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Feedbacks between city development and coastal adaptation: A systems thinking approach

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ABSTRACT

Current adaptation responses to sea-level rise tend to ignore the interplay of adaptation responses and city development, leading to unintended consequences with adverse impacts on citizens' welfare, institutional performance, and economic capacities. This study introduces a generic causal loop diagram (CLD) model, a novel approach exploring the dynamics of coastal adaptation and city development at a city scale. Unveiling key feedback mechanisms—flood risk perception, economic capacity, and trust—reveals their central role in driving negative repercussions, irrespective of the chosen strategy (protection, accommodation, planned relocation). Specifically, fiscal motivations to increase flood exposure and reinforcing dynamics between trust and institutional capacity can significantly impact socioeconomic vulnerabilities. Protection and accommodation may stimulate development in risk areas, while planned relocation faces challenges. However, well-planned relocation offer resource-effective adaptation, mitigating economic and political repercussions through long-term planning. Although the CLD lacks consideration for external drivers and spatial-temporal complexities, it provides crucial insights for coastal adaptation planning. Emphasizing holistic decision-making and multidimensional effects, this research supports informed policy formulation, fostering collaboration between urban planners and flood risk managers for robust and sustainable coastal adaptation pathways.

1. Introduction

Human activities have profoundly impacted climate and hydrological processes, contributing to changes in the frequency and severity of hydrological extremes and growing socioeconomic vulnerability (IPCC, 2022). Rising sea levels, growing urban development in low-lying coastal areas (Seto et al., 2011), and corresponding changes in flood risk have caused devastating flood impacts (Kirezci et al., 2023). Different adaptation strategies to coastal flooding (caused by, e.g., storm surges) have been adopted in various socioeconomic contexts and spatiotemporal scales, with structural protection being the most prominent. Numerous scholars have contested the effectiveness of this approach, as studies have shown that increasing protection levels can result in growing socioeconomic vulnerabilities (e.g., Kates et al., 2006). Unintended consequences of coastal adaptation with catastrophic impacts have stimulated the debate on ensuring sustainable adaptation pathways by avoiding burden-shifting and irreversible repercussions resulting from short-term fixes (Di Baldassarre et al., 2019).

The emerging field of socio-hydrology has played an essential role in exploring unintended consequences of human-water systems by developing a generalized understanding of feedback mechanisms (Pande and Sivapalan, 2017; Sivapalan et al., 2012). Socio-hydrological feedbacks often manifest in paradoxical dynamics resulting from the interplay between hydrological, technical, and social processes beyond a single sector, field, or discipline (Nicholls et al., 2008; Sivapalan et al., 2014). Several studies explore feedback mechanisms of human-water systems, including integrated water resource management (Di Baldassarre et al., 2019), paradoxes of water sustainability (Sivapalan et al., 2014), and hydropolitical effects of transboundary rivers (Li et al., 2011; Turton and Ashton, 2008). Understanding underlying feedback mechanisms of coupled human-water systems is pivotal in informing planning processes and assisting local governments in sustainable flood risk management.

However, little work has comprehensively addressed integrating the many feedback mechanisms resulting from the interplay between city development and the choice of adaptation strategy. Few studies have examined how these mechanisms manifest across socioeconomics, built and natural environments, citizen welfare, and institutions, not least at a city scale. The studies that do exist come with several limitations. Many

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studies explore feedback mechanisms specific to structural protection but leave out the impact of other adaptation strategies (e.g., Barendrecht et al., 2019; Di Baldassarre et al., 2013; Perrone et al., 2020; Rehman et al., 2019; Wenger, 2017; Woodruff et al., 2018). Several studies examine individual feedback mechanisms with a strong focus on flood risk perception, flood memory, and flood experience (e.g., Kreibich et al., 2017; Leong, 2018; Ridolfi et al., 2021; Viglione et al., 2014) and a weaker focus on social inequality (Borgomeo et al., 2018; Knighton et al., 2021; Moulds et al., 2021) but ignore their impact on wider functions across socioeconomic, ecological, and institutional dimensions. Only a few studies account for feedbacks in institutional processes while exhibiting at least one of the above limitations: Abebe et al. (2019) developed a coupled flood-agent-institution modeling framework focusing on infrastructural vulnerability and exposure but excluded cascading effects on socioeconomic vulnerabilities across wider city functions; Rehman et al. (2019) develop a comprehensive system map for flood problems across multiple domains, but do not assess feedback mechanism that may occur with different adaptation strategies; Lastly, Lawrence et al. (2020) explore the cascading impacts, feedbacks, and implications of different types of climate change impacts (e.g., sea level rise and extremes), but they do not analyze the impact and potential repercussions of individual adaptation responses.

In summary, (1) studies exploring the interactions inside the city consider only the effects of structural protection or do not consider the urban system as a whole, and (2) studies exploring the interactions across socioeconomic, ecological, and institutional spheres do not assess the unintended consequences of different adaptation responses. These shortcomings have framed the scope of our study. More specifically, we aim to:

- develop a conceptual model for coastal adaptation at a city scale, depicting the complex inter-relationships between urban system components across multiple dimensions;
- explore the feedback mechanisms and unintended consequences resulting from the interplay of socioeconomic, ecological, and institutional systems;
- compare different coastal adaptation strategies (expanding beyond protection strategies), considering their impacts on the system dynamics of the model.

By achieving these objectives, we can present a more comprehensive description of the feedback dynamics of coastal adaptation and vulnerability and its novel application to a city scale. To explore the various feedback mechanisms, we develop a causal loop diagram (CLD) depicting the generic inter-relationships among selected variables of city development and coastal adaptation. We build on a simple and generic CLD model that is sufficient to explain critical problem dynamics and can be used to communicate the most crucial insights of the modeling effort to relevant stakeholders. Based on the CLD, (1) we analyze emerging feedback mechanisms and their manifestation in theory and practice, and (2) we explore the impacts of three generic coastal adaptation strategies (i.e., *protection*, *accommodation*, and *planned relocation*) on the system dynamics of the CLD to uncover differences in resulting cross-sectoral impacts and socioeconomic vulnerabilities.

2. Methods and data

Fig. 1 illustrates the methodological key steps, including (1) the development of the CLD (steps 1-5) and (2) the system analysis of three generic coastal adaptation strategies (steps 6 and 7). In steps 1 and 2, we identified the system variables required to depict all critical processes affected by coastal adaptation measures. We then mapped the causal relationships of all variables into an initial CLD (step 3) that we aggregated into higher-level system states (step 4). We iteratively improved the CLD by validating it against well-documented socio-hydrological feedback mechanisms based on a literature review (step 5.a)) and a cross-disciplinary expert workshop (step 5.b)). Based on the final CLD, we explored key feedback mechanisms undocumented in the literature (step 6). In the last step, we reviewed the direct impacts of three generic coastal adaptation strategies (i.e., protection, accommodation, and planned relocation) (7.a)) and analyzed their cascading effects on the system dynamics of the CLD (7.b)).

2.1. Development of the causal loop diagram (CLD)

2.1.1. Selection of system components (steps 1 and 2)

We used the review of Eggert et al. (2023) as a starting point for identifying the required components of the CLD (step 1, Fig. 1). It provides a comprehensive overview of variables (totaling 82) that are commonly considered relevant to assess if city development and coastal adaptation of cities in high-income countries take place in a sustainable manner. However, many variables used in urban planning are not directly affected by coastal adaptation (e.g., *traffic fatalities* and *crime rate*), while other variables purely measure outputs without triggering feedbacks in the coastal urban system. We, therefore, assessed whether variables affect or are affected by other variables (step 2, Fig. 1). Variables that did not meet this criterion were eliminated. This assessment was, to the largest extent possible, based on the literature cited in this

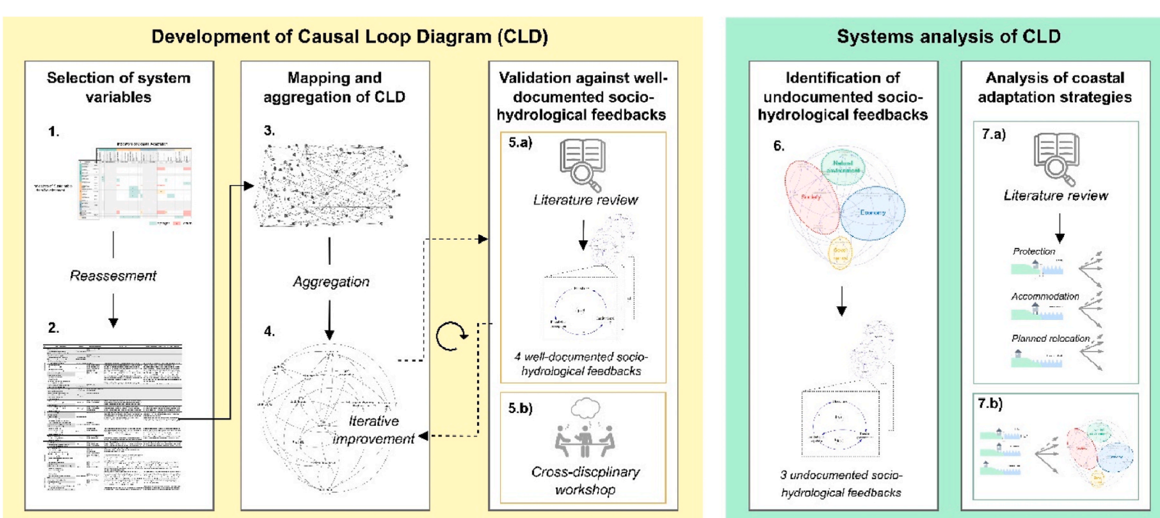


Fig. 1. Methodological key steps followed in the present study.

Table 1
Framing of the three generic coastal adaptation strategies (i.e., protection, accommodation, and planned relocation).

Coastal adaptation strategy	Characteristics
Protection (hard engineering structures, e.g., dikes, levees, seawalls)	• Focus on "hard protection" (i.e., hard engineering structures, e.g., dikes, sea walls, levees, etc.). • Financed by local government through loans, bonds, and tax revenues.
Accommodation (elevated buildings, flood-proofing)	• Focus on the improvement of infrastructure resilience (i.e., elevated buildings and flood-proofing). •Retrospective accommodation of existing buildings and accommodation of new buildings. • The cost of accommodation measures shared by homeowners and local government (cf., Kreibich et al., 2015).
Planned relocation (planned relocation of assets)	• Coordinated and permanent relocation of buildings, facilities, and infrastructure to low-risk areas. • Prohibition of new development in high-risk areas through zoning regulations and rolling easements. • Planned relocation over a longer time period as opposed to reactive retreat after a flooding disaster. • Spreading of cost burden through step-wise implementation over a long time period (cf., Gibbs, 2016). • Strategy is funded by the government (e.g., tax revenues) (cf., Boston and Lawrence, 2018). • Sufficient land for new development in low-risk areas is available.

paper and in (Eggert et al., 2023), but the final decision followed discretionary decision-making by the authors.

To ensure the completeness of represented variables, we reviewed relevant literature in the field of socio-hydrology (totaling 61 scientific articles) using the academic search engine Web of Science and the snowball sampling method (Supplementary Material S1). We eliminated irrelevant coastal adaptation variables and added critical ones (Supplementary Material S2). For example, the variable *citizen awareness of climate-related topics* is often discussed concerning *experiences with flood events* and *collective memory of floods* (Viglione et al., 2014; Wachinger et al., 2013). Hence, we added *experience with flood events* and *collective memory of floods* to the list of selected variables. The variables of *voter turnout* and *public participation in planning processes* are often mentioned in the context of trust or lack of trust in public institutions. Another proxy for citizens' trust in public institutions is the *willingness to pay for public services* (Cologna and Siegrist, 2020). As a result, *voter turnout*, *public participation in planning processes*, and *willingness to pay for public services* were included in selected variables. The reassessment of variables resulted in 57 system variables (Table 2, Supplementary Material S2).

2.1.2. Initial mapping and aggregation of selected system variables (steps 3 and 4)

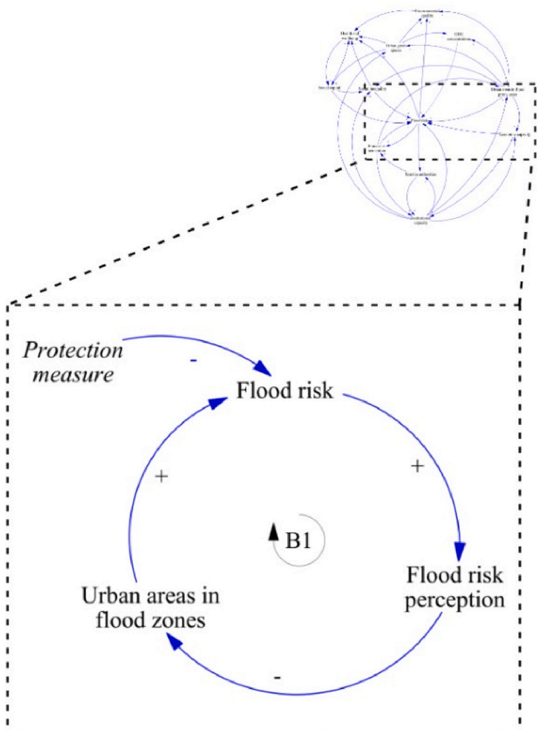
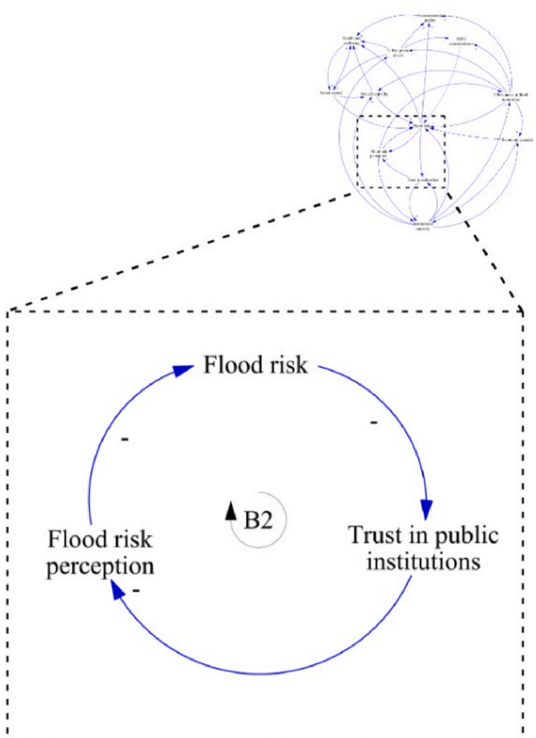
The initial CLD was based on a discretionary mapping of cause-effect relationships between each of the variables (cause-effect matrix). We focused on the direction of change between variables (i.e., the polarity) but refrained from assessing the strength of the causal relationships (i.e., the weight). This initial step is documented in Table 3 and Fig. 1 of the Supplementary Material (S3).

The initial mapping of the CLD followed an aggregation process

Table 2
States and variables for sustainable adaptation in the final CLD. Definitions of states as understood in this study.

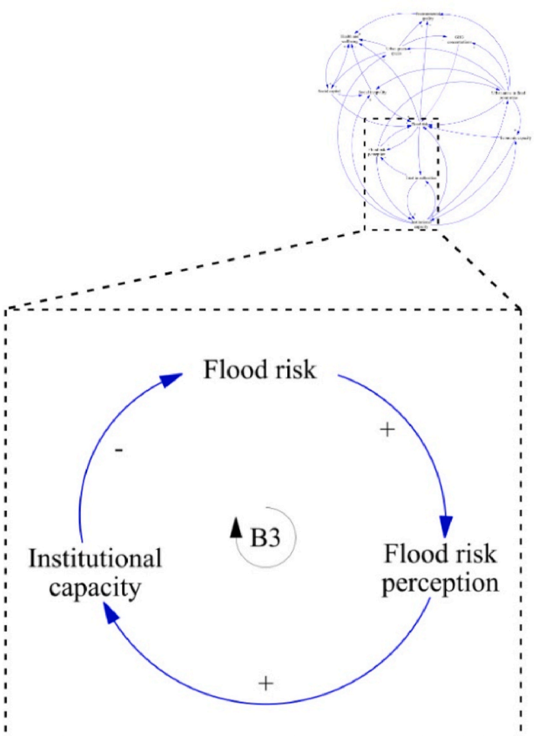
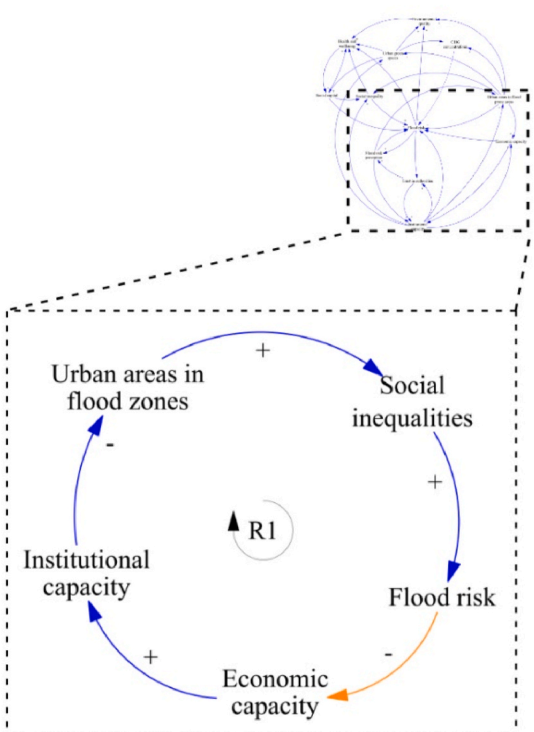
States	Definitions	System variables (adapted and reassessed from Eggert et al., 2023)
Urban green spaces	Natural and constructed ecological systems that provide functions and services, including ecosystem services and benefits for human and ecological well-being (IPCC, 2022).	Tree canopy coverage, natural protected areas, public urban green spaces
Environmental quality	Properties and characteristics of the natural and built environment as they affect human beings and other organisms, including potential effects on human and ecological well-being.	Biodiversity, coastal erosion, saltwater intrusion, noise pollution, surface water quality, air quality
Social capital	The ability of communities to collaborate and innovate through networks, shared norms, and values (IPCC, 2022).	Volunteerism, social cohesion, and networks, mixed-use development, place attachment (i.e., perception of aesthetic value, accessibility to green spaces, recreational value)
Social inequalities	Inequalities in resource distribution within a given community affecting the impact and response to climate change, as well as the distribution of costs and benefits (cf, IPCC, 2022).	Population with higher education, income inequality, affordable housing
Health & Wellbeing	Physical and mental health and well-being of the population determined by social, economic, and environmental conditions. (WHO, 2021)	Mental well-being, physical health, life expectancy, availability of physicians
Economic capacity	Existing economic resources of the local community (including citizens, the local government, and private businesses) that can be used for adaptation (including disaster risk preparedness and adaptive capacity building).	Gross domestic product (GDP), diversity of economic structures, number of businesses, median household income, insurance coverage, unemployment rate, municipal debt
Urban areas in flood zones	The presence of urban areas, including people, livelihoods, services, resources, infrastructure, or economic, social, or cultural assets in high-risk areas.	Population in high-risk areas, housing units in high-risk areas, cultural heritage in high-risk areas, critical infrastructure in high-risk areas, impervious surfaces
Institutional capacity	The capability of local governments and public institutions to create an "enabling environment" for setting and achieving city development goals through integrated and participatory planning processes (Willems and Baumert, 2003).	R&D expenditures, innovation, and technology, expenditures on climate-related activities, clime-related partnerships, municipal staff trained on climate actions
Trust in public institutions	Public support for and confidence in core political institutions such as the government and the legislation (e.g., van der Meer, 2017).	Voter turnout, public participation in planning processes, willingness to pay for public services
Flood risk perception	The subjective judgment that people make about the characteristics and severity of the risk of flooding (IPCC, 2022).	Experience with flooding events, collective memory of floods, citizen awareness of climate-related topics
Flood risk	The expected annual damage from flooding to human and ecological systems, resulting from the interplay of flood hazard (frequency and/or magnitude of flood events), the exposure (e.g., topography or infrastructure), and the vulnerability of the human settlement affected (IPCC, 2020).	Casualties, people displaced by flood events, climate-related economic loss, social vulnerability (i.e., population in poverty, lone-pensioner households, population with disabilities, population <5 and >65 years), disaster preparedness (i.e., shelter capacity, hospital beds, early warning systems, citizen preparedness for emergency)

Table 3
Well-documented socio-hydrological feedback mechanisms in the CLD; Unidirectional relationships are highlighted in orange; External inputs (i.e., adaptation measures) influencing the mechanisms are included using italic font.

Feedback loop	Description of feedback mechanisms
	*The levee effect* (White, 1945) The *levee effect* describes the phenomenon of flood defense structures generating a false sense of security that decreases people's flood risk perception and stimulates urban development in high-risk areas. This can result in a reinforcing process of raising levees to protect growing urban areas (e.g., Kates et al., 2006) In our CLD, the *levee effect* is represented as protection measures reducing flood risk, leading to reduced flood risk perception, and increasing urban areas in flood zones. Additional development in high-risk areas and increasing extremes lead to large and sometimes unpredictable losses when the levee is eventually overtopped (i.e., an increase in flood risk).
	*Trust bias in public institutions* (e.g., Wachinger et al., 2013) Lack of trust in public institutions increases risk perception (Wachinger et al., 2013), stimulating risk-reducing measures of individuals (i.e., personal disaster preparedness) (Harries, 2012; Ludy and Kondolf, 2012). In contrast, high trust in public institutions reinforces lower risk perception, reducing personal risk mitigation and increasing flood risk. Increasing flood risk can trigger these dynamics by reducing trust in public institutions that citizens tend to see as responsible for flood risk management (van Heel and van den Born, 2020) Our CLD represents these dynamics in exactly the described form.

(*continued on next page*)

Table 3 (*continued*)

<table>
<tr><th>Feedback loop</th><th>Description of feedback mechanisms</th></tr>
<tr><td>
</td><td>The adaptation effect (Kreibich et al., 2017)
If an extreme event occurs shortly after a similar event, its impact tends to be lower due to the adaptation effect (Kreibich et al., 2017). The positive effect results from increased flood risk perception that can trigger adaptive responses in an individual community or at the government level. Note that his effect may be hampered by, e.g., socioeconomic vulnerabilities, slow institutional change, political regimes, and narratives incentivizing maladaptive responses (cf., Slavíková et al., 2021).
In our CLD, the effect is represented through a positive polarity between flood risk and flood risk perception, which in turn leads to an increase in institutional capacity that results from learning from past events and better anticipating, coping with, and recovering from the adverse effects of future events (Glaus et al., 2020; Viglione et al., 2014). The adaptation effect can be reversed and reinforce the levee effect if decreasing flood risk perception and institutional capacity increases flood risk.</td></tr>
<tr><td>
</td><td>Climate gentrification (e.g., Keenan et al., 2018)
Urban expansion in high-risk areas may go hand in hand with increased social inequalities at different spatial scales. One possible pathway of climate gentrification occurs if wealthier households relocate to higher-elevation properties while low-income households are forced to reside in high-risk areas with lower rates of property appreciation (Keenan et al., 2018; Wing et al., 2022). Lower private risk mitigation and economic capacity leave low-income households more vulnerable to flooding (Grothmann and Reusswig, 2006).
In our CLD, this pathway of climate gentrification is represented through a reinforcement of social inequalities resulting from an increase of urban areas in high-risk areas, leaving low-income households in high-risk areas more vulnerable to flooding. Reduced institutional capacities in the affected areas lead to a negative spiral where urban expansion continues in high-risk areas.</td></tr>
</table>

aimed at reducing the system variables to a manageable number of higher-level states (step 4, Fig. 1). *States* characterize the status of a system. Variables can be understood as indicators (i.e., descriptions or measurements) of the states. We carried out the following iterative steps (cf., Asif et al., 2023; Bureš, 2017): (1) the aggregation of variables that only represent an output or input to another variable (see Variables 4 and 7, Fig. 2), (2) the bridging of variables with only one input and one output variable (see Variables 1, Fig. 2), and (3) the thematic grouping of remaining variables.

Complex systems such as CLDs are governed by feedback loops (i.e., closed loops of system variables) that either move the system away from the equilibrium (i.e., reinforcing loop, denoted by the letter R, cf. Fig. 2) or tend to dampen changes (i.e., balancing loop, denoted by the letter B, cf. Fig. 2). To ensure that the aggregation steps would not change the system dynamics, the polarity of the new (bridged) link (between State C and State A, Fig. 2) must be determined based on characteristics of the

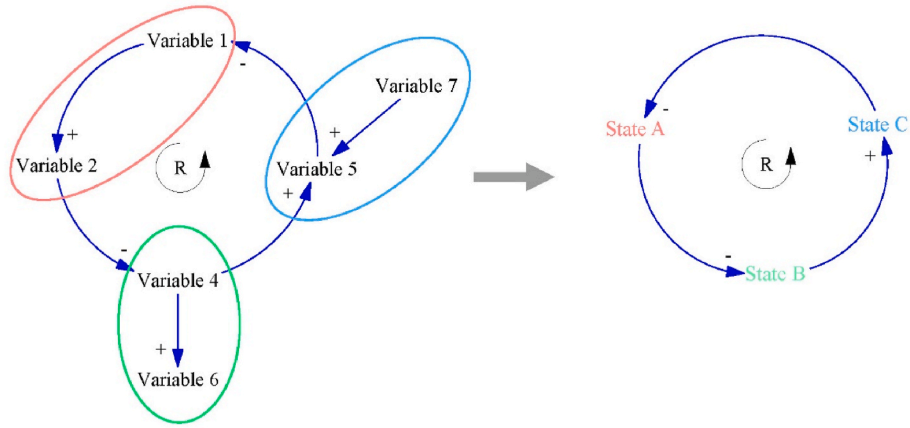


Fig. 2. Aggregation process of system variables (Variables 1–7) into higher-level states (States A, B, and C). Positive (+) and negative (−) symbols denote the polarity of the relationships.

original feedback loop (e.g., if the original feedback loop was a reinforcing loop, the "new" feedback loop must also be a reinforcing loop).

We only aggregated variables from similar thematic areas. For example, the variable *biodiversity* represents a single output affected by only the variable *natural protected areas.* We aggregated both variables into the state *urban green spaces*. The variable *air quality* is a sole-input variable to the variable *physical health.* Yet, these two variables were not aggregated, and *air quality* was merged with other variables of *environmental quality*. We added the remaining variables to aggregated variables in cases of thematic similarities. As a result, some state relationships were ambiguous and did not always comply with the previous two aggregation methods (Table 4, Supplementary Material S3). Ambiguous relationships were compared against known socio-hydrological feedback mechanisms and discussed in an expert workshop (step 5).

2.1.3. Validation against well-documented socio-hydrological feedback mechanism (step 5)

To be meaningful, our CLD should be able to explain the most common feedback mechanisms. By conducting a literature review (step 5.a), Fig. 1) and an expert workshop (step 5.b), Fig. 1), we ensured that the most critical socio-hydrological feedback mechanisms were included. In the first step, the initial CLD was validated against socio-hydrological feedback mechanisms that are well-documented in the literature (cf., Section 2.1.1). We iteratively improved the CLD in cases where identified feedback mechanisms were not reflected.

In the second step, the preliminary CLD was discussed and modified during a cross-disciplinary workshop. The workshop integrated expert knowledge from different disciplines, including two scientists from hydrology, four from landscape architecture, and three the from urban planning field. The nine workshop participants were divided into three cross-disciplinary groups. Each group received a list of states, an A0 print-out of the preliminary CLD, colorful post-its, and pens. We asked workshop participants to (1) state their understanding of the states and (2) evaluate existing and add missing states and relationships (Fig. 2, Supplementary Material S3). We set aside around 1 h for the group exercise. Afterward, we discussed the results in a plenum. We revised the initial CLD where the groups suggested similar changes (i.e., which states and variables were missing according to more than one group) (Table 6, Supplementary Material S3).

2.2. System analysis of CLD

2.2.1. Identification of undocumented socio-hydrological feedbacks (step 6)

Based on the final CLD, we identified key feedback mechanisms undocumented in the literature and emerging from our CLD. To do this, we identified all reinforcing and balancing feedback loops (see Fig. 3, Supplementary Material S3) that had not already been determined during the validation step of known feedback mechanisms (Section 2.1.3). We explored the underlying mechanisms of newly identified loops and interpreted their relevance to coastal adaptation (step 6, Fig. 1).

2.2.2. Impact analysis of coastal adaptation strategies on the CLD (step 7)

In the final step, we utilized the developed CLD to analyze the potential unintended consequences of implementing the three generic coastal adaptation strategies. Table 1 provides a framing of the strategies as understood in our study. These are simplified archetypes, while concrete strategies will depend on local topographies and socioeconomic conditions (Haasnoot et al., 2019, 2021). We identified the most common direct impacts of each strategy based on a review of 41 scientific articles (Table 8, Supplementary Material S5) (step 7.a), Fig. 1).

Subsequently, we explored the cascading effects of the direct impacts of the coastal adaptation strategies on identified feedback mechanisms (step 7.b), Fig. 1). For simplicity, we considered the three coastal adaptation strategies individually, whereas, in practice, city-scale adaptation will consist of hybrid strategies (Bongarts Lebbe et al., 2021; Haasnoot et al., 2019). We assume that the strategies trigger different system states of the CLD exogenously. We define these direct impacts (i.e., the initiated direction of change in the system states: increase or decrease) on the system states as immediate "shocks" that occur instantly after the implementation of the adaptation strategy, as opposed to resulting unintended consequences over time.

3. Results

3.1. CLD for city development and coastal adaptation

3.1.1. Mapping and aggregation of final CLD

Fig. 3 shows the final CLD, including 11 states, illustrating the interplay of city development and coastal adaptation. This CLD version incorporates changes considering the validation against known socio-hydrological feedback mechanisms and discussions in the expert workshop (Fig. 3, Supplementary Material S3).

Table 2 lists the 11 states, their definitions, and the original system variables (totaling 56) aggregated into each state. Cause-effect relationships between the states (Table 7, Supplementary Material S4) were derived from the original variables. Three generic coastal adaptation strategies (i.e., protection, accommodation, and planned relocation, see Table 1) represent the external input to the CLD. Section 3.2.2 discusses the cascading effects of the strategies' impacts on the system states.

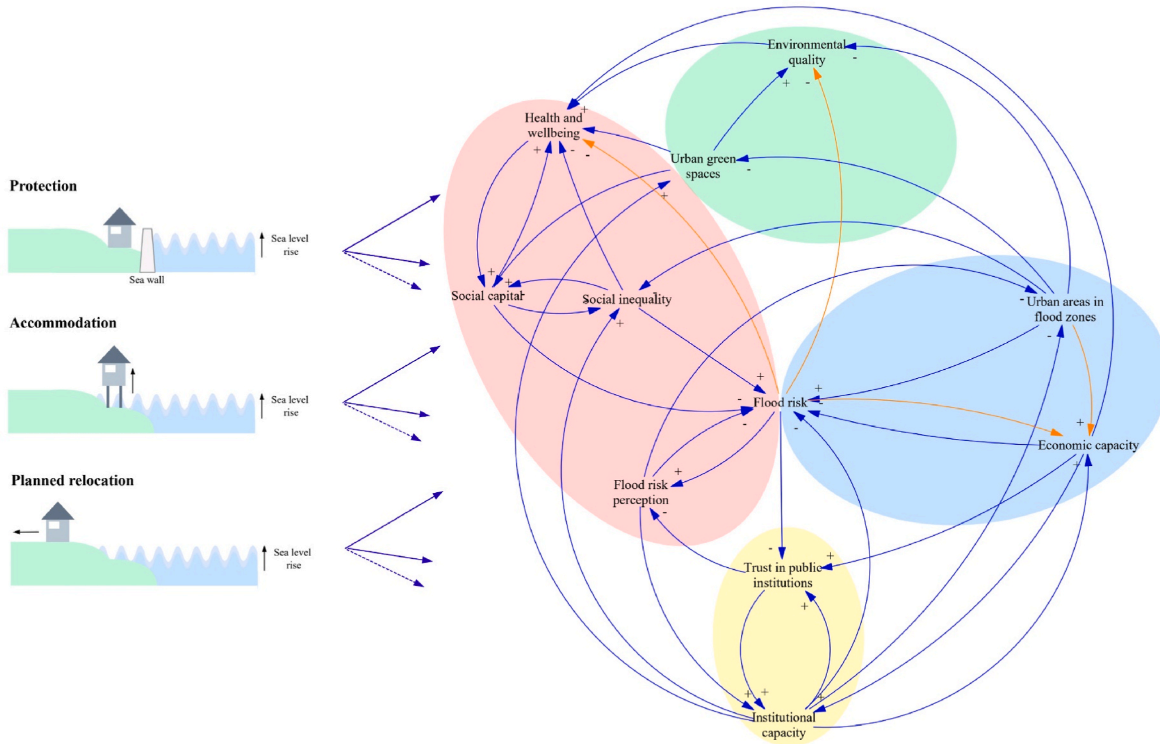


Fig. 3. Final CLD including external input of coastal adaptation strategies (i.e., protection, accommodation, and planned relocation); Unidirectional relationships are highlighted in orange; Variables are highlighted based on four dimensions: ecological (green), economic (blue), institutional (yellow), and social (red) (see online version for color representation).

The CLD illustrates interconnections across four dimensions: environment, society, economy, and institutions (Fig. 3). The state *flood risk* is located at the center of the CLD, mostly influenced by socioeconomic processes (as well as *institutional capacity*) and influencing processes across all four dimensions. *Flood risk perception* and *institutional capacity* play a vital role in the system dynamics of the CLD as they are involved in multiple feedbacks impacting flood risk. The natural environment dimension is mainly affected by the economic incentive of urban expansion in high-risk areas. Environmental performance, such as *environmental quality* and *urban green spaces,* affect, in turn, states of citizen welfare, resulting in cascading effects on flood risk and other institutional and economic processes.

Notably, the environmental dimension does not include greenhouse gas (GHG) emissions. These are frequently considered in the urban planning literature, but the emissions of an individual city are an output state that does not directly affect other states of the urban system. Global GHG emissions, on the other hand, do affect the urban system, but they should be considered an external driver that a city can influence only to a limited extent.

Several causal relationships are unidirectional, meaning that the "cause and effects" only operate in one direction. For example, an increase in flood risk adversely affects human health and well-being (IPCC, 2022), while a reduction of flood risk is a necessary but not sufficient precondition for improvements in human health and well-being (which may also be affected by other factors). Similarly, increasing flood risk leads to more flood damage and adaptation costs that reduce economic capacity, while lower flood risk will not increase economic capacities unconditionally.

3.1.2. Well-documented socio-hydrological feedbacks

Table 3 lists four well-documented socio-hydrological feedback mechanisms. We explored their underlying mechanism and described how they are reflected in our CLD (Fig. 3).

3.2. Feedbacks between city development and coastal adaptation

The CLD is useful to structure thought processes and uncover potential mechanisms in complex systems that are not obvious. This section aims to make informed hypotheses on the unintended consequences of coastal flood adaptation that have not been documented in the literature. First, we highlight relevant feedback loops in our CLD and their consequences for the interplay between city development and coastal adaptation. Second, we use the CLD to map out the effects of the three different coastal adaptation strategies.

3.2.1. Undocumented socio-hydrological feedbacks

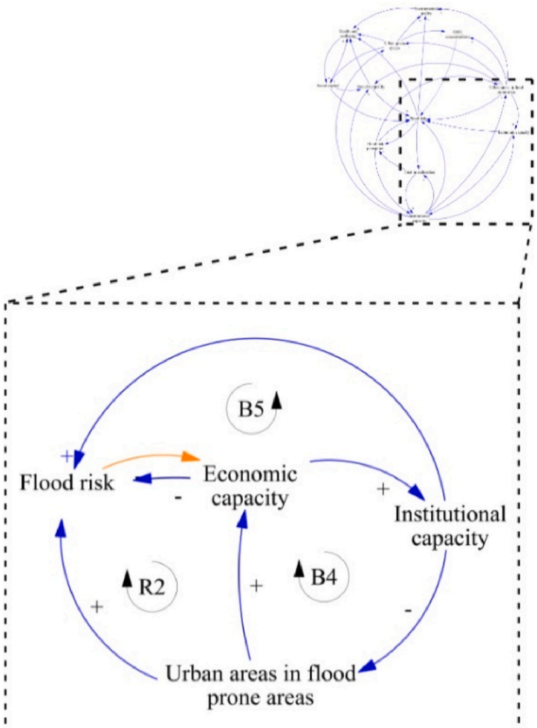
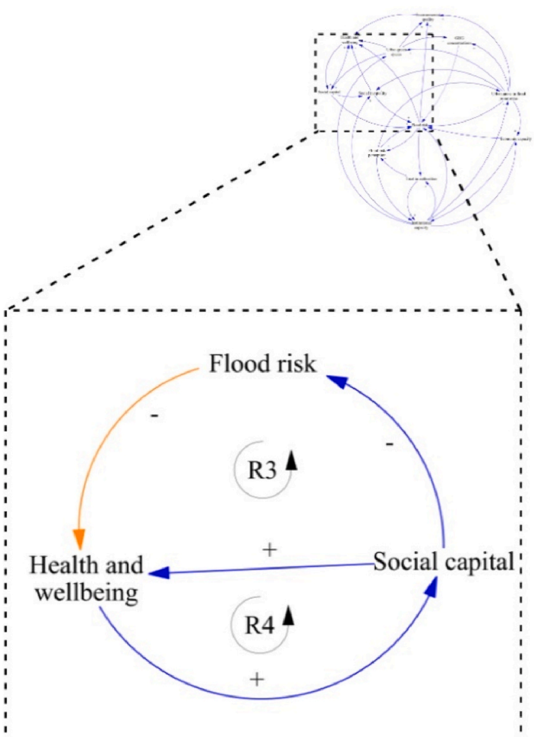
Table 4 lists three feedback mechanisms emerging from our CLD. While many of the cause-effect relationships have been documented before, to the best of our knowledge, the feedback loops have so far not appeared in the socio-hydrological literature.

3.2.2. Direct impacts of coastal adaptation strategies

Table 5 lists the direct predominant impacts of the generic coastal adaptation strategies that we have identified in the reviewed literature (Table 9, Supplementary Material S5).

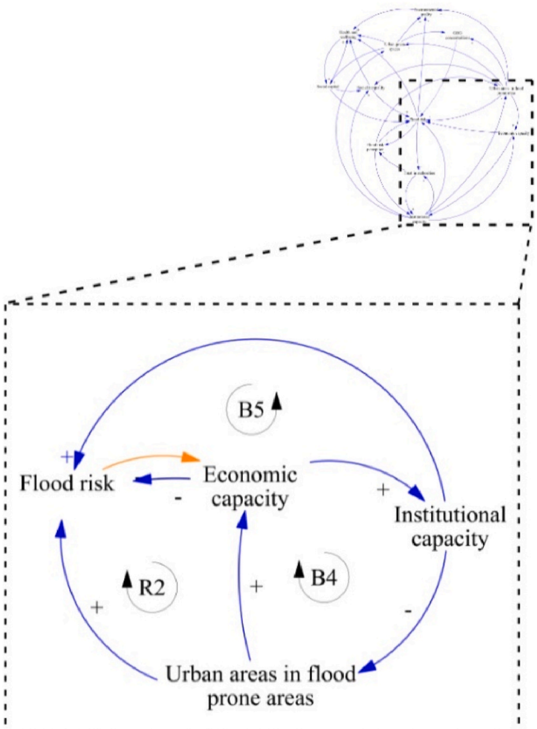
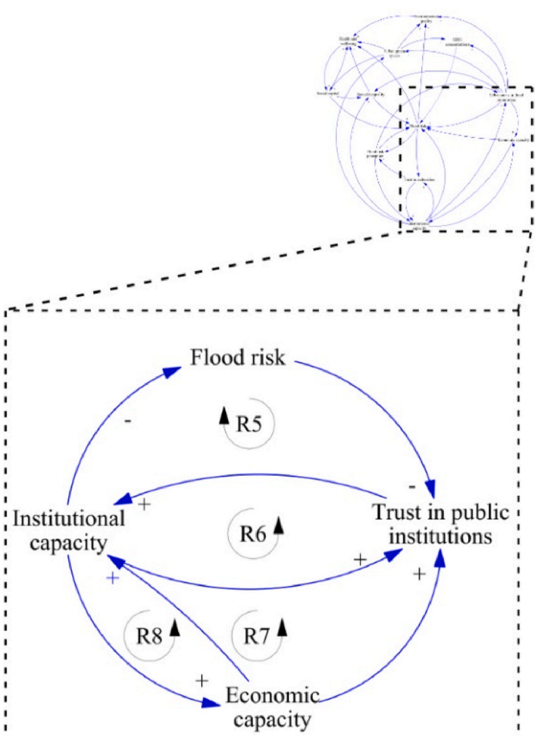
For the protection strategy, constructing a protection measure initially reduces flood risk (Di Baldassarre et al., 2018; Warner et al., 2018). A high level of trust in protection measures and a (false) sense of security makes citizens feel protected (i.e., a decrease in flood risk perception) (Viglione et al., 2014; Wachinger et al., 2013). The cost of the seawall decreases economic capacities and might bind public assets that are no longer available for, e.g., citizen welfare. Under the assumption that the local community finances adaptation projects, local economic capacities are affected (cf., Dedekorkut-Howes et al., 2020). The construction of a seawall also comes with high environmental costs, such as the loss of beaches and wetlands and stress on coastal habitats (Dedekorkut-Howes et al., 2020; Warner et al., 2018). These costs and accumulating liability for coastal flooding affect local communities

Table 4
Undocumented socio-hydrological feedback mechanisms in the CLD; Unidirectional relationships are highlighted in orange (see online version for color representation).

	*Fiscal motivations increase flood exposure* Our CLD suggests reinforcing dynamics of economic capacity and flood risk that arise from an increase in flood exposure due to fiscal motivations. Several studies have documented a continuous "development paradigm" in flood-prone areas due to pressures from property developers (Boston and Lawrence, 2018) and fiscal motivations (i.e., revenue from taxes) (Lewis, 2001). These developments increase flood risk, which eventually weakens economic capacity. However, in the short term, the developments also attract wealthy citizens and increase the city's tax base, leading to balancing dynamics because the city has more means to invest better into flood mitigation and employ qualified staff. The loop reaches a tipping point if the revenues from new developments no longer cover the cost of adaptation measures. The loop can further be triggered by increasing expenditure needs for climate change adaptation. These can be seen as a reduction of economic capacity that puts pressure on institutions and creates incentives to raise revenues through land fiscalization (Shi and Varuzzo, 2020). Land fiscalization can accelerate climate risk if development is placed in floodplains.
	*Reinforcing health, social capital, and flood risk* Our CLD suggests reinforcing feedback dynamics between social capital, flood risk, and the community's health. Communities characterized by higher levels of social capital tend to be better prepared and more effective responders to floods (Buckland and Rahman, 1999; Lo et al., 2015). Flooding can, directly and indirectly, affect human health. Adverse health impacts can decrease social capital by impairing a person's social functioning and capacity to cope with interpersonal interaction (Cullen and Whiteford, 2001). In turn, high levels of social capital are associated with positive health and well-being outcomes (Nieminen et al., 2013).

(continued on next page)

Table 4 (*continued*)

 	*Fiscal motivations increase flood exposure* Our CLD suggests reinforcing dynamics of economic capacity and flood risk that arise from an increase in flood exposure due to fiscal motivations. Several studies have documented a continuous "development paradigm" in flood-prone areas due to pressures from property developers (Boston and Lawrence, 2018) and fiscal motivations (i.e., revenue from taxes) (Lewis, 2001). These developments increase flood risk, which eventually weakens economic capacity. However, in the short term, the developments also attract wealthy citizens and increase the city's tax base, leading to balancing dynamics because the city has more means to invest better into flood mitigation and employ qualified staff. The loop reaches a tipping point if the revenues from new developments no longer cover the cost of adaptation measures. The loop can further be triggered by increasing expenditure needs for climate change adaptation. These can be seen as a reduction of economic capacity that puts pressure on institutions and creates incentives to raise revenues through land fiscalization (Shi and Varuzzo, 2020). Land fiscalization can accelerate climate risk if development is placed in floodplains.
 	*Reinforcing trust and institutional capacity* Institutional capacities strengthen citizens' trust, facilitating the implementation of flood mitigation measures (Wachinger et al., 2013). Our CLD suggests that these dynamics occur through multiple pathways that link flood risk, trust in public institutions, economic and institutional capacity: (1) institutional capacity increases trust both directly and indirectly by reducing flood risk, and (2) increasing institutional capacity results in increasing economic capacity, which again increases trust and the ability to implement flood mitigation. The same dynamics can lead to a negative spiral where increased flood risk weakens trust and institutional capacity, further increasing flood risk and weakening economic capacities. Thus, *trust bias in public institutions* can hamper personal disaster preparedness, on the one hand, and foster institutional capacities to mitigate flood risk, on the other hand.

independently from the financing scheme (Rogers et al., 2014). In addition, seawalls require large amounts of resources, with concrete being particularly carbon-intensive (Hennequin et al., 2018).

For the accommodation strategy, elevating or flood-proofing buildings can significantly reduce flood risk by improving infrastructure resilience (Attems et al., 2019; Kreibich et al., 2015). We assume that accommodation increases flood risk perception because (perceived) flood exposure and frequent experience with flooding are crucial in determining flood-risk perception (Coquet et al., 2018; O'Neill et al., 2016). Note, however, that some studies suggest that urban areas in flood zones are increasing despite high levels of flood risk perception (Hino et al., 2023; Mclean and Watson, 2009). This is because the development takes place in a supposedly safe manner (cf. *levee effect*). Finally, flood-proofing buildings is costly and resource-consuming, especially if done retrospectively for existing buildings (Aerts, 2018; Kreibich et al., 2015).

Besides decreasing flood risk, the planned relocation strategy leads to a range of benefits for the natural environment, such as the reduction

Table 5
Direct impacts of the three generic coastal adaptation strategies (i.e., protection, accommodation, and planned relocation) on the system states of the CLD (indicated by an increase in state (↑) or decrease in state (↓)). The strength (i.e., weights) of the causal relationships are not assessed.

Coastal adaptation strategy (coastal adaptation measures)	Direct impacts on system states
Protection (hard engineering structures, e.g., dikes, levees, seawalls)	↓ Flood risk ↓ Flood risk perception ↓ Economic capacity ↓ Environmental quality
Accommodation (elevated buildings, flood-proofing)	↓ Flood risk ↑ Flood risk perception ↓ Economic capacity
Planned relocation (planned relocation of assets)	↓ Urban areas in flood zones (=↓ Flood risk) ↑ Environmental quality ↓ Economic capacity ↓ Social capital ↓ Trust in public institutions

of erosion and the potential for restoration of natural features (e.g., vegetation buffers or dunes) (Rogers et al., 2014; Sierra-Correa and Cantera Kintz, 2015). Considering economic impacts, costs can be reduced due to synergies with other initiatives, including regular operations and maintenance of physical assets, when assuming a step-wise implementation of the strategy over a long time period (see Table 1). However, continued costs for acquiring properties and constructing new infrastructure are inevitable (Gibbs, 2016; Haasnoot et al., 2021). Planned relocation is often perceived as highly controversial not only economically but also politically and socially, potentially leading to reduced trust in public institutions (Dedekorkut-Howes et al., 2021; Schernewski et al., 2018) and the destruction of social capital (Bongarts Lebbe et al., 2021; Haasnoot et al., 2021).

3.2.3. Unintended consequences of coastal adaptation strategies

We used the CLD to explore and compare the unintended consequences of the three generic coastal adaptation strategies. For simplicity, we analyzed the effects of the direct impacts on key feedback mechanisms (Tables 3 and 4) individually and ignored any potential overlaying effects. This analysis is subject to the selection of potential impacts of adaptation strategies, and we do not claim completeness.

For a protection strategy, all direct impacts lead to an increase in urban development in flood zones stimulated through both decreasing flood risk (Fig. 4, part A), economic pressure due to the need for financing of the protection measure (Fig. 4, part B), and reduced flood risk perception (Fig. 4, part C). A decrease in flood risk further increases trust in public institutions, which may entail two counteracting effects: (1) public trust can reinforce institutional capacity to adapt to future flood risk, and (2) it can lead to decreasing flood risk perception that may further stimulate urban expansion in flood zones. Overall, the CLD suggests that protection strategies will lead to further urban development in flood zones due to, i.a., stakeholders trying to offset protection costs. As long as flood risk perception is low (i.e., no major flood events occur), urban development in flood zones may continue undisrupted, fostering economic capacities and opportunities for the community. This development discontinues if major flood events occur (leading to increased risk perception) or if revenues from housing development no longer offset rising expenditure for protection, resulting in economic insecurities that negatively affect flood risk mitigation and citizens' welfare and public trust.

The implementation of an accommodation strategy comes with direct impacts on flood risk (Fig. 5, part A), economic capacities (Fig. 5, part B), and flood risk perception (Fig. 5, part C). In contrast to

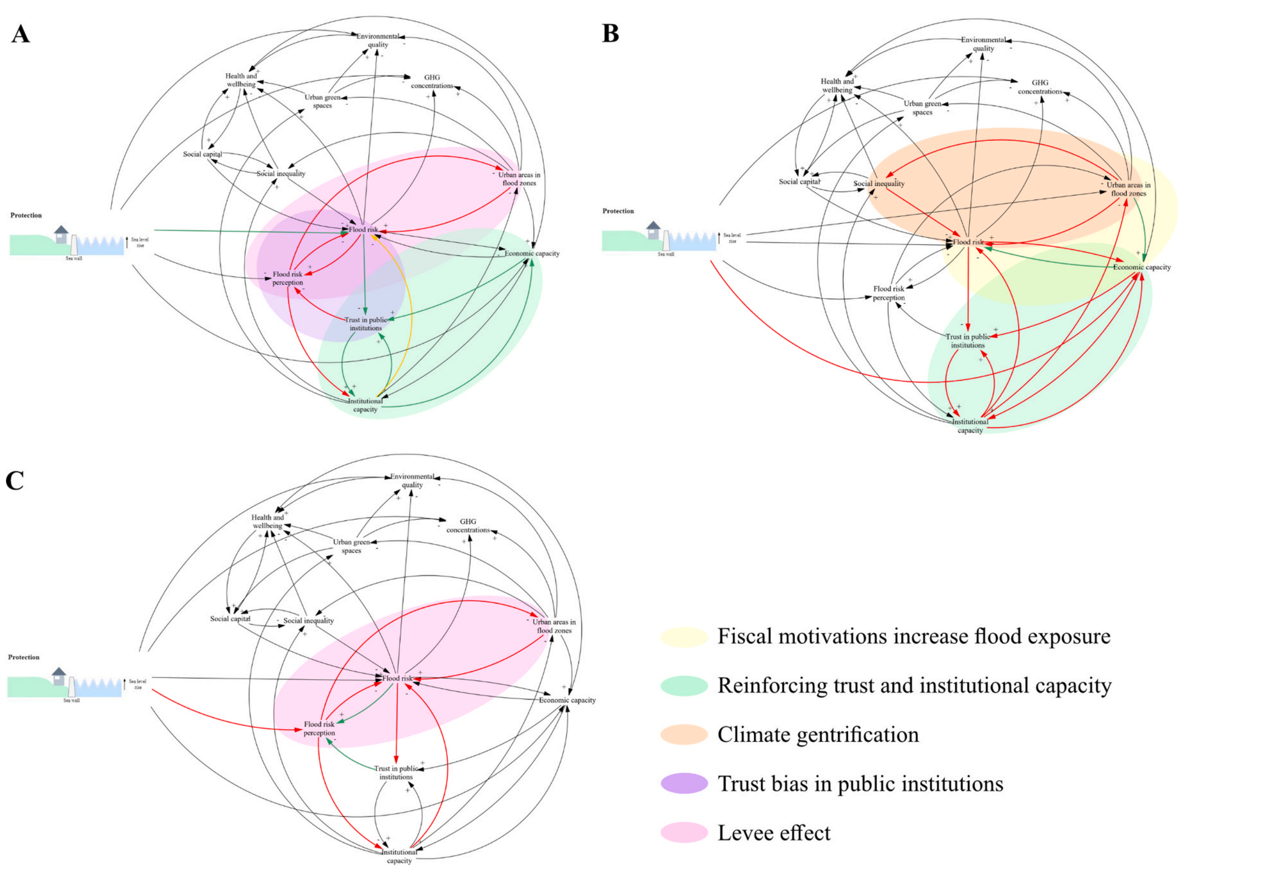


Fig. 4. Protection strategy - Unintended consequences of direct impacts: decreasing flood risk (A), decreasing economic capacity (B), and decreasing flood risk perception (C); relationships that are affected both negatively and positively are highlighted in yellow (see online version for color representation).

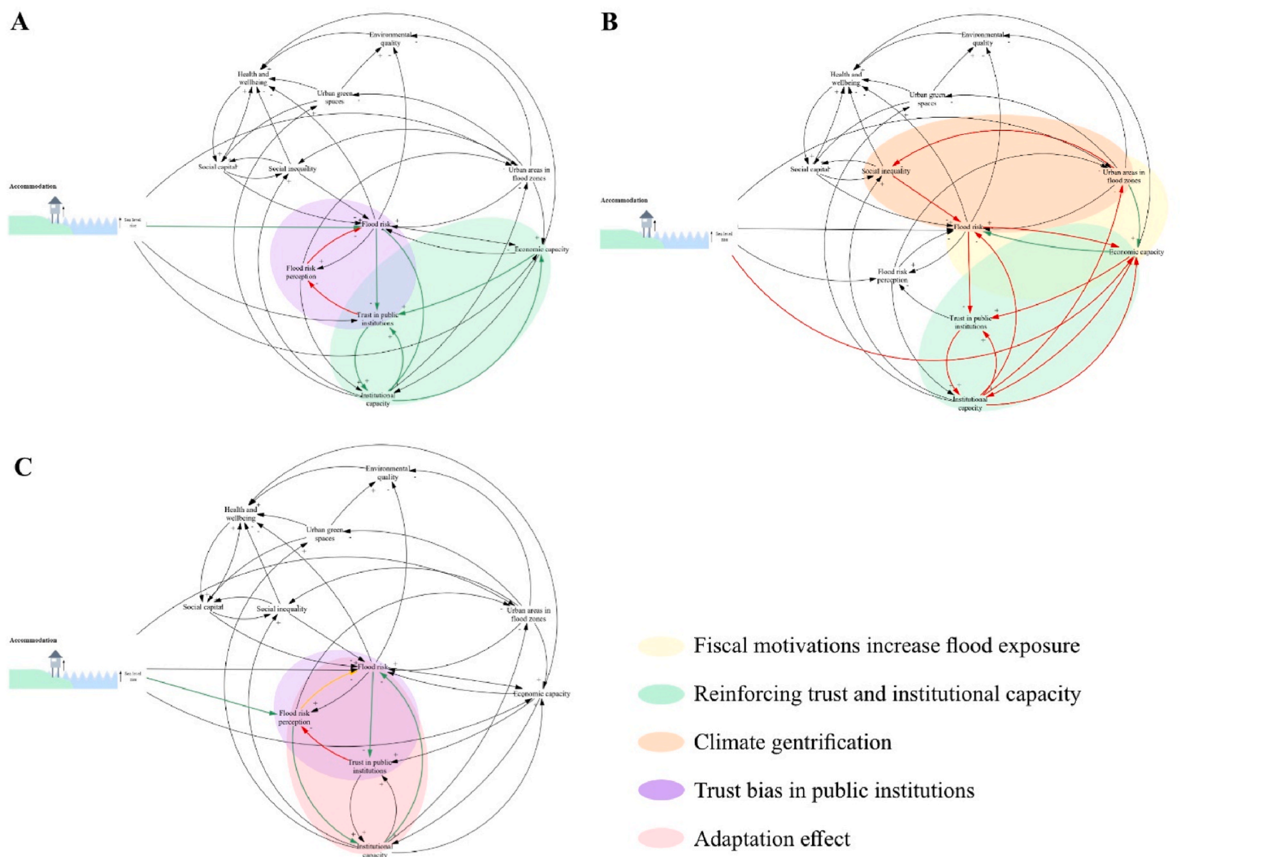


Fig. 5. Accommodation strategy - Unintended consequences of direct impacts: decreasing flood risk (A), decreasing economic capacity (B), and increasing flood risk perception (C); relationships that are affected both negatively and positively are highlighted in yellow (see online version for color representation).

protection, accommodation can lead to increased flood risk perception (Coquet et al., 2018; O'Neill et al., 2016). We argue that feedbacks between flood risk, flood risk perception, and urban areas in flood zones do not apply because (1) flood risk perception is high and (2) flood risk is decoupled from exposure by flood-proofing buildings. Continued urban development in flood zones can create financing opportunities for further flood risk mitigation, and higher levels of flood risk perception can strengthen institutional capacities to mitigate flood risk. However, a tipping point occurs if the sea level rises so much that financial resources become insufficient for adaptation, resulting in increased flood risk, compromised institutional performances, and reduced trust in public institutions. Both for protection and accommodation strategies, social inequality may increase as a direct impact of strategies being (1) a higher economic burden to lower-income households and (2) implemented to protect high-value areas rather than high-vulnerability areas (Lallemant et al., 2022; Taylor et al., 2022).

For a planned relocation strategy, unintended consequences play a crucial role in the strategy's success. Low levels of flood risk perception (due to fading collective memory of floods) may lead to migration back to high-risk areas at some point (Fig. 6, part A). The strategy may also fail if high adaptation costs create political incentives to permit new urban development in high-risk areas (Fig. 6, part B). Further, controversies around the implementation of planned relocation can lead to public mistrust and weaken institutions, making it harder to prevent developments in high-risk areas (Fig. 6, part D). Reduced institutional capacity and urban expansion in flood zones can reinforce social inequalities that further hamper flood risk mitigation efforts. Finally, relocation to new areas can lead to a decay in social capital, which can have negative implications on the welfare of citizens (Fig. 6, part C).

4. Discussions

4.1. Unintended consequences of coastal adaptation and city development

Our CLD model explores how central feedback mechanisms between city development and coastal adaptation will likely lead to unintended consequences and increasing socioeconomic vulnerabilities. We showed that negative repercussions are possible no matter which coastal adaptation strategy (i.e., protection, accommodation, and planned relocation) gets implemented. While the strategies trigger different interconnected feedback mechanisms, few independent states appear to determine the outcome of adaptation pathways: flood risk perception, economic capacity, and trust in public institutions. While elevated flood risk perception can strengthen institutional capacities to adapt (see accommodation, Fig. 6), reduced flood risk perception may lead to risk-taking actions such as return migration to high-risk areas (see planned relocation, Fig. 6) or continued development in flood zones (see protection, Fig. 4). Urban development in flood zones is further stimulated by stakeholders trying to finance adaptation measures through tax revenues. As long as no major flood events occur and tax revenues can offset adaptation costs, urban development in flood zones can continue undisrupted. It may even create financing opportunities for future adaptation. The mechanism can fail when, e.g., population growth in the city stops or when increasing sea levels exponentiates the cost of protection. Reduced economic capacities impact not only flood risk mitigation efforts but can also negatively affect public trust in institutions and further hamper the success of adaptation. Trust or lack of trust in institutions plays a crucial role as (1) it determines institutional performance while (2) it reduces flood risk perception and private risk-reducing measures that can counteract public flood mitigation intentions.

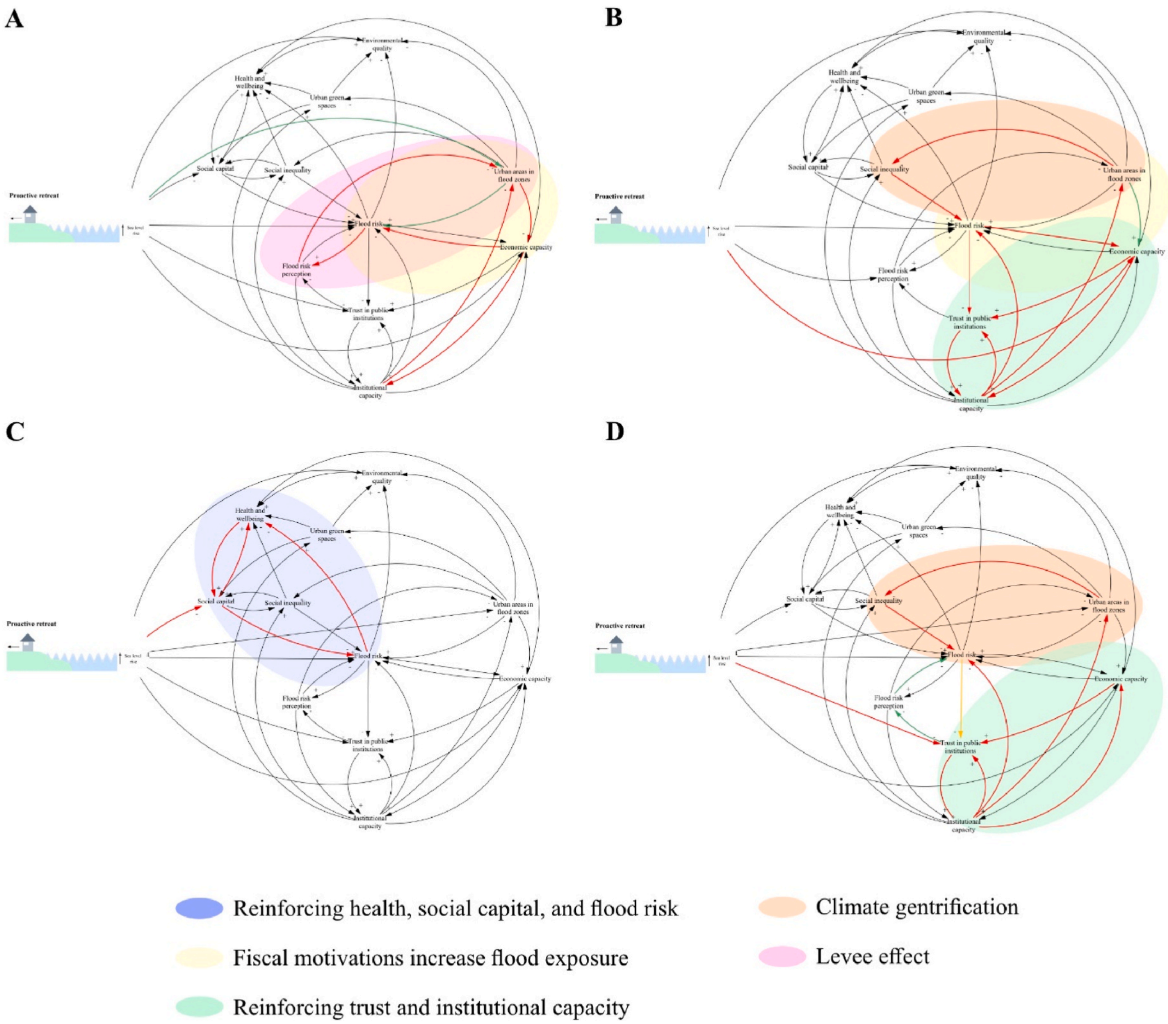


Fig. 6. Planned relocation strategy - Unintended consequences of direct impacts: decreasing urban areas in flood zones (A), decreasing economic capacity (B), decreasing social capital (C), and decreasing trust in public institutions (D); relationships that are affected both negatively and positively are highlighted in yellow (see online version for color representation).

By analyzing unintended consequences based on individual feedback mechanisms, we explored several potential benefits and weak points of three generic strategies:

- Protection is likely to stimulate further development in risk areas and fails when flood risk and/or cost of protection exceeds economic capacities;
- Accommodation comes with similar effects, but high-risk perception and flood-proofing buildings can decouple flood risk from exposure. We emphasize again that this is an assumption that has not been fully studied. Esteban et al. (2017) suggest that a false sense of security may arise, and to date, there is still little evidence for the strategy's actual reduction potential of vulnerability and exposure (IPCC, 2022). Tipping points are reached when rising sea levels lead to adaptation costs that exceed the community's economic capacity and/or when flood risk becomes unacceptable due to, for example, adverse effects on accessibility;
- Planned relocation eliminates risk, but the strategy is prone to fail due to high costs and social controversies. However, other effects may compromise adaptation outcomes and urban development goals, including citizen welfare, environmental protection, and institutional performance. For instance, weakened institutions can have wide-ranging effects on environmental quality and citizen health, jeopardizing social capital and equality.

Discussions above support the need for sequences of adaptation options (i.e., adaptation pathways) and policies to avoid burden-shifting balance tradeoffs between economic, ecological, and sociocultural imperatives. For planned relocation, the discontinued use of existing infrastructure can lead to adverse impacts on social capital and economic losses, and the temporary use of flood zones (i.e., elevated buildings) may smoothen economic impacts (cf., Haasnoot et al., 2021). For protection, continued urban development in flood zones increases direct economic losses from flooding and thus should be accompanied by land-use restrictions (Du et al., 2020).

4.2. Limitations

CLDs come with inherent shortcomings that are limitations for our analysis:

1. The weight of cause-effect relationships is not distinguished. Weights may differ not only from state relationship to state relationship but also from city to city and must be determined context-specifically.
2. The initial size of states is not considered. It is decisive as it determines if and at what scale cause-effect relationships unfold. For example, a wealthy city may easily be able to cover the cost of adaptation measures.

3. Spatial and temporal dependencies (e.g., processes taking place over different time horizons and spatial scales) are not distinguished. Some of the processes in the CLD take place in the short term (e.g., immediate increases in flood risk perception after flooding), while others happen over decades (e.g., the build-up of social capital). Similarly, some states (e.g., economic capacity) typically affect the entire city, while, for example, flood risk varies in space. For example, elevating buildings can create a "pepper-pot effect" amongst houses (cf., Tye and Williams, 1994), adversely affecting the hydrology of the area and shifting the hazard elsewhere, and building dikes can increase the vulnerability of communities outside the protection structure (Taylor et al., 2022). Lastly, it is important to note that spatial and temporal dynamics and, thus, vulnerabilities are shifting due to changes in land use and increasing flood risk (Janizadeh et al., 2021).

Further limitations arise from the literature that forms the basis of the CLD. The considered studies focus on different contexts, such as different implementation and decision levels (national or local), or consider only a few selected interactions between flood risk and urban development. Consequently, not all depicted relations are relevant in all situations, and some relations only occur conditionally.

In its current form, the CLD should, therefore, serve as a thought model that can be used to identify potential impacts of flood adaptation but requires judgment with respect to whether specific cause-effect relationships and states are relevant in a given context.

4.3. Further research and model development

In further research, our CLD model can serve as a basis for developing System Dynamics models that capture the weights and the temporal scales of the cause-effect relationships as well as state sizes. For that, we need to determine (1) context-dependent weights as well as (2) the initial size of the states through, e.g., stakeholder workshops or by calibrating the model against historical case data (cf., Woodruff et al., 2018) and lastly, (3) the temporal scales at which processes unfold. Furthermore, further model development should consider external drivers (i.e., population growth/decline, economic development, and climate change) and how these dynamics are linked to potential maladaptation. For example, external drivers can lead to reinforcing dynamics such as "growth begets growth" (Forrester, 1969), population attracts additional population, and wealth leads to more wealth (e.g., investors are attracted by cities with strong economies and growth potential). Other dynamic interdependencies may arise from compound effects of successive or multiple hazards (e.g., storm surges accompanied by extreme rainfall) (cf., Lawrence et al., 2020).

4.4. Policy recommendations

.The concept of the CLD implies that policies are connected and that addressing individual states will impact other states. As such, the objective of the CLD is to study which states are most critical to address and which ones must be addressed simultaneously. Here we highlight aspects that are essential for all adaptation strategies:

1. Repercussions can occur for all strategies. The development of coastal adaptation strategies should, therefore, involve a screening of risks that can arise as a consequence of dependencies between states and how they are influenced beyond neighboring states. City planning is frequently driven by short-term interests (e.g., fiscal motivations to increase flood exposure), and long-term planning needs to be secured through regulatory setups and financial incentives.
2. High levels of flood risk perception are central to all strategies. To maintain high levels of flood risk perception, strategies should go hand in hand with soft measures, including risk communication and public awareness programs (Wachinger et al., 2013).
3. Fiscal motivations to increase development in flood-prone areas reinforcing the levee effect seem to play a central role. Land-use policies such as temporary housing and zoning are effective measures that can restrict new development in flood zones and may curb climate gentrification.
4. Social capital is critical for the effective implementation of flood adaptation and for securing general welfare in a city. Setting up public hearings and community meetings can help to build social capital. For planned relocation, empowering legislation and community engagement processes that address the loss of place and value are critical (Boston and Lawrence, 2018).

The above-discussed points support the need for organizational structures that provide an enabling environment for cross-sectoral and participatory planning processes. Only in this way can an integrated framework raise awareness for connections, guide more collaborative work, and prevent siloed activities (Duit et al., 2010).

5. Conclusions

In our study, we expanded on the work of previous studies by developing a generic CLD that provides a holistic overview of dynamics occurring through the interplay between city development and coastal adaptation. By uncovering critical socio-hydrological feedback mechanisms, we emphasize the importance of understanding the broader dynamics spanning multiple dimensions—socioeconomic, ecological, and institutional. Based on our analysis, we draw the following conclusions:

1) We identified possible feedback mechanisms between 11 states where three independent states appear to be predominant in triggering both positive and negative side effects: flood risk perception, economic capacity, and trust in public institutions. Some of these are recognized already in existing literature, while others are unknown or only partially documented. Among those undocumented, fiscal motivations to increase flood exposure, as well as reinforcing dynamics between trust and institutional capacity, can significantly impact the outcome of coastal adaptation strategies.

2) All considered flood adaptation strategies (i.e., protection, accommodation, and planned relocation) can have unintended consequences, but the pathways differ between strategies:

A) Structural protection measures will likely lead to a build-up of assets in flood-prone areas and increased flood exposure. This effect is well-documented in the literature. Meanwhile, build-up may strengthen economic capacity and thus a community's ability to continue protecting itself at the cost of high resource consumption. This effect is less well studied, and tipping points may occur if flood risk and/or the cost of protection exceed economic gains.

B) Accommodation measures keep flood risk perception high and preserve existing communities. However, as urban developments are maintained or even increased in flood-prone areas, rising sea levels may lead to adaptation costs that exceed the community's economic capacity due to the increased frequency of disruptions in society in general.

C) Also, relocation scenarios may lead to a delayed increase of urban areas in flood zones because (1) political controversies can weaken institutions and thus their ability to uphold the relocation policy; (2) flood risk perception may decrease, and (3) the relocation may come at a high cost, creating incentives for politicians to develop new areas. On the other hand, a well-planned relocation is a resource-effective adaptation strategy, and it may be possible to avoid economic and political repercussions through long-term planning.

Our CLD model is a conceptual overview of feedback mechanisms that may occur between coastal flood risk adaptation and the urban system in its entirety. At the same time, previous studies have focused on individual aspects of this system in greater depth. The model can serve as inspiration to further explore interdependencies between flood risk management and urban development. As such, it can be a stepping stone for future model refinements and in-depth investigations of feedback mechanisms that may otherwise not be considered in urban planning and flood risk management.

CRediT authorship contribution statement

Anna Lea Eggert: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Roland Löwe:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization. **Karsten Arnbjerg-Nielsen:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the data used in the Supplementary Materials to this study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2024.107026.

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