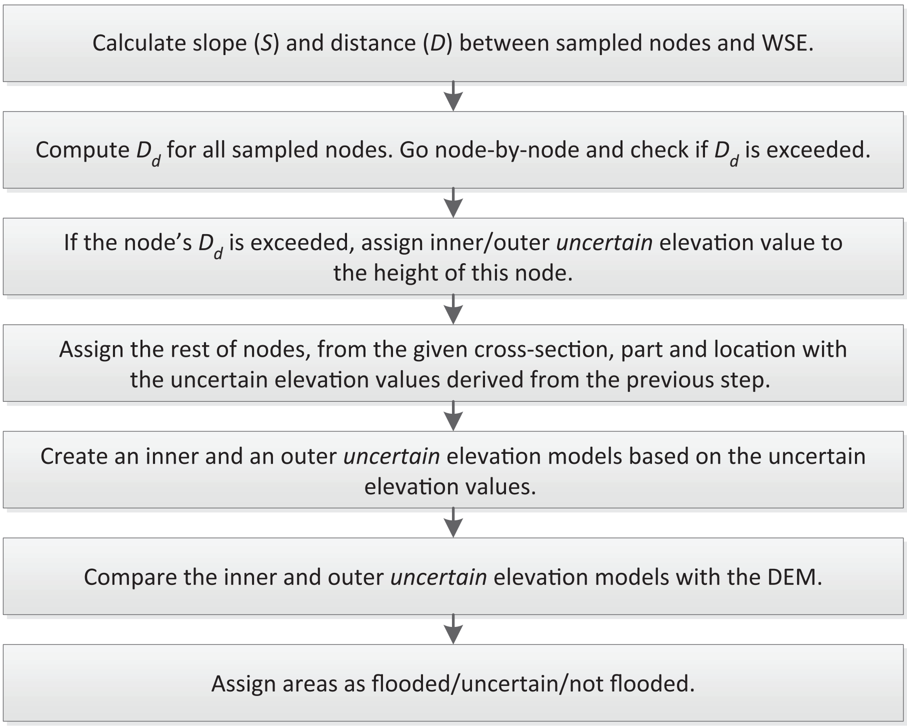


Figure 2. A simplified workflow of the D_d algorithm by Brandt (2016).

distance. Tables are then created and named based on the groupings. Prior to the implementation of the algorithm, two empty tables that contain the computed *outer* and *inner uncertain height* values are created.

The algorithm (Figure 4) starts with the table containing nodes from the first CS's left part and outer side. It begins the row iteration with the node having the closest distance from the WSE point. If the status of this node is *uncertain*, and the next adjacent node (k+1) has certain status, the algorithm gets the entire row information for the next node (k + 1) with the certain status and append this on the *outer uncertain height* table. This initially represents the outer uncertain elevation value for the specific CS and part. Otherwise, the iteration continues to the next row, until the condition is met. The algorithm then proceeds to the next table containing nodes in the inner side of the same CS and part. When the algorithm has finished appending the preliminary *inner and outer uncertain* elevation values in the tables representing all CS, the height (H) information of the nodes is assessed for wall effect, using Eq. 6 for all outer nodes, and Eq. 7 for all inner nodes. If $H_{out} < H$ and $H_{in} > H$, then the H_{out} and H_{in} values are assigned to the node, otherwise, the H of the node is used.

The computed uncertainty information is then joined with the original nodes data based on the CS and part ID. These new elevation values are used to create TIN models representing the water surface of inner and outer uncertainty limits. The created TINs are subtracted from the original TIN elevation model to determine whether the ground is flooded, uncertain, or not flooded. This is done through an overlay of polygons representing these areas.

4. Using Uncertainty Zones as a Resilience Tool

4.1. Study Area, Data, and Hydraulic Model Used

Earlier flood modeling results by Lim (2011) were used to test the tool. The study area is located along the Testebo river, in the northern parts of the city of Gävle, Sweden. The area consists of arable and pasture lands with surrounding residential areas, some which are relatively frequently flooded. The entire river is about 85 km long,

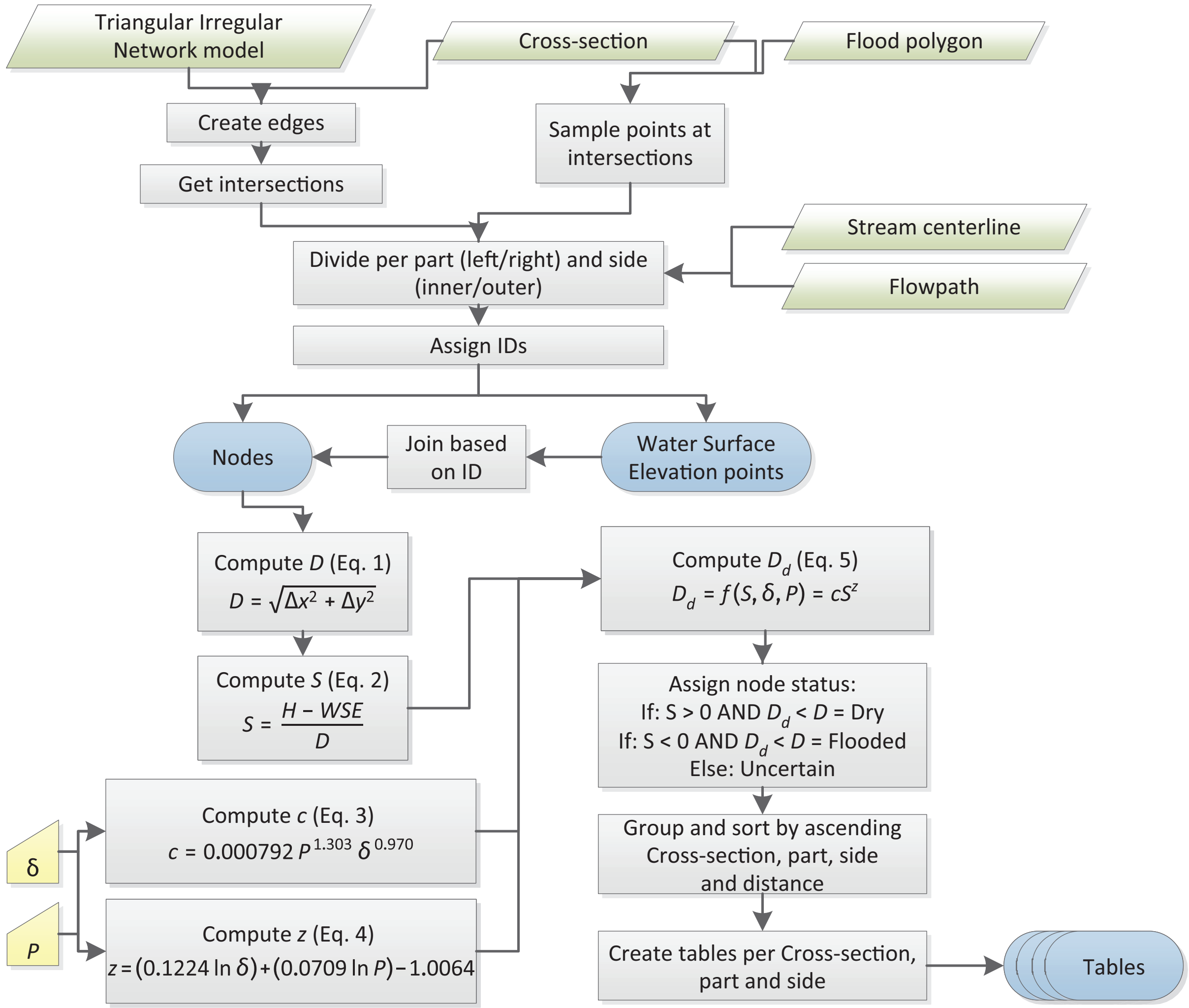


Figure 3. Workflow for preparing data and tables used in the algorithm. Main inputs are: modeled flooded area, TIN model representing the topography, and CS, stream centerline, and flowpath used in the hydraulic simulation.

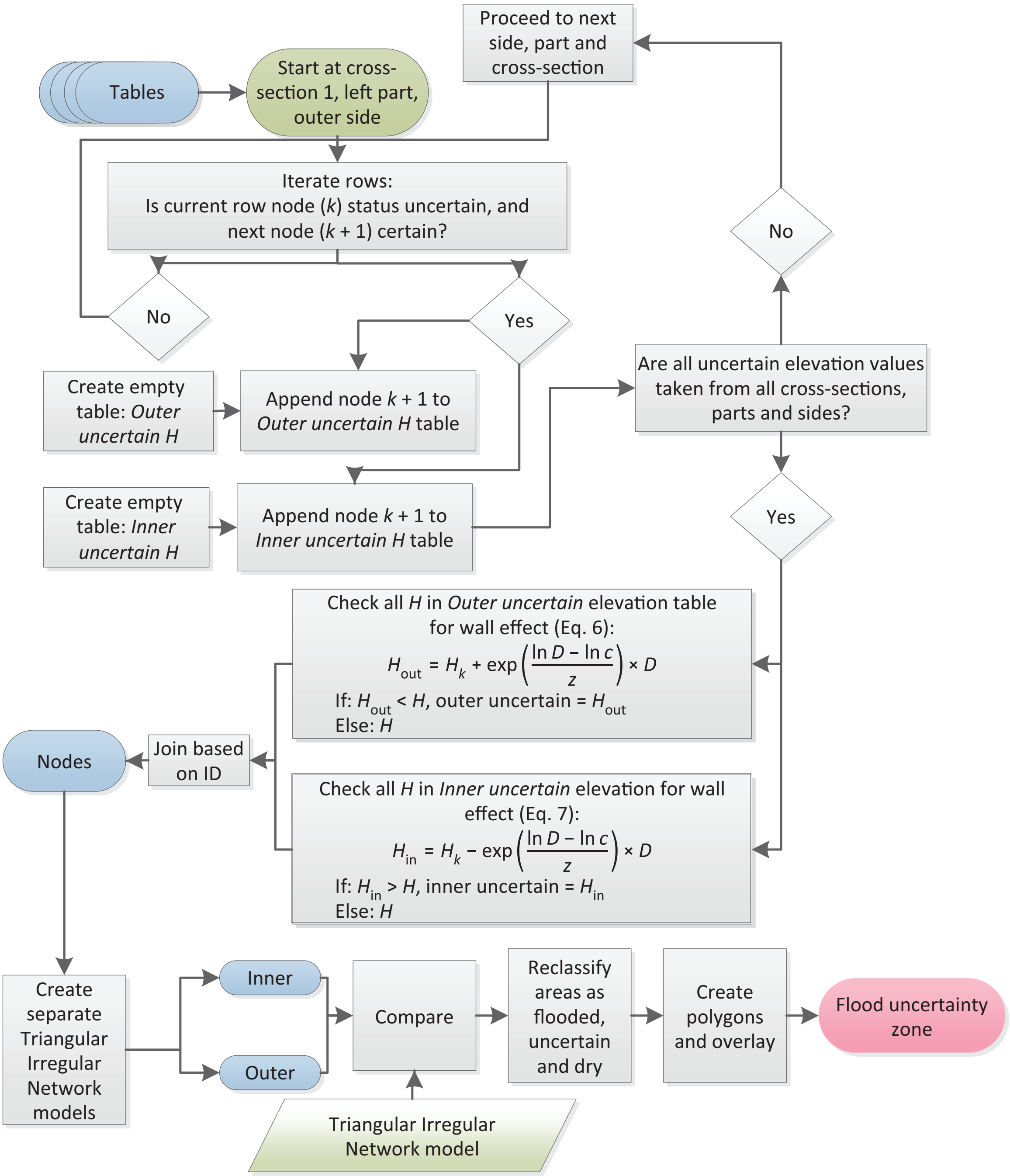


Figure 4. Implementation of the algorithm and generation of the uncertainty zone.

stretching from Åmot in Ockelbo municipality southeast to Gävle, and has a mean annual discharge of 12.1 m^3/s.

The 1D HEC-RAS steady-flow model (Hydrologic Engineering Center, 2008, 2010) was used for the hydraulic simulations. That means discharge, velocity and depth all are constant at each CS. 1D models also consider flows to be unidirectional (parallel to the channel). The topographic data used for the modeling were produced by combining point cloud Lidar data (2.1 m resolution) with bathymetric data into a TIN. The water discharge used was 160 m^3/s, corresponding to the big flood event in 1977. Lim's study ran 500 combinations of channel (ch) and floodplain (fp) Manning's n in a Monte Carlo simulation to produce multiple flood maps (Lim, 2011). Two of the results used low (n_{fl} = 0.030 and n_{ch} = 0.026) and high (n_{fl} = 0.098 and n_{ch} = 0.049) Manning's n, which were used as input data for the new GIS tool. These results were then rasterized using a cell size of 5 m.

4.2. Testing the Resilience Tool

The uncertainty zone produced by the new GIS tool is based solely on the quality of the DEM and the terrain slope characteristics. The previous study by Brandt and Lim (2016) shows, however, that the true flooded area sometimes may be considerably outside or inside this uncertainty zone. To enable capturing some of this additional uncertainty, it seems most relevant to include an estimate of roughness uncertainty. Results produced by the 1D hydraulic model with low Manning's *n* generate smaller flood areas, which are often underpredicted, whereas high Manning's roughness produces bigger inundation areas that overestimate the flooding. Therefore, a wider uncertainty zone can be created by executing two runs in the hydraulic model, one with minimum and one with maximum estimated roughness, respectively, and feeding these into the new GIS tool. The inner uncertainty boundary is then produced from the low-roughness model, while the outer boundary comes from the high-roughness model (Figure 5).

By combining the uncertainty of roughness, quality of DEM, and terrain slope, the probability of encapsulating true flood boundaries within the modeled extended uncertainty zone increases. As urban planning needs to consider the spatial extent and variation of the rivers, which can be directly linked to the uncertainty zone output of the new tool, there is an opportunity not only to link this uncertainty directly to resilience management and approaches (cf. Ashley et al., 2020), but also to facilitate resilience thinking and communication.

5. Discussion and Conclusion

New insights in urban sustainability and resilience have caught the interest of researchers to use the risk of natural hazards as a driver and opportunity to promote resilience thinking and management. Hence, a GIS tool that emphasizes *uncertainty* in flood modeling has been developed to advance such use of risk (i.e., comprising the probability of an adverse event) further. During the planning process, areas next to a river that are considered as threatened to be flooded are usually visualized as buffer zones of fixed width or having risk up to a certain WSE. Very rarely, due to their complexity and difficulty to perform, probabilistic models of flood risks are used. However, those models never include the terrain variation (slope characteristics) to our knowledge. By using Brandt's (2016) algorithm, though, it is possible to incorporate both the quality of the DEM and the terrain slope for estimating the uncertainty. The tool runs in the ArcGIS environment and works with new or already existing hydraulic model results to create uncertainty zones of varied width around a modeled flood boundary. One specific advantage of the tool is that it does not require extensive knowledge in GIS and hydraulic modeling. Another is that it will work for both rural and urban environments, provided the hydraulic modeling as such can be justified. By running the tool twice, for hydraulic model runs of low and high bed roughness, respectively, the tool will produce uncertainty zones that are wide enough to capture most of the uncertainty of the modeled flood's spatial extent. If the modeler wants to have extra uncertainty, the preceding hydraulic model can be run in a 'what if' mode, i.e., by including

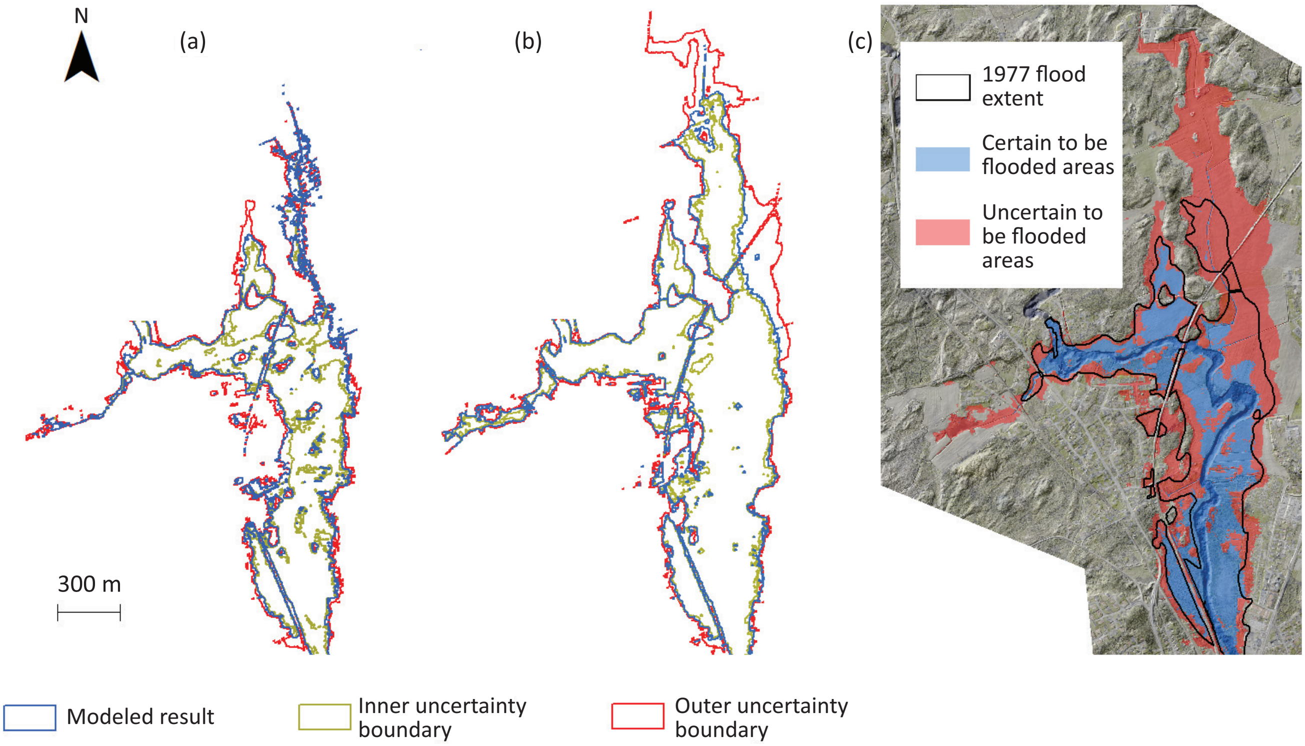


Figure 5. Example of model results for the Testebo river produced by the new GIS-tool. (a) Uncertainty zones from low-roughness 1D model; (b) uncertainty zones from high-roughness 1D model; and (c) resulting increased uncertainty zone serving as a resilience zone.

variations of infrastructure or possible levee breakages. However, there is the tradeoff that with larger uncertainty zones municipalities may be prevented from maximizing land utilization in areas with low risk probability, which could lead to loss of revenues. Nevertheless, with the uncertainties in magnitudes and frequency of huge flood events, it still remains a possibility that these low-risk areas will be flooded in the future. Thus, urban planners can use the tool's result not only for discussing resilience; it should also resort to ways on how they can utilize the extended uncertainty zones to projects that are resilient and adaptive to flooding consequences, especially with respect to climate change. We argue that whether the uncertainty is modeled with high precision is not the most important factor, but rather whether blue-green areas are included to a sufficient degree in the uncertainty zones generated. They can then function as proper and valuable resilience measures, not only for urban planning and management processes, but also for floodplain ordinances.

Despite alarming reports by the IPCC about heightened intensity and frequency of storms and flooding (IPCC, 2014), many urban areas are still planned as if climate change does not occur. Making decision-makers understand that climate change has and will have consequences is a huge challenge. Often planners completely rely on existing engineering solutions, which to a large extent ignore the natural variation of earth surface processes and climate change, and see the riverine environment just as an attractive zone to build new houses. Further, as maps are generally used as deterministic background documents, we believe there is a need to visualize zones of uncertainty in maps. These should be used both for policies and solutions that mitigate risk, and simultaneously should aim to provide citizens with a plurality of ecosystem services for human wellbeing. Hence, such zones of uncertainty in maps concurrently provide decision-makers with tools to put precautionary principles in action in urban governance processes. One reason for this not taking place is probably related to the fact that decision makers and the public often lack knowledge and confidence that blue-green infrastructure is vital for building resilience towards climate change impacts (Thorne et al., 2018). Most people now, however, do realize the negative consequences of extreme floods, and that they might be affected in the future. This makes the concept of uncertainty a promising tool for resilience planning of urban areas. If there is a risk involved, and the size of the area at risk is uncertain, there should be a fair chance during the planning process that urban planners and decision makers consider not only the originally modeled extent of a flood event, but also include an extended area. Reserving and protecting such areas from undesired urban development will automatically provide necessary resilience-rooms for the dynamic rivers. By doing so, there will be a number of positive side effects. In addition to a decrease of the negative consequences of flooding, there will also be easier access to the river and strengthening of legal rights of public access for shoreline areas, which simultaneously may hold richer levels of biodiversity. Uncertainty, as a planning approach, would enable green city designs and opportunities for a number of ecosystem services, such as flood-dependent agroforestry, and higher possibility of yielding cultural ecosystem services that promote people's health. As the UN prospects urban landscapes for another 2.5 billion people in 2050, amidst oncoming climate change (UN-Habitat, 2016, p. 38), new tools for urban resilience planning are therefore urgently needed. Such tools partly need to embrace uncertainty as a strategy for dealing with flooding.

Acknowledgments

This work was partly funded by Future Position X through its project *Bettering life through integrative GIS (BIG)* which aims to co-create knowledge for urban solutions on how healthy, sustainable, and livable cities should be built in the future. Thanks are due to the four anonymous reviewers who provided very valuable and constructive feedback on the article.

Conflict of Interests

The authors declare no conflict of interests.

References

Apel, H., Merz, B., & Thieken, A. H. (2008). Quantification of uncertainties in flood risk assessments. *International Journal of River Basin Management*, *6*(2), 149–162. https://doi.org/10.1080/15715124.2008.9635344

Arheimer, B., & Lindström, G. (2015). Climate impact on floods: Changes in high flows in Sweden in the past and the future (1911–2100). *Hydrology and Earth System Sciences*, *19*(2), 771–784. https://doi.org/10.5194/hess-19-771-2015

Ashley, R., Gersonius, B., & Horton, B. (2020). Managing flooding: From a problem to an opportunity. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2168), Article 20190214. https://doi.org/10.1098/rsta.2019.0214

Bergsma, E. J. (2017). *From flood safety to risk management: The rise and demise of engineers in the Netherlands and the United States?* [Doctoral dissertation, University of Amsterdam]. Library Wageningen University & Research. https://library.wur.nl/WebQuery/hydrotheek/2280469

Bertilsson, L., Wiklund, K., de Moura Tebaldi, I., Moura Rezende, O., Pires Veról, A., & Gomes Miguez, M. (2019). Urban flood resilience—A multi-criteria index to integrate flood resilience into urban planning. *Journal of Hydrology*, *573*, 970–982. https://doi.org/10.1016/j.jhydrol.2018.06.052

Berz, G., Kron, W., Loster, T., Rausch, J., Schimetschek, J., Schmieder, J., Siebert, A., Smolka, A., & Wirtz, A. (2001). World map of natural hazards—A global view of the distribution and intensity of significant exposures. *Natural Hazards*, *23*(2/3), 443–465. https://doi.org/10.1023/A:1011193724026

Beven, K. (2009). *Environmental modeling: An uncertain future?* Routledge.

Brandt, S. A. (2016). Modeling and visualizing uncertainties of flood boundary delineation: Algorithm for slope and DEM resolution dependencies of 1D hydraulic models. *Stochastic Environmental Research and Risk Assessment*, *30*(6), 1677–1690. https://doi.org/10.1007/s00477-016-1212-z

Brandt, S. A., & Lim, N. J. (2016). Visualising DEM-related flood-map uncertainties using a disparity-distance equation algorithm. *Proceedings of the IAHS*, *373*, 153–159. https://doi.org/10.5194/piahs-373-153-2016

Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K.-H., Haberl, H., Creutzig, F., & Seto, K. C. (2017). Future urban land expansion and implications for global croplands. *Proceedings of the National Academy of Sciences*, *114*(34), 8939–8944. https://doi.org/10.1073/pnas.1606036114

Colding, J., Elmqvist, T., & Olsson, P. (2003). Living with disturbance: Building resilience in social-ecological systems. In F. Berkes, J. Colding, & C. Folke (Eds.), *Navigating social-ecological systems: Building resilience for complexity and change* (pp. 163–185). Cambridge University Press. https://doi.org/10.1017/CBO9780511541957.011

Connell, J. H. (1978). Diversity in tropical rain forests and coral reefs. *Science*, *199*(4335), 1302–1310. https://doi.org/10.1126/science.199.4335.1302

Cook, A., & Merwade, V. (2009). Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping. *Journal of Hydrology*, *377*(1/2), 131–142. https://doi.org/10.1016/j.jhydrol.2009.08.015

de Brito, M. M., & Evers, M. (2016). Multi-criteria decision-making for flood risk management: A survey of the current state of the art. *Natural Hazards and Earth System Sciences*, *16*(4), 1019–1033. https://doi.org/10.5194/nhess-16-1019-2016

Di Baldassarre, G., & Montanari, A. (2009). Uncertainty in river discharge observations: A quantitative analysis. *Hydrology and Earth System Sciences*, *13*(6), 913–921. https://doi.org/10.5194/hess-13-913-2009

Di Baldassarre, G., Schumann, G., Bates, P. D., Freer, J. E., & Beven, K. J. (2010). Flood-plain mapping: A critical discussion of deterministic and probabilistic approaches. *Hydrological Sciences Journal*, *55*(3), 364–376. https://doi.org/10.1080/02626661003683389

Dransch, D., Rotzoll, H., & Poser, K. (2010). The contribution of maps to the challenges of risk communication to the public. *International Journal of Digital Earth*, *3*(3), 292–311. https://doi.org/10.1080/17538941003774668

Du, S., He, C., Huang, Q., & Shi, P. (2018). How did the urban land in floodplains distribute and expand in China from 1992–2015? *Environmental Research Letters*, *13*(3), Article 034018. https://doi.org/10.1088/1748-9326/aaac07

Eldho, T. I., Zope, P. E., & Kulkarni, A. T. (2018). Urban flood management in coastal regions using numerical simulation and geographic information system. In P. Samui, D. Kim, & C. Ghosh (Eds.), *Integrating disaster science and management: Global case studies in mitigation and recovery* (pp. 205–219). Elsevier. https://doi.org/10.1016/B978-0-12-812056-9.00012-9

Folke, C. (2016). Resilience (Republished). *Ecology and Society*, *21*(4), Article 44. https://doi.org/10.5751/ES-09088-210444

Folke, C., Colding, J., & Berkes, F. (2003). Synthesis: Building resilience and adaptive capacity in social-ecological systems. In F. Berkes, J. Colding, & C. Folke (Eds.), *Navigating social-ecological systems: Building resilience for complexity and change* (pp. 352–387). Cambridge University Press. https://doi.org/10.1017/CBO9780511541957.020

Głosińska, E. (2014). Floodplain management in the context of assessment and changes of flood risk and the environment: A Review. *Polish Journal of Environmental Studies*, *23*(6), 1895–1904. http://www.pjoes.com/pdf-89384-23241?filename=Floodplain%20Management%20in.pdf

Godschalk, D. R. (2003). Urban hazard mitigation: Creating resilient cities. *Natural Hazards Review*, *4*(3), 136–143. https://doi.org/10.1061/(ASCE)1527-6988(2003)4:3(136)

Hegger, D. L. T., Driessen, P. P. J., Wiering, M., van Rijswick, H. F. M. W., Kundzewicz, Z. W., Matczak, P., Crabbé, A., Raadgever, G. T., Bakker, M. H. N., Priest, S. J., Corinne, L., & Ek, K. (2016). Toward more flood resilience: Is a diversification of flood risk management strategies the way forward? *Ecology and Society*, *21*(4), Article 52. https://doi.org/10.5751/ES-08854-210452

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, *4*, 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Holling, C. S. (1986). The resilience of terrestrial ecosystems: Local surprise and global change. In W. C. Clark & R. E. Munn (Eds.), *Sustainable development of the biosphere* (pp. 292–317). Cambridge University Press.

Horritt, M. S. (2006). A methodology for the validation of uncertain flood inundation models. *Journal of Hydrology*, *326*(1/4), 153–165. https://doi.org/10.1016/j.jhydrol.2005.10.027

Hunter, N. M., Bates, P. D., Neelz, S., Pender, G., Villanueva, I., Wright, N. G., Liang, D., Falconer, R. A., Lin, B., Waller, S., Crossley, A. J., & Mason, D. C. (2008).

Benchmarking 2D hydraulic models for urban flooding. *Water Management*, *161*(1), 13–30. https://doi.org/10.1680/wama.2008.161.1.13

Hydrologic Engineering Center. (2008). *HEC-RAS: River analysis system. User's manual, version 4.0*. US Army Corps of Engineers, Hydrologic Engineering Center.

Hydrologic Engineering Center. (2010). *HEC-RAS: River analysis system. Hydraulic reference manual, version 4.1*. US Army Corps of Engineers, Hydrologic Engineering Center.

Intergovernmental Panel on Climate Change. (2014). *Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar5/syr

Intergovernmental Panel on Climate Change. (2018). *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. https://www.ipcc.ch/sr15/download

Johannessen, Å. (2015). *Integrating flood risk reduction, river basin and resilience management in planning: A case study of Kristianstad, Sweden* (Working Paper No. 2015-01). Stockholm Environment Institute. https://mediamanager.sei.org/documents/Publications/Climate/SEI-WP-2015-Kristianstad-floods-river-basin-management.pdf

Klang, D., & Klang, K. (2009). *Analys av höjdmodeller för översvämningsmodellering* [Analysis of elevation models for inundation modeling]. Myndigheten för samhällsskydd och beredskap and Lantmäteriet. https://docplayer.se/docview/57/39936952.pdf

Koivumäki, L., Alho, P., Lotsari, E., Käyhkö, J., Saari, A., & Hyyppä, H. (2010).Uncertainties in flood risk mapping: A case study on estimating building damages for a river flood in Finland. *Journal of Flood Risk Management*, *3*(2), 166–183. https://doi.org/10.1111/j.1753-318X.2010.01064.x

Kundzewicz, Z. W., Pińskwar, I., & Brakenridge, G. R. (2018). Changes in river flood hazard in Europe: A review. *Hydrology Research*, *49*(2), 294–302. https://doi.org/10.2166/nh.2017.016

Levin, S. (1999). *Fragile dominion: Complexity and the commons*. Perseus Books.

Lewis, J. A., & Ernstson, H. (2019). Contesting the coast: Ecosystems as infrastructure in the Mississippi River Delta. *Progress in Planning*, *129*, 1–30. https://doi.org/10.1016/j.progress.2017.10.003

Lewis, J. A., Zipperer, W. C., Ernstson, H., Bernik, B., Hazen, R., Elmqvist, T., & Blum, M. J. (2017). Socioecological disparities in New Orleans following Hurricane Katrina. *Ecosphere*, *8*(9), Article e01922. https://doi.org/10.1002/ecs2.1922

Liao, K.-H. (2012). A theory on urban resilience to floods—A basis for alternative planning practices. *Ecology and Society*, *17*(4), Article 48. https://doi.org/10.5751/ES-05231-170448

Lim, N. J. (2011). *Performance and uncertainty estimation of 1- and 2-dimensional flood models* [Master's thesis, University of Gävle]. University of Gävle Repository. http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-9642

Lim, N. J. (2018). *Modelling, mapping and visualisation of flood inundation uncertainties* [Doctoral Dissertation, University of Gävle]. University of Gävle Repository. http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-27995

Lim, N. J., & Brandt, S. A. (2019a). Are feature agreement statistics alone sufficient to validate modelled flood extent quality? A study on three Swedish rivers using different digital elevation model resolutions. *Mathematical Problems in Engineering*, *2019*, Article 9816098. https://doi.org/10.1155/2019/9816098

Lim, N. J., & Brandt, S. A. (2019b). Flood map boundary sensitivity due to combined effects of DEM resolution and roughness in relation to model performance. *Geomatics, Natural Hazards and Risk*, *10*(1), 1613–1647. https://doi.org/10.1080/19475705.2019.1604573

Marchese, D., Reynolds, E., Bates, M. E., Morgan, H., Clark, S. S., & Linkov, I. (2018). Resilience and sustainability: Similarities and differences in environmental management applications. *Science of the Total Environment*, *613/614*, 1275–1283. https://doi.org/10.1016/j.scitotenv.2017.09.086

Meerow, S., & Woodruff, S. C. (2020). Seven principles of strong climate change planning. *Journal of the American Planning Association*, *86*(1), 39–46. https://doi.org/10.1080/01944363.2019.1652108

Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning*, *147*, 38–49. https://doi.org/10.1016/j.landurbplan.2015.11.011

Merwade, V., Olivera, F., Arabi, M., & Edleman, S. (2008). Uncertainty in flood inundation mapping: Current issues and future direction. *Journal of Hydrologic Engineering*, *13*(7), 608–620. https://doi.org/10.1061/(ASCE)1084-0699(2008)13:7(608)

Montz, B. E. (2000). The generation of flood hazards and disasters by urban development on floodplains. In D. J. Parker (Ed.), *Floods* (pp. 116–127). Routledge.

Moroni, S., & Chiffi, D. (in press). Complexity and uncertainty: Implications for urban planning. In J. Portugali (Ed.), *Handbook on cities and complexity*. Edward Elgar Publishing.

National Research Council. (2012). *Disaster resilience: A national imperative*. The National Academies Press. https://doi.org/10.17226/13457

Nyström, M., Folke, C., & Moberg, F. (2000). Coral reef disturbance and resilience in a human-dominated environment. *Trends in Ecology and Evolution*, *15*(10), 413–417. https://doi.org/10.1016/S0169-5347(00)01948-0

Pang, A. T., Wittenbrink, C. M., & Lodha, S. K. (1997). Approaches to uncertainty visualization. *The Visual Computer*, *13*(8), 370–390. https://doi.org/10.1007/s003710050111

Pappenberger, F., & Beven, K. J. (2006). Ignorance is bliss: Or seven reasons not to use uncertainty analysis. *Water Resources Research*, *42*(5), Article W05302. https://doi.org/10.1029/2005WR004820

Pappenberger, F., Beven, K. J., Ratto, M., & Matgen, P. (2008). Multi-method global sensitivity analysis of flood inundation models. *Advances in Water Resources*, *31*(1), 1–14. https://doi.org/10.1016/j.advwatres.2007.04.009

Pine, J. C. (2015). *Hazards analysis: Reducing the impact of disasters* (2nd ed.). CRC Press.

Ranzi, R., Bacchi, B., Barontini, S., Ferri, M., & Mazzoleni, M. (2013). Levee breaches statistics, "geotechnical uncertainty," residual risk in flood hazard mapping. In *The wise find pleasure in water: Meandering through water science and engineering. Proceedings of the 35th IAHR World Congress* (Vol. 5, pp. 4516–4524). IAHR.

Restemeyer, B., van den Brink, M., & Woltjer, J. (2018). Resilience unpacked—Framing of 'uncertainty' and 'adaptability' in long-term flood risk management strategies for London and Rotterdam. *European Planning Studies*, *26*(8), 1559–1579. https://doi.org/10.1080/09654313.2018.1490393

Ritchie, H., & Roser, M. (2018). *Urbanization* [Data set]. Our World in Data. https://ourworldindata.org/urbanization

Rollason, E., Bracken, L. J., Hardy, R. J., & Large, A. R. G. (2018). Rethinking flood risk communication. *Natural Hazards*, *92*(3), 1665–1686. https://doi.org/10.1007/s11069-018-3273-4

Saksena, S., & Merwade, V. (2015). Incorporating the effect of DEM resolution and accuracy for improved flood inundation mapping. *Journal of Hydrology*, *530*, 180–194. https://doi.org/10.1016/j.jhydrol.2015.09.069

Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T., Brakenridge, G. R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., & Nicholls, R. J. (2009). Sinking deltas due to human activities. *Nature Geoscience*, *2*(10), 681–686. https://doi.org/10.1038/ngeo629

Thorne, C. R., Lawson, E. C., Ozawa, C., Hamlin, S. L., & Smith, L. A. (2018). Overcoming uncertainty and barriers to adoption of blue-green infrastructure for urban flood risk management. *Journal of Flood Risk Management*, *11*(S2), 960–972. https://doi.org/10.1111/jfr3.12218

UN-Habitat. (2016). *Urbanization and development: Emerging futures. World cities report 2016*. https://unhabitat.org/sites/default/files/download-manager-files/WCR-2016-WEB.pdf

van Alphen, J., Martini, F., Loat, R., Slomp, R., & Passchier, R. (2009). Flood risk mapping in Europe, experiences and best practices. *Journal of Flood Risk Management*, *2*(4), 285–292. https://doi.org/10.1111/j.1753-318X.2009.01045.x

Wenger, C. E. B. (2017). *Flood management in a changing climate* [Doctoral dissertation, Australian National University]. Bushfire & Natural Hazards CRC. https://www.bnhcrc.com.au/publications/biblio/bnh-5149

Zevenbergen, C., Gersonius, B., & Radhakrishan, M. (2020). Flood resilience. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2168), Article 20190212. https://doi.org/10.1098/rsta.2019.0212

About the Authors

Sven Anders Brandt is Docent (Associate Professor/Reader) in Geospatial Information Science at the University of Gävle, Sweden. He received his MSc and PhD degrees in Physical Geography from Uppsala University, Sweden, and University of Copenhagen, Denmark, respectively. His research ranges from geography didactics, over fluvial geomorphology and river flood risk mapping, to geospatial multicriteria decision analysis.

Nancy Joy Lim is a Senior Lecturer at the University of Gävle. She holds a PhD in Geospatial Information Science and has a background in Geography and Geomatics. Her research is primarily focused on modeling, geovisualization, GIS, and spatial analysis.

Johan Colding is a highly cited Urban Ecologist and Professor in Sustainability Science at the University of Gävle and the Beijer Institute of Ecological Economics. His expertise covers resilience science, complex adaptive systems, social–ecological urban systems, ecosystem services, and urban planning and design.

Stephan Barthel is a Professor in Sustainability Science and a highly cited scholar in "Web of Science" (2019, 2020). He holds a PhD in Natural Resource Management and a reader degree in Geospatial Information Science. He is the Director of a challenge-driven research direction on urban sustainability at the University of Gävle with the mission to stimulate the integration of climate transformation research with that of social-ecological resilience research.

COGITATIO

Urban Planning (ISSN: 2183–7635)
2021, Volume 6, Issue 3, Pages 272–282
https://doi.org/10.17645/up.v6i3.4246

Article

Flood-Resilient Communities: How We Can Encourage Adaptive Behaviour Through Smart Tools in Public–Private Interaction

Peter R. Davids [1],* and Thomas Thaler [2]

[1] Center for Mobility and Spatial Planning, Ghent University, Belgium; E-Mail: peter.davids@ugent.be
[2] Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences, Austria;
E-Mail: thomas.thaler@boku.ac.at

* Corresponding author

Submitted: 3 March 2021 | Accepted: 28 April 2021 | Published: 19 August 2021

Abstract
To achieve a more flood-resilient society, it is essential to involve citizens. Therefore, new instruments, such as tailor-made advice for homeowners, are being developed to inform homeowners about adaptive strategies in building to motivate them to implement these measures. This article evaluates if public–private interactions, such as tailored advice, change risk behaviour and therefore increase flood resilience among homeowners. The article conducted semi-structured interviews with homeowners who had received advice as well as involved experts in two case study regions in Europe: Flanders in Belgium and Vorarlberg in Austria. The results show how the tailored advice helps homeowners who are already aware of flood risks and provides them with answers on how to adapt a house. However, the tool seems to lack the ability to inform and "recruit" new groups of homeowners who are not as familiar with flood risks. As such, this article concludes that this initiative has a relatively low impact in raising flood risk awareness among homeowners but may be more successful in serving as a tool that suggests tailored property-level flood risk adaptation measures for those who are already aware. Alternatively, more automated tailored information systems might be more efficient for unaware homeowners.

Keywords
Austria; Belgium; flood risk management; homeowners; property level flood risk adaptation (PLFRA); risk governance; tailored risk communication

Issue
This article is part of the issue "Smart Urban Governance for Climate Change Adaptation" edited by Thomas Thaler (University of Natural Resources and Life Sciences, Austria), Patrick Witte (Utrecht University, The Netherlands), Thomas Hartmann (TU Dortmund University, Germany) and Stan Geertman (Utrecht University, The Netherlands).

1. Introduction: A Behavioural Turn in Flood Risk Management

Flood hazards that are caused due to exceptional rainfall events lead to severe damage in European urban areas (Alfieri et al., 2015; Field et al., 2012), and climate models predict an increase of such events in the coming decades (Intergovernmental Panel on Climate Change, 2018). Governments traditionally try to reduce the probability of flood events with solutions such as dikes and other technical solutions. However, the increase and unpredictability of floods leads to an increased complexity of flood risk management, as governments can no longer guarantee "dry feet" for their citizens based on governmental interventions (Meijerink & Dicke, 2008; Rauter et al., 2020). Based on the principles of resilience (Fekete et al., 2020; Folke et al., 2010; Liao, 2012), governments in the present day strive for a more holistic risk-based approach that includes uncertainties (Kuklicke & Demeritt, 2016), planning (Hartmann & Juepner, 2014), and the involvement of civil actors (Forrest et al., 2020; Seebauer & Babcicky, 2018). These new actors, such as homeowners, are becoming part of flood risk management as they can reduce their personal vulnerability (e.g., Kuhlicke et al., 2020; Mees et al., 2016; Rufat et al., 2020; Snel et al., 2020). Consequently, flood risk management requires collaborative planning for public administration. Sharing responsibility is becoming more and more common (Begg et al., 2017; Butler & Pidgeon, 2011). Influenced by these developments, flood risk management is becoming more adaptive, flexible, and dynamic (McClymont et al., 2019). As such, new actors get involved and traditional strategies diversify with new approaches, strategies, and instruments in the field of flood risk management (Hegger et al., 2016).

New actors, such as homeowners, are asked to actively participate in flood risk management because their actions can reduce potential losses in and directly around their houses and impact their vulnerability. One of the main reasons for this change of perspectives is that the government is not able to reduce risks to zero. To reduce the remaining risks (such as residual risk or lack of structural engineering solutions to protect communities) homeowners need to contribute to the solution (Kreibich et al., 2005). Therefore, in recent years, new approaches, strategies, and instruments have appeared to inform and motivate residents about their flood risks, their responsibilities, the need for adaptation, and which things can be adapted. Examples of strategies include, among others, flood risk mapping (Van Alphen et al., 2009), participatory projects (Begg, 2018), inter-regional co-operation (Thaler et al., 2016), and strategies to target direct or indirect implementation of property level flood risk adaptation (PLFRA, which includes (1) wet-proofing—controlled flooding and the adaptation of interiors, (2) the avoidance of flooding—e.g., stilts or floating structures, and (3) dry flood-proofing—e.g., watertight basement windows, etc.; Attems, Thaler, Genovese, et al., 2020; Gersonius et al., 2008). Among individual homeowners, strategies include recovery financing linked to future damage reduction (Slavíková et al., 2021), flood labelling for houses (Hartmann & Scheibel, 2016), a duty to inform during housing transactions (Mees et al., 2018), and tailored expert advice for homeowners (Davids et al., 2019). All these strategies can contribute to a behavioural turn among citizens in flood risk management (Kuhlicke et al., 2020), as these strategies: (1) try to understand and influence the willingness to act, (2) inform about the effectiveness of PLFRA measures, and (3) support homeowners on the implementation of these measures. For example, a homeowner could reduce potential damage by removing valuable furniture or moving the kitchen from the basement to the first floor, or by the installation of bulkheads and pumps. Moreover, based on an effectiveness/efficiency analysis, sometimes interventions at the local level (for example in residential buildings) are preferred over extensive spatial interventions (Hoss et al., 2011; Kaufmann et al., 2016). Consequently, this makes flood risk management no longer a solely governmental activity, as citizens can have an active role using PLFRA measures and therefore reduce flood damage (Mees et al., 2016; White et al., 2018). However, the uptake of these measures by homeowners is still low (Attems, Thaler, Genovese, et al., 2020; Grothmann & Reusswig, 2006; Kellens et al., 2013; Rözer et al., 2016). There are various explanations as to why homeowners still refuse or struggle to implement PLFRA measures. One key problem is that homeowners are not always aware of their flood risks (Thistlethwaite et al., 2018). Further, homeowners often lack information on how to implement PLFRA measures in their houses (Attems, Schlögl, et al., 2020). Aside from that, homeowners often seem unwilling to take measures as they perceive flood risk management as a governmental task or they do not have the legal rights, know-how, or financial savings to implement PLFRA measures (Botzen et al., 2013; Bubeck et al., 2012; White et al., 2018). So, there is a gap: Governments expect homeowners to participate in local flood risk management, but these homeowners are not always conscious or able to or willing to change their behaviour. This lock-in situation between government and homeowners is happening more often, and more interactive and collaborative approaches in risk communication are desired (Mees et al., 2018; Tasantab et al., 2020). The aim of the article is to address if new instruments in risk communication, such as using smart technologies, are more effective in informing and encouraging homeowners of how to implement PLFRA measures at home. An example of such smart technologies is tailored advice for homeowners. This is a tool to evaluate flood risk levels at home and provides suggestions to reduce these risks with solutions tailored to the characteristics of a specific home. As such, this tool seems to focus more on providing information and triggering adaptive behaviour than on awareness-raising. These suggestions can be automatically calculated, and in some cases additionally explained by a flood risk expert. Such smart technologies have become a more crucial aspect in flood risk management in the past few years (Neubert et al., 2016; Ran & Nedovic-Budic, 2016; Schinke et al., 2013). Smart technologies in flood risk management include two directions: (1) the innovation of new technologies in terms of PLFRA measures (White et al., 2018) and (2) information and communications technology (ICT), such as the use of artificial intelligence or new forms of communication (Attems, Thaler, Snel, et al., 2020; Kratzert et al., 2019). The advantages of using smart technologies in flood risk management are the ability to use the latest ICT innovation to reach a wide range of different people with a standardised approach (Jiang et al., 2020a, 2020b). The literature addresses the advantages of smart technologies in terms of including multiple actors at multiple political levels as well as the ability to interact within these smart technologies (Kummitha & Crutzen, 2017; Neirotti et al., 2014). There are various examples of using smart technologies in urban planning (see, e.g., Geertman & Stillwell, 2020). Nevertheless, the use of smart technologies highly depends on the willingness of people to accept and interact with the tools (Greenfield, 2013). In addition, the tools often lack certain flexibility within the design level to include the special needs of communities. For example, the housing stock in Belgium, Germany, Austria, or Switzerland shows more variety due to their individualistic designs and constructions, compared to the uniform prefabricated housing stock in countries such as the Netherlands and the UK. These varieties among individual houses result in more specific questions on risk reductions among the homeowners.

To explain if smart technologies such as tailored advice are more effective in informing and encouraging homeowners, and to analyse what factors influence the level of success of the pilots, this article uses Boelens' (2018) actor-relational approach. The actor-relational approach provides a wider perspective of spatial planning actions. The framework includes "other forms of independent action, within the business sector, the institutional community, and in everyday life" (Boelens, 2020, p. 11). This approach is able to analyse the relations and co-evolutionary interaction among factors, actors, and institutions, instead of the factors, actors, and institutions themselves (Boelens, 2010; Boelens & de Roo, 2016). When considering behavioural change of homeowners in flood risk management, we need to also consider changing behaviour of other actors and contextual factors (Davids et al., 2019). This approach offers the opportunity to analyse how tailored advice leads to institutional innovation and more specifically, to behavioural change. Therefore, in the next section and based on the structure of factors, actors, and institutions, this article considers the following research questions:

- Which contextual factors, actors, and institutions determine the use of smart technologies, such as tailored advice, in flood risk management?
- Can tailored advice encourage a behavioural change of homeowners to increase their resilience to flood hazards?
- To what extent does tailored advice result in improved community resilience at a larger scale?

In this article, we compare two international cases of these tailored advice practises, as examples of new smart technologies because it combines standardised methodologies with in-depth analyses of a house. In Belgium, we will consider a pilot that has been running in the region of Flanders, organised by the Flanders Environmental Agency. In Austria, we consider the pilot from the region Vorarlberg, organised by the regional authority in close cooperation with blue light organisations, such as the fire brigade, and insurance sector. Whereas the Belgian experiment is considered to be successful and is starting a third pilot in 2020–2021, the Austrian experiment was mostly suspended after one pilot. We are wondering what factors influence the level of success of the pilots and what factors are limiting. Here, we assume contextual factors make a difference. To clarify this statement, we will use the actor-relational approach on tailored expert advice in flood risk management.

2. Flood Risk Management as a Relational System

Behavioural change of homeowners in flood risk management can be considered as highly dependent on social and institutional contexts. Therefore, homeowner involvement in flood risk management is highly relational (Davids et al., 2019). The theoretical starting point of this article forms Luhmann's (1995) systems theory of social innovation. One cannot observe a society from the outside in its totality, only from within. However, perceived from within, these observations are too complex, interactive, and volatile. To reduce the complexity, Luhmann's distinct subsystems each have their own codes of conduct, behaviours, actors, and contexts. These interact and shape the subsystem, but also interact with other subsystems, forming a relational system where interactions cause new interactions. Through these interactions a subsystem evolves and evolves and evolves, and, as such, is always in a state of becoming (Boelens & de Roo, 2016). This leads to multiple institutional innovations happening in various directions and all happening at the same time: expanding, renewing, and innovating over and over as adaptions on the existing context (Boelens, 2018). To grasp this black box of evaluating institutions, Boelens (2018) distinguishes factors of importance, actors, and institutions that co-evolve together (see Figure 1):

- Factors of importance include elements such as geography and infrastructure. In the subsystem of flood risk management, examples of these factors include climate change, floods, risk, and the availability of structural and PLFRA measures.
- Institutions are the formal and informal codes of conduct in a subsystem. In the subsystem of flood risk management, examples include agreements on responsibility and accepted levels of residual risk.
- (Leading) actors of a subsystem include governmental, business, and civil actors. In the subsystem of flood risk management, examples include governmental flood risk managers, local leaders of citizen groups, insurers, and companies involved in PLFRA implementations.

Together, these three components and their interactions shape subsystems as we know them but are also able to interpenetrate or irritate other subsystems, which in turn can innovate and evolve (Boelens, 2018).

This system of co-evolutions is one that we recognize in flood risk management as well. As the system of flood risk management is facing more floods that have left more damage over the past few decades (new factors of importance), governments make an appeal to homeowners to take responsibility for their houses (new leading actors are invited to participate). Also, new formal and informal agreements are formed to share the responsibility of flood risk (new institutions). These innovations

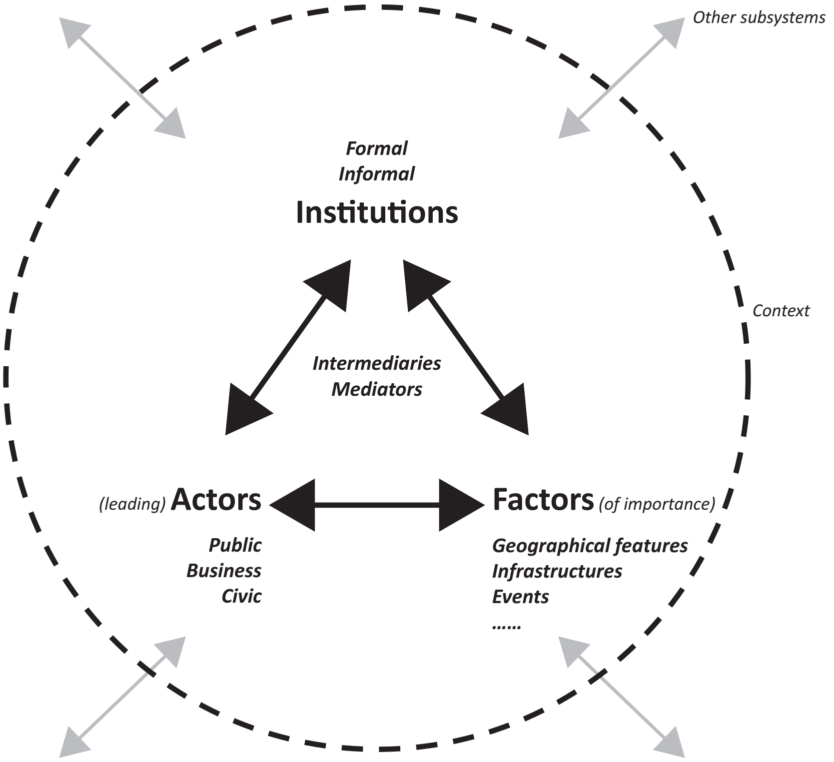


Figure 1. Scheme of an actor-relational subsystem. Source: Boelens (2018, p. 96).

influence each other back and forth and result in a new evolution being born.

Influencing this continuous interactive evolution is complex. The outcome of interventions cannot be predicted and directed due to the volatile and dynamic nature of the interactions. However, Healey (2007) highlights how, in this case, flood risk managers should be skilled to take the pulse of these interactive dynamics and generate opportunities for encounters. This is where tailored advice comes in, which can, in line with Boelens (2018), perform as an intermediary, transferring knowledge without changing it, or as a mediator, translating and aligning information mutually between factors, actors, and institutions, resulting in institutional innovation, in this case, a change of behaviour within the system. Using the actor-relational approach makes it possible to analyse the role of specific smart tools in the complexity of interrelations of flood risk management.

3. Methods

This article used a mixed-method design combining semi-structured interviews with national and regional authorities and citizens, analysis of policy documents, as well as phone interviews with citizens.

For the first study site in three towns in Flanders (Belgium), we conducted in total 14 semi-structured in-depth interviews; one interview with the project leader of the Flanders Environment Agency responsible for the pilot; and 13 interviews with homeowners that participated in the pilot. Homeowners were randomly selected in the experts' agenda and interviews took place directly after the visit of experts. The semi-structured interviewees were conducted in June and July 2017 and lasted between 60 and 75 minutes. Additionally, among all 209 participating homeowners a short telephone survey was executed. For this survey, a total of 175 out of 209 project participants were contacted. From these, 148 were willing to participate in the short telephone survey. The phone calls took about 10 minutes.

In the second study site of Vorarlberg (Austria), we conducted in total 18 semi-structured in-depth interviews; two interviews at the national level with experts from the national flood risk management policy, two experts at the regional level responsible for the implementation of the regional flood risk management strategy in the federal state of Vorarlberg, 12 interviews with homeowners, as well as two stakeholders from insurance and blue light organisations. The selection process of the sampling was one sided, based on the network between the researcher and researched as well as a snowball effect to recruit the sampling of the homeowners (Rauter et al., 2020). The semi-structured interviews were conducted between February and May 2018 and lasted between 30 and 120 minutes. The interviews were transcribed and coded within the software package f4 and NVivo.

For both studies, the themes that were covered in the interviews included experiences of past flood event(s), key actors in flood risk management, the role of various actors, barriers and drivers of the implementation of PLFRA, trigger points to implement PLFRA, interactions with governmental actors and neighbourhoods (i.e., process, type of communication), funding (e.g., financial subsidies, bank loans, etc.), legal obligations and restrictions, reflections on the communication between homeowner and expert, and the role of ICT in the process.

For both studies, we used a grounded theoretical approach to analyse the interviewees, where the code was structured around the actor-relational approach by Boelens (2018). Moreover, we analysed the national and regional policy documents dealing with the implementation of the PLFRA measures as well as the regional and local legal regulations, such as planning, building codes, and emergency management. The aim of the policy analysis is to understand how the institutional framework is framed in both countries and how the two different institutional frameworks influence the use of smart technologies in flood risk management (Thaler et al., 2020; Wildavsky, 1969).

4. Results

4.1. Factors

The towns of Sint-Pieters-Leeuw, Geraardsbergen, and Lebbeke are located in the region of Flanders, in the Dender and Zenne valleys, west of Brussels. Situated in the urban fringe of Brussels, the towns attract citizens from the capital looking for cheaper private-owned single-family detached and semi-detached housing in a green environment. The combination of a hilly landscape, and an erosion-prone soil of sand and loam, ensures rapid precipitation drainage, and makes the areas vulnerable to pluvial flooding. Despite the presence of retention basins, these basins appear to be too small to prevent flooding throughout the whole valley in the case of extreme precipitation. Recent exceptional rain showers (e.g., 2010, 2014, and 2016) resulted in incoming water in underground garages or at ground floor level, damaging up to 600 houses in Sint-Pieters-Leeuw during the 2010 flood (Hydroscan, 2018). The main causes included rainwater runoff, the overflow of the local river, or the backflow of water from the public sewer. To reduce future damage, some homeowners had already implemented some provisional PLFRA measures.

The federal state of Vorarlberg is characterised as a rural/peri-urban region with a wide range of private-owned single-family detached buildings. The federal state is located in the western part of Austria, close to the countries of Germany, Liechtenstein, and Switzerland, where a large proportion of citizens commute to work as the average earnings are higher in comparison to Vorarlberg. The region also includes a high density of manufacturers, especially in the Rhine and Walgau valley. Before the Covid-19 pandemic, the region had strong economic growth rates, which attracted a high number of national and international citizens to relocate to the region. Further, the Walgau valley connects the main transport lines to Switzerland. However, a large number of the residential and non-residential buildings can be found in floodplain areas, due to a lack of permanent settlement and economic prospective within the region. Mountain communities, such as in the Bregenzerwald, show a marked decline of the population and an increase of second-home residents. Consequently, Vorarlberg was affected by several flood events in the past 20 years, such as river floods, torrential floods, debris flow, surface runoff, or groundwater flooding. In particular, the 2005 flood event caused high economic losses in the region as well as new policy concepts as a response to the event, such as encouragement of the implementation of PLFRA.

4.2. Actors

In federally organised Belgium, flood risk management is predominantly regionally organised. Only emergency planning and recovery and insurance policy are organised on a national level. For the management of floods, the region of Flanders distinguishes responsibility based on navigability of waters. Navigable waters are a responsibility of the regional Department of Mobility and Public Works; flood alleviation in non-navigable water is a responsibility of Flanders Environment Agency. Coordination between these two departments and municipal, provincial, and regional actors is organised by the Commission on Integrated Water Policy. Flood recovery compensation after a flood event is covered in household or fire insurance. If the insurance is not covered (e.g., when a flood is acknowledged as national disaster), homeowners can submit a claim with the federal disaster fund, and decisions on disbursements are made on a regional level.

As these governmental actors are not always able to prevent flooding, Flanders Environment Agency funds and organises tailored expert advice for homeowners to motivate the implementation of PLFRA. The case study that is considered for this article entails a pilot among 210 homeowners that ran from 2017 to 2018 in the municipalities of Sint-Pieters-Leeuw, Lebbeke, and Geraardsbergen. Previously, between 2013 and 2015, a first pilot ran among 85 homeowners living in Beersel and Sint-Genesius-Rode. A third pilot to advise about 150 households will be running in the town of Moelingen, and in municipalities along the brooks of Zwalmbeek and Kerkebeek in 2020 and 2021.

The Flanders Environment Agency uses an active strategy to recruit participants. This recruitment campaign started with an invitation letter that was sent out to everyone in flood-prone areas within the municipality as well as announcements in local newspapers. In both the letter and announcement, a reference to a website was made providing background information on the project and project process. The website also provided registration for a first general meeting in the community centre. Besides personal details, the registrant had to provide information on their flood risk experience and tenure status. From the 300+ registrations, the agency selected 210 homeowners that suffered the most based on recent flood data from the fire brigade.

The advising process included a meeting between a homeowner and two experts at home. One expert has a background in loss-adjusting for insurance, and the second has expertise in urban water management. During a house visit, the experts collected data for the final report, which contained information on recent flood damage, building features, position of the house on flood risk maps, insurer details, overview of measures already taken, photos of the house and surroundings, and a list of proposed PLFRA measures and an estimation of the costs. In a final meeting between homeowner and experts in the city hall, these final reports were presented, clarified, and discussed between the expert and homeowner. In most cases the experts advised on the introduction of a pump to remove incoming water, floodwalls, backup valves, or a combination of these mentioned PLFRA measures. The estimated costs varied considerably from €500–600 for simple interventions such as a backup valve, and up to tens of thousands of euros for more complicated solutions. Almost half of the participants implemented (at least partially) the experts' advice on PLFRA: 32% from selected sampling implemented some PLFRA and 15% from selected sampling implemented all suggested PLFRA. Some homeowners have not yet implemented any PLFRA, but are still planning to, and a minority of homeowners is not willing to take further action for several reasons, including the costs of PLFRA and age of the homeowner.

The main actors in the Austrian flood risk management policy are two organisations: the national authority—Forest Engineering Service for Torrent and Avalanche Control (responsible for mountain hazards)—and the regional authority, the Federal Water Engineering Administration (responsible for river floods). Both organisations are responsible for the development of the policy framework in flood risk management, planning, and implementation of flood alleviation schemes in the region, providing hazard and risk maps, as well as contributing 80% of the costs for the realization of flood alleviation schemes. The local authorities are mainly responsible for the maintenance of flood alleviation schemes, contributing up to 20% of the costs of these, as well as for emergency management and land use management. The compensation scheme includes a mixture of private and public compensation, where the public administration provides a disaster-aid payment rate of up to 75% of the losses. The implementation of PLFRA measures is mainly in the hands of private landowners. Following the 2005 flood event, the region installed a temporary tailored expert position at the Regional Fire Brigade Association of Vorarlberg. The aim of the tailored expert position has been to inform homeowners how to implement PLFRA measures at their buildings. Initially this position was funded as a public–private partnership between public administration and the insurance sector.

Between 2013 and 2016 more than 80 homeowners received tailored advice from the Regional Fire Brigade Association of Vorarlberg. The recruitment was based on direct communications, newspapers, or presentations. Most homeowners acted on the recommendations made by insurance companies or the local fire brigade to take active PLFRA measures, others came directly to the expert based on newspaper articles, public presentations by the experts, or leaflets. However, most recruited homeowners had already implemented various PLFRA measures. A minority of homeowners implemented no further PLFRA measures after being given advice for several reasons, such as age—as some homeowners were already 70+ and did not expect any flood event in the near future—or the homeowners had high trust in the public flood alleviation schemes. Interestingly, financial restrictions played no role in the implementation or rejection of PLFRA measures. Nevertheless, the interviews stated that only a small number of homeowners in the region showed an interest in tailored expert advice (around 80 homeowners used the ability to interact with the office). This was also a main argument why the insurance sector left the partnership after this initial period. Using other communication channels failed as the homeowners requested face-to-face interactions with the Regional Fire Brigade Association of Vorarlberg.

4.3. Institutions

The role of PLFRA measures plays a secondary perspective in the Austrian flood risk management policy. The key focus still lies on structural measures, such as dams or flood retention measures, across the country. The implementation of PLFRA measures (for already existing buildings) is mainly voluntary and is organised in Vorarlberg. Private property rights ensure that homeowners can freely make decisions about their property. This makes it so that public administration cannot force already existing buildings in hazard-prone areas to conduct any measures to reduce the losses from future flood hazard events. On the other hand, the public administration is also restricted by the law in providing financial subsidies to support homeowners to implement PLFRA measures. In terms of land use restrictions, the only influence is to design hazard-prone areas to avoid placing new residential and non-residential buildings in high-risk areas. Vorarlberg, for example, classifies "unfavourable natural circumstances" as a reason for land restriction, but does not provide a quantitative number, such as 1:100 (Rauter et al., 2019, p. 9). Additionally, the compensation regulation (after an event) does not provide any regulations or guidance to encourage homeowners to implement PLFRA measures (neither from insurance nor public administration). Consequently, the main activities are the provision of websites, newsletters, articles in newspapers, or public presentations by public administration that are strongly supported and managed by the tailored expertise of the Regional Fire Brigade Association of

Vorarlberg. However, the regional policy encourages the implementation of PLFRA measures, but not as the highest priority within flood risk management. Therefore, the project with the tailored expertise in the Regional Fire Brigade Association of Vorarlberg still exists, but it is limited in its activities as the insurance sector is no longer part of the project.

In Flanders, PLFRA gained more attention since the introduction of multi-layered water safety as policy discourse in 2013. This concept is the Flemish translation of the EU Floods Directive 2007/60/EC and aims to optimally combine measures of structural defence, spatial planning, and emergency planning in order to reduce risk in the region to a minimum. This approach emphasizes a multi-actor approach and suggests active involvement of water managers, spatial planners, the insurance, and construction sectors, as well as citizens. This has resulted in new tools and instruments to involve these sectors. To involve citizens, a “duty-to-inform” was introduced by the Flemish government in 2013 and indicates flood vulnerability levels of a property in real estate advertisements. For the Flanders Environment Agency, this policy discourse implies that homeowners could actively reduce residual risk, even though citizens generally expect the government to be exclusively responsible and able to avoid flood damage. Through these pilots, the agency wants to inform homeowners about this shared responsibility and about the homeowners’ ability to reduce flood risks. Moreover, as flood risk maps only provide information on the plot of a house—and not on the construction of the house—and as the government cannot enforce homeowners to implement any PLFRA, the agency started the pilots on tailored advice. The project leader stipulated that in the future they would like to involve more actors, such as insurers and construction industries, to develop related incentives such as modified insurance premiums. However, involvement in these pilots is limited to a generous subsidy scheme organised by province and municipality, which covers the costs up to 90% for the participants in Sint-Pieters-Leeuw (up to a maximum of €10,000). Yet, even with the subsidies, interventions did not happen more frequently when compared to the other two municipalities where limited or no subsidy options were available. Tailored technical advice therefore seems to have more effect than a generic subsidy policy.

5. Discussion and Conclusion

Smart tools to involve homeowners in flood risk management are being developed in many countries that include tailored expert advice. These tools might be able to communicate risk and influence homeowners’ behaviour (Attems, Thaler, Snel, et al., 2020). The results illustrate that homeowners become informed of risks and are encouraged to implement PLFRA, as the advice meets the characteristics of the behavioural turn (Kuhlicke et al., 2020) as well as explaining the effectiveness of PLFRA, and the experts are able to support homeowners with tailored information. The comparison of these two case studies illustrates how different selection procedures—passive in Vorarlberg, and active in Flanders—result in similar groups of homeowners, namely those with flood risk experience.

However, Davids et al. (2019) propose a more relational approach when evaluating these tools, to find out if the advice is also serving as a mediating tool. To measure and explain the success of a tool, we should not only look at the levels of PLFRA implementation but consider contextual factors as well. These instruments do not function on their own, but their success depends on a context of factors, actors, and institutions that shape flood risk management.

The results show how the introduction of tailored flood risk advice, provided by an expert both in Flanders and Vorarlberg contributed to an uptake of PLFRA measures among homeowners. Nevertheless, the Flanders Environment Agency perceives their pilots as successful, while in Austria the activities have been suspended. Factors in both countries are similar. Both regions struggle with similar floods, and similar structural measures are implemented. Actors, however, differ. In Flanders, the pilot is perceived as a learning path and should lead to the involvement of multiple actors in the long run, while in Austria the experiment started as a cooperation between public authorities and the insurance sector, where the insurance sector withdrew before the advising finished. Institutions also differ. Homeowner involvement in Flanders is directly related to the multi-layered water safety approach, while in Austria the role of PLFRA seems more perceived as “an extra.” Also, the dynamic and highly fragmented flood risk governance in Flanders contributes to windows of opportunity for new developments in flood risk management in general (Mees et al., 2018), and for uptake of tailored advice as institutional innovation specifically. Austrian flood risk management, however, is more stable and does not encourage the introduction of PLFRA at all. Instead, the stability of the system predominantly supports a continuation of government-led engineered interventions that prevent flooding (Rauter et al., 2020).

Based on this comparison, this article concludes that tailored advice has a relatively low impact on raising flood risk awareness among homeowners, and it seems unable to recruit new people. As the tool only targets homeowners with high interest and some knowledge of flood risk, it seems to be more successful in serving to inform those who have specific questions and needs concerning PLFRA. As such, this tool can be perceived as successful, and it could be even more successful if the tool is perceived in a wider context that includes other actors’ behaviour. Nevertheless, the impact of the tool as a stand-alone remains limited. Alternatively, more automated tailored information systems, aimed at a larger less specific public, and that are less resource intensive, might be more efficient to inform the unaware

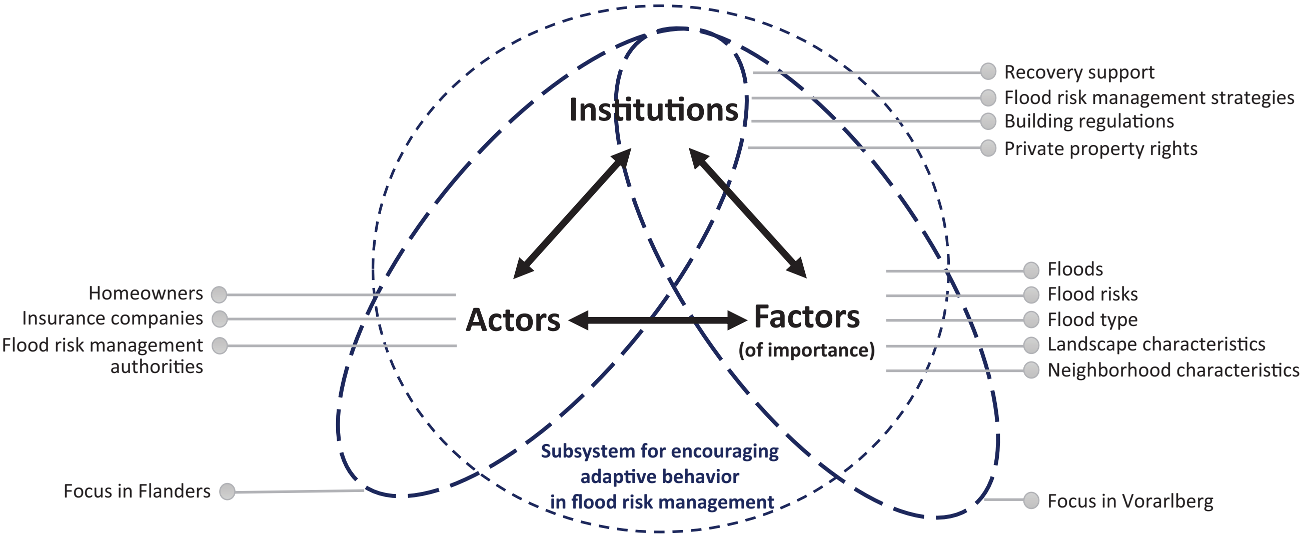


Figure 2. Scheme illustrating the dominant focus of both Flanders and Vorarlberg in encouraging adaptive behavior in flood risk management as an application of the actor-relational subsystem by Boelens (2018).

homeowners. In summary, the key question is if the costs outweigh the benefits, considering that these smart tools mostly involve and inform those who are already eager to implement PLFRA measures and not a broader target group, which is what is actually needed to reach the goal of improving the preparedness level of homeowners for future flood events. The personal interaction shows a "success" story in terms of increasing the preparedness level of the homeowners. However, this personal interaction relies heavily on face-to-face meetings, which are resource-intensive in terms of human resources, financial resources, and time needed within this process. Using a more ICT-oriented solution would not increase the behavioural turn of a larger group of homeowners as this article shows that homeowners request this face-to-face interaction.

The article adds to the current debate on how to increase flood-resilience in urban and rural communities (Fekete et al., 2020; Kuhlicke et al., 2020; Rufat et al., 2020). The focus on homeowners is essential as homeowners are a central factor in successfully reducing losses from future flood events (Attems, Thaler, Genovese, et al., 2020; Snel et al., 2020). Consequently, implementation of PLFRA measures have wide-ranging consequences for public administration and homeowners in terms of collaboration, who is responsible for what, who takes the risk of successful implementation, or who takes the lead of interacting and managing the process. Using the actor-relational subsystem helps us to understand how different factors (infrastructure, past events, geographical features), different actors (public, business, civic), and different institutional frameworks (formal and informal) influence the aim to reach a flood-resilient community. The Flanders example shows a stronger focus on the actor-institution relationship (see Figure 2).

The implementation of smart technologies is mainly driven by the institutional framework with the aim to actively involve homeowners (and other private actors in general) and implement instruments at a larger scale. Consequently, the interaction (i.e., tailored advice) between the different actors needs a strong standardised interface. In contrast, the Vorarlberg example demonstrates a focus more on the relationship between factors and institutions (see Figure 2). The 2005 flood event encourages some new instruments and frameworks in the regional flood risk management system, where the implementation of PLFRA measures mainly becomes an additional goal for the public administration. The implementation of PLFRA measures is organised and managed as public–private collaboration between regional authorities, fire brigades, and the insurance sector. Nevertheless, PLFRA strategy was always seen as an "extra" strategy as the primary goal of the Vorarlberg flood risk management strategy is still based on engineering solutions (i.e., infrastructures), such as dams or flood storage. The minor role of PLFRA is mainly defined by the existing and planned infrastructure in Vorarlberg. In summary, the co-evolutionary interaction between factors, actors, and institutions shows the politically normative dimension of flood risk management and the potential role of smart technologies in flood risk management.

Acknowledgments

This work was funded by the Austrian Research Promotion Agency (FFG) within the framework of the JPI Urban Europe project FLOODLABEL (Grant/Award Number: 693443) and Land4flood COST Action (Grant/Award Number: CA16209). We are grateful for the cooperative participation of the interview partners, as this was the basis for this analysis. Sincere thanks go to Paul Demuth and Mathias Peter for support in interviewing households. We would also like to thank the four anonymous reviewers for their insightful comments on an earlier version of this manuscript. Open access funding was provided by BOKU Vienna Open Access Publishing Fund.

Conflict of Interests

The authors declare no conflict of interests.

References

Alfieri, L., Burek, P., Feyen, L., & Forzieri, G. (2015). Global warming increases the frequency of river floods in Europe. *Hydrology and Earth System Sciences*, *19*(5), 2247–2260.

Attems, M., Schlögl, M., Thaler, T., Rauter, M., & Fuchs, S. (2020). Risk communication and adaptive behaviour in flood-prone areas of Austria: A Q-methodology study on opinions of affected homeowners. *PloS one*, *15*(5), Article e0233551.

Attems, M., Thaler, T., Genovese, E., & Fuchs, S. (2020). Implementation of property-level flood risk adaptation (PLFRA) measures: Choices and decisions. *WIREs Water*, *7*(1), Article e1404.

Attems, M.-S., Thaler, T., Snel, K. A. W., Davids, P., Hartmann, T., & Fuchs, S. (2020). The influence of tailored risk communication on individual adaptive behaviour. *International Journal of Disaster Risk Reduction*, *49*, Article 101618.

Begg, C. (2018). Power, responsibility and justice: A review of local stakeholder participation in European flood risk management. *Local Environment*, *23*(4), 383–397.

Begg, C., Ueberham, M., Masson, T., & Kuhlicke, C. (2017). Interactions between citizen responsibilization, flood experience and household resilience: Insights from the 2013 flood in Germany. *International Journal of Water Resources Development*, *33*(4), 591–608. https://doi.org/10.1080/07900627.2016.1200961

Boelens, L. (2010). Theorizing practice and practising theory: Outlines for an actor-relational-approach in planning. *Planning Theory*, *9*(1), 28–62.

Boelens, L. (2018). Moving towards a flat ontology of institutional innovation: Actor-relational lessons learned from early water management perspectives. In W. Salet (Ed.), *The Routledge handbook of institutions and planning in action* (pp. 92–107). Routledge.

Boelens, L. (2020). Opening up new planning landscapes: An introduction in the actor-relational approach of planning. In B. Boonstra, P. Davids, & A. Staessen (Eds.), *Opening up the planning landscape—15 years of actor-relational approaches to spatial planning in Flanders, the Netherlands and beyond* (pp. 11–34). InPlanning.

Boelens, L., & de Roo, G. (2016). Planning of undefined becoming: First encounters of planners beyond the plan. *Planning Theory*, *15*(1), 42–67.

Botzen, W., Aerts, J., & Van den Bergh, J. (2013). Individual preferences for reducing flood risk to near zero through elevation. *Mitigation and Adaptation Strategies for Global Change*, *18*(2), 229–244.

Bubeck, P., Botzen, W. J., & Aerts, J. C. (2012). A review of risk perceptions and other factors that influence flood mitigation behavior. *Risk Analysis: An International Journal*, *32*(9), 1481–1495.

Butler, C., & Pidgeon, N. (2011). From ‘flood defence’ to ‘flood risk management’: Exploring governance, responsibility, and blame. *Environment and Planning C: Government and Policy*, *29*(3), 533–547.

Davids, P., Boelens, L., & Tempels, B. (2019). The effects of tailor-made flood risk advice for homeowners in Flanders, Belgium. *Water International*, *44*(5), 539–553.

Fekete, A., Hartmann, T., & Jüpner, R. (2020). Resilience: On-going wave or subsiding trend in flood risk research and practice? *WIREs Water*, *7*(1), Article e1397.

Field, C. B., Barros, V., Stocker, T. F., & Dahe, Q. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the Intergovernmental Panel On Climate Change*. Cambridge University Press.

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: Integrating resilience, adaptability and transformability. *Ecology and Society*, *15*(4), Article 20.

Forrest, S. A., Trell, E.-M., & Woltjer, J. (2020). Emerging citizen contributions, roles and interactions with public authorities in Dutch pluvial flood risk management. *International Journal of Water Resources Development*, *37*, 1–23.

Geertman, S., & Stillwell, J. (2020). *Handbook of planning support science*. Edward Elgar Publishing.

Gersonius, B., Zevenbergen, C., Puyan, N., & Billah, M. (2008). Efficiency of private flood proofing of new buildings—Adapted redevelopment of a floodplain in The Netherlands. *WIT Transactions on Ecology and the Environment*, *118*, 247–259.

Greenfield, A. (2013). *Against the smart city.* Do projects.

Grothmann, T., & Reusswig, F. (2006). People at risk of flooding: Why some residents take precautionary action while others do not. *Natural Hazards*, *38*(1/2), 101–120. https://doi.org/10.1007/s11069-005-8604-6

Hartmann, T., & Juepner, R. (2014). The flood risk management plan between spatial planning and water engineering. *Journal of Flood Risk Management*, *10*(2), 143–144.

Hartmann, T., & Scheibel, M. (2016). Flood Label for buildings—A tool for more flood-resilient cities. *E3S Web of Conferences*, *7*(1), Article 13006. https://doi.org/10.1051/e3sconf/20160713006

Healey, P. (2007). *Urban complexity and spatial strategies: Towards a relational planning approach*. Routledge.

Hegger, D. L. T., Driessen, P. P. J., Wiering, M., van

Rijswick, H. F. M. W., Kundzewicz, Z. W., Matczak, P., Crabbé, A., Raadgever, G. T., Bakker, M. H. N., Priest, S. J., Larrue, C., & Ek, K. (2016). Toward more flood resilience: Is a diversification of flood risk management strategies the way forward? *Ecology and Society*, *21*(4), Article 52.

Hoss, F., Jonkman, S. N., & Maaskant, B. (2011). A comprehensive assessment of multilayered safety in flood risk management—The Dordrecht case study. In ICFM5 Secretariat at ICHARM & PWRI (Eds.), *Proceedings of the 5th international conference on flood management* (pp. 57–65).

Hydroscan. (2018). *Het implementeren van individuele beschermingsmaatregelen tegen overstromingen in drie pilootgebieden*. [Implementing individual protection measures against flooding in three pilot areas]. Hydroscan.

Intergovernmental Panel on Climate Change. (2018). *Global warming of 1.5ºC*. https://www.ipcc.ch/sr15

Jiang, H., Geertman, S., & Witte, P. (2020a). Smart urban governance: An alternative to technocratic "smartness." *GeoJournal*. https://doi.org/10.1007/s10708-020-10326-w

Jiang, H., Geertman, S., & Witte, P. (2020b). Smartening urban governance: An evidence-based perspective. *Regional Science Policy & Practice*, *13*(3), 744–758. https://doi.org/10.1111/rsp3.12304

Kaufmann, M., Mees, H., Liefferink, D., & Crabbé, A. (2016). A game of give and take: The introduction of multi-layer (water) safety in the Netherlands and Flanders. *Land Use Policy*, *57*, 277–286.

Kellens, W., Terpstra, T., & De Maeyer, P. (2013). Perception and communication of flood risks: A systematic review of empirical research. *Risk Analysis: An International Journal*, *33*(1), 24–49. https://doi.org/10.1111/j.1539-6924.2012.01844.x

Kratzert, F., Klotz, D., Herrnegger, M., Sampson, A. K., Hochreiter, S., & Nearing, G. S. (2019). Toward improved predictions in ungauged basins: Exploiting the power of machine learning. *Water Resources Research*, *55*(12), 11344–11354.

Kreibich, H., Thieken, A. H., Petrow, T., Müller, M., & Merz, B. (2005). Flood loss reduction of private households due to building precautionary measures—Lessons learned from the Elbe flood in August 2002. *Natural Hazards and Earth System Sciences*, *5*(1), 117–126.

Kuhlicke, C., Seebauer, S., Hudson, P., Begg, C., Bubeck, P., Dittmer, C., Grothmann, T., Heidenreich, A., Kreibich, H., Lorenz, D. F., Masson, T., Reiter, J., Thaler, T., Thieken, A. H., & Bamberg, S. (2020). The behavioral turn in flood risk management, its assumptions and potential implications. *WIREs Water*, *7*(3), Article e1418.

Kuklicke, C., & Demeritt, D. (2016). Adaptive and risk-based approaches to climate change and the management of uncertainty and institutional risk: The case of future flooding in England. *Global Environmental Change*, *37*, 56–68.

Kummitha, R. K. R., & Crutzen, N. (2017). How do we understand smart cities? An evolutionary perspective. *Cities*, *67*, 43–52.

Liao, K.-H. (2012). A theory on urban resilience to floods—A basis for alternative planning practices. *Ecology and Society*, *17*(4), Article 48.

Luhmann, N. (1995). *Social systems*. Stanford University Press.

McClymont, K., Morrison, D., Beevers, L., & Carmen, E. (2019). Flood resilience: A systematic review. *Journal of Environmental Planning and Management*, *63*(7), 1151–1176.

Mees, H., Crabbe, A., & Suykens, C. (2018). Belgian flood risk governance: Explaining the dynamics within a fragmented governance arrangement. *Journal of Flood Risk Management*, *11*(3), 271–280.

Mees, H., Tempels, B., Crabbé, A., & Boelens, L. (2016). Shifting public–private responsibilities in Flemish flood risk management. Towards a co-evolutionary approach. *Land Use Policy*, *57*, 23–33. https://doi.org/10.1016/j.landusepol.2016.05.012

Meijerink, S., & Dicke, W. (2008). Shifts in the public–private divide in flood management. *International Journal of Water Resources Development*, *24*(4), 499–512.

Neirotti, P., De Marco, A., Cagliano, A. C., Mangano, G., & Scorrano, F. (2014). Current trends in smart city initiatives: Some stylised facts. *Cities*, *38*, 25–36.

Neubert, M., Naumann, T., Hennersdorf, J., & Nikolowski, J. (2016). The geographic information system-based flood damage simulation model HOWAD. *Journal of Flood Risk Management*, *9*(1), 36–49.

Ran, J., & Nedovic-Budic, Z. (2016). Integrating spatial planning and flood risk management: A new conceptual framework for the spatially integrated policy infrastructure. *Computers, Environment and Urban Systems*, *57*, 68–79.

Rauter, M., Schindeleger, A., Fuchs, S., & Thaler, T. (2019). Deconstructing the legal framework for flood protection in Austria: Individual and state responsibilities from a planning perspective. *Water International*, *44*(5), 571–587.

Rauter, M., Kaufmann, M., Thaler, T., & Fuchs, S. (2020). Flood risk management in Austria: Analysing the shift in responsibility-sharing between public and private actors from a public stakeholder's perspective. *Land Use Policy*, *99*, Article 105017.

Rözer, V., Müller, M., Bubeck, P., Kienzler, S., Thieken, A., Pech, I., Schröter, K., Buchholz, O., & Kreibich, H. (2016). Coping with pluvial floods by private households. *Water*, *8*(7), Article 304.

Rufat, S., Fekete, A., Armaş, I., Hartmann, T., Kuhlicke, C., Prior, T., Thaler, T., & Wisner, B. (2020). Swimming alone? Why linking flood risk perception and behavior requires more than "it's the individual, stupid." *WIREs Water*, *7*(5), Article e1462.

Schinke, R., Neubert, M., & Hennersdorf, J. (2013). Modellierung von Gebäudeschäden infolge von Grundhochwasser auf Grundlage gebäudetypologischer Untersuchungen und synthetisch ermittelter Schadensfunktionen [Modelling of building damage due to groundwater flooding on the basis of building typological investigations and synthetically determined damage functions]. *Technischer und organisatorischer Hochwasserschutz-Bauwerke, Anforderungen, Modelle*, *48*, 365–372.

Seebauer, S., & Babcicky, P. (2018). Trust and the communication of flood risks: Comparing the roles of local governments, volunteers in emergency services, and neighbours. *Journal of Flood Risk Management*, *11*(3), 305–316.

Slavíková, L., Hartmann, T., & Thaler, T. (2021). *Financial schemes for resilient flood recovery*. Taylor & Francis.

Snel, K. A. W., Witte, P. A., Hartmann, T., & Geertman, S. C. M. (2020). The shifting position of homeowners in flood resilience: From recipients to key-stakeholders. *WIREs Water*, *7*(4), Article e1451.

Tasantab, J. C., Gajendran, T., von Meding, J., & Maund, K. (2020). Perceptions and deeply held beliefs about responsibility for flood risk adaptation in Accra Ghana. *International Journal of Disaster Resilience in the Built Environment*, *11*(5), 631–644.

Thaler, T. A., Priest, S. J., & Fuchs, S. (2016). Evolving inter-regional co-operation in flood risk management: Distances and types of partnership approaches in Austria. *Regional Environmental Change*, *16*(3), 841–853. https://doi.org/10.1007/s10113-015-0796-z

Thaler, T., Seebauer, S., & Schindelegger, A. (2020). Patience, persistence and pre-signals: Policy dynamics of planned relocation in Austria. *Global Environmental Change*, *63*, Article 102122.

Thistlethwaite, J., Henstra, D., Brown, C., & Scott, D. (2018). How flood experience and risk perception influences protective actions and behaviours among Canadian homeowners. *Environmental Management*, *61*(2), 197–208.

Van Alphen, J., Martini, F., Loat, R., Slomp, R., & Passchier, R. (2009). Flood risk mapping in Europe, experiences and best practices. *Journal of Flood Risk Management*, *2*(4), 285–292.

White, I., Connelly, A., Garvin, S., Lawson, N., & O'Hare, P. (2018). Flood resilience technology in Europe: Identifying barriers and co-producing best practice. *Journal of Flood Risk Management*, *11*, S468–S478.

Wildavsky, A. (1969). Rescuing policy analysis from PPBS. *Public Administration Review*, *29*(2), 189–202.

About the Authors

Peter R. Davids is currently finalizing his PhD-research in flood risk management at the Centre of Mobility and Spatial Planning at Ghent University. His research activities focus on flood risk management, risk governance, and marine spatial planning from a co-evolutionary perspective.

Thomas Thaler holds a PhD in Environmental Science and is currently working as a Post-Doc Researcher at the Institute of Mountain Risk Engineering at the University of Natural Resources and Life Sciences. His research and teaching activities focus on social justice, risk governance, and flood risk management.

COGITATIO

Urban Planning (ISSN: 2183–7635)
2021, Volume 6, Issue 3, Pages 283–294
https://doi.org/10.17645/up.v6i3.4257

Article

Less is More? Evaluating Technical Aspects and User Experiences of Smart Flood Risk Assessment Tools

Patrick A. Witte *, Karin A. W. Snel and Stan C. M. Geertman

Department of Human Geography and Planning, Utrecht University, The Netherlands; E-Mails: p.a.witte@uu.nl (P.A.W.), k.a.w.snel@uu.nl (K.A.W.S.), s.c.m.geertman@uu.nl (S.C.M.G.)

* Corresponding author

Submitted: 6 March 2021 | Accepted: 19 April 2021 | Published: 19 August 2021

Abstract
In light of several recent large-scale flooding events worldwide, the urgency of involving residents in the flood risk management debate is growing. However, this has so far proven to be problematic, mainly because of lacking or ineffective communication between stakeholders. One way to better involve residents in the flood risk management debate is by developing smart applications, dedicated to facilitate and increase the insights of residents into the flood risk and vulnerability of their private properties. However, what is lacking thus far is a systematic evaluation of the technical aspects and the user experiences of such tools. The goal of this article is to explore and evaluate the technical, analytical, and communicative qualities of smart flood risk assessment tools. To this end, a new smart application named FLOODLABEL is used, aiming to inform residents of flood-prone areas about potential flood risks and associated protection measures of their dwellings. Based on this, the article concludes that a smart application like FLOODLABEL can be beneficial for informing residents about flood risks and potential protection measures. However, it also shows that a one-size-fits-all approach is not suitable for informing residents on flood risks, inter alia because how residents perceive risks is not homogeneous. This research is therefore just the first step towards a more systematic evaluation method of smart applications.

Keywords
flood risk governance; planning support; pluralism; risk communication; task-technology fit; user-technology fit

Issue
This article is part of the issue "Smart Urban Governance for Climate Change Adaptation" edited by Thomas Thaler (University of Natural Resources and Life Sciences, Austria), Patrick Witte (Utrecht University, The Netherlands), Thomas Hartmann (TU Dortmund University, Germany) and Stan Geertman (Utrecht University, The Netherlands).

1. Introduction

Urban areas worldwide are facing increasing flood risks due to sea-level rise, increasing heavy rainfall, and rising groundwater levels. In light of several recent large-scale flooding events worldwide, the growing insight is that traditional structural protection measures need to be complemented by non-structural measures, such as homeowners adapting their properties against flooding (Bradford et al., 2012; O'Neill et al., 2016). The background of this insight is the conviction that damage costs can be substantially reduced by increasing the flood resilience of individual buildings (Grothmann & Reusswig, 2006; Kreibich et al., 2005). Structural protection measures have generally been a governmental task, yet the main actors in these non-structural measures are individuals. So, responsibilities concerning flood resilience are spreading from solely governmental organisations to include individual residents as well. This shift envisions more involvement of residents in the sense that they are expected to adjust their homes to prevent flood damage and to take responsibility in minimising the risk that their property might flood.

However, so far this has proven problematic, in the sense that homeowners, in general, do not feel responsible or just feel partly responsible for taking flood protection measures (Bergsma et al., 2012). Even though information on flood risk and potential measures is generally available, homeowners are seldom aware of the urgency of flooding and often do not sufficiently prepare their properties or implement adaptation measures (Snel et al., 2019). Research shows that if Europeans would take flood adaptation measures, they could reduce the costs of flood damage by as much as 80% (Grothmann & Reusswig, 2006). However, what homeowners perceive as their responsibility is of particular importance here. So far, it has proven difficult to increase homeowners' responsibility and involvement in flood risk governance. This can largely be attributed to the lack of effective communication between public administration, water management experts, and residents (Soane et al., 2010). Furthermore, existing barriers may stem from discussions on divisions of responsibility among stakeholders and discrepancies in the sense of urgency. For instance, in climate adaptation studies in general, it is concluded that the adaptive actions of residents are hindered because responsibilities are vague and ambiguous, which can lead to a lack of necessary adaptation (e.g., Runhaar et al., 2012). Additionally, residents tend to lack a sense of urgency with regards to taking flood adaptive actions (e.g., Kaufmann & Wiering, 2019).

To improve communication on flood risk management, developing a smart application that facilitates residents' insight into flood risk and the vulnerability of private properties is a suitable way to provide flood risk information, like Floodtoolkit in the United Kingdom. This is a website with local information on flood risks, risk prevention responsibilities, flood protection measures, etc. (see, e.g., Oxfordshire County Council, n.d.). More recently, another smart application was launched—FLOODLABEL—aiming to inform residents in flood-prone areas about potential flood risks and the associated adaptation measures of their dwellings. Compared to the mentioned Floodtoolkit, FLOODLABEL (n.d.) indicates risks and potential measures at a much finer scale level—the parcel. Nevertheless, in general, what has been lacking until now is a systematic evaluation of the technical aspects and the user experiences of such smart applications concerning flood risks. The goal of this article is to explore and evaluate the technical, analytical, and communicative qualities of smart flood risk assessment tools. We aim to evaluate how a smart application like FLOODLABEL, which is dedicated to communicating technical flood risk information, can be supportive for laymen in flood-prone areas in a technical, analytical, and communicative sense. This will be researched in the context of the Netherlands, a country in which flooding is a continuous risk, given the fact that a substantial part of the country is located below sea level.

2. Literature Review

2.1. Plural Resident Perspectives in Flood Risk Management

In present-day flood risk management, governmental agencies play a decisive role, both in the decision-making process (foremost intergovernmental) and in the implementation of decisions taken (e.g., Casiano & Crompvoets, 2020; Mees et al., 2018). As a consequence, the communication of information is mostly performed in a one-directional and top-down manner: from foremost experts spanning from governmental organisations to the general public, i.e., laymen. However, when scientific (expert) information is communicated, e.g., about flood risks, laypeople mostly do not have the capabilities and/or knowledge to interpret the information as intended by the experts. Because of this gap between experts and laymen, the resulting behaviour of laymen is influenced accordingly (Dickson, 2005). Additionally, laymen's respective actions are not easy to influence, since their knowledge and perception is based on what information they already possess (lay knowledge) and receive by communication (Faulkner et al., 2010; Terpstra et al., 2009). As a consequence of insufficient expert-laymen communication, laymen will not always feel responsible for taking protection measures, e.g., to prevent and/or adapt to floods (Snel et al., 2019).

Although this one-directional and top-down risk communication model has been criticised for decades, flood risk communication has not yet fully distanced itself from it (Rollason et al., 2018). In flood risk management, the top-down communication orientation (from experts to laymen) is persistent with aims such as enhancing risk awareness, knowledge transfer, and giving subsequent advice to take action (Höppner et al., 2012). This is striking, since through the years it has been shown that the perception of (flood) risk is made up of various elements, including previous experiences, conversations with others (e.g., neighbours), culture, institutions, demography, and geography (e.g., Maidl & Buchecker, 2015; Papagiannaki et al., 2019), which have hardly been considered in flood risk communication strategies until now.

Research by Snel et al. (2019) shows that the communication preferences of residents on flood risk communication are very diverse, implying that it is impossible to develop one standard communication method to inform and motivate all residents effectively. All respondents are willing to visit a website to inform themselves about flood risks, but a great variety of communication methods is needed to meet the diverse preferences of all residents, such as face-to-face communication, national campaigns and receiving flyers. Considering this, one can conclude that the "layman" does not exist as a label for an entire group of residents, but consists of different types of laymen, who all have different preferences for flood risk communication. Snel et al. (2019)

define four groups through cultural theory (Douglas & Wildavsky, 1983).

This theory identifies four distinct rationalities on which people base their perception of the world and by which their actions are determined: fatalism, hierarchism, individualism, and egalitarianism (Hartmann, 2012; Schwarz & Thompson, 1990). These rationalities are portrayed in a matrix (Figure 1). *Group* represents the attachment to social values such as democracy, frequency of interaction, and equality, whereas *grid* represents the value of autonomy, control, and institutional integrity (Mamadouh, 1999). The position of the rationalities in the matrix represents the extent to which they associate with either strong or weak 'group' or 'grid' values.

In short, people with fatalistic rationality (weak group, strong grid) are characterised by the idea that the world and events cannot be controlled. The world can move freely both ways, and there is no "falling down" as shown in Figure 1. The strong grid is externally determined, as it is not possible for individuals (i.e., weak group) to drastically influence it. Fatalism is overall a passive rationality. Hierarchists (strong group, strong grid) envision the world to be on top of a hill and in a small dip, which makes for a relatively robust equilibrium. This creates opportunities for trial and error, but only to a certain extent, as they do not want to destroy the equilibrium. They set up boundaries through rules and regulations, and hierarchy (strong grid). Additionally, they believe all members of society are equal and give power to an institution (strong group). Individualists (weak group, weak grid) have a robust worldview. Disturbances will only temporarily disrupt the equilibrium. Therefore, they can experiment, and each fault is also seen as an opportunity for benefit. Overall, self-determination and individual liberty are important values. Egalitarianists (weak grid, strong group) perceive the world to be on top of a hill, which causes such instability that already a small disturbance can destroy the equilibrium. Experimenting is very risky because failure means that the balance will be destroyed. They perceive the results of action as more important than the process (Hartmann, 2012; Schwarz & Thompson, 1990; Snel et al., 2019).

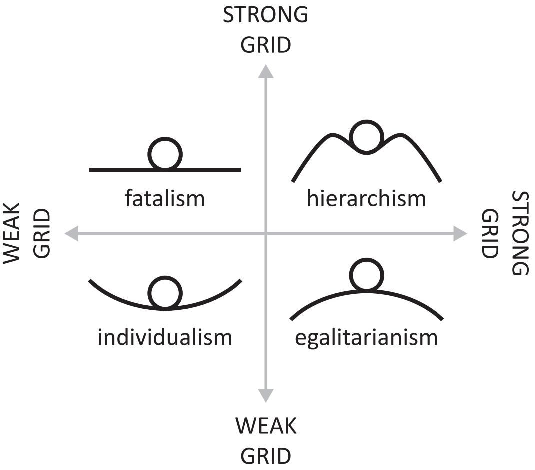


Figure 1. Group and grid diagram and pluralistic rationalities of cultural theory. Source: Authors based on Hartmann (2012), Schwarz and Thompson (1990), and Snel et al. (2019).

The four groups are briefly described below based on their preferences for flood risk communication and link to the rationalities of cultural theory:

- Insusceptible confident (Fatalists): This group knows they are in danger but are not likely to act on this themselves because they believe their actions will not make a difference in case of a flood event. A website, face-to-face contact, expert advice, a television commercial, or a flyer are not preferred. The government should provide the public with flood risk information, i.e., they themselves take a passive role.
- Self-assured omniscient (Hierarchists): This group trusts in current flood risk management as done by the government. In other words, they trust in rules and regulations as outlined by the government, which is responsible for flood risk management in their eyes. They are not interested in expert advice, a detailed report or face-to-face communication. Rather they prefer a national campaign, i.e., a television commercial or flyers, and they need the government to stimulate them financially to take measures. This is the perspective that is mostly addressed in current flood risk communication.
- Acknowledged inexpert (Individualists): This group prefers face-to-face communication methods over a website. Ideally, they would like to be informed extensively by an expert, also about background information. This group is not a big advocate of a national campaign on flood risk or collaborations. They regard the individual residents as main actors responsible for protecting themselves against floods.
- Insufficiently connected (Egalitarianists): This group is most concerned about climate change-induced floods, and therefore feel the need to take measures themselves. This group would like to obtain more information on what actual measures they can implement, and what the costs and benefits of these measures are. They prefer to use a website to obtain more of this information. Furthermore, this group would like to work together (community-based solutions) and they stand for common values and trust.

To enhance the action motivation of residents in flood-prone areas, the intersubjectivity, and the sense of responsibility among individual residents, flood risk communication should address the above-mentioned plurality in its communicative approach (Snel et al., 2019).

Besides pluralities in user preferences, the technical elements of flood risk communication remain important to be able to communicate the risks of flooding appropriately.

2.2. Assessing Appropriate Characteristics of Smart Applications for Residents

To evaluate smart applications for residents such as FLOODLABEL, use will be made of assessment criteria which are common practice in similar systems like Spatial Decision Support Systems (SDSS) and WebGIS applications. Janssen (1992) defines SDSS as a computer program that: (1) helps both individuals and groups making a decision; (2) supports (and does not replace) individuals' thoughts; and (3) enhances the effectiveness (instead of efficiency) of decision-making. In addition, Sugumaran and DeGroote (2010) indicate that SDSS must have sufficient analytical capabilities to process stakeholders' preferences, but also have an easy-to-use user interface, so communicative rationality capabilities should be part of the requirements too.

A focus on the laymen's interaction with a smart application is of particular interest here. Within the research field of WebGIS applications, the user perspective and the associated human-computer interaction are of prime importance. It is acknowledged that multiple users of an application differ in perspectives, needs, demands, etc. (Sluter et al., 2017) and these differences should be taken into consideration explicitly when assessing the quality of an application. Furthermore, besides the characteristics of the user (age, education, goals, etc.) and the qualities of the WebGIS product itself (e.g., functional suitability) in particular, the quality-in-use characteristics (i.e., human-computer interaction characteristics like efficiency and effectiveness) are also important in assessing the overall quality of a WebGIS application.

In 2017, we conducted a comparative study on likewise smart applications, foremost web-GIS applications, all heading to inform residents about the risks of flooding of their area/property (reported in Attems et al., 2020). The most important outcome of this comparison entails that, however useful such user-centred and participatory approaches may be, we still see a clear gap between informing homeowners about measures and them actually implementing the proposed measures. Based on these insights, the authors of this contribution developed, together with the Dutch firm Nelen and Schuurmans, the FLOODLABEL smart application, which was launched in 2020 (Utrecht University, 2020).

From the literature, several suggestions can be derived on how to optimise the human-computer interaction by taking into account distinctive user perspectives. First, Janssen and Uran (2003) found that in general the usage of maps and graphs is preferred over tables and text. Second, the level of detail affects the ability of users to successfully use the information. Third, the timing in the process is important. According to Andrienko et al. (2003), visualisation should be considered in the phase where the options for a decision are evaluated and finally chosen. Fourth, the user, i.e., the layman, needs to be able to check what reasoning is used for a particular decision. To state it differently, the process in the sense of arguments, discussions, trade-offs, etc., that results in a particular decision should be sufficiently transparent.

From the above, it can be concluded that communication plays a prominent role in the interaction of expert knowledge to the layman user. As such, it needs to have a prominent place in a measurement framework of a smart application. Communicative support is given more meaning by not only focusing on the message but also on the target group (general public, laymen), the individual focus (individual risks and individual responsibilities), and the use of a combination of visualisation and non-visualisation/textual communication methods. Communicative support indicates whether the smart application is beneficial for the communication of information between all actors involved, which include both experts and a diverse group of laymen (Pelzer, 2017).

3. Methodology and Data Collection

3.1. Methodological Approach

This section operationalises how the smart application FLOODLABEL used in this research can support tasks technically and communicatively. Considering that residents usually make decisions without such a smart application, it is questioned whether residents are better informed about flood risks and the opportunities for adaptation measures when using the smart application FLOODLABEL, whether they are better able to make a well-informed decision, and whether they are motivated to implement this decision in the end. First, the technical/analytical support is analysed by examining the informative role of the tool for three aspects: (1) the informative role regarding flood impact in general; (2) the informative role regarding flood impact around the dwelling of the respondent; and (3) the informative role regarding potential measures to be taken to reduce the impact. The more respondents positively answer the statements about these three aspects, the better the analytical support. Second, the communicative support is determined by analysing statements that question whether certain parts of the tool are understandable, whether the entire tool is clear in terms of text and figures, whether the tool is easy to use and easy to understand, and whether it provides useful information on what happens behind the scenes. All combined answers to these statements make up the communicative support of the tool. Third, for the determination of the correct cultural theory perspective per respondent, distinct statements and interview questions are used to categorise the respondents into one of the four rationalities.

3.2. Data Collection and Analysis

In this research, we made use of the smart application FLOODLABEL, a product outcome from the JPI Urban Europe research project FLOODLABEL. We made use of a two-step research process in conducting the empirical research. In the first step, we collected 109 respondents via door-to-door surveys with valid results combined over the three case studies (Dordrecht, Venlo, and Zwolle). Each respondent was asked to share his or her level of education (from basic education to university), age (mean age of 39 years old, youngest 18 years old while oldest 73 years old) and type of device used (most used a desktop or laptop, smaller amounts used a mobile phone or tablet), in combination with some general questions about the application. Then, in the second step, respondents out of the first group were asked whether they would be willing to participate in the in-depth interview on the details of the application. In this second group, 17 in-depth interviews have been conducted, of which 6 in Zwolle, 7 in Dordrecht, and 4 in Venlo. The interviews lasted up to an hour. In this contribution, we focus on the 17 in-depth responses from the latter group.

The respondents were asked to use the FLOODLABEL website right before the interview to let them test it as if they were using it for their own dwelling. The interviewees were living in flood-prone areas that were predefined by the researchers to arrive at a preferred selection of interviewees. Furthermore, it was foremost due to the heavy demand we put on the respondents (asking them to make use of the website in advance and having them interviewed extensively thereafter) that the number of interviewees was not as high as expected at the start of the research. The themes of the interview itself were centred on analytical and communicative support (see Supplementary File). It is conceivable that only partial analytical or communicative support is found. It is thus examined how the tool performs analytically and communicatively among all respondents, and thus whether the smart application is optimally addressing the plural communication preferences of these residents.

3.3. Case Studies and Respondents' Characteristics

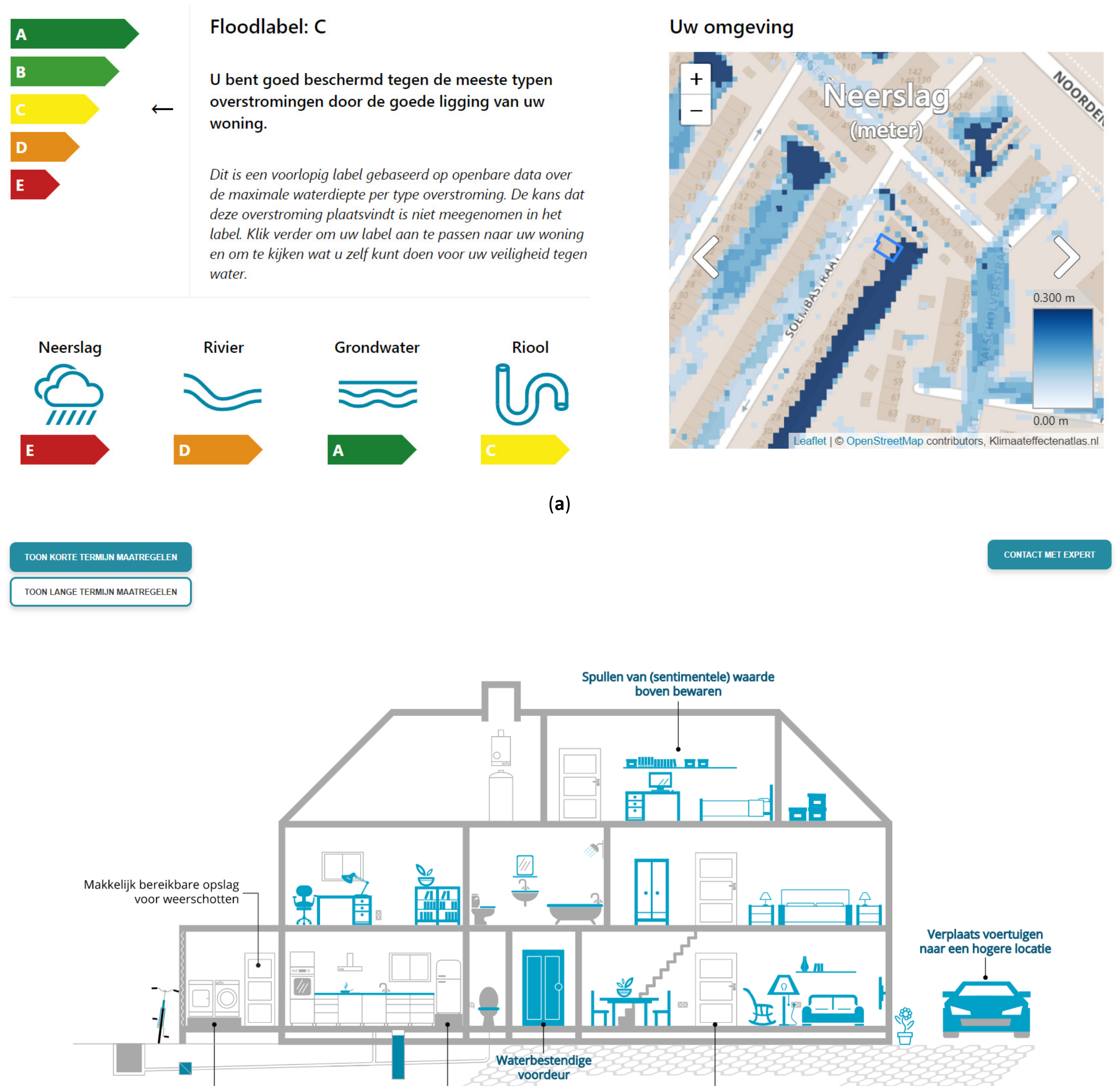
The smart application FLOODLABEL, based on its German analogue predecessor "the Hochwasserpass" (Hartmann & Scheibel, 2016), generates for each Dutch premise the calculated flood risks and potential adaptation measures, including their effects on the recalculated flood risks. This is all based on geo-referenced data sets. Most relevant is the integrated map showing precipitation, river flooding, and groundwater information. On this map, the user can switch between different layers, zoom in and out, and navigate through the data. The risk calculation is divided into four types of flood risks: fluvial floods, pluvial floods, groundwater floods, and sewage flooding. This leads to one cumulative label ranging from green to red (A to E), indicating well-protected to vulnerable to flooding. For each of the specific types of floods a sub-label is indicated, also with a range of A to E (Figure 2a). Another feature of FLOODLABEL is that people can see what kind of measures they will have to take for their home to adapt to their flood risk. The range spans from simple preparations for flooding like moving valuable belongings from the ground floor to upper floors to more technical solutions like water protected windows to prevent floodwater from entering a house. Additionally, a differentiation is made between the short-term measures, like moving your car to a higher situated area, and long-term measures, like replacing the regular front door by one with better water resistance function (Figure 2b).

All respondents in the study are residents living in a flood-prone area. Zwolle, Venlo, and Dordrecht are chosen as case cities because of their geographical location within flood-prone areas (Figure 3). Furthermore, all three medium-sized cities are located in three geographically distinct areas in the country, representing the range of Dutch flood risks. Zwolle is located near the rivers IJssel and Vecht. The latter is a rain-fed river, whereas the IJssel is a tributary of the Rhine, which is a combination of a glacier-fed and rain-fed river. The residential areas in the city are susceptible to floods with a depth varying from 2 to 4 meters. Venlo is located in the southeast of the country, in the Meuse River basin at 20 to 35 meters above sea level. In 1993 and 1995 the area suffered two 1-in-200-year floods, which led to evacuations of the neighbourhoods alongside the river. Dordrecht is located in the southwest of the country. The city is an island surrounded by two major rivers: the Meuse and the Waal. In general, the city's land is 4 to 5 meters below sea level, but it is surrounded by a main dike ring protecting against a 1-in-1000-year (sea and river) flood. The three cities are chosen to be representative of flood risks in the entire country.

4. Results

4.1. General Impression of the Tool

Most respondents indicate that they are not concerned about the increasing risk of flooding to their home. Most of them did not worry, because they considered their location to be sufficiently safe. They state that they are aware of flood risk and substantiate their awareness with their living experience or their location concerning the rivers: "I am safe where I live, relatively new neighbourhood, 25 years old. The river is far away, there is a dike in between, so I am not concerned for the place where I live" (respondent 12). Several respondents did describe two sides of the story: "We are reasonably protected, we have it under control pretty well, we know what to do. Still, there is a chance that the water rises due to climate change" (respondent 16). Overall, respondents think their dwelling is safe because they do not expect a flood to happen in the short term.



Floodlabel: C

U bent goed beschermd tegen de meeste typen overstromingen door de goede ligging van uw woning.

Dit is een voorlopig label gebaseerd op openbare data over de maximale waterdiepte per type overstroming. De kans dat deze overstroming plaatsvindt is niet meegenomen in het label. Klik verder om uw label aan te passen naar uw woning en om te kijken wat u zelf kunt doen voor uw veiligheid tegen water.

Uw omgeving

Leaflet | © OpenStreetMap contributors, Klimaateffectenatlas.nl

(**a**)

(**b**)

Figure 2. Screenshots from the FLOODLABEL application. (**a**) The left panel presents the flood label for different types of flooding (see symbols). The right panel shows the precipitation at the parcel level, but the user can also switch to the fluvial flooding or groundwater level maps. (**b**) The tool displays two figures for both short-term and long-term measures to implement in and around the house. On the website, below the figures, detailed information on each of the suggested measures is given. Source: FLOODLABEL (n.d.).

Although respondents are generally not concerned about flood risk, most of them are positive about the idea of a tool with personal flood risk information. Respondents who valued the smart application and its communicative function positively would like to additionally see another communication method (e.g., a flyer or television commercial) to lead them to the application. In other words, they indicated that they require a clear trigger to lead them to the smart application. Respondent 10 considers the tool more as a platform for real estate agents than for individual residents. Among those who are positive about the application, the statements "It is easy" and "I prefer doing this online and on my own" are the most common responses.

4.2. Analytical Support Function of the Tool

The valuation of the analytical support elements varies across the respondents. Generally, the informative role of the application is valued neither negatively nor

Figure 3. Case study locations within the Netherlands. Source: Snel et al. (2019).

positively. Only the different kinds of information are valued differently. The informative role of floods, in general, is valued more negatively than positively. Also, the informative role about flood impact specifically for the own dwelling of the respondent has more negative than positive answers. The informative role about potential measures is valued more positively, although nobody indicates that he or she is planning to actually implement any of the measures presented. In that sense, the analytical support can be considered as low. As respondent 12 states: "Beforehand I had no clue about flood risks, so compared to that I did get a little grasp from it, but I will not call myself an expert on floods, not at all."

The respondents from Venlo distinguished themselves from the respondents in Zwolle and Dordrecht. They all experienced the floods of 1993 and 1995, while the respondents from Zwolle and Dordrecht generally did not have any experience with floods at all. This leads to a totally different interpretation of the measures page. Where the respondents from Zwolle and Dordrecht were overall positive about the measures presented in the application, the respondents from Venlo found the measures inappropriate for the floods they experienced in 1993 and 1995. In other words, the measures proposed could be informative, but were in their particular case not appropriate to the scale of the floods that did occur. Respondents 15 and 17 illustrate the issue with the measures clearly:

> You can purchase waterproof doors, you can insulate the walls, you can insulate the basement, but then still the water comes through those holes or it comes through the window. I had a water level of 1m12, then it just comes through the window. There were measures you could actually implement, but I did not feel that it protected me in the end. (respondent 15)

> Then you need totally different information….For me, my dwelling is of importance. That is why you go to this website. Currently, I do not see any information that could have helped me in that situation. (respondent 17)

4.3. Communicative Support Function of the Tool

Communicative support is measured by ten statements about different parts of the smart application, plus additional questions. In terms of clarity, the potential measures are valued the most positively. All respondents were positive about the potential measures that were presented in the application. The most negatively judged is the statement "I can easily see what happens behind the scenes of the website." Most respondents also stated that they would like to see more of what happens in the background of the smart application to better comprehend the information presented.

Other results show that most respondents think that the application is easy-to-use and contains clear texts. The first part with the four flood labels is clear for most respondents, as is the extra information about the four types of floods. The questions about the own dwelling to specify the vulnerability to flooding are also clear. However, concerning the individuality of information (i.e., sufficiency of the level of detail per dwelling), there is no broad consensus among respondents. There is also no consensus about whether the application addresses individual responsibilities. It should be noted that, although the questions asked within the application were clear and comprehensible for most respondents, for many it was still unclear how to discover which measures they had already taken. For example, respondent 1 noted: "First, explain what a water barrier is, how you can get such a door, and how you can measure how high your front door is. These are the things you do not know."

4.4. Plural Resident Perspectives on the Tool

Comparing our findings to the plurality in residents' preferences as distinguished by Snel et al. (2019), we found that all four groups identified are slightly positive about the communicative support of the website, but they differ in degree. Of the 17 interviewees, two could be positioned in the first group (Fatalist), six in the second group (Hierarchist), four in the third group (Individualist), and five in the last group (Egalitarian).

First, the group of "insusceptible confident" (Fatalists) was slightly positive about the smart application FLOODLABEL, especially about the measures, the provided labels, and the extra information about the four flood types. They do not think that the smart application addresses individual responsibilities, i.e., it does not show what the responsibilities are of individual residents.

Second, the group of "self-assured omniscient" (Hierarchists) showed similar results, but ask for more clarity on the underlying reasons for the application: "You are confronted with all kinds of risks, but I think it is also good to explain in advance why you let people do that" (respondent 2). Also, this group asks for more specific information. Respondent 15, who experienced the 1993 and 1995 floods in Venlo, stated: "Because I experienced floods before, I do get the right information out of the website. Someone who has just moved here would perceive that differently. I think this information should be more specific." She added that the information should be even more specific for those dwellings that are located in the high flood risk area, i.e., right along the river Meuse.

Third, the group of "acknowledged inexpert" (Individualists) is the least positive about the communicative support of the smart application. What happens behind the scenes is not shown, while these respondents would like to see that. Also, this group does not agree with the statement that the application addresses individual responsibilities and that the information is communicated on an individual level. This group asks for more explanation across the entire smart application, for example for the map and for why a specific label is chosen. Some respondents in this group indicate that the application does not see a flood as a dynamic event (i.e., a "wave") but as a static thing. For instance, for a certain dwelling, the river label is "good," but when the dikes break and thus the impact is high, this information is very much misleading.

Fourth, the group of "insufficiently connected" (Egalitarians) is the most positive regarding the communicative support. They are most positive about the potential measures and least positive about whether what happens behind the scenes is shown. This group is also positive about whether the information is communicated at an individual level. Still, there are also critiques. Some respondents would also like to see the probability of flooding:

> I miss a probability....Are we talking about once every ten years, once every 100 years, or once every 1000 years? The website says: In case of a flood, you are protected in these ways, but what is the probability of such a flood?....For me, this influences my feeling of urgency. (respondent 5)

Further, it is recommended that the inclusion of a source together with a probability would make the application much more reliable.

4.5. Conclusion on the Tool's Support Function

When asking whether the smart application raised respondents' awareness, the majority of the respondents answered positively. For those who have become more aware due to the application, most did not even think that a flood could happen near their home. All respondents from Venlo answered "no," as they already possessed a high awareness of flood risks due to previous experiences.

Even though respondents indicate a raised awareness of flood risk after using the application, this does not mean that they make plans to actually take action. This shows that based on the outcomes of the application, nobody is planning to implement flood adaption measures. Many respondents indicate there is no feeling of urgency and, as a consequence, they do not plan to take adaptive actions themselves. There is a distinction between the "bigger" and expensive measures (e.g., waterproof floors) and the "smaller" and cheaper investments (e.g., bring belongings of sentimental value to a higher floor). Respondents would consider the latter, only in some cases, for example when a severe flood is about to occur or has occurred already. None of the respondents seriously considered the large investments to protect their homes in the short term:

> When it rains a lot, sometimes water does not flow into the garden. Something like that must happen and be even more extreme, making the water reach the house. Perhaps then you will really start to think about what you can adjust. But no, not at the moment. (respondent 12)

Looking at the differences between the four identified groups, both the insusceptible confidents and self-assured omniscient do not feel more responsible after making use of the application, which for them just partly raised awareness. "I do not think there are many flooding events in the Netherlands" (respondent 1) is an often-heard reason for why the application did not contribute to raising the respondents' awareness. Acknowledged non-experts show similar results to insusceptible confidents: Nobody feels more responsible for taking adaption/protection measures after making use of the application and only half of them showed increased awareness. A small majority of the group of insufficiently connected respondents feels more responsible for taking adaption measures after making use of the application. Most of them think their awareness has been raised due to the application, but, just as the other three groups, nobody is planning to actually take adaption measures. In the next section, the differences in flood risk awareness among different groups of residents are further discussed.

5. Discussion, Conclusions, and Future Research

5.1. Discussion

This research identified the existence of plural resident perspectives on flood risk communication and how this has a strong influence on how flood risk information should be communicated to residents, as also discussed by Snel et al. (2019). For example, some respondents, i.e., laymen, prefer flood probabilities as the main communication method (i.e., the "expert way" of communication, like for instance the chance of flooding as 1-in-10000 years), while other respondents have no clue what such probabilities entail. Also, responses vary based on whether respondents have had previous experiences with floods. To illustrate, since all respondents from Venlo have had experiences with the 1993 and 1995 floods, this influences their view on flood risk management and makes them probably more aware of what their flood risk is. Additionally, differences in the perceptions are also influenced by culture (e.g., political culture), institutions, demography (e.g., background in dealing with flooding), and geography (e.g., Faulkner et al., 2010; Maidl & Buchecker, 2015).

Additional interesting differences can be found between the four identified groups of residents. According to Snel et al. (2019), acknowledged non-experts are solely interested in their personal flood risks and the reasoning behind that. Since the FLOODLABEL application is developed as a platform to discover your personal flood risk, it was expected that this group would value the application positively. However, the results of this study showed otherwise. This group prefers the information to be much more specific for their own dwelling, while the other three groups consider the measures presented by the application to be of help in making informed decisions regarding flood adaptation. Currently, the background information about the data and content of the tool as presented by the application is uniform for all users. Therefore, due to the lack of tailored information on, e.g., the measures, the application is not a call-to-action for acknowledged non-experts, as it does not address their individual responsibilities.

Besides group differences regarding information preferences, uniform perspectives resulted in some issues as well. In the previous sections, it was indicated by Andrienko et al. (2003) that the user of a smart application needs to be able to check what reasoning or calculation is used for a particular decision, what factors are considered, what trade-offs are made, and thus how an application arrives at a certain decision. It can be observed that the smart application FLOODLABEL does not have the option to provide any insights into the calculations for the label allocation. Therefore, the respondents indeed collectively indicated that they want to see what happens behind the scenes of the application. The resulting labels and information presented are considered correct and informative, but provide insufficient insight into the process to arrive at a certain decision.

5.2. Conclusions and Future Research Directions

First, to fulfil the technical rationale of a smart application, FLOODLABEL should simply work and show the right information. Regarding this informative role, it can be stated that the application was considered insufficiently informative for flood risk information, concerning both flood risk information in general and residents' personal flood risk of their home. In contrast, the application showed to be mostly informative about potential effective adaption measures. In other words, the smart application FLOODLABEL is considered not entirely analytically supportive from a resident's (i.e., user) perspective.

Second, to fulfil the communicative rationale of a smart application, FLOODLABEL should provide clear and understandable information, targeted at the general public, showing what happens behind the scenes, communicating information on an individual level, addressing individual responsibilities, and using a combination of communication and visualisation methods. The empirical research shows that FLOODLABEL is clear in its presentation of adaption/protection measures; it is an application that is easy-to-use and the information communicated is clear. However, the application fails to provide insight into what is happening behind the scenes, while respondents indicate being very much interested in this kind of information.

In terms of future research, first, it shows there is a missing sense of urgency among many residents concerning flood risk information and adaptation. As climate change will likely increase the chance of flooding and its impact in the future, this missing sense of urgency needs to be addressed in flood risk communication. Second, it can be stated that the most challenging aspect of a smart application is to communicate flood risk information to residents while acknowledging the plurality of those residents' perspectives. These differences in preferences make it impossible to develop a uniform communication strategy that fulfils the wishes of all perspectives. As shown by Snel et al. (2019), current flood risk communication is mostly directed at self-assured omniscients, e.g., by using flood probabilities, and is thus not directed at all four perspectives. However, the probability-oriented communication method is insufficient in bringing all residents into action. Therefore, the other groups should be addressed in a better-targeted way too.

All in all, this article concludes that, on the one hand, a smart application like FLOODLABEL can be beneficial for informing residents about flood risks and potential adaption measures and in that better involving them as active stakeholders in the flood risk management debate. However, it also shows that a one-size-fits-all approach is not suitable for informing residents about flood risks, inter alia because how residents perceive risks is not homogeneous. Additionally, this article concludes that this research is just the first step towards a more systematic evaluation of smart applications in this research domain. As indicated, the number of respondents willing to test the smart application and be part of the semi-structured interviews was small. A much bigger research population would be needed to come up with firmer statements about their wishes and demands. Nevertheless, the research performed provides some valuable insights into the distinctive groups that can be identified based on cultural theory and how this relates to the issue of flood risk perception and opinions concerning willingness to take flood protection and adaption measures. Given the need for more awareness on flooding providing climate change developments, this kind of additional insight is urgently needed.

Acknowledgments

This study was supported by the ERA-NET Smart Urban Futures and Joint Programming Initiatives (JPI) Urban Europe; FLOODLABEL (Project No. 693443). The authors would like to thank Niels Venema and Danny van Hienen for their valuable contributions to the research underlying this article.

Conflict of Interests

The authors declare no conflict of interests.

Supplementary Material

Supplementary material for this article is available online in the format provided by the authors (unedited).

References

Andrienko, N., Andrienko, G., & Gatalsky, P. (2003). Exploratory spatio-temporal visualization: An analytical review. *Journal of Visual Languages & Computing*, *14*(6), 503–541.

Attems, M. S., Thaler, T., Snel, K. A., Davids, P., Hartmann, T., & Fuchs, S. (2020). The influence of tailored risk communication on individual adaptive behaviour. *International Journal of Disaster Risk Reduction*, *49*, Article 101618.

Bergsma, E., Gupta, J., & Jong, P. (2012). Does individual responsibility increase the adaptive capacity of society? The case of local water management in the Netherlands. *Resources, Conservation and Recycling*, *64*, 13–22.

Bradford, R. A., O'Sullivan, J. J., Van Der Craats, I. M., Krywkow, J., Rotko, P., Aaltonen, J., & Schelfaut, K. (2012). Risk perception—Issues for flood management in Europe. *Natural Hazards and Earth System Sciences*, *12*(7), 2299–2309. https://doi.org/10.5194/nhess-12-2299-2012

Casiano, C., & Crompvoets, J. (2020). Assessing the governance context support for creating a pluvial flood risk map with climate change scenarios: The Flemish subnational case. *ISPRS International Journal of Geo-Information*, *9*(7), Article 460. https://doi.org/10.3390/ijgi9070460

Dickson, D. (2005, June 24). The case for a 'deficit model' of science communication. *SciDev.Net*. https://www.scidev.net/global/editorials/the-case-for-a-deficit-model-of-science-communic

Douglas, M., & Wildavsky, A. (1983). *Risk and culture: An essay on the selection of technological and environmental dangers*. University of California Press.

Faulkner, H. P., Tunstall, S. M., & McCarthy, S. (2010). Flood risk communication. In G. Pernder & H. P. Faulkner (Eds.), *Flood risk science and management* (pp. 386–406). Wiley-Blackwell.

FLOODLABEL. (n.d.). *Homepage*. www.floodlabel.net

Grothmann, T., & Reusswig, F. (2006). People at risk of flooding: Why some residents take precautionary action while others do not. *Natural Hazards*, *38*(1), 101–120.

Hartmann, T. (2012). Wicked problems and clumsy solutions: Planning as expectation management. *Planning Theory*, *11*(3), 242–256.

Hartmann, T., & Scheibel, M. (2016). Flood Label for buildings—A tool for more flood-resilient cities. *E3S*

Web of Conferences, *7*, Article 13006. https://doi.org/10.1051/e3sconf/20160713006

Höppner, C., Whittle, R., Bründl, M., & Buchecker, M. (2012). Linking social capacities and risk communication in Europe: A gap between theory and practice? *Natural hazards*, *64*(2), 1753–1778.

Janssen, R. (1992). *Multiobjective decision support for environmental management*. Springer.

Janssen, R., & Uran, O. (2003). Presentation of information for spatial decision support: A survey on the use of maps by participants in quantitative water management in the IJsselmeer region, the Netherlands. *Physics and Chemistry of the Earth, Parts A/B/C*, *28*(14/15), 611–620.

Kaufmann, M., & Wiering, M. (2019). Dilemmas of an integrated multi-use climate adaptation project in the Netherlands: The Oekense Beek. In T. Hartmann, L. Slavíková, & S. McCarthy (Eds.), *Nature-based flood risk management on private land* (pp. 193–207). Springer.

Kreibich, H., Thieken, A. H., Petrow, T., Müller, M., & Merz, B. (2005). Flood loss reduction of private households due to building precautionary measures—Lessons learned from the Elbe flood in August 2002. *Natural Hazards and Earth System Sciences*, *5*(1), 117–126.

Maidl, E., & Buchecker, M. (2015). Raising risk preparedness by flood risk communication. *Natural Hazards and Earth System Sciences*, *15*(7), 1577–1595.

Mamadouh, V. (1999). Grid-group cultural theory: An introduction. *GeoJournal*, *47*(3), 395–409.

Mees, H., Crabbé, A., & Suykens, C. (2018). Belgian flood risk governance: Explaining the dynamics within a fragmented governance arrangement. *Journal of Flood Risk Management*, *11*(3), 271–280.

O’Neill, E., Brereton, F., Shahumyan, H., & Clinch, J. P. (2016). The impact of perceived flood exposure on flood-risk perception: The role of distance. *Risk Analysis*, *36*(11), 2158–2186. https://doi.org/10.1111/risa.12597

Oxfordshire County Council. (n.d.). *Homepage*. www.oxfordshirefloodtoolkit.com

Papagiannaki, K., Kotroni, V., Lagouvardos, K., & Papagiannakis, G. (2019). How awareness and confidence affect flood-risk precautionary behavior of Greek citizens: The role of perceptual and emotional mechanisms. *Natural Hazards and Earth System Sciences*, *19*(7), 1329–1346. https://doi.org/10.5194/nhess-19-1329-2019

Pelzer, P. (2017). Usefulness of planning support systems: A conceptual framework and an empirical illustration. *Transportation Research Part A: Policy and Practice*, *104*, 84–95.

Rollason, E., Bracken, L. J., Hardy, R. J., & Large, A. R. G. (2018). Rethinking flood risk communication. *Natural Hazards*, *92*(3), 1665–1686.

Runhaar, H., Mees, H., Wardekker, A., Van Der Sluijs, J., & Driessen, P. P. J. (2012). Adaptation to climate change-related risks in Dutch urban areas: Stimuli and barriers. *Regional Environmental Change*, *12*, 777–790. https://doi.org/10.1007/s10113-012-0292-7

Schwarz, M., & Thompson, M. (1990). *Divided we stand: Redefining politics, technology and social choice*. University of Pennsylvania Press.

Sluter, C. R., van Elzakker, C. P., & Ivanova, I. (2017). Requirements elicitation for geo-information solutions. *The Cartographic Journal*, *54*(1), 77–90.

Snel, K. A., Witte, P. A., Hartmann, T., & Geertman, S. C. (2019). More than a one-size-fits-all approach: Tailoring flood risk communication to plural residents’ perspectives. *Water International*, *44*(5), 554–570.

Soane, E., Schubert, I., Challenor, P., Lunn, R., Narendran, S., & Pollard, S. (2010) Flood perception and mitigation: The role of severity, agency, and experience in purchase of flood protection, and the communication of flood information. *Environment and Planning A*, *42*(12), 3023–3038.

Sugumaran, R., & DeGroote, J. (2010). *Spatial decision support systems: Principles and practices*. CRC Press.

Terpstra, T., Lindell, M. K., & Gutteling, J. M. (2009). Does communicating (flood) risk affect (flood) risk perceptions? Results of a quasi-experimental study. *Risk Analysis*, *29*(8), 1141–1155.

Utrecht University. (2020). *FLOODLABEL: A smart tool for governance towards flood-resilient cities*. https://www.uu.nl/en/research/human-geography-and-planning/floodlabel-a-smart-tool-for-governance-towards-flood-resilient-cities

About the Authors

Patrick A. Witte (PhD) is Assistant Professor in Spatial Planning at Utrecht University. He is specialised in the interconnection of land use and transportation planning, with a particular focus on integrated corridor development and inland port development. He was the project coordinator of the JPI Urban Europe ENSUF project FLOODLABEL. His research interests are integrated spatial planning, transport infrastructure systems, transformations of cities, land use planning, and economic effects assessment.

Karin A. W. Snel (MSc) is a Doctoral Student at Utrecht University. She has a background in anthropology and spatial planning. She was Project Officer on the JPI Urban Europe ENSUF project FLOODLABEL. Her research interests are urban planning, resilience and sustainability, flood risk management, and climate governance. She is currently finalising her doctoral dissertation on residents' involvement in flood risk governance.

Stan C. M. Geertman (PhD) is Professor of Planning Support Science and Chair of Spatial Planning at Utrecht University. He has published widely in both national and international journals and has published a range of (editorial) books. He is Editor of the international peer-reviewed journal *ASAP/Journal* and Member of the editorial board of several other scientific journals. He has been a member of several international conference organisations. He was principal investigator of the JPI Urban Europe ENSUF project FLOODLABEL.

COGITATIO

Urban Planning (ISSN: 2183–7635)
2021, Volume 6, Issue 3, Pages 295–305
https://doi.org/10.17645/up.v6i3.4044

Article

Landscape as a Potential Key Concept in Urban Environmental Planning: The Case of Poland

Aleksandra Sas-Bojarska

Department of Urban and Regional Planning, Faculty of Architecture, Gdańsk University of Technology, Poland;
E-Mail: asasbo@pg.edu.pl

Submitted: 21 January 2021 | Accepted: 20 May 2021 | Published: 19 August 2021

Abstract

Rapid urban development increases the consumption of materials, energy, and water, resulting in an overproduction of waste and emissions. These cause many environmental threats, such as ozone layer depletion and rain acidification, leading to climate change. Therefore, the question arises on how to improve the effectiveness of tools that strengthen environmental protection. This discursive article presents an approach stressing the role of landscape in environmental protection in Poland. It indicates that landscape protection is an ecological, not just an aesthetic activity, as it is often considered in Poland. The landscape reflects all changes occurring in individual elements of the environment resulting from urban development. Through landscape transformations, one can track the growth and accumulation of adverse effects in the chain of environmental changes. Knowledge regarding the dynamics and scope of these transformations can improve ecological design and technologies. Therefore, the landscape condition should be treated as an indicator of sustainable development. If so, one could hypothesise that effective landscape protection contributes to minimising environmental and climate changes. The relationships between the landscape and environmental/climate threats discussed in this article prompt combining some tools related to these threats, which may ensure both effective landscape protection and sustainable development, leading to reduced climate change. The possibilities and benefits of integrating these tools are presented here as well. General considerations are supplemented with references to the situation in Poland to support the need for implementing a more policy-oriented and interdisciplinary approach to landscape protection.

Keywords

climate change; combining tools; environmental impacts; landscape protection; Poland; urban development

Issue

This article is part of the issue “Smart Urban Governance for Climate Change Adaptation” edited by Thomas Thaler (University of Natural Resources and Life Sciences, Austria), Patrick Witte (Utrecht University, The Netherlands), Thomas Hartmann (TU Dortmund University, Germany) and Stan Geertman (Utrecht University, The Netherlands).

1. Introduction

The sustainable design of urban structures is related to many factors. Among them, the energy aspect (zero-energy buildings, energy efficiency), strongly associated with preventing the depletion of natural resources and the greenhouse effect, is currently one of the most important issues. Other factors include zero-waste development, saving materials, water and land as non-renewable goods, and recycling. Numerous procedures are used to solve sustainable design problems: strategic environmental assessment (SEA) and environmental impact assessment (EIA), including landscape and visual impact assessment (LVIA), together forming an environmental assessment (EA) system; life cycle assessment (LCA); material flow analysis (MFA); and many more. They all strive to support the design and decision-making process in terms of reducing adverse environmental effects. Their use is especially true for the dramatic climate change and an urgent need to stop it. The Polish situation serves as an example of serious environmental and landscape threats resulting from excessive investment pressure and a weak legal system of environmental protection, leading to enormous climate change in some regions.

If we consider saving energy, minimising the use of resources, and limiting the amount of waste and supporting environmental protection crucial to pro-ecological planning, it is equally legitimate to state that landscape protection should also be included in it. Although it does not bring measurable and direct effects, it may be considered a sustainable development indicator. Increasing investment pressure and excessive natural resource consumption may cause various changes to individual elements of the environment and the environment as a system, leading to noticeable impacts on the landscape, sometimes shifted in time and space, e.g., desertification, flooding, and changes in vegetation.

The author attempts to answer the questions of why landscape degradation occurs, how it is related to climate change, how to minimise, reduce, or prevent it, and what is the role of landscape in environmental protection, emphasising that the lack of a broad, integrated approach to landscape in investment processes is a symptom of a fragmentary treatment of the environment which results in a weakening of its protection and consequently landscape degradation and ultimately climate change. The aim is to open a discussion at a local (Polish) and international scale on enhancing landscape protection by combining existing tools in a holistic approach.

Several methods have been employed to highlight mentioned problems: literature studies; critical review of existing tools for preventing environmental threats; analysis of Poland’s planning context; formulating new hypotheses about combining presented tools; diagrammatic representation of such integration; review of EIA reports; and outlining the directions for future research. In summary, a kind of “abductive” approach is presented to discover new relationships and connections, aiming to develop a theory of environmental and landscape protection (for more on different research approaches see Dubois & Gadde, 2002).

In Section 2, arguments and tools for applying a landscape approach in environmental planning are given, taking current planning in Poland as an example of this need. In Section 3, several tools for landscape-based planning are presented. Prospects and potentials for integrating these tools in practical planning are the topic of Section 4, followed by Section 5, where the landscape approach to environmental planning is illustrated by systematic reference to the Polish planning situation, including a reflection on the need for further research. In the final section (Conclusions), the arguments favouring a landscape approach in planning for the environment and reducing climate change are summarised.

2. Landscape and Climate Changes: Relations

The relationship between landscape and climate changes is not obvious. However, understanding the nature of the landscape and the cause-and-effect chain leading to landscape changes can help understand how climate changes are linked to landscape degradation.

2.1. The Essence of the Landscape

According to the European Landscape Convention (Council of Europe, 2000, p. 2), the landscape is “an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors.” This definition emphasises landscape dynamics and its variability resulting from the interaction between natural and anthropogenic factors. A similar understanding of landscape was presented in connection with the emergence of the EA system in Europe:

> Landscape is the result of interdependencies between physical and biological elements and cultural heritage. It includes not only the physical features of terrain and land cover, but also the way these features are perceived, and the value that people give to space. (Department of the Environment, Planning Research Programme, 1995, p. 107)

The landscape covers all physical elements of natural and anthropogenic origins, created not only by physical structures but also by the relations between them and immaterial assets.

2.2. Landscape and Climate Changes: Effects of Environmental Damage

Inextricably linked to urban development, every architecture and engineering object needs to be erected, operated, and maintained. The final stage is demolition and material recycling or storage. All of these phases cause material and energy flows. These flows are discharged to valuable products, such as housing estates. However, at some stages of products’ lifetime, they become waste or are emitted as pollutants into the environment (Li et al., 2016). Therefore, they directly influence the environment. Finally, they accelerate climate change and have different impacts on the landscape.

New objects have a different character, scale and layout, shape, dimensions and textures; occupy different spaces; and are built of various materials. Some emit noise, lighting, gases, dust, water vapour, sewage, and solid waste, and others emit heat, radiation, and vibrations, causing different environmental effects at various stages of their life cycle (construction, functioning, liquidation).

The production of building materials requires the extraction of natural resources and their transport and processing, which often results in landscape destruction—directly or indirectly—through the pollution of the atmosphere. Moreover, all of these activities demand a significant amount of energy, the production of which leads directly to climate change and landscape impacts, such as opencast lignite mines or air pollination from coal storage sites.

During the construction stage, activities changing the environment, landscape, and climate are in progress. For example, construction equipment causes noise and atmospheric emissions. As a result, there is a deterioration in air quality and dust deposition on plants and objects, which negatively influence the landscape. Some changes, such as tree felling, can be repaired, e.g., with new plantings. We call these effects reversible. However, sometimes the change is irreversible, e.g., changes in terrain, separation of the unity of natural systems or landscape systems, breaking aquifers, or the emergence of new engineering facilities—all of them negatively change the landscape.

Other types of environmental effects occur during the operation time, the longest stage of the object's life. The investment may cause noise and exhaust emissions, an increase in air pollution, sewage discharge, constant lighting, etc. It may impact the physical and mental health of exposed residents. After some time, renovations are necessary to extend the operation stage of the facility. Noise and emissions into the atmosphere may occur again, changing the landscape and the climate.

At the end comes the demolition of the facility, removal of materials, their reuse, recycling, and storage. Demolition works and transport of waste cause emission of noise, vibration, and dust, increasing air pollution. In addition, waste must be stored somewhere and thus takes up space, which is a non-renewable resource. These effects significantly reduce the quality of the landscape. And what is more dangerous, they lead to global climate change, which may cause global landscape destruction in a negative feedback loop, such as drastic devastation of regional ecosystems caused by drought.

The effects appearing in the environment and consequently in the landscape and climate can be classified by stages of the investment's lifetime, the scale of the object as well as the scale of changes, the reversibility of these changes, their durability or variability, duration, spatial extent, the possibilities of minimising them, and finally their source, which is crucial in avoiding and mitigating them. This diversity requires a comprehensive approach to studying and reducing them. Consequently, the disconnected use of specific prognostic methods does not bring satisfactory results, which can be seen in the scale of environmental and landscape damage and climate change.

2.3. Landscape Protection: Circumstances and Needs in Poland

The principles of landscape-related policies in Poland are outlined very generally in the National Development Strategy 2020 (Polish Council of Ministers, 2012) and more specific in the strategies of voivodeships (regions), districts, and communes concerning development. The National Development Strategy underlines the need to protect resources and environmental diversity and extrimily shortly highlights aspects of protecting the landscape. In addition, legal provisions regarding the landscape are included in regulations and planning documents at various levels: the concept of spatial development of the country, voivodeship spatial development plans, metropolitan plans, studies of conditions and directions of the spatial development of communes, local land use plans, and the provisions specifying the functioning of the EA system in Poland.

Despite the existence of extensive legal regulations concerning landscape protection in Poland, there are numerous reasons for landscape devastation:

- Formal and legal: defects, ineffectiveness, and lack of precision of legal regulations (Böhm, 2008; Giedych & Szumański, 2003; Górka, 2016); no integration of issues related to spatial planning, the environment, monuments, and landscape with socio-economic planning (Szulczewska, 2002); weak competencies of administrative services in the field of landscape protection; general nature of the provisions of laws and regulations regarding landscape (Chmielewski, 2013); individual approach to different elements of the environment by the law; inconsistent landscape policy (Lipińska, 2011).
- Economic and social: dynamics of new development; low level of space management; imitation of foreign patterns (Lipińska, 2011); misunderstanding of the idea of spatial planning in market economy conditions (Jędraszko, 2005; Świetlik, 2003); low level of public debate; short-term approach; omission of quality criteria in administrative procedures; marginalisation of the landscape; low landscape awareness (Górka, 2016).
- Insufficient use of existing tools in the decision-making processes in spatial/urban planning due to: organisational shortcomings of the system of environmental protection; underinvestment of this system; administrative staff competency shortages originating from the lack of a coherent system of teaching these tools at universities, among others (see Section 4.2).

Landscape protection is a broad and still topical issue in Poland because the landscape is frequently underestimated. In common opinion, it does not refer to sustainable development but only to its aesthetic aspect. The variety of "landscape" definitions and interpretations is not only a Polish issue. The landscape concept has multiple meanings, scales, and applications in a general and national context, e.g., the Swedish case described by Sandström and Hedfors (2018). Meanwhile, the previous section shows that both landscape and climate changes stem from environmental damage. Therefore, there is a need to implement methods that may support spatial planning because spatial planning is not effective enough to protect the environment, climate, and landscape.

3. Smart Tools Reducing Environmental, Landscape, and Climate Changes

The methods dedicated to landscape protection have been selected for further analysis. These are SEA, EIA, LVIA, and complementary tools, such as LCA and MFA, which together play an essential role in sustainable planning (Table 1). Combined, they check a multitude of different effects in the entire chain of environmental transformation resulting from development. Thereby, they relate to the landscape that reflects the accumulation of these changes.

SEA, EIA, LVIA, LCA, and MFA enable environmental threats, potentially caused by increasing development, to be minimised, but their goals and scope are different. Some of them are procedure-oriented and refer directly to environmental and landscape protection (SEA, EIA, LVIA), helping to make a balanced decision concerning future development. In contrast, others (LCA, MFA) support them as analytical tools focused on technical issues (see Supplementary File). But none of them—when treated separately—is sufficient to stop the increasing destruction of the environment and consequently protect landscape and climate.

Table 1. Tools reducing environmental and climate changes and their functions, advantages, and relationship to landscape.

Tool	Function	Advantages	Relationship to landscape
SEA	Delivering objective and detailed information on the project of strategic documents (policies, plans, programmes), environmental goals, endangered environment, potential environmental effects, mitigation measures and recommendations; mitigating environmental impacts at policy/planning level	Allowing open decision-making due to public participation; supporting and influencing policies, plans and programmes in sustainable development; improving EIA through considering economic, ecological and social aspects at a higher level; wider than in EIA scope of effects; showing alternative possibilities of achieving goals	Very general relationship to landscape and landscape changes resulting from project implementation; general guidance on the landscape at the national, regional or commune level; general references to other documents related to landscape
EIA	Delivering objective and detailed information on the planned harmful activity, endangered environmental resources and values, potential environmental impacts and the possibilities of their minimising; considering alternatives; mitigating environmental impacts at the local level	Allowing open decision-making due to public participation; enabling choices best for the environment; enabling balanced decisions; environmental protection; sustainable development; promoting ecological education	The landscape is one of many issues; direct or indirect relationship to landscape; general or specific guidance related to the landscape at different scales
LVIA	Assessing and mitigating landscape impacts at the local/regional level within EIA; presenting visual problems in a way understandable for recipients	Creating landscape framework for governance arrangements and planning policies in terms of spatial planning	Directly related to the landscape; specific and detailed guidance related to landscape shaping and protecting
LCA	Assessing environmental impacts connected with products and activities based on analysing product lifetime; selection of environmentally friendly materials and technologies	Enhancing EIA at different stages; minimising waste production and resource consumption; enabling energy efficiency; reducing greenhouse gas emissions	Indirectly related to the landscape—only by combining with other tools; no direct guidance related to the landscape
MFA	Identification of inefficiencies in the use of resources; prediction of the future natural resources and energy demand and possible environmental impacts of a development	Studying and limiting the demand for materials and energy arising from development; supporting decision-making related to environmental, resource- and water-quality management	Indirectly related to the landscape—only by combining with other tools; no direct guidance related to the landscape

Note: Based on the information available in the Supplementary File.

4. Integration of Tools: Perspectives and Possibilities

At each stage of the investment lifetime, the potential environmental effects resulting from implementing the concepts, strategies, policies, plans, spatial development plans, and projects should be examined using SEA, EIA, LVIA, LCA, and MFA. But they are not always used according to their role and capabilities. They are usually not treated as a complementary system but used individually at various stages of the product's lifetime. However, they have the potential to be used comprehensively and systemically to minimise environmental damage and consequently climate change.

4.1. Benefits of SEA, EIA, LVIA, LCA, and MFA Integration

Due to the complexity of the problems to be solved, researchers emphasise the need to integrate various methods related to decision-making processes connected with development. The merits of combining MFA and LCA have been proven to help evaluate and implement sustainable development and support decision-making (Brunner & Rechberger, 2004; Guaita et al., 2018; Westin et al., 2019), and predict material flows and environmental benefits of the recycling chain, such as natural resource savings (de Meester et al., 2019). Consolidation of LCA and MFA may improve effective decision-making, leading to a halt in negative trends and introducing environmentally friendly technologies. LCA and MFA help understand the importance of reducing raw material consumption, energy use, quantities of waste, and CO_2 emissions by recycling, eco-technologies and prolonging the lifetime of buildings. Despite this, in some countries, there is a lack of connection between LCA and MFA. Although MFA can measure the material flows in and out of the system, it cannot assess the environmental consequences of the emission of this flow, which can be achieved using LCA (Guaita et al., 2018).

According to some researchers, the role of LCA may be much broader. Among few other tools, LCA may enhance the SEA by identifying and modelling environmental changes (Finnveden et al., 2003). The assessment of environmental impacts in SEA is generally based on qualitative descriptions and general statements, lacking analytical methods (Geneletti, 2015). Therefore, combining SEA with LCA and MFA may enrich quantitative research, increasing the effectiveness of environmental prognoses.

LCA can enhance EIA because regional and global effects can be considered thanks to LCA, in contrast to EIA (Manuinova et al., 2009). The use of LCA during a few critical stages of EIA may provide broader knowledge on the environmental effects of planned activities (considering the global aspects) compared to using EIA alone (Larrey-Lassalle et al., 2017). Scoping (impact identification), environmental impact assessment and indicating mitigation measures are crucial stages in EIA. At the scoping stage, LCA may help in the quantitative comparison of alternatives. During the impact assessment, LCA may provide quality assessment connected with the life cycle. Methods used under LCA may apply to EIA to increase the accuracy and detail of EAs (Manuinova et al., 2009). Companies rarely use LCA as a costly and time-consuming method, so simplified EA methods are recommended (Zafeirakopoulos & Genevois, 2015). The combination of EIA and LCA can be used for this purpose, focusing only on the most significant potential environmental impacts.

The new proposal for the advanced integration of EIA and LCA systems is based on practical research. Until now, only theoretical considerations on this topic could be found in the literature, with EIA and LCA systems combined only in a fragmentary way. The described approach aims to use all of the benefits of LCA in the comprehensive procedure, indicating specific EIA stages to use LCA and proposing a recommended methodology for this integration. It has been proven that in most EIA procedures not supported by LCA, the environmental effects of all technologies are not studied, and indirect and off-site impacts are not included. It has been stated that using LCA within EIA could help to analyse global effects, such as resource and ozone depletionand climate change (Larrey-Lassalle et al., 2017).

The benefits of supplementing EIA with LCA relate to Directive 2014/52/EU, which underlines the need to consider the broader catalogue of environmental effects associated with the depletion of natural resources, climate change, energy, and human health (Larrey-Lassalle et al., 2017). LCA allows the evaluation of more holistic environmental problems than EIA. Still, on the other hand, it does not apply to local conditions and interference, which is the function of EIA (Larrey-Lassalle et al., 2017). As a support tool for EIA, MFA has been described using the example of chosen case studies (Brunner & Rechberger, 2004).

Comprehensive analysis of many tools for land use impact assessment, including among others MFA, LCA, EIA, SEA, and ecological footprint (EF) described in 60 articles (chosen from 187), showed their most common combination: LCA and MFA—10 examples; LCA and EF—10; MFA and EF—7; EIA and EF—2; EIA and MFA—1 (Perminova et al., 2016). But no combination of all these tools has been found in this review. Perminova et al. (2016) recommended combining various methods and different aspects of each method, but neither the use of LVIA procedure nor the references to the landscape were suggested.

4.2. The Need for SEA, EIA, LVIA, LCA, and MFA Integration in Poland

Although SEA, EIA, LVIA, LCA, and MFA are known and used in Poland, their functioning is not related to each-other. The level of implementation of the idea of a circular economy, which should cover all lifetime cycles, is still unsatisfactory in Poland (Polish Council of Ministers, 2019). Legal regulations do not require combining LCA and MFA with EA. They are used separately. The information obtained during EA studies is not connected with the material flow; therefore, data concerning construction materials or energy consumption during its whole lifetime are not included.

The EA system is not consistent either. SEAs of strategies and planning documents often strongly depend on political goals; therefore, environmental protection plays a minor role. SEA and EIA do not create a complementary system. Various types of strategic documents or planned activities and the accompanying SEA, EIA, and LVIA are subject to the opinion and approval of many institutions at various government and local administration levels, which results in ambiguities in competencies and responsibilities. Moreover, governmental and local administrations are often guided by different priorities in matters of environmental protection, which makes it difficult to use the potential of tools to make balanced administrative decisions. Only EIAs of great controversial activities are bound with SEA.

In general, SEA in Poland at the lowest levels (concerning local land use plans and studies of conditions and directions of the spatial development of communes) is rarely used for the management of urban areas in the context of spatial planning. The guidances from such SEAs are usually very general. They contain recommendations to be detailed only at the next stage—assessments of planned activities during the EIA procedures. Moreover, the most commonly used SEAs in Poland concern local land use plans, which are small-scale and fragmentary and make it impossible to assess cumulative, long-term and secondary impacts. Avoiding them is possible only at the higher levels of environmental planning, i.e., the stage of creating regional plans, policies, and programmes.

The situation is different for SEA of strategic documents, e.g., the National Road Construction Program (Polish Council of Ministers, 2015) or Voivodeship Development Strategies, because their implementation in the future will involve possible co-financing from EU funds. In such cases, before the grant is awarded, it will be checked if a specific activity has been included in the strategic document together with the SEA. That is why SEAs are and will be so crucial for decision-makers and beneficiaries applying for funding. Furthermore, recommendations from SEAs are essential for administrative bodies adopting strategic documents at the national and regional level. The example from the Pomeranian Voivodeship is perfect. SEA related to the project of the Pomeranian Voivodeship Development Strategy 2030 (Pomeranian Voivodeship, 2020), contains, e.g., mitigation measures and recommendations concerning landscape and cultural landscape. Under the influence of the recommendations, the project of the Pomeranian Voivodeship Development Strategy 2030 (Pomeranian Voivodeship, 2021), was significantly revised. Following public participation consultations, Pomeranian Voivodeship Development Strategy 2030 was then, along with SEA, agreed with all relevant institutions almost without any reservations, which means that, in this case, SEA significantly influenced the arrangements for the management of the voivodeship in the context of spatial planning.

The EIA procedure in Poland is carried out at an early stage of investment planning, when neither the investor nor experts have sufficient knowledge about all potential environmental effects. Therefore, the EIA reports are somewhat general, making it impossible to mitigate adverse effects, including landscape effects, adequately. Usually, the analysis of impacts on various environmental elements is carried out independently by the experts. Consequently, the synergistic and cumulative effects are not taken into account. In addition, investors sometimes consider EIA a burdensome but necessary formality that can be completed by operating in the grey area of regulations.

Landscape in EIA, dominated by technical and ecological specialities, is considered the least important element of the environment. The landscape is sometimes regarded only in geographical or aesthetic terms. This approach stems from the definition of landscape in Polish law (Sejm, 2015), which does not underline relationships and interactions of natural and cultural factors. Therefore, the landscape is seen as an isolated element of the environment, directly related to the visual aspects, without showing a clear correlation with effects occurring in other elements of the environment (Lipińska, 2011; Sas-Bojarska, 2017), which limits the effectiveness of mitigation measures. As a result, the potential of LVIA is used to a small extent. It is not the landscape values that are an argument against the implementation of controversial activities but the geographic and natural aspects (especially the Natura 2000, which concerns the most valuable and threatened species and habitats listed in the Birds Directive and the Habitats Directive) and economic and social aspects. Supporting tools, such as LCA and MFA, are practically not considered when making planning decisions. All this undermines landscape protection.

All of the above shortcomings prevent the potential of the described tools from being fully used, which results in a lack of coherent planning of sustainable development in Poland, especially concerning landscape and climate changes.

4.3. Conclusions From the Integration

SEA, EIA, LVIA, LCA, and MFA have great potential for the implementation of sustainable development, although their goals, methodologies, scope, and merits differ. In protecting the environment, they can also preserve its general image, i.e., the landscape. Large-scale activities, especially those consuming a tremendous amount of energy and water, and causing emissions and waste, require interacting tools.

The benefits briefly outlined indicate that SEA, EIA, LVIA, LCA, and MFA should be used together to assess environmental impacts in terms of various stages of the lifecycle, spatial scope (local, regional, global), magnitude, and significance (the shortcomings and need to broaden the scope of impact significance are underlined in Lawrence, 2007). Only then can these impacts be effectively limited. Recommendations regarding development directions, related threats, and possibilities of mitigating them resulting from interacting procedures should be used not only in assessing a specific investment but also more broadly when creating spatial policy principles. Emphasising the importance of the landscape issues both at wider and local scales can contribute to greater involvement in environmental actions at the local level, which is the most effective. The potential of these combined tools indicates that in-depth research should be undertaken to strengthen bridging ideas and improve the effectiveness in environmental, landscape and climate protection, which is a crucial issue, especially in Poland.

5. Towards Sustainability: Combining Tools in Landscape Impact Assessment

This new approach to increasing the effectiveness of landscape protection is based on combining a few existing methods (SEA, EIA, LVIA, LCA and MFA), which have only been used separately in Poland until now. This improvement is based on the notion that only the enhancement of the role of the landscape in investment processes through simultaneous use of different tools related to the landscape can enable adequate prediction and minimisation of changes in the landscape and environment and consequently mitigate climate change.

5.1. Landscape: The Image of Relationships

The suggested approach of considering all interrelations between individual elements of the environment, and the effects appearing in them, becomes possible thanks to various methods supporting landscape impact assessment. Only cooperation of the experts from many fields can ensure comprehensive prediction of landscape changes and consequently its successful protection. Figure 1 shows the multitude of dependencies to be considered and, although difficult to analyse, offers a perspective on the complexity of the subject matter as opposed to the current, often overly simplistic, practice based on separate studies in specific elements of the environment.

The landscape is treated here not only as a separate component of the environment, but it becomes the synthesis of all environmental research because it is the final recipient of the accumulation of effects appearing in subsequent elements of the environment and the environment as a whole. It reflects both direct changes caused by the implementation and functioning of the activity and indirect, cumulative and synergistic effects and dynamic interactions, emerging at various stages of the investment lifetime. Such an approach refers to the European Landscape Convention presenting the

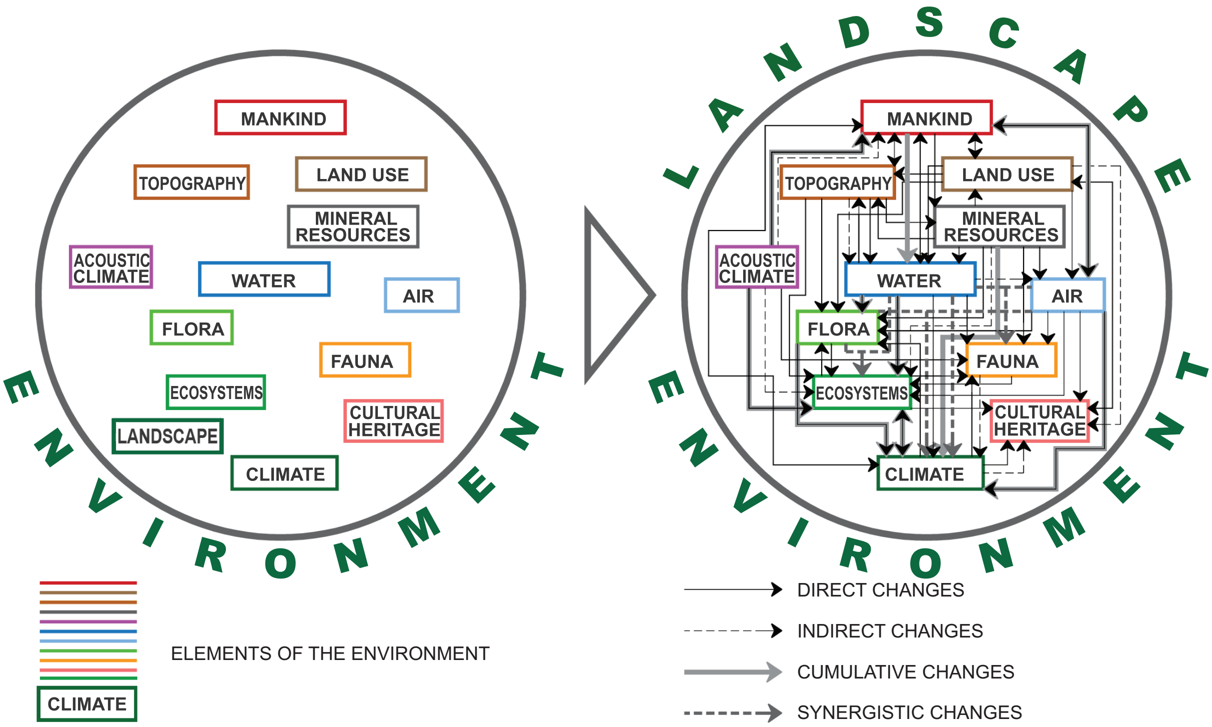


Figure 1. Linking studies in EIA. Current practice in Poland: Landscape as a separated element of the environment. Recommended approach: Landscape as the indicator of changes in different elements of the environment.

landscape, according to Sandström and Hedfors (2018), as a general matrix of the planning arena of different interacting systems, bridging sectorial initiatives. In sum, the landscape is considered a medium connecting all prognoses, a reference point for other environmental studies. Thus, the effectiveness of predictions of landscape change increases, enhancing the possibilities of mitigating adverse impacts, which is imperative in light of the growing social role of the landscape. Fortin and Gagnon (2006) underline the importance of considering the values and expectations of local residents and actors affected by the project. Taking into account the landscape meanings may, in their opinion, enrich formal practices associated with EIA and regional planning. A great number of mandatory and voluntary integration tools promote more integrated policies, planning, and practices (such as EIAs and SEAs). Still, their implementation is usually insufficient, so further research is recommended (Runhaar, 2016). The presented approach may be regarded as a modest contribution towards this recommendation, not only in Poland.

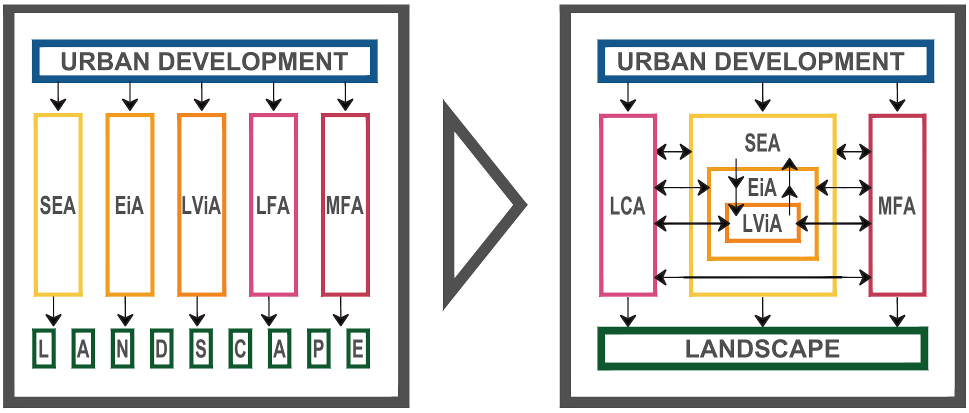
5.2. Introducing the Landscape Approach to the Polish Environmental Planning Practice

Because the current practice of environmental studies in Poland is based on the separate use of different methods, one could conclude that some procedures, such as SEA, EIA, LVIA, LCA and MFA, should be integrated (Figure 2).

When used together, these methods make it possible to improve the LVIA effectiveness, thereby increasing the effectiveness of landscape protection in spatial management and development. This is recommended especially in complex cases, where the interrelationships between various effects in specific elements of the environment make it difficult to forecast changes in the landscape. Moreover, it somewhat replaces the lack of standards in assessing the significance of landscape impacts. However, standardisation, perceived as beneficial in EIA, is still a challenging task (Fonseca et al., 2020).

In the recommended approach, the landscape becomes a leading aspect in EIA/LVIA, supported by SEA, LCA, and MFA, and can thus have a significant impact on planning decisions. Obligatory considerations of the landscape when forecasting any environmental effects require integrating information from various fields and studies and assessing cause–effect relationships, leading to cumulative and synergistic effects. This approach increases the effectiveness of forecasting changes in the environment as a complex system, reduces the uncertainties associated with prognosis, and enables the identification of irreversible and unacceptable effects. There is a positive feedback loop between environmental protection and landscape protection—when the environment is protected effectively, the landscape is protected effectively and vice versa. Such complementarity of protection should influence the current governance arrangements in terms of urban and spatial planning. As a consequence, minimising environmental and landscape impacts will become more effective, thus reducing climate change.

The key challenge with practically implementing the recommendation of combining SEA, EIA, LVIA, LCA, and MFA is incentivising the stakeholders to follow this framework, disregarding it might be time-consuming and economically inefficient for the investors. Furthermore, the idea for integrating presented tools is so far more hypothetical than actually concrete and measurable for evaluation. Therefore, this hypothesis requires confirmation in detailed studies. Without them, it cannot be verified. Referring to the conclusions from Section 4.1, a proposed procedure for examining EIA reports concerning the landscape is presented below. The reference to the landscape is considered crucial because the landscape impact prediction, at least in Poland, is still not connected well enough with other studies. The difficulties in finding useful tools for analysing effects on landscapes in SEA have been recognised (Finnveden et al., 2003). EIA/LVIA also require finding supporting tools. LCA and MFA could fill this gap.



CURRENT PRACTICE — SEPARATE STUDIES

NEW APPROACH — INTEGRATED STUDIES

Figure 2. Integration of tools: The recommended holistic approach to landscape protection.

5.3. Further Research

The proposed study intends to show if and to what extent different tools are practically combined in EIA procedures and indicate the impact of such combinations on the environment and landscape. The methodology of further research presented below is universal, but its creation relates to Polish conditions. A review of 79 randomly selected EIA reports from various years (1993–2018), related to 11 voivodeships in Poland and concerning controversial investments of different character (large-scale objects, linear infrastructural structures, and large-area activities), showed that none referred to LCA or MFA. This finding indicates that the integration of these procedures is not practised in Poland.

Because it was found that conducting an EIA requires additional tools, and all studies should relate to the landscape, the recommended course of action is shown below.

The proposed study aims to enable the assessment and validation of the new approach by answering the following questions after analysing a sample of EIA reports and related procedures:

The first phase—checking the content of EIA reports:

- Is there a reference to SEA in the EIA report? Are any conclusions from SEA related to landscape? Are they included in the EIA report?
- Is there a reference to landscape in the EIA report? Was LVIA performed? What percentage of the content relates to the landscape? Did the predicted landscape threat influence the conclusions of the report?
- Is there a reference to LCA/MFA in the report? If so, is there a reference to landscape in the LCA/MFA chapter? What percentage of the content does it take up? Did it affect the conclusions?
- What is the difference between EIA reports without LCA/MFA reference and reports with such reference in terms of the landscape? A comparison should be made.
- If there is no direct reference to the landscape in LCA/MFA chapters, a forecast must be made of what landscape changes will occur (such a study should be carried out by an architect/landscape architect based on LCA/MFA studies).

The second phase—analysis of the results of environmental audits:

- Was the monitoring and/or post-implementation environmental audit carried out? Did the audit somehow relate to the landscape? Did it show any damage to the landscape?
- What was the cause of landscape damage? Which environmental element's destruction influenced the changes in the landscape?
- What was the nature of the destruction of the landscape? Were these effects long-term, irreversible, significant, mitigable, unacceptable? Did they interfere with tourist activity? Did they cause social controversy?
- Would carrying out an LCA/MFA under the EIA indicate the possibility of landscape degradation? Any such relationship should be indicated.
- What are the actual changes in the landscape when conducting EIA using LCA/MFA? And without them? A comparison should be made.

It should be noted that the second phase may pose many difficulties because "the most critical condition seems to be the monitoring of how tools are used and what they achieve" (Runhaar, 2016, p. 7).

Recommended research should show if and to what extent it is possible to effectively predict landscape changes when combining SEA, EIA, LVIA, LCA and MFA. This methodology is intended to enable specific studies to confirm the presented hypothesis and evaluate the effectiveness of the proposed approach.

6. Conclusions

The world is facing rapidly growing urban development and industrialisation, causing irreversible environmental threats and leading to the most dangerous of all, i.e., climate change. That is why urgent actions are needed to stop these trends. In the context of the increasing complexity of socio-economic processes and uncertainty of their forecasting, it seems that one of the most effective tools for implementing sustainable development is the EA system applied to all levels of human activity (local, regional, global), including various spheres—natural, socio-cultural, visual, and technical. It enables a multi-criteria assessment of planning/design solutions and the choice of better alternatives for the environment. However, it is only in cooperation with instruments such as LCA and MFA that an opportunity to prevent damage to the environment at every stage of the lifetime of planned activities can be created. The key message of this article is that landscape protection in investment processes is part of pro-ecological and not just aesthetic activities because the effects on the landscape arising from the development reflect the changes in all elements of the environment. Therefore, understanding the relationships between the environmental effects and the landscape can contribute, especially in Poland, to improving the use of tools supporting spatial planning, such as EA, LCA, and MFA.

In Poland, there are well-developed tools for protecting the environment and landscape (e.g., the EA system), but their functioning is not satisfactory. The use of tools such as SEA, EIA, LVIA, LCA, and MFA depends largely on the efficiency of the environmental management system. This system in Poland is poorly organised and ineffective. Therefore, the potential of the described tools is not fully unlocked, aggravating spatial chaos and environmental and landscape degradation. Moreover, issues related to the landscape have a low rank in local, regional, and national administration policies and activities. Landscape protection tends to fail when confronted with social or economic arguments. All this leads to the progressive degradation of the landscape. Therefore, it is necessary to strengthen the role of landscape criteria in decision-making processes. There is an opportunity to link the landscape problems more closely with the environmental and climate issues, which have already gained significant importance in the world. This can be achieved by combining the described tools to better forecast the unfavourable effects of development processes. Such an approach shows that the protection of the landscape, i.e., the synthesis of the environment, can at the same time positively influence the reduction of climate change. Further detailed research, necessary to confirm this hypothesis, is yet to be adequately tested in practice.

Acknowledgments

The author is grateful for the exceptionally valuable comments from the reviewers and editors. Furthermore, the author would like to thank M. Kiejzik-Głowińska of *EKO-PERSPEKTYWA* for collecting EIA reports for this study and her comments; M. Bednarska, the author of SEA related to the Project of the Pomeranian Voivodeship Development Strategy 2030 of the Pomeranian Regional Planning Office; and A. Tyszecki, the EA consultant, for their constructive remarks concerning the Polish EA system.

Conflict of Interests

The author declares no conflict of interests.

Supplementary Material

Supplementary material for this article is available online in the format provided by the author (unedited).

References

Böhm, A. (2008). Skuteczność istniejących w Polsce instrumentów prawnych [The effectiveness of existing legal instruments in Poland]. *Czasopismo Techniczne*, *1*(A), 137–146.

Brunner, P. B., & Rechberger, H. (2004). *Practical handbook of material flow analysis.* Lewis Publishers, CRC Press.

Chmielewski, T. J. (2013). *Systemy krajobrazowe. Struktura—funkcjonowanie—planowanie* [Landscape systems. Structure—functioning—planning]. PWN Scientific Publishing House.

Council of Europe. (2000). *European Landscape Convention* (European treaty series, No. 176). https://rm.coe.int/1680080621

de Meester, S., Nachtergaele, P., Debaveye, S., Vos, P., & Dewul, J. (2019). Using material flow analysis and life cycle assessment in decision support: Case study on WEEE valorization in Belgium. *Resources, Conservation & Recycling*, *142*, 1–9. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Department of the Environment, Planning Research Programme. (1995). *Preparation of environmental statements for planning projects that require environmental assessment*: *A good practice guide*. HMSO Publications Centre.

Dubois, A., & Gadde, L.-E. (2002). Systematic combining: An abductive approach to case research. *Journal of Business Research*, *55*, 553–560. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Finnveden, G., Nilsson, M., Johansson, J., Persson, Å., Moberg, Å., & Carlsson, T. (2003). Strategic environmental assessment methodologies—Applications within the energy sector. *Environmental Impact Assessment Review*, *23*, 91–123. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Fonseca, A., de Brito, L. L., & Gibson, R. B. (2020). Methodological pluralism in environmental impact prediction and significance evaluation: A case for standardization? *Environmental Impact Assessment Review*, *80*, 1–9. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Fortin, M., & Gagnon, C. (2006). Interpreting major industrial landscapes: Social follow-up on meanings, the case of two aluminium smelters, Alcan (Alma, Canada) and Pechiney (Dunkirk, France). *Environmental Impact Assessment Review*, *26*, 725–745. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Geneletti, D. (2015). Research in strategic environmental assessment needs to better address analytical methods. *Journal of Environmental Assessment Policy and Management*, *17*(1), 1–7. http://dx.doi.org/10.1142/S1464333215500143

Giedych, R., & Szumański, M. (2003). Krajobraz w systemie planowania przestrzennego [Landscape in the spatial planning system]. *Urbanista*, *7*, 18–22.

Górka, A. (2016). *Krajobrazowy wymiar ruralistyki* [The landscape dimension of ruralism]. Gdańsk University of Technology Publisher.

Guaita, F. G., García, S. G., Villanueva-Rey, P., Moreira, M. T., & Feijoo, G. (2018). Integrating urban metabolism, material flow analysis and life cycle assessment in the environmental evaluation of Santiago de Compostela. *Sustainable Cities and Society*, *40*, 569–580. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Jędraszko, A. (2005). *Zagospodarowanie przestrzenne w Polsce—drogi i bezdroża regulacji ustawowych* [Spatial development in Poland—Ways and sideways of statutory regulations]. Union of Metropolises of Polish Cities.

Larrey-Lassalle, P., Catel, L., Roux, P., Rosenbaum, R. K., Lopez-Ferber, M., Junqua, G., & Loiseau, E. (2017). An innovative implementation of LCA within the EIA procedure: Lessons learned from two wastewater treatment plant case studies. *Environmental Impact*

Assessment Review, *63*, 95–106. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Lawrence, D. P. (2007). Impact significance determination—Pushing the boundaries. *Environmental Impact Assessment Review*, *27*, 770–788. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Li, Y., Beeton, R. J. S., Halog, A., & Sigler, T. (2016). Evaluating urban sustainability potential based on material flow analysis of inputs and outputs: A case study in Jinchang City, China. *Resources, Conservation & Recycling*, *110*, 87–98. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Lipińska, B. (2011). *Ochrona dziedzictwa kulturowego. Ujęcie krajobrazowe* [Protection of cultural heritage. Landscape perspective]. Gdańsk University of Technology Publisher.

Manuinova, A., Suebsiri, J., & Wilson, M. (2009). Should life cycle assessment be part of the environmental impact assessment? Case study: EIA of CO2 capture and storage in Canada. *Energy Procedia*, *1*, 4511–4518. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Perminova, T., Sirina, N., Laratte, B., Baranovskaya, N., & Rikhvanov, L. (2016). Methods for land use impact assessment: A review. *Environmental Impact Assessment Review*, *60*, 64–74. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Polish Council of Ministers. (2012). *Strategia Rozwoju Kraju 2020* [National development strategy 2020] (Polish Monitor, item 882, Resolution No. 157 of the Council of Ministers of September 25, 2012).

Polish Council of Ministers. (2015). *Program Budowy Dróg Krajowych na lata 2014-2023 (z perspektywą do 2025 r.*) [National road construction program for 2014–2023 (with perspective until 2025)]. https://www.gov.pl/web/infrastruktura/program-budowy-drog-krajowych-na-lata-2014-2023-z-perspektywa-do-2025-r

Polish Council of Ministers. (2019). *Polityka ekologiczna państwa 2030—strategia rozwoju w obszarze środowiska i gospodarki wodnej* [*National ecological policy 2030—Development strategy in the area of environment and water management*].

Pomeranian Voivodeship. (2020). *Prognoza oddziaływania na środowisko projektu Strategii Rozwoju Województwa Pomorskiego 2030* [SEA related to the project of the Pomeranian Voivodeship development strategy 2030]. https://strategia2030.pomorskie.eu/-/konsultacje-projektu-strategii-rozwoju-wojewodztwa-pomorskiego-2030-w-ramach-strategicznej-oceny-oddzialywania-na-srodowisko

Pomeranian Voivodeship. (2021). *Strategia Rozwoju Województwa Pomorskiego 2030* [Pomeranian Voivodeship development strategy 2030]. https://strategia2030.pomorskie.eu/-/uzasadnienie-i-podsumowanie-do-strategii-rozwoju-wojewodztwa-pomorskiego-2030

Runhaar, H. (2016). Tools for integrating environmental objectives into policy and practice: What works where? *Environmental Impact Assessment Review*, *59*, 1–9. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Sandström, U. G., & Hedfors, P. (2018). Uses of the word ‘landskap’ in Swedish municipalities’ comprehensive plans: Does the European Landscape Convention require a modified understanding? *Land Use Policy*, *70*, 52–62. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Sas-Bojarska, A. (2017). *Wielkie inwestycje w kontekście zagrożeń i ochrony krajobrazu* [Big-scale activities in the context of landscape threats and protection]. Gdańsk University of Technology Publisher.

Sejm. (2015). *Ustawa z dnia 24 kwietnia 2015 r. o zmianie niektórych ustaw w związku ze wzmocnieniem narzędzi ochrony krajobrazu, Dz.U. 2015 poz. 774* [Act of 24 April 2015 on amending certain acts in connection with the strengthening of landscape protection tools, Journal of Laws of 10 June 2015. Art. 774].

Szulczewska, B. (2002). *Teoria ekosystemu w koncepcjach rozwoju miast* [Ecosystem theory in urban development concepts]. SGGW Publisher.

Świetlik, M. (2003). Planowanie przestrzenne versus ekonomia [Spatial planning versus economics]. *Urbanista*, *9*, 34–38.

Westin, A. L., Kamykova, Y., Rosado, L., Oloveira, F., Laurenti, R., & Rydberg, T. (2019). Combining material flow analysis with life cycle assessment to identify environmental hotspots of urban consumption. *Journal of Cleaner Production*, *226*, 526–539. https://pg.edu.pl/biblioteka-pg/alfabetycznie

Zafeirakopoulos, I. B., & Genevois, M. E. (2015). An analytic network process approach for the environmental aspect selection problem—A case study for a hand blender. *Environmental Impact Assessment Review*, *54*, 101–109. https://pg.edu.pl/biblioteka-pg/alfabetycznie

About the Author

Aleksandra Sas-Bojarska is a Professor at the Department of Urban and Regional Planning, Faculty of Architecture, Gdańsk University of Technology, Poland. Her research efforts focus on sustainable development, revitalisation, landscape protection, EIA in urban planning, and LVIA methodology. She has participated in many EIA procedures concerning large-scale activities in urban and rural areas. In addition, she is an expert of the Pomeranian Voivodship’s Commission on Environmental Impact Assessment in Gdańsk, under the Regional Direction of Environmental Protection.

COGITATIO

Urban Planning (ISSN: 2183–7635)
2021, Volume 6, Issue 3, Pages 306–320
https://doi.org/10.17645/up.v6i3.4269

Article

Comparing Climate Impact Assessments for Rural Adaptation Planning in Germany and the Netherlands

Juliane Wright [1,]*, Johannes Flacke [2], Jörg Peter Schmitt [1], Jürgen Schultze [3] and Stefan Greiving [1]

[1] Faculty of Spatial Planning, TU Dortmund University, Germany; E-Mails: juliane.wright@tu-dortmund.de (J.W.), joerg.schmitt@tu-dortmund.de (J.P.S.), stefan.greiving@tu-dortmund.de (S.G.)
[2] Faculty of Geo-Information Science and Earth Observation, University of Twente, The Netherlands; E-Mail: j.flacke@utwente.nl
[3] Social Research Center, TU Dortmund University, Germany; E-Mail: juergen.schultze@tu-dortmund.de

* Corresponding author

Submitted: 15 March 2021 | Accepted: 17 June 2021 | Published: 19 August 2021

Abstract
The consensus nowadays is that there is a need to adapt to increasingly occurring climate impacts by means of adaptation plans. However, only a minority of European cities has an approved climate adaptation plan by now. To support stakeholder dialogue and decision-making processes in climate adaptation planning, a detailed spatial information and evidence base in terms of a climate impact assessment is needed. This article aims to compare the climate impact assessment done in the context of two regional climate change adaptation planning processes in a Dutch and a German region. To do so, a comparison of guidelines and handbooks, methodological approaches, available data, and resulting maps and products is conducted. Similarities and differences between the two approaches with a particular focus on the input and output of such analysis are identified and both processes are assessed using a set of previously defined quality criteria. Both studies apply a similar conceptualisation of climate impacts and focus strongly on issues concerning their visualisation and communication. At the same time, the methods of how climate impacts are calculated and mapped are quite different. The discussion and conclusion section highlights the need to systematically consider climatic and socio-economic changes when carrying out a climate impact assessment, to focus on a strong visualisation of results for different stakeholder groups, and to link the results to planning processes and especially funding opportunities.

Keywords
adaptation; climate change; Germany; impact assessment; stress test; the Netherlands

Issue
This article is part of the issue "Smart Urban Governance for Climate Change Adaptation" edited by Thomas Thaler (University of Natural Resources and Life Sciences, Austria), Patrick Witte (Utrecht University, The Netherlands), Thomas Hartmann (TU Dortmund University, Germany) and Stan Geertman (Utrecht University, The Netherlands).

1. Introduction

The need to adapt to increasingly occurring climate impacts by means of adaptation plans is more or less a consensus among scholars. However, so far only a minority of European cities has an approved climate adaptation plan. Reckien et al. (2018) found that only about 11% had a dedicated climate adaptation plan in 2018, with western European cities being better represented than eastern European cities. Aguiar et al. (2018) analysed that large cities can often fund the development of adaptation plans locally, while smaller and more rural municipalities depend on external funding and subsidies. The degree of the cities' vulnerability to climate change (Aguiar et al., 2018) is a driving factor, among others.

In line with that, scholars report a multitude of barriers affecting the development of climate adaptation plans (e.g., Archie et al., 2014; Runhaar et al., 2012). Biesbroek et al. (2013) distinguish, based on the fourth Intergovernmental Panel on Climate Change (IPCC) assessment report (Adger et al., 2007), institutional, social, informational, financial, and cognitive categories of barriers to adaptation. While institutional and social aspects, such as lack of political commitment or limited awareness of climate adaptation needs, are found to be key barriers to adaptation (Greiving & Fleischhauer, 2012), informational barriers, such as the lack of scientific knowledge on climate impacts and vulnerability, are hardly found to be important in empirical studies. However, Ford and King (2015) describe, for a region in Canada, that the existence of impact, vulnerability, and adaptation assessments is crucial for the adaptation readiness of the community, and Runhaar et al. (2012) report that the lack of insight into local impacts of climate change is making it difficult to translate climate change challenges to the local level.

We conclude that a detailed spatial information and evidence base in terms of a climate impact assessment is needed to stimulate adaptation planning (Greiving, 2019). However, it is not only the demand for more information that is important, but rather the quality of the information and how it is presented and made available. Hanger et al. (2013, p. 98) found in eight European countries the "need of policymakers at all stages of adaptation planning was not a lack of information but the need for better filtered and accessible information." Therefore, the "art in geovisualisation supporting climate change adaptation" (Neset et al., 2016, p. 3) is essential. In other words, besides the methods and data used for climate impact assessment, the way potential impacts are presented and communicated also determines its usability for adaptation planning. In science and practice, there are different definitions and methods for determining climate impacts. Therefore, this article aims at international comparative research, analysing two different analytic approaches in rural areas in the Netherlands and Germany, two neighbouring countries in central Europe, that face similar challenges in terms of climate adaptation.

This article investigates the research question of whether the two climate impact analyses serve to provide quantitative evidence supporting (regional, local, and individual) climate adaptation focussing on rural areas in Germany and the Netherlands. To answer the question, the following sub-questions will be discussed:

- What are the similarities and differences concerning the input and conduction of climate impact assessments?
- What are the similarities and differences concerning the output of the climate impact assessments?
- How can the quality of both methodologies be evaluated based on defined quality criteria?

2. Background

To discuss the differences of the named climate impact assessments, the term climate impact is defined as follows: Climate impacts result according to the IPCC (2014, p. 5) "from the interaction of climate-related hazards with the vulnerability and exposure of human and natural systems." Climate hazards, in this article referred as climate stressors, are extreme weather events such as flooding or extreme heat, while sensitivity refers to the presence of people, infrastructure or other assets in places and settings that are affected by the hazard, and vulnerability depicts their predisposition to be adversely affected, e.g., because of high sensitivity and a limited capacity to adapt to it. In this article, we will make use of the following terminology to distinguish the different components of a climate impact assessment. Climate stressors describe the potential effect of the changing climate on the system taking a spatial occurrence into account. Climate sensitivity describes the affected systems (e.g., economic sector, population group, ecosystems) due to their characteristics. Climate impacts describe the observed or potential effect of the climate (change) on the system, taking into account the corresponding sensitivity and climate stressors.

Assessment methods generally serve to inform evaluation processes with evidence. Accordingly, they consist of a factual model, a target system and a set of allocation and aggregation rules. Overall, there is no one-size-fits-all assessment method, but more or less appropriate procedures, whereby the appropriateness can only be judged in the individual case and by considering the given context, while it is undisputed that the chosen methodological approach must be consistent in itself (Faßbender, 2012). In science, there are different criteria to judge the different approaches. Whereas some criteria strongly focus on the technical conduction of the assessment (see Greiving, 2019; Scholles, 2005), others focus more on the overall process, stakeholder integration, communication, and visualisation (see Hanger et al., 2013; Neset et al., 2016).

Following Scholles (2005) and Greiving (2019), we consider the following criteria to be relevant concerning the conduction of climate impact assessments. It should be possible to carry out a climate impact assessment objectively, i.e., independently of the person conducting it. In other words, a repeated run of the assessment under the same contextual conditions should produce the same results. At the same time, individual cases must be treated according to uniform standards based on a politically legitimised target system and, if they are comparable, must also be treated equally. Both criteria—intersubjectivity and reliability–are only given when the climate impact assessments entail a high degree of standardisation. Furthermore, the process and result of the climate impact assessment need to be transparent and comprehensible for the decision maker, but also for those who are affected by these decisions (Greiving, 2019; Scholles, 2005).

Several studies have demonstrated that it is not only a matter of how a climate impact assessment is conducted but how it is communicated to policymakers

(Mabon, 2020; Neset et al., 2016). Particularly, the communication of the uncertainty of a climate impact assessment is of great importance (Hanger et al., 2013). Therefore, the tools used for their visualisation are essential. In 2016, Neset et al. developed four categories of tools, distinguishing between their data content and functionalities (Neset et al., 2016, p. 14). Accordingly, the categories differentiate between viewers with basic interactive functions and explorers with a high amount of interactive features and therefore more possibilities for the users. Also, they differentiate between the content, meaning climate data and impacts. Whereas some tools only contain information on climate data, others include information such as climate impacts, risk zones, and vulnerabilities. Namely, the four categories are: climate data viewers, impact viewers, climate data explorers, and impact explorers (Neset et al., 2016, p. 14). Moreover, Hanger et al. (2013, p. 92) especially emphasise the need for participation and dual accountability to cross the science-policy boundary.

3. Case Study

The location of the two case study areas is shown in Figure 1. The Dutch RIVUS region (RIVUS, 2021) is a cooperation of the cities of Zwolle and Deventer and six rather rural municipalities (Kampen, Zwartewaterland, Staphorst, Dalfsen, Raalte, and Olst-Wijhe) located to the west of the province of Overijssel. The seven German regions lie within the federal state of North Rhine-Westphalia (NRW). The seven regions are formal administrative counties consisting of different numbers (100 in total) of municipalities and responsible for governing environmental issues including climate change challenges and required response actions. In the following, these regions will be referred to as Evolving Regions (ER). As both regions are rather vulnerable concerning heat and too much as well as too little water and both have a rather rural character, a comparison is possible.

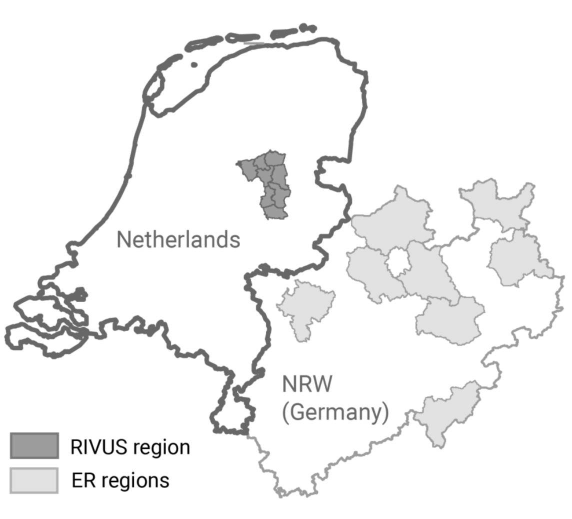


Figure 1. Location of the case study.

3.1. RIVUS Region

The following localisation of the case study RIVUS into the Dutch climate adaptation system aims to clarify the overarching setting. The Netherlands has a long history of adapting to water-related issues due to its low land topography with more than 60% of the country being prone to river flooding and storm surges. The start of the Dutch knowledge portal for climate adaptation (Foundation Climate Adaptation Services, n.d.-a) in 2014 marked the beginning of a new era in Dutch climate adaptation planning (Laudien et al., 2019). Two policy documents are key to the current Dutch adaptation policymaking. The National Climate Adaptation Strategy describes the main climate risks the Netherlands is facing and sets the goals and objectives for addressing these risks (Ministry of Infrastructure and the Environment, 2016). The Delta Plan on Spatial Adaptation (DPRA) defines key elements and steps of spatial adaptation plans and processes (Ministry of Infrastructure and the Environment & Ministry of Economic Affairs, 2018). According to the DPRA from 2018 to 2020, all Dutch municipalities, district water boards, provinces, and the central government have to develop a so-called DPRA based on three main steps: (1) an analysis of climate impacts and vulnerabilities in the so-called stress test; (2) the conducting of a risk dialogue with relevant stakeholders for drawing up a climate adaptation strategy; and (3) the development and approval of an implementation agenda. According to the Ministry of Infrastructure and the Environment, the analysis aims to collect and create information about the effects of the present and future climate on the sensitivity of various objects and functions in a certain area (Ministry of Infrastructure and the Environment & Ministry of Economic Affairs, 2018). Next to the formal planning levels, working regions, consisting of water boards, provinces, and municipalities, were established to structure and monitor the process and address the challenges of climate change beyond administrative borders.

In the Netherlands, the case study is the working region RIVUS, which is also part of the research project ER. Next to the named climatic challenges, the region can be characterised as rather vulnerable to flooding due to its location in the IJssel-Vecht river delta. In the context of the conduction of nationwide stress tests on different spatial levels, the regional cluster RIVUS collected all the data and published them online. The RIVUS stress test does not aim at conducting a new stress test and generating new data, but rather collecting and visualising different data from the mentioned planning levels to tackle climate adaptation across administrative borders. The results of the stress test are made public and are accessible via https://tinyurl.com/hsny2da6.

3.2. ER Regions

The following localisation of the case study in NRW into the German climate adaptation system aims to clarify the overarching setting. The German national climate adaptation process started in 2008 with the publication of the German Adaptation Strategy, further specified through the Adaptation Action Plan (Bundesregierung, 2011), most recently updated in the Adaptation Action Plan III (Bundesregierung, 2020). The German spatial planning law stipulates the identification and balance of climate issues with other public and private interests. Thus, climate adaptation is one concern of many within the German planning process. According to the German building code, significant impacts on the climate as an object of protection are described as relevant for consideration. According to Annex IV of the German Federal Building Act, the report to an environmental impact assessment must contain a description of the effects of the project on the climate and the vulnerability of the plan or project (Othmer et al., 2020). In 2017, the Federal Environment Agency published a guideline providing methodological recommendations for conducting regional and national climate impact and vulnerability analyses (Buth et al., 2017). The guideline suggests the conduction of the following three steps: First, preparing and designing the analysis; second, conducting the climate impact and/or vulnerability analysis; and third, communicating and using the results (Buth et al., 2017, p. 14).

In Germany, the focus lies on seven regions in NRW, which are part of the research project ER, and for which a climate impact analysis (CIA) is being conducted. The analyses aim to identify both spatial hot spots and specific local areas with high climate impacts and thus afford measures for adaptation to climate change (Buth et al., 2017). A scenario-based approach is carried out to map possible future scenarios in addition to current conditions (Greiving et al., 2018). To be able to classify and interpret the results of the climate impact analyses in individual regions, a schematically uniform and transferable methodological approach across all regions is essential. This explicitly includes the normalisation of the values concerning climatic influences and sensitivities. An essential point is an understandable presentation of the results in the context of interactive dashboards to increase the willingness of the stakeholders to use the results. The results of the CIA will be made available through the project but are not public yet. This case study aims at operationalising national-level guidelines and tools, leading to a scientific and research-driven approach, with the ER project being a project of the EU-Life programme.

4. Method

This case study analysis compares the stress test conducted for RIVUS, a regional Dutch cooperation that comprises 11 municipalities located in the province of Overijssel (RIVUS, 2021) with the methodology applied for seven regions, comprising 100 municipalities in NRW (TU Dortmund University, n.d.). Two remarks are essential in this respect. First, it is important to note that the focus of this article lies on the comparison of the analytic approaches and less on the spatial specifics of the case study areas. Second, the impact assessment of the Dutch region is already partially institutionalised into administrative actions, as the region has conducted it independently, whereas the assessment of the German regions is being conducted as part of the research project ER.

A comparative research study draws attention to the relevance of the contextual environment for a specific outcome and therefore helps to understand how the context shapes the actions in different settings (Esser & Vliegenthart, 2017, p. 4). Referring to climate adaptation, Purdon and Thornton (2019, p. 175) name comparative methods as one major strategy within the research concerning adaptation policies, as this “allow[s] researchers to draw on the rich trove of existing adaptation case studies to identify generali[s]able trends across them.” Therefore, this comparison aims to create a mutual learning process, generate as well as transfer knowledge across national borders, and lead to a richer international research environment. The goal is to identify differences and similarities of the stress test in RIVUS and the CIA of the regions in NRW to create synergies and improvements for both approaches and to discuss the quality of both approaches.

The methodology of this research entails secondary and primary data collection. The methods applied include the analysis of relevant documents and climate impact maps, the conduction of expert interviews, and a follow-up discussion of the results with the interviewees. The expert interviews were conducted on July 7 and November 11, 2020, with two planning practitioners in charge of the climate adaptation process and the analysis in the Dutch region. Three of the co-authors, as researchers, developed and implemented the CIA for the German case study.

We aim to analyse and compare the climate impact assessment done in two case studies in two neighbouring countries facing similar climate stressors to elicit good practices and lessons to be learned. Building on the theoretical background, a distinction between the methodological and technical realisation and the presentation and communication of the results is made. Also, quality criteria will be applied for the discussion of the comparison. Therefore, our analysis is conducted at two levels: (1) comparing the input and output of the conducted climate impact assessments, meaning the methodology and data as well as the results obtained and how they are made available and communicated; and (2) discussing both approaches according to defined quality criteria (see Figure 2).

For the comparative analysis, the categories input and output need to be further differentiated and conceptualised to enable a structured comparison of both climate impact assessments. Concerning the input, the working steps, methodology, climate stressors and sensitivities, data, time reference and scenarios, and the involve-

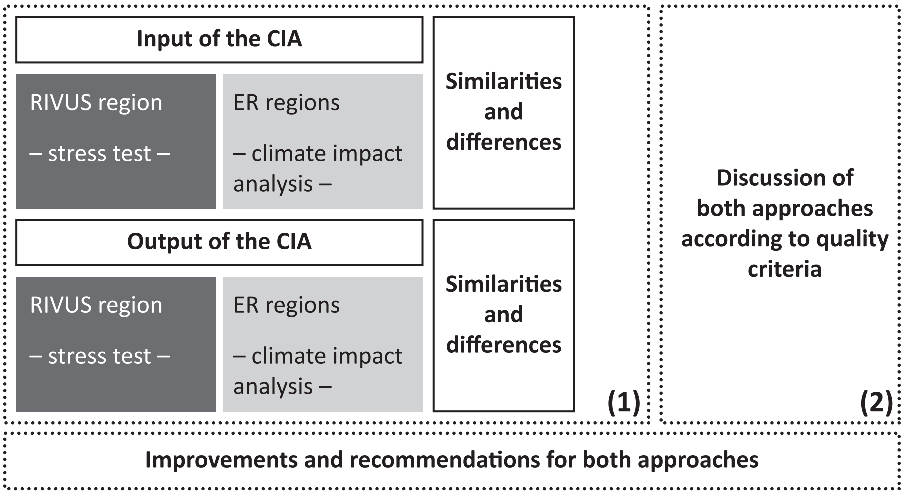


Figure 2. Methodological approach of the international comparative research.

ment of stakeholders will be considered (see Table 1). Concerning the output products, visualisation, availability, and integration will be compared (see Table 2).

From the multitude of technical and process-related criteria discussed in the background chapter, the following selection was made for the discussion of the two approaches:

1) Standardisation: High standardisation of the assessment process and methodology leads to high intersubjectivity and reliability;
2) Transparency: Transparent documentation of the analysis steps leads to an independent and clear interpretation and understanding of the results;
3) Communication of uncertainty: As no data is perfect and the future climatic and socio-economic situation is dependent on various factors, there are always sources of uncertainty that are essential for the users to understand;
4) Stakeholder involvement: A clear separation of factual and value elements requires the involvement of stakeholders for certain decisions within the conduction of the climate impact assessment;
5) Comprehensibility of visualisations: The processing and visualisation of the results play a central role when it comes to application and usability for the stakeholders.

Table 1. Conceptualisation of the input.

Element	Content
Working steps	Which working steps are conducted within the analysis?
Methodology	What methodology is applied? How is the climate impact measured or calculated? How is the sensitivity combined or intersected with the climate signal?
Climate stressors and sensitivity	What climate stressors and sensitivities are taken into account? Which correlations and impact chains have been analysed?
Data	What data is used for the assessment? Is additional data collected?
Time reference and scenarios	What time references are modelled? What climate and sensitivity scenarios are used?
Stakeholder involvement	Are any stakeholders involved in the assessment and the development of the methodology? If so, which stakeholders, and in what steps?

Table 2. Conceptualisation of the output.

Element	Content
Products	What outputs and products are being produced?
Visualisation	How are the outputs visualised?
Accessibility	How is the analysis made available and for whom is the data accessible?
Integration	How is the outcome of the analysis integrated into other planning processes and funding schemes?

5. Results

In the following section, we compare the climate impacts assessments conducted in the two case study regions, divided into two parts. First, we compare the inputs to the analysis, i.e., the general approach and methodology, the role of different actors, climate stressors and sensitivities considered, and input data and scenarios used for the analysis (see Table 1). Then, we study the outputs of the analysis and its dissemination, i.e., the results that have been developed, and how the results are visualised, communicated, and made available (see Table 2).

5.1. Input

Concerning the overall approach of the CIA, both regions follow a similar process and apply a comparable conceptualisation of climate impacts and how to assess these. Both approaches follow a similar order of working steps: first the data collection, followed by the selection of climate stressors and sensitivities, and finally the identification and visualisation of climate impacts. In both cases, climate stressors are mapped as specific spatial indicators, such as the number of days per year above 25°C, and sensitivities are mapped as the spatial distribution of certain indicators which represent sensitive sectors. Both analyses build on mainly existing data. Concerning the climate stressors, the same aspects were covered in both approaches, namely heat, drought, heavy rain, and river flooding. Concerning the selection of sensitive sectors, not identical but similar sectors are addressed in both approaches, namely water, nature, agriculture, forestry, recreation, health, infrastructures, and civil protection. Next to the named similarities, four main differences can be ascertained and will be discussed in detail in the following:

- First (1), the impact assessments are conducted within a different context, the approach of RIVUS already being embedded into the administration, and the ER approach being developed within the named research project, leading to different overall approaches and especially different stakeholder settings;
- Second (2), the approach of RIVUS is a pure data collection, processing, and visually overlaying data, whereby the ER approach generates new data and is not only a visual but mathematical intersection of data;
- Third (3), the RIVUS approach of mapping climate impacts considers single climate stressors and sensitivities, while the ER approach combines various indicators which are aggregated into one index per climate impact;
- Fourth (4), while the RIVUS approach maps one reference and one future climate stressors scenario and the future scenario does not consider the future sensitivity, the ER approach maps different future scenarios concerning the climate stressors and sensitivity, according to the concept of parallel modelling.

(1): As both processes are conducted in a different context (see Section 3), the role of different actors participating in the stress test varies slightly. The RIVUS stress test was coordinated by the regional RIVUS steering group and conducted by a consultancy. Various regional stakeholders were involved in deciding which climate impacts need to be addressed at the regional level, and for interpreting climate impacts for the five selected topics. In the ER case study, the process was coordinated and conducted by a university research group in close cooperation with administrative stakeholders from various departments of the region and experts from different sectors. The regular exchange took place in the context of the research project to constantly improve the methodology and data basis for the CIA.

(2): The RIVUS approach is a collection of climate and sensitivity data, and climate impacts are assessed by visually overlaying climatic indicators with one or more spatial indicators for sensitivity (see Figure 3). The RIVUS stress test used data from various national, provincial, and municipal databases, such as the climate impact atlas and stress tests conducted at national, provincial, and water board levels. Depending on data needs discussed during the stakeholder activities, the database was partially enriched with local data, e.g., data for the local sewage system. The main task was the filtering of issues to be addressed at the regional level.

For the ER regions, existing data sets from the regional authorities (LANUV, 2020) and relevant data sets from national-level agencies were used. Where needed, data was produced, e.g., by means of heavy rainfall-runoff modelling. In the ER approach, sensitivities and climate stressors are normalised across all involved counties and intersected based on multiple (climate and sensitivity) indicators to calculate climate impacts (see Figure 4). The analysis thus determines the comparative impacts of climate change.

(3): The RIVUS process aims at collecting and visualising existing climate and sensitivity data that mainly comes from the national climate impact assessment programme. For assessing climate impacts in the RIVUS region single indicators of climate stressors are combined one to one with single indicators of sensitivity. In ER, the climate signal and sensitivity are represented by different indicators, which are integrated by applying a spatial multi-criteria analysis. This normalisation process leads to abstract values that represent the comparative level of affliction (see Figure 5).

(4): Both climate impact assessments are conducted for the current situation and future scenarios, in the German case for the year 2040, in the Dutch case for the year 2050. In the ER case study, two alternative scenarios are included, contrasting a moderate development with weak, and a worst-case scenario with strong, climatic,

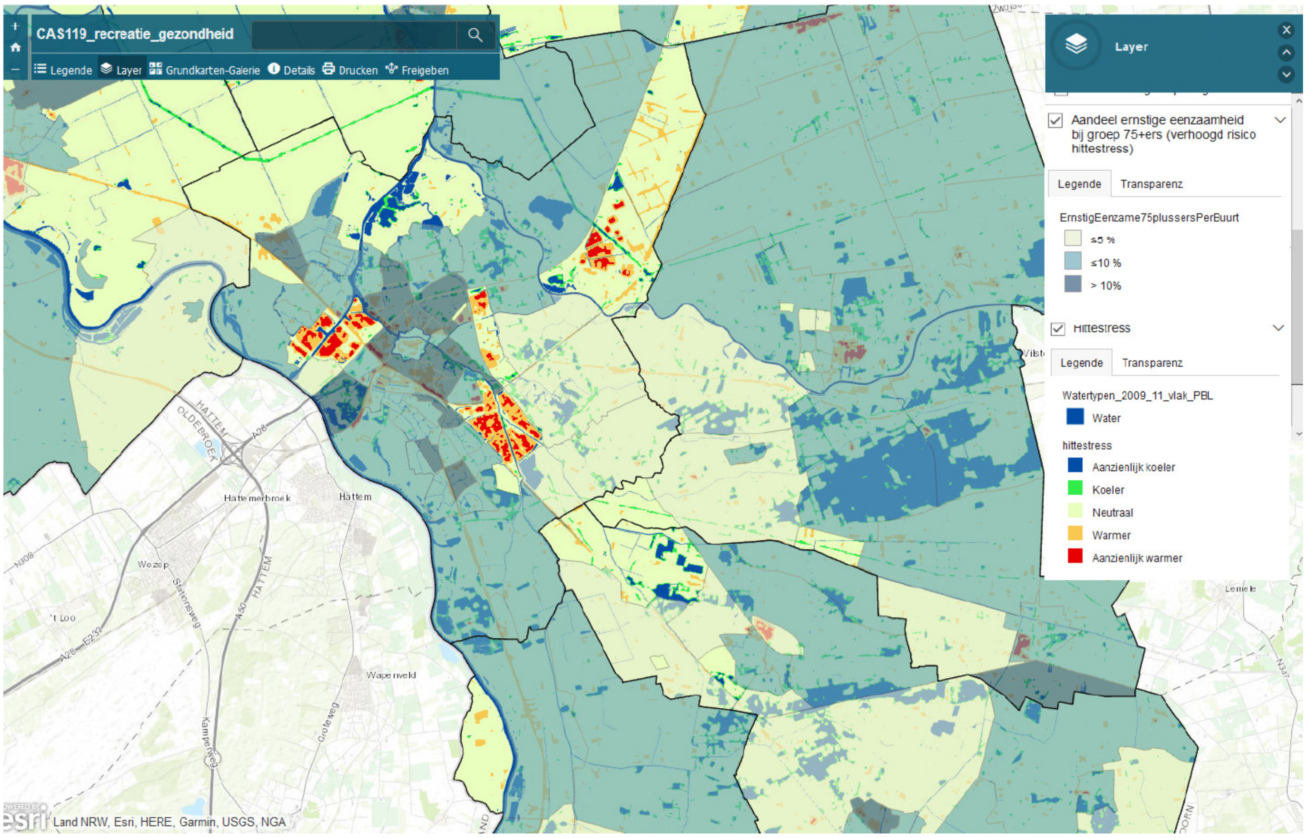


Figure 3. RIVUS region: Overlay of climate stressors and sensitivity, example heat, and population. Source: Foundation Climate Adaptation Services (n.d.-b).

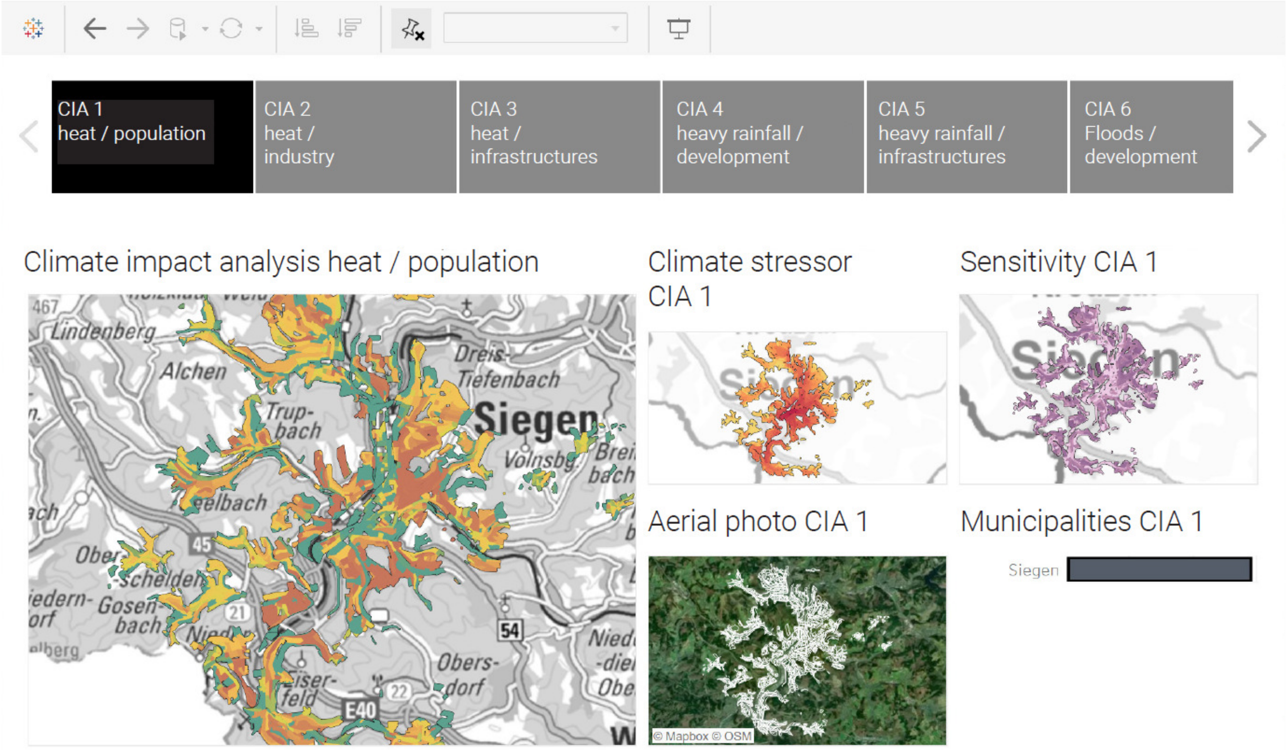
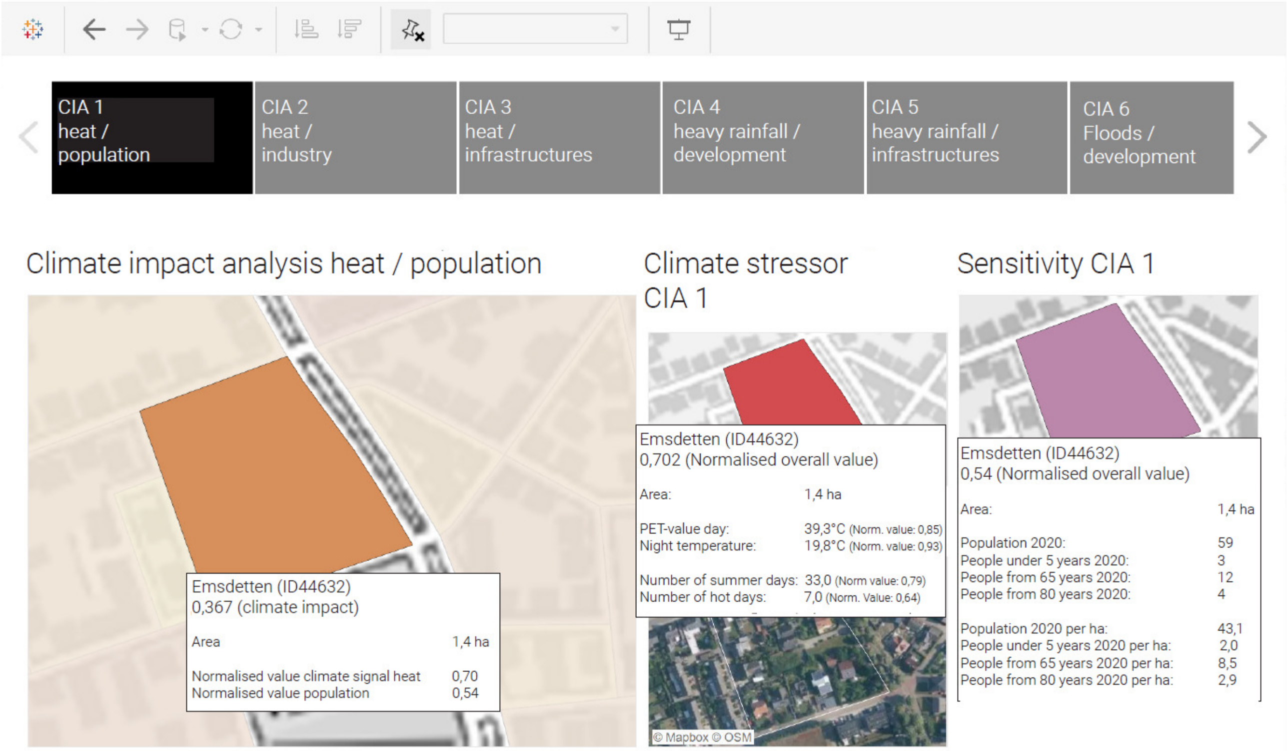


Figure 4. ER regions: Intersection of climate stressors and sensitivity, example heat, and population. Source: Schmitt and Wright (2021).



Emsdetten (ID44632)
0,367 (climate impact)

Area 1,4 ha

Normalised value climate signal heat 0,70
Normalised value population 0,54

Emsdetten (ID44632)
0,702 (Normalised overall value)

Area: 1,4 ha

PET-value day: 39,3°C (Norm. value: 0,85)
Night temperature: 19,8°C (Norm. value: 0,93)

Number of summer days: 33,0 (Norm value: 0,79)
Number of hot days: 7,0 (Norm. Value: 0,64)

Emsdetten (ID44632)
0,54 (Normalised overall value)

Area: 1,4 ha

Population 2020: 59
People under 5 years 2020: 3
People from 65 years 2020: 12
People from 80 years 2020: 4

Population 2020 per ha: 43,1
People under 5 years 2020 per ha: 2,0
People from 65 years 2020 per ha: 8,5
People from 80 years 2020 per ha: 2,9

Figure 5. ER regions: Methodology of multi-criteria analysis. Source: Schmitt and Wright (2021).

and socio-economic changes (in terms of demographic and land-use changes). The RIVUS case makes use of one future scenario "that in most cases shows the most forceful changes" (Foundation Climate Adaptation Services, n.d.-c). While the RIVUS future scenario only considers changes in climate stressors and overlays these with the current sensitivities, the ER approach integrates future climate stressors and sensitivities based on a population projection and reasonable alternatives of further settlement expansion or urban renewal (Greiving et al., 2018; see Table 3).

5.2. Output

In both case studies, results of the climate impact assessments have been produced, visualised, and made available to address various target groups. Also, both outputs show different levels of data presentation for different stakeholders and a varying degree of complexity and depth. While some products aim at visualising basic interrelationships between climate stressors and sensitivities, interactive maps allow professional users to study a combination of single factors at a high spatial resolution. Next to the named similarities, three main differences can be ascertained and will be discussed in detail in the following:

- First (1), the visualisation of the relationship between climate stressors and sensitivities is more striking and memorable in the Dutch example, as more pictures than words were used;
- Second (2), in the Netherlands, the data and different levels of results are made available via a public accessible story map, while the ER approaches use the interactive tool Tableau to bundle and present the data within dashboards;
- Third (3), the conduction of stress tests in the Netherlands is linked to national adaptation funding, providing a clear timeframe and creating incentives for municipalities and regions. In NRW, such a formal linkage does not yet exist.

(1): The pictorial illustrations in birds-eye views of the spatial complexities and interdependencies of regional climate impacts for each topic provide a simple non-spatial overview for the RIVUS region (see Figure 6). Especially when it comes to raising awareness among homeowners, such pictorial representations are helpful to raise awareness and clarify possible impacts. In the German case study, mainly textual fact sheets and posters were produced uncovering the complexities of regional climate impacts. Although these represent a compression of knowledge, they use fewer pictorial elements.

(2): All results in the Dutch example, as well as the spatial data, are publicly available and accessible in an online story map (Tauw, n.d.). This story map contains three different levels of information for different actors. For the German ER case study, interactive maps are being prepared and the overall results are made available to the county and its municipalities in the form of an interactive dashboard (Schmitt & Wright, 2021). It is planned

Table 3. Overview of the comparison criteria of the input.

Criteria	RIVUS region	ER regions
Working steps	1. Data collection and preparation; 2. selection and interpretation of regional stressors and sensitivities per topic; and 3. visualisation of climate impacts	1. Data collection and preparation; 2. mapping of relevant climate stressors and sensitivities; and 3. calculation and visualisation of climate impacts
Methodology	Visually overlaying spatial indicators for relevant stressors and sensitivities to indicate levels of impacts	Intersecting spatial indicators for multiple relevant climate stressors and sensitivities to calculate levels of impact
Climate stressors	Heat, drought, heavy rain events, river flooding	Heat, drought, heavy rain events, river flooding
Sensitivities (topics)	Water and space, nature and agriculture, recreation, health, critical infrastructures	Human health, buildings, agriculture, forestry and forest management, transport infrastructure, civil protection
Input data	Collection of data sets concerning climate stressors and the sensitivities from existing databases and national, provincial and water board level stress tests	Collection of different data sets concerning climate stressors and the sensitivities from existing state-level databases, open data sets, national meteorological service
Time reference and future scenarios	Current situation: reference period climate 1980–2010, socio-economic 2018–2019; climate scenario: KNMI Wh scenario 2050 including most forceful changes; no socio-economic scenario	Current situation: reference period climate 1981–2010, socio-economic 2020; climate scenario: IPCC representative concentration pathways 4.5 and 8.5 scenarios 2040 (weak change/strong change); socio-economic scenario based on population projections 2040 and new settlement areas laid down by regional plans
Involvement of actors	Analysis led by a regional steering group, conducted by consultancy; interviews with relevant stakeholders, stakeholder workshops per topic	Development and application of methodology by German university in close cooperation with State Agency for Nature, Environment and Consumer Protection NRW; normative decisions are made by planners concerning the selection of climate scenarios, the spatial development scenario.

to make the data accessible as online maps, web map services, and geodata download within the duration of the project. The interactive maps enable the display of large amounts of data for large areas compactly and interactively. This added value was confirmed by participants in the workshops.

(3): In the Netherlands, the DPRA, which is a central guideline for promoting climate adaptation, gives clear and chronological specifications on the elements and their chronological procedure for climate adaptation, including the stress test. This clear timeframe was rated as very helpful during the expert interviews as it set a clear starting point for all Dutch municipalities and regions. In Germany, such a structured process does not exist. So far, the analyses have been used in the context of formal environmental assessments and for the acquisition of funding for selective cases.

6. Discussion

The two case studies for regional climate impact assessment show quite specific and different approaches, mainly because they are conducted in two different countries and thus under two different planning frameworks, but also because of the different contexts they are developed in. Despite these specific details, similarities, as well as significant differences in the approach and methodology, can be observed, which help to derive overall conclusions for the conduction of climate impact assessments. As mentioned in the methodology, there is no universally correct method, but only consistent methodological approaches that are appropriate for the set objectives and target system. Regardless, the five defined quality criteria will be used to discuss both approaches.

6.1. Standardisation

In the Netherlands, the conduction of a stress test is required, although not legally binding, but the details concerning the conduction are unclear. The stress tests are typically carried out by various consultancies. These consultancies have certain flexibility concerning the conduction of the analyses. The interviews showed that this

Figure 6. RIVUS region: Example of a birds-eye view to illustrate potential climate impacts in the region. Source: Foundation Climate Adaptation Services (n.d.-b).

Table 4. Overview of the comparison criteria of the output.

Criteria	RIVUS region	ER regions
Products	Illustration of climate impacts and their interrelations for relevant topics; interactive map of climate impacts; data download for further analysis	Modelled regional climate stressors; interactive maps and dashboards of climate impacts; fact sheets and posters on the complexity of climate change impacts; report including methodical approach and indications for the interpretation of results
Visualisation	Report with all results and interpretation as an online story map	Interactive dashboard showing climate impacts with the software Tableau
Availability	Online story map and spatial data of climate stressors and sensitivities publicly available	Dashboards and interactive maps accessible for county and municipalities, data available as WMS and download (planned)
Integration	Clear and chronological procedure for climate adaptation, including the stress test (DPRA)	Use of CIA as part of the workshops in ER; CIA already used in the context of environmental assessments and for the acquisition of funding for selective cases

procedure should be further standardised to achieve comparable results. Concerning heat (De Nijs et al., 2019; Koopmans et al., 2020) and flooding (Stowa, 2020) such specifications are available, but for drought and heavy rainfall, they are still lacking. In Germany, there is the guideline of the Federal Environment Agency, which creates a basis but leaves space for specific technical implementation. The aim of ER is to develop a methodical approach with a high degree of standardisation, which can ideally be transferred to the entire federal state of NRW. As there is a strong need for standardisation of climate impact assessments (Greiving, 2019; Scholles, 2005), both approaches should further improve this aspect.

6.2. Transparency

Both approaches aim for a high degree of transparency, which is essential to raise the comprehensibility and acceptance of decision-makers and affected stakeholders (Greiving, 2019). However, the Dutch case conducted in the RIVUS region only complies partly with this ambition. The presentation and accessibility of the results on the website fully match the criterion of transparency. Nevertheless, the methodology and process of conducting the climate impact assessment are not presented transparently at all. As the analysis for the regions in NRW has not yet been completed, this aspect cannot be assessed conclusively. Nevertheless, all working steps are documented and will be made available.

6.3. Display of the Uncertainty

Typical characteristics of the ER approach are that two alternative future climate scenarios are developed. Socio-economic scenarios are also modelled to reflect the bandwidth of potential future conditions, the latter often being mentioned as missing in current climate risk and vulnerability studies (Rohat et al., 2019). The main reason for the stronger data production and modelling-focused approach is that most of the involved regions do not yet have sufficient data nor the competencies and capacities to conduct an impact assessment on their own. In RIVUS, no bandwidth of possible scenarios is considered, with only one scenario showing the greatest changes. Thus, this approach does not represent a range of uncertainties, but only a possible state. Also, the RIVUS approach does not consider future sensitivities.

6.4. Stakeholder Involvement

Specific to mention about the Dutch case is the rather strong involvement and participation of various stakeholders already in the stress test phase. This can be explained by a quite strong tradition of consensus-oriented policy-making in the Netherlands, which is often referred to as the “polder model” (Van Eerd et al., 2014, p. 103). The climate impact analyses done in the project ER is strongly embedded in a roadmap process within the research project. Concerning the conduction of the analysis, the planners were involved in the selection of climate and spatial development scenarios.

In the context of governance of climate adaptation, both approaches enable an extension of spatial governance to contribute and offer potentials for each of the governance modes distinguished in the discussion (Molenveld et al., 2020). In the network mode of governance, both approaches target fostering co-creation and self-organisation (Molenveld et al., 2020). The development of a shared analysis of different stakeholders can be based on mutually intelligible and visualised data. Network governance, characterised by lateral leadership without issues directives (Birke et al., 2015), can frame issues and moderate individual interests with back reference to a piece of spatial evidence.

6.5. Comprehensibility of the Visualisation

A classification of the tools into the four previously mentioned tools (Neset et al., 2016) leads to the result that the ER approach is an impact viewer and the RIVUS approach is something between a climate data and impact viewer. The RIVUS story map shows climate impacts which are mapped by visually overlaying climate stressors and sensitivities. The user can make choices in the dashboard, but no weighting of indicators or similar can be done. The ER approach clearly visualises climate impacts as an aggregated result based on multiple climate stressors and sensitivity indicators are calculated and used for mapping regional and local hotspots. Particularly this mapping of hotspots through the normalisation has been perceived positively by planning practitioners in workshops of the ER project as it allows identifying areas that require particular attention for climate adaptation interventions and thereby provides arguments when applying for funds for the implementation of such measures. However, the interpretation of normalised values is a challenge for some users in this context. The used software Tableau has an interactive character that entails selection options but does not allow further individual settings.

One key difference between the two approaches is how climate impacts are analysed and mapped. The provision and availability of results can be singled out as a significant difference between the two case studies. In the Dutch case, the reports and resulting maps and illustrations, as well as the raw data, are made available to all stakeholders, including the general public for further use. In the German case, reports, results, and data are being made available in the first instance to the regional administration and the involved municipalities as the methodology and database are being improved constantly throughout the research project. However, all data and results of the ER approach will also be made freely accessible.

7. Conclusion

Key similarities between the two case studies are that both studies apply a similar conceptualisation of climate impacts and do map these, but not explicitly vulnerabilities. What is remarkable is that both processes put quite some focus on the issues of visualisation and communication of the climate impact (Mabon, 2020) through developing and using different platforms and tools to disseminate the results and knowledge. How these platforms contribute to bridging the information gaps discussed above and support better climate adaptation decision-making would need to be explored in follow up study.

What is specific about the Dutch case study is that the climate stress test is initiated through a national programme and conducted more or less parallelly in the entire country and at various planning levels. That results on the one hand in broad availability of relevant data as well as specific tools and methods for conducting a stress test. On the other hand, it might abet, as seen in the RIVUS case study, rather a collecting, filtering, and selection of topics with a strong focus on visualising data for different target groups. While the conducting of a stress test as part of a climate adaptation process has a strong statutory role in the Dutch governance system through its embedding in the Delta act (Bauer & Steurer, 2015, p. 348), there is no legal obligation to carry out a stress test as the DPRA has no binding character.

What is specific about the German case study is the strong consideration of scenarios and especially the attention also on future sensitivities according to the method of parallel modelling (Greiving et al., 2018). The consideration of future sensitivity is relevant for at least two reasons. First, it reflects and underlines the significance of the sensitivity for the extent of climate impacts, as this is not only determined by climatic changes but also future planning decisions. Second, the collection and inclusion of future planning offers a climatic pre-assessment and builds upon this the development of reasonable planning alternatives.

Accordingly, the following recommendations can be derived for the respective impact assessment approaches. The innovative, interactive and target group-oriented presentation of results can be identified as a key improvement for the ER approach and therefore the regions in NRW. The importance to also consider scenarios and future sensitivity can be identified as a key learning for the RIVUS approach. The RIVUS approach can potentially benefit from the consistent method of parallel modelling, which considers different scenarios and periods for the climate stressors, as well as the sensitivity.

The following overall conclusions and lessons learned can be derived from the comparison:

- Modelling alternative scenarios of both climate stressors and sensitivities allows identifying reliable scenarios for future patterns of climate change impacts, but requires careful communication to gain the necessary data and to enable stakeholder participation. Experience from the ER research project has shown that collecting data on future sensitivities is very time-consuming and often involves sensitive data that municipalities are careful to share. However, the added value for practice and science is clearly present.
- Engaging decision-makers and stakeholders in climate adaptation-related planning activities requires the availability and accessibility of results from climate impact assessment studies in intuitive and interactive formats and digital platforms that address different the levels of knowledge and capabilities of stakeholders.
- Linking climate impact assessment and adaptation planning to the provision of funds for implementing suitable interventions strengthens the execution of adaptation planning processes. However, such a timeline should be discussed and coordinated with the capacities and resources of the municipalities so as not to set unrealistic targets, as especially smaller municipalities often do not have sufficient financial and human resources at their disposal.

As already mentioned, the comparability of both approaches can be seen critically. While the officially adopted stress test in the Netherlands is already being carried out by regions with the support of consulting companies, the analysis for the regions in NRW is currently being conducted within a research project and is not fully completed. Nevertheless, the comparison leads to clear and beneficial improvements for both approaches. In the case of the ER regions, the results can be implemented into the on-going process of the research project and subsequently be used by the participating municipalities within their land-use planning. The RIVUS region is planning to implement the results into the conduction of the next stress test, which will take place in approximately five years. The relationship between the results of the analysis and the implementation as well as the financing of such implementation should be further investigated from a scientific perspective. Accordingly, further research should be conducted for further case studies in other European countries.

Acknowledgments

We thank Stan Vergeer (Climate Director at the municipality of Kampen) and Joren Zwaan (Advisor Climate Adaptation at Tauw Group) for their willingness to act as interview partners and for the useful discussions and provision of data.

Conflict of Interests

The authors declare no conflict of interests.

References

Adger, W. N., Agrawala, S., Mirza, M. M. Q., Conde, C., O'Brien, K., Pulhin, J., Pulwarty, R., Smit, B., & Takahashi, K. (2007). Assessment of adaptation practices, options, constraints and capacity. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson (Eds.), *Climate change 2007: Impacts, adaptation and vulnerability* (pp. 717–743). Cambridge University Press.

Aguiar, F. C., Bentz, B., Silva, J. M. N., Fonseca, A. L., Swart, R., Santos, F. D., & Penha-Lopes, G. (2018). Adaptation to climate change at local level in Europe: An overview. *Environmental Science & Policy*, *86*, 38–63. https://doi.org/10.1016/j.envsci.2018.04.010

Archie, K. M., Dilling, L., Milford, J., & Pampel, F. (2014). Unpacking the 'information barrier': Comparing perspectives on information as a barrier to climate change adaptation in the Interior Mountain West. *Journal of Environmental Management*, *14*, 397–410.

Bauer, A., & Steurer, R. (2015). National adaptation strategies, what else? Comparing adaptation mainstreaming in German and Dutch water management. *Regional Environmental Change*, *15*(2), 341–352. https://doi.org/10.1007/s10113-014-0655-3

Biesbroek, R. G., Klostermann, J. E. M., Termeer, C. J. A. M., & Kabat, P. (2013). On the nature of barriers to climate change adaptation. *Regional Environmental Change*, *13*(5), 1119–1129. https://doi.org/10.1007/s10113-013-0421-y

Birke, M., Schultze, J., Hasse, J., & Rauscher, N. (2015). Roadmapping eine Governance-Innovation für den Weg zur klimarobusten und klimakompetenten Region [Roadmapping a governance innovation for the path to a climate resilient and climate competent region]. In J. Knieling & A. Roßnagel (Eds.), *Governance der Klimaanpassung* [Governance of climate adaptation] (pp. 283–302). Oekom.

Bundesregierung. (2011). *Aktionsplan Anpassung der Deutschen Anpassungsstrategie an den Klimawandel* [Adaptation action plan of the German strategy for adaptation to climate change].

Bundesregierung. (2020). *Zweiter Fortschrittsbericht zur Deutschen Anpassungsstrategie an den Klimawandel* [Second progress report on the German strategy for adaptation to climate change].

Buth, M., Kahlenborn, W., Greiving, S., Fleischhauer, M., Zebisch, M., Schneiderbauer, S., & Schauser, I. (2017). *Leitfaden für Klimawirkungs—und Vulnerabilitätsanalysen* [Guideline for climate impact and vulnerability analyses]. Umweltbundesamt.

De Nijs, T., Bosch, P., Brand, E., Heusinkveld, B., Van der Hoeven, F., Jacobs, C., Klok, L., Kluck, J., Koekoek, A., Koopmans, S., Van Nieuwaal, K., Ronda, R., & Steeneveld, G. (2019). *Ontwikkeling Standaard Stresstest Hitte* (RIVM briefrapport 2019–0008) [Development of a standardised heat stress test]. Rijksinstituut voor Volksgezondheid en Milieu.

Esser, F., & Vliegenthart, R. (2017). Comparative research methods. In J. Matthes, C. S. Davis, & R. Potter (Eds.), *The international encyclopedia of communication research methods* (pp. 1–22). Wiley-Blackwell.

Faßbender, K. (2012). *Rechtsgutachten zu den Anforderungen an regionalplanerische Festlegungen zur Hochwasservorsorge erstattet im Auftrag des Regionalen Planungsverbands Oberes Elbtal/Osterzgebirge* [Legal opinion on the requirements for regional planning specifications for flood prevention prepared on behalf of the Regional Planning Association Upper Elbe Valley/Eastern Ore Mountains].

Ford, J. D., & King, D. (2015). A framework for examining adaptation readiness. *Mitigation and Adaptation Strategies for Global Change*, *20*(4), 505–526. https://doi.org/10.1007/s11027-013-9505-8

Foundation Climate Adaptation Services. (n.d.-a). *Homepage*. https://klimaatadadaptatienederland.nl/en

Foundation Climate Adaptation Services. (n.d.-b). *RIVUS Regionale stresstest klimaatadaptatie* [RIVUS regional climate adaptation stress test]. https://climadapserv.maps.arcgis.com/apps/Cascade/index.html?appid=76a5cc59dbe44cb4b471753c09d9f27e

Foundation Climate Adaptation Services. (n.d.-c). *Climate impact atlas*. https://www.klimaateffectatlas.nl/en

Greiving, S. (2019). Analyse—und Bewertungskonzepte für Risiken im Vergleich [Comparison of analysis and assessment concepts for risks]. *Informationen zur Raumentwicklung*, *46*(4), 62–73.

Greiving, S., & Fleischhauer, M. (2012). national climate change adaptation strategies of European states from a spatial planning and development perspective. *European Planning Studies*, *20*(1), 27–48. https://doi.org/10.1080/09654313.2011.638493

Greiving, S., Arens, S., Becker, D., & Fleischhauer, M. (2018). Improving the assessment of potential and actual impacts of climate change and extreme events through a parallel modeling of climatic and societal changes at different scales. *Journal of Extreme Events*, *4*(4). https://doi.org/10.1142/S2345737618500033

Hanger, S., Pfenninger, S., Dreyfus, M., & Patt, A. (2013). Knowledge and information needs of adaptation policy-makers: A European study. *Regional Environmental Change*, *13*(1), 91–101. https://doi.org/10.1007/s10113-012-0317-2

Intergovernmental Panel on Climate Change. (2014). Summary for policymakers. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White (Eds.), *Climate change 2014: Impacts, adaptation, and vulnerability: Working group II contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change* (pp. 1–32). Cambridge University Press.

Koopmans, S., Heusinkveld, B. G., & Steeneveld, G. J. (2020). A standardized physical equivalent temperature urban heat map at 1-m spatial resolution to facilitate climate stress tests in the Netherlands. *Building and Environment*, *181*, Article 106984. https://doi.org/10.1016/j.buildenv.2020.106984

LANUV. (2020). *Fachinformationssystem Klimaanpassung* [Information system concerning climate adaptation]. http://www.klimaanpassung-karte.nrw.de

Laudien, R., Boon, E., Goosen, H., & Van Nieuwaal, K. (2019). The Dutch adaptation web portal: Seven lessons learnt from a co-production point of view. *Climatic Change*, *153*(4), 509–521. https://doi.org/10.1007/s10584-018-2179-1

Mabon, L. (2020). Making climate information services accessible to communities: What can we learn from environmental risk communication research? *Urban Climate*, *31*, Article 100537. https://doi.org/10.1016/j.uclim.2019.100537

Ministry of Infrastructure and the Environment. (2016). *National climate adaptation strategy 2016*.

Ministry of Infrastructure and the Environment, & Ministry of Economic Affairs. (2018). *Delta programme 2018*.

Molenveld, A., Van Buuren, A., & Ellen, G. (2020). Governance of climate adaptation, which mode? An exploration of stakeholder viewpoints on how to organize adaptation. *Climatic Change*, *162*, 233–254. https://doi.org/10.1007/s10584-020-02683-9

Neset, T.-S., Opach, T., Lion, P., Lilja, A., & Johansson, J. (2016). Map-based web tools supporting climate change adaptation. *The Professional Geographer*, *68*(1), 103–114. https://doi.org/10.1080/00330124.2015.1033670

Othmer, F. J., Schmitt, J. P., & Greiving, S. (2020). Numerical modelling of the urban climate as an integrated part of environmental assessments. *Science of The Total Environment*, *731*, Article 138774. https://doi.org/10.1016/j.scitotenv.2020.138774

Purdon, M., & Thornton, P. (2019). Research methodology for adaptation policy analysis: Embracing the eclectic messy centre. In E. C. H. Keskitalo & B. L. Preston (Eds.), *Research handbook on climate change adaptation policy* (pp. 157–192). Edward Elgar Publishing.

Reckien, D., Salvia, M., Heidrich, O., Church, J. M., Pietrapertosa, F., Gregorio-Hurtado, S., D'Alonzo, V., Foley, A., Simoes, S. G., Krkoška, E., Orru, H., Orru, K., Wejs, A., Flacke, J., Olazabal, M., Geneletti, D., Feliu, E., Vasilie, S., Nador, C., . . . Dawson, R. (2018). How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28. *Journal of Cleaner Production*, *191*, 207–219. https://doi.org/10.1016/j.jclepro.2018.03.220

RIVUS. (2021). *Homepage*. https://www.rivus.net

Rohat, G., Flacke, J., Dosio, A., Pedde, S., Dao, H., & Van Maarseveen, M. (2019). Influence of changes in socioeconomic and climatic conditions on future heat-related health challenges in Europe. *Global and Planetary Change*, *172*, 45–59. https://doi.org/10.1016/j.gloplacha.2018.09.013

Runhaar, H., Mees, H., Wardekker, A., Van der Sluijs, J., & Driessen, P. P. J. (2012). Adaptation to climate change-related risks in Dutch urban areas: Stimuli and barriers. *Regional Environmental Change*, *12*(4), 777–790. https://doi.org/10.1007/s10113-012-0292-7

Schmitt, J. P., & Wright, J. (2021). *Regionale Klimawirkungsanalysen für sieben Kreise in NRW im Rahmen des Forschungsvorhabens Evolving Regions* [Regional climate impact analyses for seven regions in North Rhine-Westphalia within the framework of the research project Evolving Regions]. Unpublished manuscript.

Scholles, F. (2005). Bewertungs—und Entscheidungsmethoden [Evaluation and decision-making methods]. In Akademie für Raumforschung und Landesplanung (Ed.), *Handwörterbuch der Raumordnung* [Handbook of regional planning] (pp. 97–106). Akademie für Raumforschung und Landesplanung.

Stowa. (2020). *Standaarden voor de stresstest wateroverlast (herzien o.b.v. nieuwe neerslagstatistiek 2019)* [Standards for the flood stress test (revised based on new precipitation statistics 2019)].

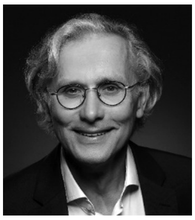
Tauw. (n.d.). *Regionale stresstest klimaatadaptatie RIVUS* [Regional climate adaptation stress test RIVUS]. RIVUS. https://climadapserv.maps.arcgis.com/apps/Cascade/index.html?appid=76a5cc59dbe44cb4b471753c09d9f27e

TU Dortmund University. (n.d.). *Evolving Regions—NRW becomes climate robust*. Evolving Regions. https://evolvingregions.com/en

Van Eerd, M. C. J., Wiering, M. A., & Dieperink, C. (2014). Exploring the prospects for cross-border climate change adaptation between North Rhine-Westphalia and the Netherlands. *Utrecht Law Review*, *10*(2), 91–106. https://doi.org/10.18352/ulr.271

About the Authors

Juliane Wright studied spatial planning at TU Dortmund University and graduated with a Master of Science. Within her current position at the Research Group IRPUD at TU Dortmund's Department of Spatial Planning, she is involved in two research projects being co-responsible for the conduction and knowledge transfer of climate impact analysis on different spatial scales. Her main research interest is climate adaptation in planning, dealing with a wide range of climate stressors such as heat, heavy rain, river flooding, and drought.



Johannes Flacke (PhD) is Assistant Professor for Spatial Planning and Decision Support Systems in the Department of Urban and Regional Planning and Geo-Information Management, Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, the Netherlands. His research centres on the development and use of geo-information and planning support tools for the transition of urban areas into sustainable and resilient places for all. Further research interests include local climate change adaption planning, energy transition, and environmental health-related inequalities.

Jörg Peter Schmitt studied spatial planning at TU Dortmund University and graduated as an engineer. In the course of his professional career, he has already worked for various planning offices and as a freelancer in the field of urban development. In addition to his current position at the Institute of Spatial Planning at TU Dortmund, he is working as a freelancer in the field of information-based urban development. Within Evolving Regions, he is co-responsible for the development of regional climate impact analyses. His research focuses on GIS-based analysis methods, climate impact analyses, and innovative methods for the preparation of results.

Jürgen Schultze is a Senior Researcher at TU Dortmund University (Social Research Centre) and Coordinator of the research area "Transformative Governance in Municipalities and Regions." He is implementing transition elements from labs to large scale dialogues, enabling shared visions and co-creation between different stakeholder groups. His main research interests are the enrichment of urban planning by citizen participation, regional roadmap processes for climate adaptation, the establishment of social innovation labs on a municipal level, and cross-sectoral dialogue for the specification of new climate models. Currently, he is the project coordinator of the large-scale project Evolving Regions.

Stefan Greiving (PhD) has been Head of the Research Group IRPUD at TU Dortmund's Department of Spatial Planning since 2011. His main research interests are disaster risk assessment and management, climate impact assessments, and adaptation to climate change. He has been coordinator and PI of about 30 international research projects in Europe, Africa, Asia, and Latin America and more than 70 national projects and expert statements in Germany. Prof. Greiving's publication record encompasses more than 220 papers, books, and book contributions.

Urban Planning (ISSN: 2183-7635)

Urban Planning is an international peer-reviewed open access journal of urban studies aimed at advancing understandings and ideas of humankind’s habitats.

www.cogitatiopress.com/urbanplanning

COGITATIO