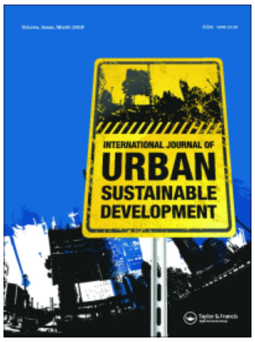

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Towards a socio-ecological system understanding of urban flood risk and barriers to climate change adaptation using causal loop diagrams

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Towards a socio-ecological system understanding of urban flood risk and barriers to climate change adaptation using causal loop diagrams

Franziska S. Hanf[a], Felix Ament[a], Marita Boettcher[a], Finn Burgemeister[a], Lidia Gaslikova[b], Peter Hoffmann[c], Jörg Knieling[d], Volker Matthias[e], Linda Meier[f], Johannes Pein[b], Benjamin Poschlod[g], Markus Quante[e], Leonie Ratzke[h,i], Elisabeth Rudolph[j], Jürgen Scheffran[f], K. Heinke Schlünzen[a], Nima Shokri[j,k], Jana Sillmann[g,l], Anastasia Vogelbacher[j,k], Malte von Szombathely[g] and Martin Wickel[d]

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ABSTRACT

While cities are facing increasing challenges of flood risk due to combined effects of climate change and socioeconomic development, understanding of the complexity of urban flood risk is still limited, hampering decision-making and urban adaptation planning. This study presents a qualitative system dynamics modelling framework to investigate urban flood risk and adaptation under climate change in a coupled socio-ecological system, the city of Hamburg. The developed integrated conceptual model provides a holistic understanding of key physical and socio-economic processes and the role of feedback loops underlying the urban system, and contributes to the understanding of vicious cycles of barriers that perpetuate and hinder adaptation processes within cities. The qualitative approach can help to break down silo-thinking in urban flood risk assessments. Decision-makers could use the framework to understand the complexity of interactions among multiple drivers of flood risk to overcome barriers and lock-in effects to adaptation in cities.

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1. Introduction

Cities are at the forefront of climate change impacts not only because of increasing frequency and intensity of natural hazard events, but also because of ongoing urban growth, densification processes and the increasing complexity of society (Berndtsson et al. 2019). In particular, flooding poses a key risk for urban

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areas. Heavy rainfall (98%) and flooding (86%) were mentioned as main urban hazards by WMO members answering an international survey on hazards (WMO 2021, p.10). Only storms cause more losses worldwide than flood events (MunichRE 2022). However, 'water in itself, is not a threat', rather it is the constantly changing relationship between water and humankind that determines the potential danger (Mauch 2012, p. 63). Flood risks in urban areas arise from hydrometeorological events that interact with the urban system (Dodman et al. 2022). It is the dynamic interaction of climate-related hazards with the exposure and vulnerability of the affected system that decides the magnitude of a water disaster (Ara Begum et al. 2022). Combinations of multiple climate drivers and/or hazards, known as *compound events* (Zscheischler et al. 2018) also play an important role. For example, the compounding effects of inland precipitation, high wind speeds, storm surge and increased river discharge can exacerbate the climate (change) impacts. Cities and settlements by the sea are among those facing the highest climate-compounded risks (Glavovic et al. 2022).

Risk can also arise from human responses to climate change through adaptation and mitigation measures that fail to achieve the intended outcome or create adverse outcomes (Reisinger et al. 2020). Deciding how, when, and where to adapt is thus a difficult even *wicked problem* (Rittel and Webber 1973) involving multiple actors, uncertainty and contested goals (Siders and Pierce 2021). According to Rittel and Webber (1973), *wicked problems* are complex, multi-dimensional, difficult to define, interconnected with other problems, persistent and have no obvious solutions. Adaptation to climate change 'embodies the classic wicked problem' (Siders and Pierce 2021, p. 1) and has even been described as a 'wicked problem par excellence' (Termeer et al. 2013, p. 27). Accounting for the complexity of risk (i.e. interactions across sectoral, temporal and spatial boundaries and multiple response options) is crucial for risk assessments that aim to inform decision-makers and to understand and manage risks towards sustainable cities (Simpson et al. 2021).

Sustainable adaptation, defined as 'adaptation that contributes to socially and environmentally sustainable development pathways, including both social justice and environmental integrity' (Eriksen et al. 2011, p. 8), requires considering the consequences of actions in a broader social and environmental context. This means that sustainable adaptation is all about understanding human–environmental relationships. A framework that has become increasingly important for meeting the complexity of sustainability challenges is systems thinking (Voulvoulis et al. 2022). Systems thinking is a 'discipline for seeing wholes' focusing on interrelations and patterns of change rather than things and static snapshots (Randle and Stroink 2018, p. 1) and to 'see the world as a collection of feedback processes' (Meadows 2008, p. 25). It is the intentional process of understanding the underlying drivers of problems, of how components and structures cause a system to behave in a certain direction. In the urban context, this means considering cities as complex *socio-ecological systems* (i.e. natural and social systems as one integrated system with critical feedbacks across temporal and spatial scales; Berkes and Folke 1998; Frank et al. 2017; Zhou et al. 2024). Humans interact with their surrounding physical environment in numerous multifaceted ways; therefore, when approaching *socio-ecological systems*, it is necessary to focus on relationships rather than specific objects (Stenseke 2018). This also applies to urban areas which are focal points of human, social, economic, institutional and ecological interests (Frank et al. 2017). Cities can therefore be understood as small microcosms of things that happen on a global scale, 'making them informative test cases for understanding socioecological system dynamics and responses to change' (Grimm et al. 2008, p. 756). Place-based socio-ecological research could be a way forward in finding solutions to global sustainability challenges (Balvanera et al. 2017).

To successfully adapt to climate change, it is necessary to understand the nature of the problem to respond to (Knieling and Klindworth 2016). A focus on the entanglement of the system's dynamics can, on the one hand, reveal how *vicious cycles of barriers*, 'also known as reinforcing feedback loops' (Meadows 2008, p. 187), prevent the planning and implementation of adaptation measures in cities, and on the other hand, help to develop more appropriate strategies for overcoming the barriers (Zea-Reyes et al. 2021; Dorst et al. 2022).

Methodologically, research on complex societal challenges requires a shift from traditional disciplinary (reductionist) to integrated approaches (interdisciplinary and transdisciplinary) which are oriented towards contexts of application (Mauser et al. 2013; Bai et al. 2016; Abson et al. 2017). Involving all relevant actors in a collaborative process enables a constant exchange of ideas, worldviews, needs, values and interests. Such collaborative approaches often face challenges related to different epistemologies, methodologies, vocabularies, values, cultures and power relations between different disciplines; however, they have the potential to result in novel insights (Allington et al. 2018). Participatory modelling is a way of structuring the deliberative process around formal models (Voinov 2017). This stakeholder-based modelling has emerged as a powerful methodology for developing a better understanding of a system and its dynamics, as well as the impacts of solutions to a given problem (Voinov and Bousquet 2010). By using a model as a *boundary object* (i.e. a tangible, visual representation of shared experience and knowledge that creates a common identity among participants; Black 2013), participatory modelling creates a framework for shared understanding and facilitates collaborative learning. This makes it particularly relevant in the context of *wicked problems*. The model becomes an 'object of mediation' that can facilitate the exchange of ideas and worldviews between participants and promote conflict resolution and collective decision-making (Voinov et al. 2018, p. 234).

One way to implement participatory modelling is group model building (Vennix 1996). Group model building is based on system dynamics (SD; Forrester 1958, 1961), an analytical approach that complements systems thinking by quantifying the causality and interrelations between systems variables and developing a time-dependent view of the behaviour of the system (Systems Dynamics Society 2022). Qualitative SD refers to the stages of problem identification and system conceptualisation resulting in a visual representation of the problem in the form of causal loop diagrams (CLDs) or flow diagrams. Building a conceptual model can contribute to an improved understanding of the system when dealing with complex problems, thus helping to generate ideas for change (Vennix 1996, 1999; Wolstenholme 1999; Coyle 2000). In the last decade, the application of qualitative SD approaches in analysing human-environment interactions has been increasingly taken up; e.g. for water resources planning and management, energy and food security management, policy analysis and sustainable development (e.g. Máñez et al. 2015; Kotir et al. 2017; Purwanto et al. 2019; Daniel et al. 2021; Egerer et al. 2021; Valencia Cotera et al. 2022). Qualitative participative SD modelling has also shown promise for application in the urban context (e.g. Williams et al. 2019; Pluchinotta et al. 2021; Castro 2022; Quang Dao and Thi Thu Huong 2022; Coletta et al. 2024; Pluchinotta et al. 2024).

With the aforementioned in mind, the objectives of this study are twofold: (i) to holistically examine urban flood risk under climate change through qualitative SD modelling based on interdisciplinary expert knowledge using the case study of the city of Hamburg, Germany; and (ii) to identify and analyse the *vicious cycles of barriers* (i.e. reinforcing feedback loops; Meadows 2008) that perpetuate and hinder adaptation processes and reinforce flood risk within the city. Focusing on the dynamic intertwining of barriers can provide insights into how reinforcing feedback loops perpetuate the difficulties faced by cities in planning for climate change adaptation (Zea-Reyes et al. 2021). This study explicitly focuses on qualitative SD approaches because they provide space for local and scientific knowledge in the analysis of *wicked problems*. Recognising the importance of relations between humans and their physical environment in the strive for sustainable solutions (Stenseke 2018), we seek to develop a holistic picture of flood risk and adaptation under climate change within the urban system by explicitly incorporating the linkages and complex feedback processes between social, economic, policy, institutional and environmental factors.

Many of the most severe weather- and climate-related impacts are caused by compound events (Zscheischler et al. 2018, 2020) and with climate change, compound events become even more likely, especially in the context of unprecedented events and low-likelihood, high-impact outcomes (Arias et al. 2021). Compounding effects from multiple hazards increase the complexity of risk and how to respond to it (Zscheischler et al. 2018). This highlights the need for more systemic assessments to analyse the interactions of risks and responses across space and time to support the development of adaptation plans (Simpson et al. 2023). Exploring the *vicious cycles of barriers* in flood risk management and adaptation processes within cities might be best achieved by examining special cases of multi-hazard hotspots. The city of Hamburg provides such a case. With its specific location facing *water from 4 sides* – i.e. vulnerable to flood hazards from local heavy precipitation (pluvial floods), high flows in adjacent river systems (fluvial floods), storm surges (coastal floods) and uncontrolled rise in the groundwater level (groundwater floods), the city of Hamburg is an ideal case study for analysing complex urban flood risk. Several studies have previously addressed issues related to understanding drivers of urban flood risk to improve urban flood risk management and adaptation to climate change (e.g. KLIMZUG-NORD Verbund 2014; Muis et al. 2015; Hammond et al. 2018; Berndtsson et al. 2019; O'Donnell and Thorne 2020). None of the previous studies have taken into account the multiple and dynamic interactions and feedbacks between the physical hazards and the human, socio-economic, ecological and institutional dimensions of urban flood risk and management in such an integrated, systemic way. Furthermore, none of those urban studies have focused on all four dimensions of water-related hazards (i.e. *water from 4 sides*) and their interrelationships with the other dimensions of climate risk (i.e. exposure, vulnerability and human responses). Using a system dynamics approach, we manage to distil the complex interactions into a model that captures both the dynamic and reciprocal relationships. This study, therefore, advances the knowledge of complex flood risk interactions within cities holding immediate relevance for policymakers working on urban flood risk management.

The paper starts (Section 2) with a presentation of the qualitative SD modelling framework for investigating risk under climate change in coupled urban *socio-ecological systems* based on multiple disciplinary perspectives. It then introduces the case study Hamburg by briefly describing the physical *water from 4 sides* flood hazards affecting the city and the municipal governance approach in terms of adaptation to climate change (in Section 3). The application of the framework and the development of the qualitative SD model is then presented in Section 4. Section 5 describes the model structure and dynamics. This is followed by a thorough discussion of the system's feedback loops, with a focus on reinforcing feedback loops that constitute barriers in adaptation processes, as well as a note on limitations and implications of using qualitative SD modelling for understanding climate risk in coupled urban *socio-ecological systems* in Section 6. The paper is brought to a close (Section 7) by a brief summary of the results and an outlook.

2. Method

The study draws on the group model building approach of Vennix (1996), which focuses on building SD models with teams. In addition, the modelling process is also guided by numerous examples of participatory SD modelling conducted in various complex socio-economic and environmental systems (e.g. Inam et al. 2015; Máñez et al. 2015; Kotir et al. 2017; Perrone et al. 2020; Valencia Cotera et al. 2022). Here, CLDs were chosen for the analysis because they allow for a flexible qualitative modelling process and the inclusion of social, economic and environmental variables, which supports the investigation of dynamic linkages between variables from multiple sectors (Videira et al. 2009; Perrone et al. 2020). CLDs represent causal relationships between system variables by arrows and highlight the polarity of these relationships by distinguishing between positive and negative relationships. A positive causal relationship means that both variables will change in the same direction, while a negative relationship implies that both variables change in opposite directions, i.e. that there is an inverse relationship between the variables (Vennix 1996). 'A combination of positive and negative causal relationships gives rise to the system's feedback loops' (Kotir et al. 2017, p. 107). From a SD perspective, the dynamic behaviour of the system is determined by the structure of interacting feedback loops within the system boundary. A distinction is made between positive and negative feedback loops. A positive (reinforcing) loop creates action that increases a system state, which in turn leads to further action that further increases the system state; i.e. a positive feedback loop is self-reinforcing. A negative (balancing) loop, on the other hand, leads to stabilising behaviour (Vennix 1996). CLDs also mark time delays (arrows with double hash marks), which are often responsible for difficulties in controlling inherent dynamics (Inam et al. 2015). Overall, the CLDs represent a hypothesis of the feedback structure of the system (Pluchinotta et al. 2021). Even if not simulated, qualitative system dynamics models (QSDMs) are useful to describe a system in itself and to gain a better understanding of the problem in question (Coyle 2000). Moreover, when simplified, CLDs can easily be understood by non-technical users, which makes them an ideal modelling tool in a participatory setting (Kotir et al. 2017; Perrone et al. 2020). They support definition and structuring of complex problems, aid visual communication about choices and consequences of actions, and facilitate shared understanding and testing of their long-term effects (BenDor and Scheffran 2019). There are various levels of stakeholder engagement, i.e. stakeholders can be involved at different stages of the participatory process, and there is no generalised participatory modelling strategy (Voinov et al. 2016; Voinov 2017).

Voinov et al. (2018) emphasised the careful and conscious selection of methods that best fit the project purpose and context. To investigate urban flood risk and adaptation under climate change in the context of *water from 4 sides* hazards, an interdisciplinary endeavour is required that aims to pool expert knowledge on the urban *socio-ecological system*, taking into account the diversity of knowledge and perspectives. Often, CLDs are developed directly with the stakeholders involved (e.g. Inam et al. 2015; Perrone et al. 2020; Valencia Cotera et al. 2022). We explicitly started the modelling process based on scientific knowledge of an interdisciplinary team. This choice was made because there is already a wide range of different perspectives within various scientific disciplines, leaving room for potentially conflicting views on the same problem. Here, the QSDM is used as a *boundary object* for communicating and integrating different disciplinary worldviews to create a common understanding of a problem. Embedded within the methodological framework of Vennix (1996), the participatory modelling process was structured around the following stages: problem identification and model purpose, system conceptualisation, model formulation, analysis of model behaviour, model evaluation, policy analysis and model use. The present study focuses on the first four stages: (1) problem identification and model purpose, (2) system conceptualisation, (3) model formulation and (4) analysis of model behaviour (see Table 1). These stages took place as a team learning process (Vennix 1996) based on interdisciplinary scientific knowledge. The remaining stages of model evaluation, policy analysis and model use will involve stakeholders from various sectors. These results will be presented in a follow-up paper. Nevertheless, it should be emphasised that the whole model building process is seen as an iterative one (Voinov 2017), which means that the model can be enriched by the stakeholders' local knowledge in later stages. Overall, this interactive process provides an opportunity for all participants, both researchers and stakeholders, to develop a more detailed understanding of how flood risk evolves in the complex urban *socio-ecological system*. The CLDs were developed using the SD software package Vensim PLE (Ventana Systems 2021).

3. Characterisation of the case study

The qualitative modelling framework outlined in Section 2 was applied to Hamburg. Hamburg is the second largest city in Germany with a population of around 1.85 million and the core of a metropolitan agglomeration in Northern Germany. The city is located in the Elbe Estuary at the mouth of several smaller rivers into the Elbe River, about 110 km upstream from the North Sea (Gönnert and Müller 2014). The Elbe Estuary is the largest estuary on the German coast of the North Sea and an important waterway connecting Hamburg with the sea. Hamburg serves as an ideal case study for a complex urban flood risk study. Due to the existing physical environment and its special location, Hamburg is subject to a variety of flood hazards that are characteristic of coastal and inland cities (Bosserelle et al. 2022; Glavovic et al. 2022): sea-level rise and associated groundwater rise (groundwater flooding) as well as storm surges (coastal flooding) in the area of the Tidal

Table 1. Methodological framework of the model building process as proposed by Vennix (1996) and characteristics of the different stages of this study. The stages highlighted with * are the focus of this paper.

No.	Stages	Characteristics
1	*Problem identification and model purpose	Urban flood risks and sustainable climate change adaptation in the case study area
2	*System conceptualisation	Group interviews, mental modelling exercise, partial mental models, group model
3	*Model formulation	Qualitative system dynamics model (QSDM)
4	*Analysis of model behaviour	Analysis of systemic feedback loops and vicious cycles of barriers in adaptation processes within the city
5	Model evaluation	Model validity through stakeholder
6	Policy analysis	Analysis of leverage points for climate change adaptation, policy measures and analysis of the potential for their implementation
7	Model use	Use of the QSDM as a consultative tool in decision-making processes and for scenario testing

Elbe; hinterland/fluvial flooding in the area of inland waters; and pluvial flooding in all areas. Hamburg's particular vulnerability to both inland and coastal flooding may provide insights that could benefit other cities facing similar challenges.

The Port of Hamburg, which is one of the top three ports in Europe for trade (Schubert 2020), is the main German maritime hub for the country's exports and a major engine in regional wealth creation (Acciaro et al. 2020). What is special about it is that the port is a 'city harbour', one of the few worldwide, which takes up around 10% of Hamburg's area (Schubert 2020). From a historical perspective, the port has been a central part of the city's identity as a city of trade. The port-city relationship is characterised by shared development paths with private and public actors working together and sharing common values around shipping and trade, which has pointed the way for both the expanding port and the growing city. While waterfront development initiatives are intended to reconnect the city and the older port areas in a sustainable way, new port infrastructures have been created south and further downstream of the Elbe River. In the future, however, conflicts between the port and the city are likely to intensify, especially as demand for housing increases and port expansion is constrained by the state boundaries (Acciaro et al. 2020; Schubert 2020; Hein and Schubert 2021). Likewise, environmental conflicts over the deepening of the river for shipping and the disposal of dredged material have intensified, and the demands of structural change are leading to a rethinking of the role of the port in urban development.

A special characteristic of the governance context in the case study city is that Hamburg is a city-state, i.e. Hamburg is a municipality and at the same time one of the 16 federal states of Germany. On the city-level, Hamburg is divided into seven districts that are responsible for local issues. Also, some public tasks have been put in the hands of public companies, such as water supply and wastewater disposal, waste treatment and port management. The resulting multilevel governance system is characterised by overlapping administrative functions and responsibilities as well as numerous vertical and horizontal interdependencies. At the European and transnational level, Hamburg cooperates with its partners in city networks such as Climate Alliance (since 1993), Covenant of Mayors (since 2008), ICLEI (Local Governments for Sustainability; since 2008), or METREX (Network of European Metropolitan Regions and Areas).

Hamburg has been engaged in climate protection policy since 1990 with parallel activities in the area of adaptation to climate change (HmbBü-Drs. 21/2521 2015). When Hamburg joined the Aalborg-Agenda in 1996, responsibility for climate adaptation and mitigation was officially transferred to the Ministry for Environment and Energy of Hamburg, which has since been reorganised as the Ministry for Environment, Climate, Energy and Agriculture (BUKEA: Behörde für Umwelt, Klima, Energie und Agrarwirtschaft). This ministry also has the official duty to take care of flood protection in Hamburg, which it has delegated to the local authority for streets, bridges and water bodies (LSBG: Landesbetrieb Straßen, Brücken und Gewässer), a service provider for the Hamburg administration (Mees et al. 2013). Since 2007, the Coordination Unit for Climate Issues of the city government (LSK: Leitstelle Klima) has taken on a formal role in harmonising approaches and developing planning documents to guide climate-related policy activities at the city level (Kohler et al. 2021). The Senate Commission for Climate Protection and Mobility Transition (Senatskommision für Klimaschutz und Mobilitätswende), established in 2020, is also relevant in this context. This commission, led by the First Mayor, is a cross-departmental coordination body to support the implementation of the Hamburg Climate Plan and the local mobility transition. In order to take account of the increasing importance of adaptation in Hamburg, a separated Coordination Unit for Climate Adaptation/Rain InfraStructure Adaption (SKR: Stabstelle Klimafolgenanpassung/RISA) was set up in 2020. It coordinates Hamburg's activities to adapt to the impacts of climate change and leads the implementation of the adaptation of urban rainwater infrastructure.

Looking at the historical development of water adaptation in Hamburg, dyke improvements and thus conventional flood management measures that follow a 'dominant *defense* paradigm' (Mees et al. 2013, p. 3) were at the forefront. Technical coastal flood protection in Hamburg comprises public flood protection (more than 100 km of dykes and walls), private flood protection (mainly as individual object protection in the HafenCity) and flood protection in the harbour area (Gönnert and Müller 2014; Müller and Gönnert 2014). To ensure long-term security against floods, the level of protection of the public flood protection facilities is constantly reviewed. In order to take climate change into account, a construction program is currently being implemented to reinforce the dykes by a further 80–100 cm to ensure the necessary flood safety until 2050 (Mees et al. 2013; Müller and Gönnert 2014). Improved information and risk communication for the affected citizens serve as a further flood protection instrument.

However, there are indications that perceptions of risks and adaptation to water risks in Hamburg are beginning to change (Hanf et al. 2024a). Innovative 'adaptive flood risk governance' approaches include, for example, network arrangements with joint public–private responsibilities. In contrast to traditional flood management, they focus on managing water through strategies such as 'space for the rivers' and 'managed retreat' to reduce the impacts of floods (Mees et al. 2014). In Hamburg, HafenCity is one of the largest urban regeneration projects in Europe, transforming former port areas into residential areas. The so-called 'Warftenkonzept' of the HafenCity, where buildings are constructed on elevated plots at heights of + 7,5 m NHN and more (NHN: Normalhöhennull is the standard elevation zero of the German reference height system and corresponds approximately to the mean sea level), as well as built-in flood resistance strategies (i.e. flood protection measures to individual buildings) and civic flood protection communities are examples of 'living with water' (Knieling and Fellmer 2013).

Another example reflects a development towards an innovative approach in wastewater and especially in stormwater adaptation and management in Hamburg. The State Ministry for Environment and Energy together with the municipal water supply and wastewater disposal authority Hamburg Wasser launched the project 'Rain InfraStructure Adaption' (RISA, 2009–2015) to develop a strategy for sustainable rainwater management that goes beyond conventional rainwater drainage. In order to address the intensifying conflicts related to urban development and stormwater management, a concept for decentralised water management was developed that aims to achieve a near-natural local water balance (Bertram et al. 2017). The project became the starting point for an improved integration of water management issues into urban and regional planning and a corresponding adaptation of the institutional framework. The resulting strategy, the 'Structural Plan Rainwater 2030', has become part of the climate protection concept and the climate change adaptation strategy of the state of Hamburg (Hamburg Wasser 2023).

4. Application of the framework – Qualitative modelling of the coupled urban *socio-ecological system* of Hamburg

In the following, we present and discuss the first four stages of the qualitative modelling framework outlined in Section 2, which was empirically applied using the city of Hamburg, Germany, as a case study. Figure 1 summarises the model building process and

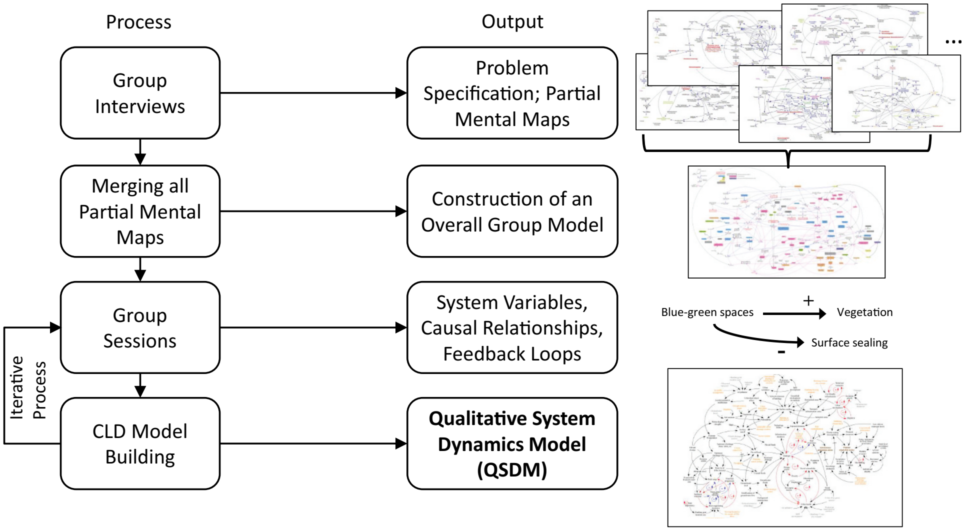


Figure 1. Schematic overview of the model building process for the case study of the city of Hamburg, Germany.

the respective outputs. Although presented linearly, some stages of the process were generally conducted iteratively, with some loops between them.

4.1. Stages 1 and 2 – Problem identification, model purpose and system conceptualisation

4.1.1. Group interviews and mental modelling exercise

The participatory model building process was initiated by a mental modelling exercise in the form of group interviews. The aim of this mental modelling exercise was not to produce fully developed CLDs, but to capture disciplinary views of the complex problem to be addressed in order to develop a shared understanding of it. The problem to be explored was defined by the context of the research project (see Hanf et al. 2024b) in which this study was embedded: 'the complexity of flood risk and sustainable climate change adaptation in cities'.

Thirteen group interviews were carried out with researchers from different disciplines centred on the topics of urban water risks, climate change and adaptation options for the city of Hamburg. Each group was composed according to its overarching field of expertise.[1] The size of the groups varied between one and six persons. All interviews had to be conducted online due to restrictions during the COVID-19 pandemic. The participants involved in the group interviews gave written informed consent prior to the data collection. The first author acted as a facilitator and opened each of the interviews with a 15-min introduction to the purpose of the mental modelling exercise and the basics of building a CLD based on Vennix (1996). The group interviews lasted between 90 and 140 min, depending on the size of the group. The qualitative interviews were structured according to the interview guide approach Vennix (1996). In each group interview, a disciplinary *mental model* (i.e. a 'view of reality'; Vennix 1996) was created together with the interviewees representing each group's view on the problem. The facilitator asked questions to help each group to develop their own mental model. A data manager assisted the facilitator in capturing the information directly in the SD software Vensim PLE (Ventana Systems 2021). The participants were asked to identify current and future water risks and conflicts related to climate change for the case study area, their causes and consequences as well as relevant actors, responsibilities, and already existing intervention measures and future options for action. These were then recorded in the form of a qualitative model and colour-coded for clarity. The predetermined topics and questions ensured that similar information was collected from each group, but still allowed a certain degree of freedom and adaptability. Throughout the interview process, both the facilitator and the data manager remained neutral to ensure the development of unbiased mental models.

Typically, CLDs are already developed in such a mental modelling process to capture the views and ideas of the participants (e.g. Inam et al. 2015; Valencia Cotera et al. 2022). However, we deviated from this approach by not strictly adhering to the syntax of CLDs when the disciplinary groups were first asked to build a visual understanding of the problem. It was difficult for the participants to engage with the specific syntax in the short time available, and it was therefore more important to capture the general perspective on the problem. The development of a CLD took place at a later stage in our approach. One advantage of the online process was that every participant could follow the creation of the model live on screen and initiate corrections at any time. By the end of this mental modelling exercise, a total of 13 disciplinary mental models had been created.

4.1.2. Construction of an overall group model

Following the group interviews, an overall group model was constructed by analysing, comparing and merging all 13 partial mental models. The resulting model aims at representing the divergent perspectives of all disciplines of the research team regarding the problem. The overall group model was developed using the visual workspace MURAL (https://www.mural.co/), which enabled a flexible feedback process by all participants during the subsequent online group sessions (an idea that arose due to the restrictions during the COVID-19 pandemic). It should be noted that at this stage the model was still a mental model and not a CLD.

Merging partial models of several experts' views can improve the details of the overall model so that sub-processes on different aspects of the problem can be identified (Perrone et al. 2020). However, the merging process is not just about putting the partial models together, but rather about identifying similarities as well as dissimilarities and missing information in the models that form a starting point for further discussion (Vennix 1996). There are various methods for building a preliminary QSDM based on individual models (e.g. Inam et al. 2015; Valencia Cotera et al. 2022). This study used the approach of Inam et al. (2015)[2] to generate a merged model. However, instead of building the overall group model on one of the partial models, this study started with a blank sheet of paper. The 13 partial mental models were compared and analysed to identify complementary and controversial elements (i.e. variables and relationships). All model elements from all partial models were added to the blank sheet. In doing so, we carried out an inclusive process. Controversial and conflicting elements were included and highlighted (e.g. colour-coded) in the merged model for subsequent discussions with the whole research team. In case of variables with the same meaning (e.g. 'vegetation' and 'urban green'), only one variable was added to the merged model, but it was highlighted in colour and the multiple labels were presented to the group for joint decision-making. The merging was done by the first author, who took on the role of a facilitator during the disciplinary group interviews.

4.2. Stage 3 – Model formulation

4.2.1. Group sessions – Towards a QSDM

Once the overall group model had been created, several online and two face-to-face workshops were held to further develop the model, validate the variables and develop the actual causal relationships between them (i.e. the polarity of the relationships). This step was an iterative process. During these group sessions, the key variables of the system were identified in order to condense the merged model and develop the actual QSDM in the form of a CLD using Vensim PLE (Ventana Systems 2021). Controversial elements were discussed and clarified together. Only the model elements that the research team considered relevant to understanding the problem were kept. In addition, new variables from secondary sources, such as the Hamburg Climate Futures Outlook 2023 (Engels et al. 2023), were included in the model after joint discussion and agreement within the research team. The research team has also carefully reviewed the wording of the variable names and revised them where necessary so that they are clear and concise, and can take high or low values as required in SD modelling (Vennix 1996). The whole process allowed the exchange of ideas between the disciplinary groups and a joint integration of these. In the online sessions, the visual workspace MURAL was used as an online forum to discuss the model. In the face-to-face workshops, printouts of the model were used and the ideas that arose during the discussions were collected using flip-charts and post-it notes.

In addition to the QSDM (Figure 2), a jointly developed glossary of system variables was produced as an output of the group sessions (see Supplementary Material 2). Both the visual representation of the problem and the glossary served as *boundary objects* for the interdisciplinary research team and contributed to collective meaning-making (Black 2013).

4.3. Stage 4 – Analysis of model behaviour

In a next step, sub-processes of the QSDM were brought into focus for detailed analysis. This is necessary because the level of detail and sheer size of the overall model (number of variables and relationships) can be overwhelming and is not intuitive. Complexity is a problem in SD modelling because 'it restricts the ability of stakeholder with limited modelling skills to understand complex holistic systems' (Perrone et al. 2020, p. 8). Behavioural and neural studies have shown that there is an upper limit to the amount of visual elements that can be processed simultaneously by humans and actively maintained in working memory (e.g. Miller 1956; Fukuda et al. 2010).

Bearing these aspects in mind, causal chains of interconnected thematic sub-processes (see Supplementary Material 1) and feedback loops (Figure 3) were visually isolated for emphasis according to the approach for structured model analysis of Egerer et al. (2021). However, it is important to note that the thematic sub-processes should not be regarded in isolation; they are linked by common system variables and are thus part of the overall system structure. The overall objective was a process-oriented analysis of the structure and dynamics of the coupled *socio-ecological system* and not a disciplinary analysis. The method of subdividing the QSDM into interconnected thematic sub-models to handle system complexity is very common in SD modelling (e.g. Purwanto et al. 2019; Perrone et al. 2020; Coletta et al. 2024). For this study, the participants worked in small groups (grouped according to their area of expertise and the thematic sub-processes) to further elaborate the dynamics and feedback structures of the sub-processes. This procedure helped to gain deeper insights into the various interconnected thematic sub-processes and to actually identify feedback loops within the system. The results were brought together again into an overall synthesis focusing on the systemic feedback effects of the coupled urban system.

5. Results

This section presents the final QSDM (Figure 2), its system structure (Subsection 5.1) and dynamics (Subsection 5.2). For the sake of brevity, only the feedback loops identified in the model (Figure 3) and their implications for urban adaptation are presented and discussed in Subsection 5.2. For a detailed analysis of the individual thematic sub-processes, the reader is referred to Supplementary Material 1.

5.1. The QSDM structure

The QSDM (Figure 2) shows the important system elements and qualitative dynamics of the urban system, focusing on the problem of urban flood risks in the context of *water from 4 sides* and climate change adaptation in the city of Hamburg. The model is built upon the IPCC risk framing (IPCC 2022). According to this risk framing, risk can arise from the potential impacts of (i) climate change resulting from the dynamic interactions between climate-related hazards, exposure and vulnerability of the affected human or ecological system, as well as (ii) human responses to climate change not achieving the intended objectives (Reisinger et al. 2020; Ara Begum et al. 2022). In this study, we build on this dynamic approach and introduce *Damage* as a central variable in our model. *Damage* refers here to 'adverse observed impacts and/or projected risks that can be economic and/or non-economic' IPCC (2022, p. 7) in the context of urban flooding. Given this dynamic risk approach, damage from flooding can be reduced, even if the frequency of flooding increases, if intervention measures are taken to reduce the exposure or the vulnerability of the affected systems, or both (Reisinger et al. 2020). For Hamburg, we take into account that damage from flooding can be caused by the interaction of any of the flood hazards (i.e. pluvial floods, fluvial floods, coastal floods or groundwater floods) with the exposure of the affected system (i.e. exposed elements such as people, buildings, infrastructure, etc.) and the social vulnerability of the urban population (i.e. the propensity or predisposition of the urban society to be adversely affected). It should be noted that vulnerability in the model is only conceptualised in terms of the vulnerability of the urban society (i.e. social vulnerability; von Szombathely et al. 2023). This is related to the expertise of the participants involved and represents a limitation of the study. With regard to 'compound flooding' in coastal settings (Santos et al. 2021), flood damage for Hamburg can also result from the interaction of multiple flood hazards.

Overall, the model includes 97 variables related to biophysical/environmental, human, socio-economic, institutional and political dimensions. All model variables are described in Table S2 (Supplementary Material 2). The variables in orange represent interventions measures identified by the research team that modify the state of the system and its dynamics. Variables in brown highlight the two different classification types of adaptation: *Autonomous adaptation action* and *Planned adaptation action*. These variables are meant to represent all other interventions in the model (i.e. the variables marked in orange). In a 3D representation of the model, these two would therefore appear as a third dimension. This is important in terms of the links within the model, because it means that these two model variables (i.e. *Autonomous adaptation action* and *Planned adaptation action*) are linked to the rest of the model.

5.2. Model dynamics and feedback loops

A central concept of SD is that system behaviour evolves through reinforcing and balancing feedback loops that promote balance or imbalance in a system (Muttalib et al. 2021). So unravelling and understanding the system's feedback loops (especially reinforcing feedback loops) helps to understand why and how system behaviour evolves in a certain direction. For this study, this means whether urban flood risk is reinforced or weakened and whether adaptation processes within the city are inhibited or promoted by the system's own dynamics and feedback processes.

We identified a total of 11 reinforcing and 4 balancing feedback loops in the model. These 15 feedback

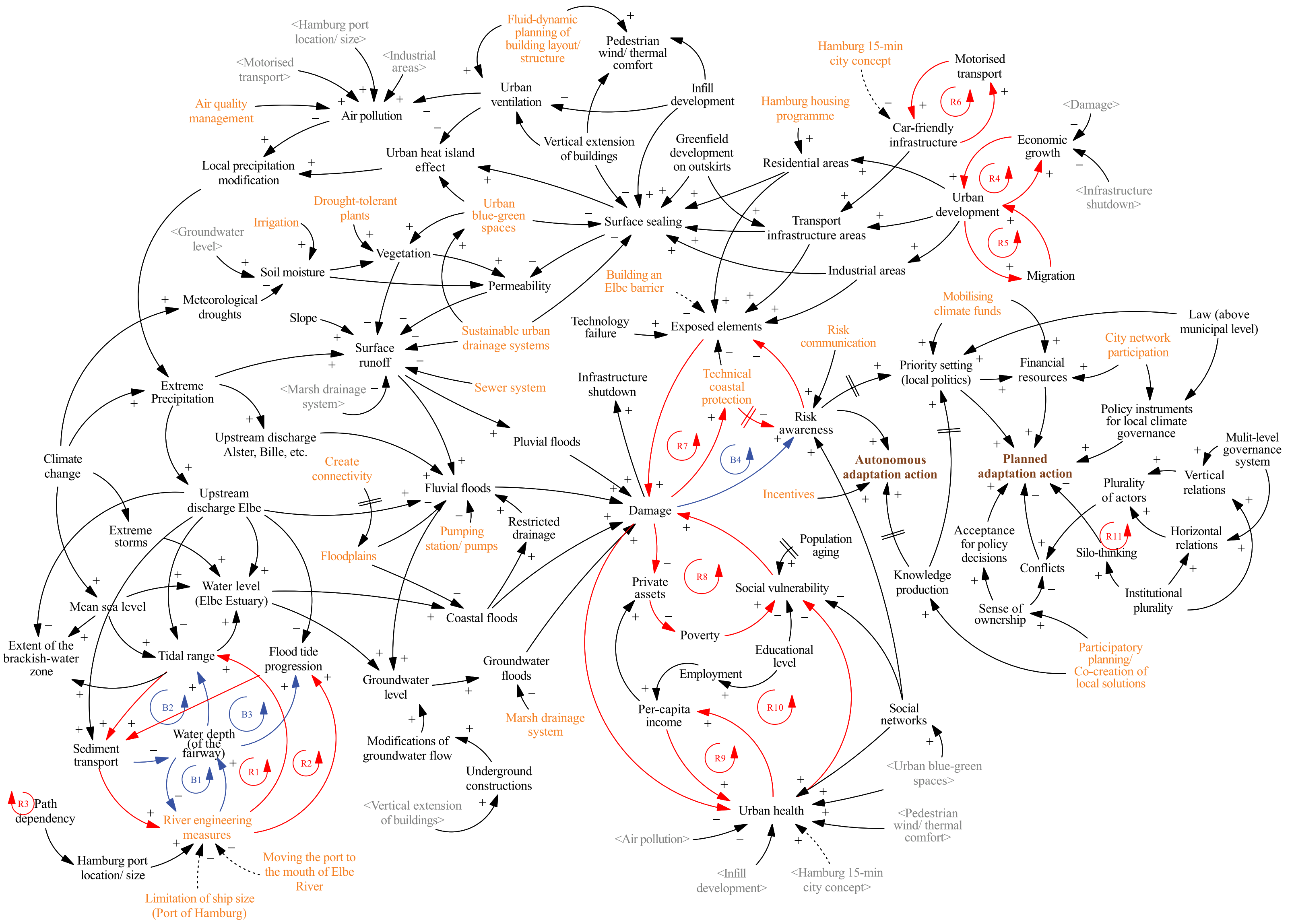


Figure 2. QSDM of the coupled urban socio-ecological system of Hamburg. Variables in orange indicate intervention measures that are considered relevant; variables in brown highlight the two different classification types of adaptation. Variables with angle brackets represent shadow variables that refer to variables already defined elsewhere in the model and help to reduce clutter and increase clarity (Ventana Systems 2021). Arrows with + (–) indicate positive (negative) causal relationships. Dashed arrows denote possible future causal relationships. Arrows without a sign mean that there is either a positive and a negative causal relationship between the linked variables depending on the variable state or that a clear causal effect has not yet been scientifically proven. Double hash marks || on the arrows indicate time delays that are considered relevant to the dynamics of the system. Balancing (B) and reinforcing (R) feedback loops are highlighted in blue and red, respectively.

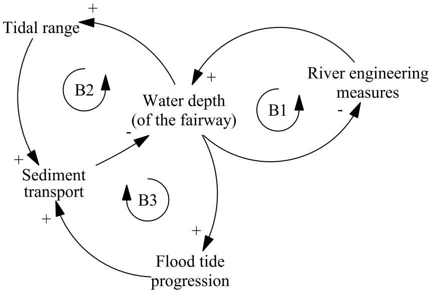
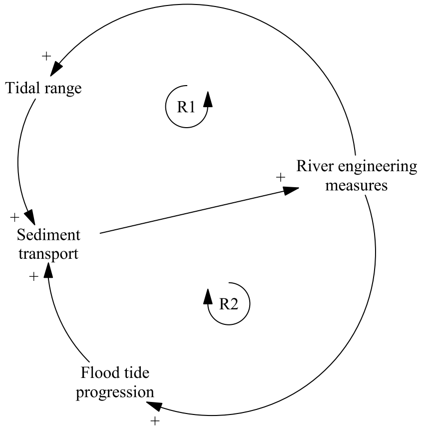
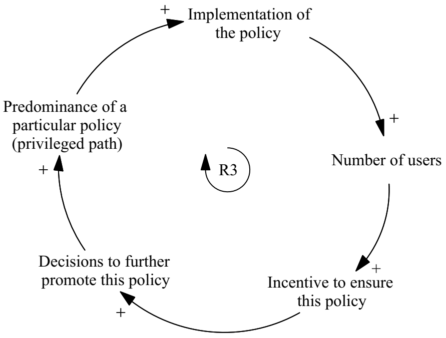
Feedback Loops	Description of the Feedback Stories
(a) Morphological equilibrium of the estuary – Loops B1, B2, B3 	Given a political objective to maintain a certain water depth in the Elbe fairway, *River engineering measures* are required as long as *Water depth* is insufficient for safe navigation (B1). However, physical processes act towards an equilibrium configuration of the estuary (Bolla Pittaluga et al. 2015); i.e. to achieve a morphological equilibrium of the estuary with a balance between tide-induced up-estuary transport and down-estuary transport (Dronkers 2017). Increased *Water depth* increases both the *Tidal range* and the *Flood tide progression*, which in turn increase the tide-induced up-estuary *Sediment transport*. Both are compensatory processes that reduce the previously increased *Water depth* of the fairway (B2 and B3).
(b) River engineering measure and sediment transport loops – R1 and R2 	The feedback loops R1 and R2 explain why river engineering measures are an ongoing process. *River engineering measures* increase the water depth in the navigation channel. However, these measures also lead to an increase in *Sediment transport* by increasing the *Tidal range* and the *Flood tide progression*. This in turn makes further maintenance measures necessary, leading to further *River engineering measures*.
(c) Path dependency loop – R3 	*Path dependency* can be understood as 'social processes that exhibit positive feedback' (Pierson 2004) and thus generate self-reinforcing dynamics. Path dependency is conceptualised here in terms of public policy and political processes. The choice of a particular policy leads to the implementation of this policy and the introduction of a certain practice. With each year that this policy continues to be implemented, the number of users increases and with it the incentive to maintain the system, which in turn leads to the dominance of that policy. Overall, the path dependency loop (R3) explains the reinforcing feedback effect that creates continuity.

Figure 3. Balancing (B) and reinforcing (R) feedback loops identified in the QSDM. (a) Morphological equilibrium of the estuary – Loops B1, B2 and B3. (b) River engineering measures and sediment transport loops – R1 and R2. (c) Path dependency loop – R3. (d) Urban development loops – R4 and R5. (e) Car dependency loop – R6. (f) Risk awareness and "levee effect" loops – B4 and R7. (g) Poverty loop – R8. (h) Urban health and health-related damage loop – R9. (i) Urban health and income loop – R10. (j) Silo-thinking loop – R11.

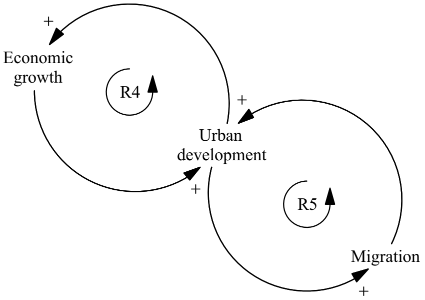
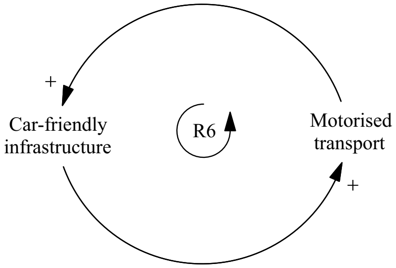
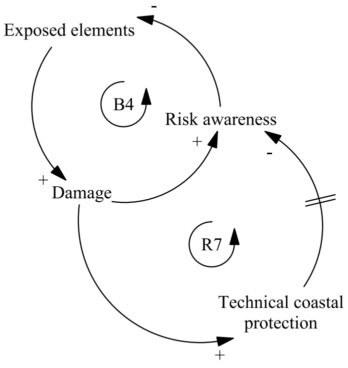
Feedback Loops	Description of the Feedback Stories
(d) Urban development loops – R4 and R5  	Urbanisation is a complex socio-economic process (UN 2019). Here, the reinforcing processes of economic growth, urban development and migration are conceptualised in the feedback loops R4 and R5. *Economic growth* promotes the spread of modern industries, an in-crease in urban population and *Urban development*; in turn, *Urban development*, also promotes *Economic growth* to some extent through economies of scale in infrastructure and advantages in capital, labour and managerial resources (Chen et al. 2014; Liddle and Messinis 2015; Martin and Ottaviano 2001; Mahtta et al. 2022). The process of industrialisation in urban areas attracts rural labour forces to cities for employment prospects and is a key reason for urban *Migration*. In addition, *Urban development* can encourage people to move from rural to urban areas for opportunities such as access to culture, education and health care (Liddle and Messinis 2015). *Migration* to the cities in turn leads to further *Urban development*.
(e) Car dependency loop – R6  	The car dependency loop (R6) summarises the reinforcing process of car-friendly infrastructures and motorised transport. Modal split behaviour is the result of a complex inter-play of man-made factors such as infrastructure, traffic system organisation, costs, convenience, lifestyle and housing preferences and advertising. Human behaviour depends on "irritation from the environment", with car oriented environment leading to car mobility (Knoflacher 1991, p.79). The existence and expansion of *Car-friendly infrastructure* attracts more *Motorised transport*. Conversely, more people using *Motorised transport* leads to more *Car-friendly infrastructure*.
(f) Risk awareness and "levee effect" loops – B4 and R7  	Environmental disasters and the associated *Damage* create a "community memory" (de Guttry and Ratter 2022) which leads to higher levels of *Risk awareness*. This in turn reduces the number of *Exposed elements* assuming that increased risk awareness increases self-protective action, leading to less *Damage* in case of another flood event (B4). Structural flood protection (e.g. dykes) favours the loss of "flood memory" by consistently reducing the frequency of flood events (Climate-ADAPT 2023). The result is increasing exposure in flood-prone areas (e.g. through increased development on floodplains; Serra-Llobet et al. 2022). Against the background of this so-called "levee effect", increased *Technical coastal protection* can lead to lower *Risk awareness* in the long term (delay), which in turn increases the number of *Exposed elements*, resulting in higher *Damage* from flooding in case of an extreme event (R7)

Figure 3. (Continued).

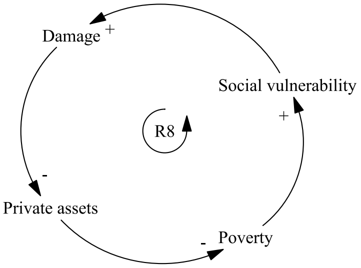
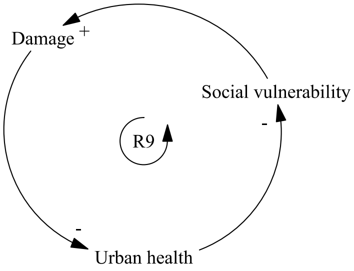
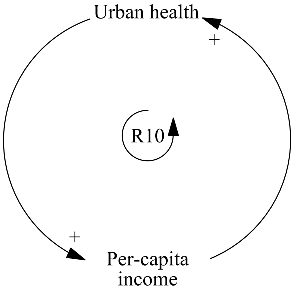
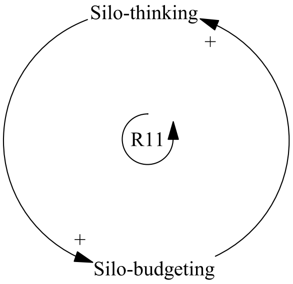
Feedback Loops	Description of the Feedback Stories
(g) Poverty loop – R8  	While poverty is a multi-dimensional construct, it is contextualised here around flood damage and loss of private assets. *Damage* reduces *Private assets*, which can lead to *Poverty* or worsen existing poverty. This increases *Social vulnerability*, which in turn increases the likelihood of higher *Damage* in case of another flood event. Overall, the poverty loop (R8) explains the reinforcing effect of damage, poverty and social vulnerability.
(h) Urban health and health-related damage loop – R9  	The feedback loop (R9) summarises the reinforcing effects of damage, urban health and social vulnerability. Among other aspects, social vulnerability is directly linked to the health of urban residents (e.g. Fatemi 2017; Foster et al. 2019), which involves both objective (physical health) and subjective (mental health) dimensions (Krefis et al. 2018). As urban flooding entails not only economic burden but also health-related *Damage* (e.g. through contact with contaminated water and mental stress issues in case of pluvial flooding and sewer overflows; Mobini et al. 2020), *Social vulnerability* may be reinforced by poorer *Urban health*, which in turn increases the likelihood of higher *Damage* in case of another flood event.
(i) Urban health and income loop – R10  	Another health-related reinforcing feedback loop (R10) is associated with household income. Higher *Per-capita income* enables better access to better nutrition, which can promote health (e.g. by reducing the prevalence of obesity), and also provides more access to health services. Better *Urban health* in turn promotes higher *Per-capita income* through fewer sick days and higher efficiency (Eker and Ilmola-Sheppard 2020).
(j) Silo thinking loop – R11  	Public administrations tend to operate in silos, i.e. sectoral divisions of the management either by task or thematic area (Oseland 2019). Resource allocation and *Silo-budgeting* practices within silo-oriented administrative structures contribute to inefficiency and limited progress. The existence of silo budgets creates incentives that prioritise sectorial goals over collective goals (i.e. *Silo-thinking*), which hinders cross-departmental collaboration and integrated solutions (Bohman et al. 2020; Dorst et al. 2022). This is manifested in the reinforcing feedback loop R11, where existing structures and behaviours become self-reinforcing and resistant to change, leading to institutional lock-in.

Figure 3. (Continued).

loops are highlighted in blue (balancing feedback loops; B) and red (reinforcing feedback loops; R) in the QSDM (see Figure 2). To make the processes depicted in the feedback loops more understandable and concrete, especially for non-technical users, they are visually isolated and shown in Figure 3a-j together with a description of the individual 'feedback stories' (i.e. descriptions of the real-world processes that the feedback loops attempt to represent; Rajah and Kopainsky 2024). In the following subsections, we present the results of the detailed analysis of the system's feedback loops.

5.2.1. *Morphological equilibrium of the estuary, river engineering measures and sediment transport – Loops B1, B2, B3, R1 and R2*

Since approximately the thirteenth century, the tidal Elbe has been considerably altered by river engineering measures to ensure safe ship navigation to the port of Hamburg and for coastal protection. Since 1834, effective devices were available to undertake major changes to the navigation channel (Boehlich and Strotmann 2008). The increase in storm surge heights recorded since 1962 is mainly associated with coastal protection measures and other factors such as the loss of shallow water through land reclaiming as well as modifications of the navigation channel and in the harbour basins of Hamburg (von Storch et al. 2008). Also, primarily associated with conducted river engineering measures over the last century, the tidal[3] Elbe River showed a critical evolution of tidal wave transformation. Since 1880, the tidal range doubled from 1.9 m to 3.8 m in the port of Hamburg (Hein et al. 2021). The gradient of the mean high tide has increased from Glückstadt to Hamburg (Boehlich and Strotmann 2008), which means that the tidal wave progresses faster in Hamburg than downstream. During storm surges, this can cause the wind-enhanced tidal waves to propagate faster and with higher extreme water levels, thus increasing the hazard of coastal flooding for Hamburg. The stronger flood currents and relatively weaker ebb currents have led to a net effect of an increased flood tide induced up-estuary sediment transport towards the Hamburg region (von Storch et al. 2008). To cope with these difficulties in the Elbe, the annual costs for maintaining the waterway run into the tens to hundreds of millions (Hein et al. 2021).

Provided the political goal is to accommodate ships with a certain draught by maintaining a certain water depth in the Elbe fairway, river engineering measures will be necessary as long as water depth is insufficient for safe navigation. This balancing loop (B1; Figure 3a) illustrates that water depth and river engineering measures are linked to each other by a feedback process. However, physical processes act towards an equilibrium configuration of the estuary (Bolla Pittaluga et al. 2015); i.e. to achieve a morphological equilibrium of the estuary with a balance between tide-induced up-estuary transport and down-estuary transport (Dronkers 2017). The increased water depth of the fairway due to river engineering measures increases the tide-induced up-estuary sediment transport, a compensatory process which in turn reduces the previously increased water depth of the fairway (see two balancing loops B2 and B3; Figure 3a). This means that river engineering measures will be necessary again and again. The measures lead to an increase in sediment transport, which in turn requires further maintenance measures, as illustrated by the two reinforcing feedback loops R1 and R2 (Figure 3b).

The cumulative impacts of human activity and climate change may cause threshold values to be exceeded, which in turn would significantly alter the morphology of the estuary (i.e. reaching 'a tipping point towards a regime shift'; Wang et al. (2015), p. 8). This would jeopardise the environmental sustainability of the entire tidal basin. In this case, the return to a new state of equilibrium may be associated with a different new morphological state of equilibrium (e.g. a deeper estuary associated with irreversible changes in sediment transport), as discussed, for example, in Wang et al. (2015) for the Western Scheldt Estuary in the Netherlands.

5.2.2. *Path dependency – Loop R3*

Enduring trajectories of institutional development where some pathways are privileged over others and where ongoing decisions almost necessarily follow these privileged paths, refer to path dependency (Hein and Schubert 2021). Path dependency must be seen against the background of the availability of other alternatives from which to choose. The idea of path dependence emphasises that 'history matters' (Sorensen 2015, p. 21). Path-dependent processes can be understood as 'social processes that exhibit positive feedback' (Pierson 2004) and thus generate self-reinforcing dynamics. Looking at path dependency in terms of public policy and political processes, the choice of a particular policy leads to the adoption of that policy and the implementation of a particular system/practice. With each year that the system grows (i.e. further implementation of the policy), the number of users increases and so does the incentive to maintain the system, which in turn leads to the dominance of that policy. Path dependency is thus linked to a reinforcing feedback loop (R3; Figure 3c) that creates continuity. Many decision-making processes taken in seaport cities at the beginning of the nineteenth century (e.g. the organisation of port operations, the type of port development, the redevelopment of port areas) had a major impact and are still effective in terms of infrastructures in city and port development today (Schubert 2020; Hein and Schubert 2021). Notteboom et al. (2013), in a study on path dependence and lock-in for seaports, conclude that a process of institutional stretching takes place (i.e. existing institutional arrangements are stretched to accommodate new routines) when port authorities see a need to develop new capabilities and activities, gradually leading to formalised governance reforms but without breaking out of the existing path of development.

For Hamburg, an important decision to this day was the development of the port as an open-tidal seaport, not as a dock port like London (Schubert 2020). The Port of Hamburg can thus be seen as embedded in a shared maritime development path that determines the functioning of the port and the city in the long term (Hein and Schubert 2021). The trend towards ever larger vessels necessitates further dredging of the navigation channel (i.e. 'ships design the port'; Schubert 2020, p. 115). A possible future intervention measure to reduce the extent of dredging of the fairway would be to limit the size and associated draught of ships authorised to operate in the port of Hamburg. A cooperation between the ports of northern Germany, Hamburg, Bremen and Wilhelmshaven, could counteract possible future draught restrictions in Hamburg and strategically exploit the strengths of the individual ports in European competition. Another measure that was discussed in the 1960s and 1970s but not implemented is the relocation of the port to the mouth of the Elbe River as a deep-water port in the Wadden Sea region of the Elbe Estuary near Neuwerk-Scharhörn (Hundt et al. 1977; Schubert 2020). Today, these areas are strictly protected as part of the German Wadden Sea National Park, the largest tidal flat system in the world, which has been recognised by UNESCO as World Heritage (Wadden Sea World Heritage 2024).

5.2.3. *Urban development – Loops R4 and R5*

Exposure is the presence of people, livelihoods, species or ecosystems, environmental functions, services and resources, infrastructure and economic, social or cultural values in places and environments that could be adversely affected (IPCC 2021). Non-climatic factors can contribute to more elements being exposed to climate hazards, potentially increasing the magnitude of damage. Urbanisation is a complex socio-economic process that changes the environment by transforming formerly rural into urban settlements and at the same time shifting the spatial distribution of a population from rural to urban areas (UN 2019). Poorly planned and managed urban development where urban areas grew simultaneously larger and denser in hazardous areas, can translate into increased exposure of cities (Davis et al. 2015; Hemmati et al. 2020).

Urbanisation and economic growth are closely linked (Henderson 2010). It is generally accepted that economic growth promotes the spread of modern industries and an increase in urban population; in turn, urbanisation also promotes economic growth to some extent (Chen et al. 2014) via advantages in economies of scale in infrastructure, capital, labour and managerial resources (Liddle and Messinis 2015). The process of industrialisation, which attracts the rural labour forces to cities for employment prospects, is a key reason for urban migration. In addition, urban development can encourage people to move from rural to urban areas for opportunities such as access to culture, education and health care (Liddle and Messinis 2015). In summary, economic growth, urban development and migration are linked in two reinforcing feedback loops (R4 and R5; Figure 3d), indicating reinforcing processes (Martin and Ottaviano 2001; Gross and Ouyang 2021; Mahtta et al. 2022).

Climate change-related urban flood damage poses a threat to the city's economy, with infrastructure shutdowns having a negative impact. Critical infrastructures that provide services such as energy, water, sanitation, transport and communications are essential for socio-economic activities and are highly interdependent, so that failures in one system often affect other systems and the resulting losses are substantial (Chang 2016). In Hamburg, there is a network of technical coastal protection measures that reduces the exposure of the city and thus the risk from flooding. However, an unexpected and sudden technology failure of flood defences (such as dyke failure), could lead to catastrophic consequences (Climate-ADAPT 2023) and high damage due to a sudden increase of exposed elements in the flood-prone area. The possible intervention measure of building an Elbe barrier at the mouth of the Elbe River, which was discussed in 1960s and 1970s (Hein and Schubert 2021), would be a way to reduce the potential exposure of the city resulting in a lower flood risk, while restricting navigation (e.g. Seiffert and Hesser 2014).

The process of urbanisation generally involves new land take and soil sealing (Naumann et al. 2019). In context of urban development, increasing surface sealing can in turn influence surface runoff processes and the hazard of pluvial flooding. In growing urban areas, especially the need for new housing and expansion of residential infrastructures is driving land take (Pejchar et al. 2015; Ehrhardt et al. 2022). The demand for housing, in turn, depends in particular on the size of households, where a smaller household size is found to increase land take (Colsaet et al. 2018). In Hamburg, more than 50% of households are single-person households, with up to two-thirds in inner-city locations (Statistisches Amt für Hamburg und Schleswig-Holstein 2022). Additionally, the housing construction program formulated by the Hamburg Senate to create the conditions for 10,000 new flats per year (Freie und Hansestadt Hamburg 2023) possibly exacerbates the problem of land sealing through further expansion of residential areas.

While greenfield development on outskirts (i.e. conversion of areas not previously used for urban purposes on the urban fringe; Kent et al. 2019) and infill development (i.e. new development on vacant land within the city previously overlooked for urbanisation; Mohammadi-Hamidi et al. 2022; Xu and Ehlers 2022) generally increase the amount of land sealing, vertical extension of buildings (i.e. construction of new floors above existing buildings; Gillott et al. 2022) is identified as an opportunity to reduce additional surface sealing. Vertical extension of buildings, using the remaining buildable area of older buildings, has the positive side effect of refurbishing the housing block and improving standards for energy efficiency, safety and accessibility (Artés et al. 2017; Gillott et al. 2022). On the other hand, both vertical extension of buildings and infill development are associated with higher density urban living, which is increasingly criticised for negative effects on subjective wellbeing (Holden 2019). Greenfield development on the outskirts of cities can increase car-dependence (Kent et al. 2019) and the amount of transport infrastructure areas leading to more urban sealing. In addition, recent studies showed that commuting and wellbeing are closely related, with increased commute time leading to decreased indices of subjective wellbeing (Kent et al. 2019; Chatterjee et al. 2020). In Hamburg, the focus is currently on the densification of existing settlement areas (i.e. 'Hamburger Maß'; BSW 2020).

5.2.4. Car dependency – Loop R6

Modal split behaviour is the result of a complex interplay of man-made factors such as infrastructure, traffic system organisation, costs, convenience, lifestyle and housing preferences and advertising. Human behaviour depends on 'irritation from the environment', with car oriented environment leading to car mobility (Knoflacher 1991, p. 79). More car-friendly infrastructures lead to more motorised transport; conversely, more motorised transport leads to more car-friendly infrastructures. In summary, car-friendly infrastructures and motorised transport are linked by a reinforcing feedback loop (R6; Figure 3e). To reduce the amount of car mobility, the positive stimuli for car drivers have to be reduced (Knoflacher 1991), and incentives for a modal-shift from individual motorised mobility to substitutes such as biking, carpooling or public transport could also be made more attractive (Santos et al. 2013; Tyrinopoulos and Antoniou 2013; Lee et al. 2022). The 15-min city is an urban planning concept (Moreno 2019; Moreno et al. 2021) that aims to reduce car dependency and at the same time improves the general health and wellbeing of city dwellers. This approach is based on a greater mix of residential and commercial areas at neighbourhood level, so that city dwellers can reach basic services within 15 min of their homes, promoting walkability

(Whittle 2021). Currently, this 15-min city concept is also being discussed for the city of Hamburg (Hamburger Abendblatt 2023).

5.2.5. Risk awareness and 'levee effect' – Loops B4 and R7

Recognising the complexity of risk and the fact that 'risk is socially constructed' is a prerequisite for successful risk management (Slovic 1999, p. 690). Risk perception and awareness as well as consideration of historical framing are essential for developing risk management strategies that match societal needs and concerns (Gerkensmeier and Ratter 2018). People perceive the severity of a risk differently depending on where and when they live, their past experiences and how much it affects their daily lives (Zwickle and Wilson 2013). And without an awareness of the risks, 'self-protective action is not likely' (Poortvliet et al. 2020, p. 3). For instance, environmental disasters, in this case damage from urban flooding, firstly increases the community memory of a society (de Guttry and Ratter 2022) and thus leads to higher levels of awareness. This in turn can reduce the number of exposed elements if one hypothesises that increased risk awareness increases self-protective action leading to less damage in case of another flood event. This manifests in the balancing feedback loop B4 (Figure 3f).

Communicating risks can also create risk perceptions and risk awareness that eventually affect behaviours (Hemmati et al. 2021). Developing programmes to get people to take preventive, risk-reducing action requires a detailed understanding of their decision making (van der Pligt 1996). As disaster risk management is foremost a societal task (Gerkensmeier and Ratter 2018), this is also where the responsibility lies. In order to deconstruct the community's memories of catastrophic events, a continuous and dynamic learning process must develop within societies (Eiser et al. 2012). This means that disaster risk management needs to be addressed at both policy and community levels. Those who are most at risk have to be aware of this and be willing to take further steps, such as preventive measurements.

While technical coastal protection can reduce exposure to flood hazards, it can also promote the 'loss of flood' memory by consistently reducing the frequency of flood events (Climate-ADAPT 2023). This can lead to increasing exposure in flood-prone areas, commonly referred to as the 'levee effect' (Serra-Llobet et al. 2022; Climate-ADAPT 2023). The learning process has been shown to be very sensitive to changes in structural measures (e.g. dykes) to protect against flooding, with the decay rate of memory increasing significantly with the introduction of structural measures (Collenteur et al. 2015). With regard to Hamburg, massive investments have been made in technical coastal protection after the Great Flood of 1962 (von Storch et al. 2008). Against the background of the 'levee effect', it should be taken into account that increased technical coastal protection could lead to reduced risk awareness in the long term (marked by a delay in R7; Figure 3f), which could increase the number of exposed elements, resulting in higher damage from flooding in case of an extreme storm surge event. This process, which may be relevant for Hamburg manifests in the reinforcing feedback loop R7 (Figure 3f).

5.2.6. Poverty, urban health and income – Loops R8, R9 and R10

According to IPCC (2022) and von Szombathely et al. (2023), we define social vulnerability as the propensity or predisposition of the urban society to be adversely affected. Higher social vulnerability may be associated with higher risk and possibly with higher damage (in this case harm to human health). Social vulnerability is affected by factors as poverty, educational level and age (Fekete 2009; Holand et al. 2011; Foster et al. 2019). Higher levels of education can increase the likelihood of employment, which can increase per-capita income and ultimately the amount of private assets, which in turn result in less poverty and lower social vulnerability. The feedback loop R8 (Figure 3g) shows the reinforcing effect of damage, poverty and social vulnerability: higher damage reduces private assets resulting in more poverty and higher social vulnerability, which in turn could increase the possibility of higher damage in case of another flood event.

Additionally, social vulnerability is directly linked to the health of urban residents (e.g. Fatemi et al. 2017; Foster et al. 2019). Urban health involves both objective (physical health) as well as subjective (mental health) dimensions (Krefis et al. 2018). Urban health, social vulnerability and damage are interrelated by the reinforcing feedback loop R9 (Figure 3h): as urban flooding entails not only economic burden but also health-related damage (e.g. through contact with contaminated water and mental stress issues in case of pluvial flooding and sewer overflows; Mobini et al. 2020), social vulnerability may be reinforced by poorer health, which in turn could lead to higher damage in case of another flood event. Another health-related reinforcing feedback loop (R10; Figure 3i) is associated with household income. Higher per-capita income provides more access to better nutrition, reducing obesity prevalence, and more access to health services, and better urban health in turn promotes higher income through fewer sick days and higher efficiency (Eker and Ilmola-Sheppard 2020).

5.2.7. Silo-thinking – Loop R11

Public administrations tend to operate in silos. A silo is understood as the sectoral division of management, whether by tasks or thematic divisions; there are differences in institutional logics, working practices and culture between silos (Oseland 2019). Such division of responsibilities into sectors or silos hinders local climate planning and its implementation. Empirical evidence suggests that while climate change policy is an issue that affects a wide range of departments in local administrations, the expertise and responsibility for climate change policy tends to remain concentrated in the environmental department which may lead to problems in implementing comprehensive concepts (Kern and Alber 2009). Apart from these thematic silos, resource allocation and budgeting practices within silo-oriented administrative structures contribute to inefficiency and limited progress. The existence of silo budgets creates incentives that prioritise sectorial goals over collective goals, which hinders cross-departmental collaboration and integrated solutions (Bohman et al. 2020; Dorst et al. 2022). This is manifested in the reinforcing feedback loop R11 (Figure 3j), where existing structures and behaviours become self-reinforcing and resistant to change, leading to institutional lock-in. Increased silo-thinking can thus reduce the potential for planned adaptation action. To improve policy coherence towards sustainable development, a mindset that transcends political, institutional and mental silos is needed, and intervention measures such as raising awareness of existing mindsets and integrating informal cross-silo working into existing training programmes are recommended (Meuleman 2021).

6. Discussion

The integrated QSDM is characterised by being non-linear, but cyclical, giving the opportunity to consider complex feedback processes between environmental, social, economic, policy and institutional factors that govern the structure and dynamic behaviour of the urban system. The feedback loops that result from this interaction are of paramount importance for this study. They are seen as 'the main engine of change for the system' (Kotir et al. 2017, p. 114). To achieve transformative adaptation and systemic change in coupled human-environment systems, it is imperative to first identify the underlying drivers of the problems and their interrelations in order to respond to them. With this work, we demonstrate that using a system dynamics approach and integrating multiple disciplinary perspectives into a single model allows us to distil these intricate interactions and provides valuable insights into the systemic nature of urban flood risk. More specifically, this work shows that by unravelling and understanding the governing feedback processes, we are able to gain insights into the *vicious cycles of barriers* (i.e. reinforcing feedback loops; Meadows 2008; Zea-Reyes et al. 2021) that perpetuate and hinder the process of adapting to climate change in the city. This makes this article an important contribution to the literature on urban flood risk management and urban climate change adaptation.

In the remainder of this section, the *vicious cycles of barriers* in the city of Hamburg with regard to flood risk and their implications for adaptation strategies are discussed in Subsection 6.1, followed by a critical reflection on the qualitative modelling framework in Subsection 6.2

6.1. Overall system narrative – The *vicious cycles of barriers* of the coupled urban *socio-ecological system* of Hamburg

This study attempts to go beyond a pure description of the modelled feedback loops by connecting the individual feedback stories within the system to discuss an overall system narrative (Melles et al. 2021; Rajah and Kopainsky 2024). This feedback narrative makes the identified feedback structure more concrete (Rajah and Kopainsky 2024) and serves as an invitation to an integrated discussion and debate. Ultimately, it bridges the abstraction gap of the model and supports communication of the feedback processes to stakeholders.

The QSDM of the *socio-ecological system* of the city of Hamburg shows that with regard to flood risk the urban system is dominated by reinforcing feedback loops (see Figure 2). The dominance of reinforcing feedback loops indicates that with respect to flood risk there are 'sources of growth, erosion, and collapse' (Kotir et al. 2017, p. 114) in the urban system. This means that the system is characterised by an increase of flood risk due to their internal, systemic feedback processes that cascade and amplify negative effects within the system, even in the absence of further flood hazards. This can be associated with 'systemic risk' (Sillmann et al. 2022). Without sustainable adaptation actions that go beyond conventional risk management and governance, the system is likely to reach a state where it becomes challenging to manage.

Path dependency (feedback loop R3) in relation to the port of Hamburg poses a major barrier to sustainable adaptation. Continuous river engineering measures on the Elbe River represent lock-in effects that ultimately pose a threat of reaching a tipping point towards a regime shift in the entire Elbe Estuary (Wang et al. 2015). These measures are triggered, on the one hand, by the demand for ever larger ships in the port of Hamburg (Schubert 2020) and, on the other hand, by the constantly increased up-estuary sediment transport (due to the river engineering measures; feedback loops R1 and R2). Measures to overcome this vicious cycle, e.g. limiting the size or draught of ships, involve trade-offs with other policy goals, such as economic growth. It is possible that these management options become more attractive, the closer the Elbe ecosystem gets to the mentioned tipping point. London is an example of a global city with an 'outplaced port' (Hein and Schubert 2021, p. 391). The historical 'integration of port city functions has given way to separate development paths for port and city' (Hein and Schubert 2021, p. 398), i.e. the seaport has been relocated and only its administration is based in the city centre. Cooperation between the North German ports could also counteract possible future draught restrictions in Hamburg and strategically exploit the strengths of the individual ports in European competition.

From a system dynamics point of view, i.e. thinking in terms of feedback processes, the interrelation between urban development, economic growth and migration (feedback loops R4 and R5) represent sources of increased flood risk in the urban system. Economic growth usually results in increased job opportunities and agglomeration of amenities which are significant factors driving migration into urban areas. The resulting increased demand of housing is a major cause of urban development and associated surface sealing (e.g. Pejchar et al. 2015), which in turn increases the surface runoff potential of the urban system and thus the hazard of pluvial floods. Furthermore, economic growth and new urban developments, particularly in flood-prone areas, and associated increasing values at risk represent a high impact driver for urban flood risk (Berndtsson et al. 2019). Balancing new urban development in ways of sustainable urban planning is crucial in mediating urban flood risk. It is thus important to discuss adaptation in a broader framework of sustainable development and identify relevant trade-offs and synergies between adaptation measures and other relevant policy goals (Dodman et al. 2022; Glavovic et al. 2022; Gresse et al. 2023) such as the provision of affordable housing or climate mitigation.

Another major barrier is the lock-in effect triggered by the continued car dependency of the urban system. The regime of automobility envisioned by urban planners across the US, Europe and elsewhere during the post-World War period is now widely regarded as a failure (Haarstad et al. 2022). However, the lock-in effects of this past failure persist and also hinder transformative innovations. New technologies are mostly locked into the infrastructure of the automobilty regime (e.g. by the existing road network), which justifies further investments in that infrastructure. This vicious cycle of increasingly car-friendly infrastructures (feedback loop R6) also exacerbates the land-use conflict as well as surface sealing. To break this vicious cycle and reduce the share of car-based mobility and infrastructures in cities, positive incentives for car drivers have to be reduced, i.e. the 'car oriented environment' has to be changed in favour of an environment optimised for pedestrians, public transport or bicycles (Knoflacher 1991, p. 81). Examples include designing parking places in a more responsible way while investing in a balanced public transportation infrastructure with a dense network and high-frequency connections. Some cities are beginning to address this car dependency loop. In Copenhagen, the cycling mode share is very high. However, car ownership is still increasing and the share of cycling decreases with distance from the city centre. Although Denmark is a pioneer in sustainable urban development, car culture is still very widespread and represents the biggest challenge in working towards sustainable mobility (Freudendal-Pedersen et al. 2020). The City of Oslo has implemented a new approach to urban planning that recognises that streets need to be spaces for recreation that promote interaction, social functions as well as transport and travel, and that emphasises the priority of pedestrians, cyclists and urban quality over cars on the streets (City of Oslo 2020). For the city of Hamburg, it is likely that with increasing land use conflicts (limited by the state boundaries), a change in modal split will become more attractive, leaving more room for urban blue-green spaces. A corrected calculation of the costs of the effects between the modes of transport, e.g. between car and public transport, from a systemic perspective would highlight the advantages much more clearly (i.e. calculating the costs of illness from air pollution, costs of missing recreational areas, costs of hospitals, police, fire brigade due to accidents, etc.; Knoflacher 1991).

Conventional flood management systems such as dyke improvements are more prevalent in Hamburg. While institutional adaptation is a critical point to consider, relying solely on state action can lead to underestimation of risk by and increased exposure of the local population. In particular, the reinforcing feedback loop (R7) associated with the 'levee effect' (Climate-ADAPT 2023) indicates sources of risk growth in the system. This feedback process arises from the loss of flood memory combined with a complete trust in technical coastal protection and too great sense of security. While storm surge protection is relatively well established in institutional structures and public awareness, de Guttry and Ratter (2022) emphasise that the city has so far paid comparatively little attention to the fact that extreme rainfall events and subsequent flooding are at least as likely as storm surges. They underscore the significance of acknowledging pluvial and fluvial flood risk alongside coastal flood risk and emphasise the crucial role of promoting individual adaptation measures alongside administrative disaster protection. It is important to address the possible consequences of a solely institutional approach. As an excessive sense of security among the population can lead to complacency and negligence, this could jeopardise preparedness for future flood hazards. This might be problematic especially for vulnerable population groups such as children, the elderly and low-income households. In comparison to the past (1980–1999), heavy rainfall events in Europe are already affected by climate change emphasising the need to consider climate change in today's risk assessment and risk transfer (Lang and Poschlod 2024). With the publication of the heavy rain hazard map ('Starkregengefahrenkarte'; Freie und Hansestadt Hamburg 2024), Hamburg is now putting a strong focus on pluvial flood risk communication. This map is based on a state-of-the-art high-resolution pluvial flood modelling, placing Hamburg at the forefront of pluvial flood mapping. Although the map has no legal consequences and is for information purposes only, the heavy rain hazard map shows Hamburg's citizens where they could be at danger from heavy rainfall, enabling them to take precautions. Reconnecting the society to the importance of water as an integral part of everyday life, instead of considering water as a threat (Bell 2015), is the first step towards a holistic perception of water that can lead to sustainable transformations.

The reinforcing effects associated with poverty, social vulnerability and damage (feedback loop R8) as well as urban health, social vulnerability and damage (feedback loop R9) also represent sources of growth of flood risk in the urban system. Flood damage can be associated with significant financial burdens, which can lead to or intensify poverty thus contributing to social vulnerability. On the other hand, flood damage can be associated with health damage (both physical and mental health) which in turn lead to poorer health and contribute to social vulnerability. Socially vulnerable groups may be more affected by flood events than others, as they generally have less means or capacity for individual/

autonomous adaptation. The reinforcing negative effects between urban health and income (feedback loop R10; Eker and Ilmola-Sheppard 2020) could further exacerbate the problem, particularly among vulnerable groups. Thus poverty and health issues can be seen as major barriers to adapting to a changing climate. To overcome these *vicious cycles of barriers*, it is important to bring social aspects such as equity to the heart of the adaptation process (Adger 2003).

Silo-thinking and associated silo-budgeting are found to reinforce each other in a vicious cycle (feedback loop R11) and thereby represent a major institutional barrier to sustainable urban flood management and climate change adaptation. Governance on the municipal level is often trapped in formalised ways of working and constrained by institutional logics (Coaffee et al. 2018). The phenomenon of silo-thinking is partly generated by the sector-oriented character of departments and entities. Apart from these thematic silos, resource allocations and budgeting practices within silo-oriented organisational structures contribute to inefficiency and limited progress. Bohman et al. (2020) have shown that such silo-structures hinder the cross-sectoral implementation of sustainable stormwater strategies, such as multifunctional stormwater solutions. Breaking down siloed ways of working requires a mindset that transcends political, institutional and mental silos (Meuleman 2021). Measures such as raising awareness of existing ways of thinking and integrating informal cross-silo working arrangements are key to getting started, even in the scientific community. *Socio-ecological systems* thinking and system dynamics modelling can play an important role here, as they call for an integrative approach that brings together multiple sectors and disciplines to understand and address complex problems.

Finally, integrated research knowledge (indirectly represented here by the model as a representation of the current state of integrated interdisciplinary knowledge on urban flood risk) and thus bringing together researchers from different disciplines that go beyond sector-level analyses, is an important way to achieve sustainability and resilience. The lack of ‘actionable knowledge’ (Bai et al. 2016, p. 71) can be thus seen as another barrier to sustainable adaptation. For example, the impact of individual urban planning measures to prevent extreme precipitation cannot yet be reliably demonstrated, despite a wide range of literature. As precipitation initiation and resulting damage are not co-located, the demonstration of such lines of evidence will be essential to generate societal acceptance for corresponding urban adaptation measures.

As cities are complex *socio-ecological systems*, multiple actors and processes interact, often across geographic, institutional and governance scales. Hamburg’s situation as a city and federal state makes the administrative structures more complex than may be the case in many other cities (see SP 11 in Supplementary Material 1). The complex structures might be a hindrance to cooperation and commitment to implementing flood management and climate change adaptation measures. A siloed view of systemic urban problems and knowledge gaps in terms of understanding the interfaces, interactions and interdependencies between sectors and components of the urban system can lead to negative side effects of political actions (Bai et al. 2016). So far, a holistic and systemic approach to understanding urban flood risk has been lacking, in particular with a focus on how internal system dynamics drive this risk. The lessons learned for the city of Hamburg can be generalised to other cities with similar geographical, climatic and socio-economic conditions.

6.2. Reflections on the qualitative modelling framework

The model building process encouraged the interdisciplinary team of researchers to find common ground and to focus on the interactions of the system rather than on disciplinary views. In particular, the system dynamics perspective was helpful to raise the participants to a systemic level and to create a holistic view of the urban system in the team. In addition, the participatory modelling framework helped to keep track of and to structure the large amount of ideas, knowledge and opinions gathered in the group interviews and sessions. The QSDM in form of a causal loop diagram served as *boundary object* (Voinov et al. 2018) for the interdisciplinary research team and contributed to collective meaning-making. However, a limitation of QSDMs is that they do not allow for the representation of tipping points in the system, such as in the case of the system variables soil moisture and permeability, where both high and low values of soil moisture are associated with low permeability. Furthermore, it is not possible to link a causal relationship between two variables to the state of a third variable. Overall, these limitations of the QSDM require a certain degree of abstraction by the user, resulting in a simplified representation of the interrelationships. However, this abstraction provided an excellent object of mediation for exchanging views and learning from each other while developing a more thorough and holistic understanding of the urban system.

Although the QSDM provides valuable insights into the systemic nature of urban flood risk, it lacks the predictive capacity of more quantitative models in the way it is formulated. A quantitative system dynamics model would offer the possibility of quantifying the system, and this work could provide an important basis for doing so. Agent-based models offer another way of modelling complex systems using agents as elements (e.g. Yang et al. 2018; González-Méndez et al. 2021). However, these models are also based on a set of assumptions and parameter estimates, meaning that a holistic representation of *socio-ecological systems* remains a challenge even with these tools (An et al. 2021).

Some valuable lessons for the general design and application of future group model building studies were also drawn from this study. In order to examine the coupled dynamics of urban flood risk and the associated systemic problems from a holistic perspective and to develop an integrated model, it is crucial to involve as many disciplines as possible, including those that at first glance have nothing to do with flood risk. Previous studies have highlighted the importance of active stakeholder involvement at early stages through participation in the development of a holistic model of the policy problem at stake (e.g. Inam et al. 2015; Máñez et al. 2015; Kotir et al. 2017; Valencia Cotera et al. 2022). However, it is reasonable to initially develop a QSDM based on interdisciplinary scientific knowledge and to involve stakeholders at a later stage (e.g. model evaluation and policy analysis), as the different disciplines already offer enough potential for conflict and mediation in the form of differing vocabularies and definitions. With regards to the system conceptualisation, it was very helpful not to conduct individual interviews but to group the researchers by disciplines, since the number of participants was quite high. Such sub-group discussions also helped to narrow down disciplinary ambiguities and discard unnecessary details. Prior to the interviews, sufficient time should be planned to familiarise the participants with the system dynamics approach. A short introduction to the method at the beginning of each interview is not enough. For the intermediate step of collecting the disciplinary views in the group interviews, mental models were quite sufficient as a method, as participants were not yet fully familiar with the syntax of a CLD at this stage. Due to restrictions during the COVID-19 pandemic, all group interviews had to be conducted online. This actually turned out to be an advantage afterwards, because the online procedure allowed each participant to follow the creation of the model live on screen with the Vensim software and make corrections at any time. Another challenge was that participants were tempted to add too much detail that they felt was relevant to the model. To avoid an excessively sophisticated model, it is important to keep focus and constantly remind participants of the purpose of the model and system boundaries.

System boundary setting is an important necessity in SD modelling, as the boundary encloses the system of interest and the distinction between dynamically significant model variables and external variables can only be made according to this boundary (Vennix 1996). This study focused on urban flooding and processes associated with too much water in the city. Water scarcity in cities is also a problem that is becoming more urgent with climate change. That's also the case for the city of Hamburg, as compound hot and dry summers will get more frequent and intense in a warmer climate (Felsche et al. 2024). However, water scarcity and droughts are not in the focus of this study. So far, climate change has been included as a variable in the model, but it is a variable without incoming arrows within the system. Climate change thus represents a system boundary. This is a (simplifying) assumption of the model, which can also be explained by the fact that we are focusing on adaptation rather than mitigation. However, this may change if further knowledge is integrated into the model in the next stages. The conceptual model reflects the state of knowledge of the interdisciplinary research team that was involved in the model building process. As such, it should be noted that it represents only a 'dynamic hypothesis' (Kotir et al. 2017, p. 116) of the structure and dynamics of the *socio-ecological system* of the city of Hamburg.

7. Conclusion and outlook

This paper discusses the first four stages of a long-term participatory modelling study on urban flood risk and adaptation under climate change that involves an interdisciplinary research team and stakeholders. The study focuses in particular on urban flood risk in context of *water from 4 sides*, taking into account the growing research field on climate hazard interactions and *compound events* (Zscheischler et al. 2020; Simpson et al. 2021). A qualitative system dynamics model (QSDM) was developed using *socio-ecological system* thinking and system dynamics modelling approaches to explicitly address the complexity of urban flood risk and adaptation under climate change in the case study area of the city of Hamburg, Germany. We managed to distil the interrelations between environmental, social, economic, policy and institutional factors into a model that captures both the dynamic and reciprocal relationships. In particular, the integration of multiple disciplinary perspectives into a single model adds depth to this SD modelling process. We identified and visualised *vicious cycles of barriers*, i.e. the governing feedback loops that perpetuate and hinder adaptation processes and reinforce flood risk within the city. The study provides valuable insights into the systemic nature of flood risk, thus expanding the knowledge of complex flood risk interactions within cities. This is of direct relevance to policymakers dealing with both flood risk management and climate change adaptation in urban areas.

So far, the modelling process was embedded in an interdisciplinary setting, with transdisciplinary work to follow in a next step. The long-term goal is to develop a holistic understanding of the complex dynamics and feedback processes related to flood risk and adaptation in the urban *socio-ecological system* of the city of Hamburg. The first stages (i.e. problem identification and model purpose, system conceptualisation, model formulation and analysis of model behaviour) took place as a team learning process based on the interdisciplinary scientific knowledge of the researchers involved. In the remaining three stages (i.e. model evaluation, policy analysis and model use) stakeholders will be explicitly involved. However, the entire model building process should be understood as iterative, i.e. it is explicitly intended that the model will be complemented with local knowledge from stakeholders in later stages as well. The model developed in this study represents a preliminary model based on scientific knowledge and is therefore only a hypothesis of the overall dynamics of the urban system. To complete the visual story, local knowledge from practitioners is needed.

The QSDM developed for the city of Hamburg indicates that the main engines for increasing urban flood risk in the system are associated with socio-economic and institutional processes. The study showed that climate change affects the city mainly from the outside through flood hazards, contributing to flood risk. However, the city also generates flood risk internally through exposure and social vulnerability and even amplifies the flood risk through reinforcing feedback processes. The analysis of the system's feedback structure has highlighted that the challenges and barriers to flood risk management and adaptation of the city are linked to the reinforcing feedback loops of path dependency, river engineering measures, urban development, car dependency, 'levee effect', poverty, urban health and institutional silo-thinking.

Further work is needed in placing this qualitative model in the broader context of decision support and policy analysis (e.g. Egerer et al. 2021; Kunimitsu et al. 2023). The QSDM will be the basis for a joint analysis by researchers and stakeholders to identify opportunities that can help overcome barriers and advance climate change adaptation in the city of Hamburg. A follow-up paper will present the results of the remaining three stages of the participatory modelling framework developed here, focusing on model evaluation, policy analysis (deep leverage points for transformative adaptation) and model use (scenario investigation).

Research on individual sub-processes of the QSDM is and will be based on very different methods ranging form surveys to satellite observations or from conceptual models to detailed numerical flow simulations. Despite the numerous differences and incompatibilities among these individual approaches, they can all be connected to the QSDM. Thus, the QSDM is proposed as a common framework to place these specific research outcomes in a holistic context and to identify links between the different contributions. The qualitative modelling framework has improved the ability to understand the feedback-based dynamic processes of a dynamically complex *socio-ecological system* by incorporating multidisciplinary perspectives through the development of causal loop diagrams and the analysis of feedback loops. Such an integrated framework could be explored by local decision-makers to improve understanding of the dynamic nature of barriers to governmental planning for climate change adaptation in urban systems and to identify synergistic opportunities for reducing flood risk and achieving other Sustainable Development Goals. In particular, the model can be used as foundation for a joint discussion of very different interest groups helping participants think holistically to identify social-ecological trade-offs and multi-dimensional benefits for sustainable urban development. In such discussions, the model would serve as a neutral object of knowledge and negotiation bringing together conflicting interests in urban planning (e.g. flood protection, social justice, space for housing, ecological integrity, economic efficiency, etc.) on eye level. Furthermore, this approach, and in particular the use of QSDMs could be a relevant analysis method for the growing field of *compound events* and integrated climate change risk assessments.

Notes

1. In total, the sample of 13 groups consists of 34 researchers from 17 different disciplines (meteorology; physics; river and coastal engineering; marine sciences; biology; soil sciences; seismology; geo-hydro informatics; physical geography; integrative geography; human geography; urban and regional planning; planning, building and environmental law; transport planning; environmental governance; environmental economics; knowledge transfer and communication), ensuring a wide range of scientific backgrounds.
2. The approach of Inam et al. (2015) starts with the most comprehensive model (i.e. the model with the maximum number of variables), adds the variables from the other partial models and continues until all complementary, redundant and controversial elements are accounted for in the overall merged model.
3. Tides are an important mechanical factor determining hydrodynamic processes, sediment dynamics and morphological response in the Elbe Estuary (Rolinski and Eichweber 2000; Boehlich and Strotmann 2008). The tidal wave propagates from the mouth of the Elbe River to the artificial tidal limit at the weir at Geesthacht (Elbe-km 586). The tidal range varies along the Elbe Estuary and depends mainly on water depth, bottom friction and the influence of the Elbe River discharge (Hein et al. 2021), but changes in the converging estuarine geometry also play a role (Kappenberg and Grabemann 2001) (see also Supplementary Material 1, SP 6).

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Franziska S. Hanf: Study design, Conceptualisation, Development of methodology for the model building process, Design, coordination and technical realisation of the group interviews and workshops, Knowledge elicitation from the interviews, Data processing and visualisation with Vensim PLE, Formal analysis including the model and feedback loop analysis, Writing – original draft, Writing – review and editing, Writing – final manuscript. **Felix Ament, Marita Boettcher, Finn Burgemeister, Lidia Gaslikova, Peter Hoffmann, Jörg Knieling, Volker Matthias, Linda Meier, Johannes Pein, Benjamin Poschlod, Markus Quante, Elisabeth Rudolph, Jürgen Scheffran, Nima Shokri, Anastasia Vogelbacher, Martin Wicke**: Participation in group interviews and group workshops, Support in detailed analysis of the thematic sub-processes of the model (see Supplementary material), Reviewing and editing. **Leonie Ratzke**: Participation in group interviews and workshops, Support in detailed analysis of the thematic sub-processes of the model (see Supplementary material), Support in writing the original draft of the discussion section, Writing - review and editing. **K. Heinke Schlünzen**: Initial idea for developing a conceptual model, Support with conceptualisation, Mentoring, Participation in group interviews and workshops, Support in detailed analysis of the thematic sub-processes of the model (see Supplementary material), Writing - review and editing. **Jana Sillmann**: Support with conceptualisation, Writing - review and editing. **Malte von Szombathely**: Participation in group interviews and workshops, Support with technical realisation of the group interviews, Support in detailed analysis of the thematic sub-processes of the model (see Supplementary material), Writing - review and editing. All authors have read and agreed to the final version of the manuscript.

Data availability statement

Raw data containing non-anonymised information, i.e. audio recordings, transcripts and partial mental models of group interviews and group sessions, are not intended to be freely available to maintain participants' confidentiality.

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