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A socio-ecological system perspective on urban flood risk and barriers to adaptation under climate change using causal loop diagrams – Case study of the city of Hamburg, Germany

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Cities are facing increasing challenges of flood risk due to combined effects of climate change and socioeconomic development. At the same time understanding of the complexity of urban flood risk is still limited, hampering decision-making and effective urban adaptation planning. A socio-ecological system (SES) perspective offers a promising approach to analyze risk as a non-isolated entity by recognizing human and natural systems as complex and coupled structures and considering their interactive dynamics (e.g., delays, feedbacks, and non-linearity). Qualitative system dynamics modeling tools, such as causal loop diagrams, are particularly useful for this, as they allow the inclusion of different kinds of system variables.

This study applies a qualitative system dynamics modeling framework to holistically investigate urban flood risk under climate change and barriers to adaptation in a coupled SES using the city of Hamburg as a case study. The study deals with urban flood risk in the context of *'water from 4 sides'* addressing questions in the growing research field of climate hazard interactions and compound risks. In a stepwise approach, a qualitative system dynamics model was developed based on an integrated interdisciplinary knowledge of researchers. Disciplinary mental maps were created by the researchers in various group interviews, followed by the development of an overall group causal loop diagram based on the disciplinary mental maps to form a holistic qualitative model. For the model analysis, causal chains of sub-processes and feedback loops were visually isolated and highlighted. Particular emphasis is placed on identifying and analyzing the reinforcing feedback loops underlying the complex urban system in order to understand the vicious circles of barriers that perpetuate and thus hinder the adaptation process. The findings on the system's feedback loops help to understand why and how system behavior evolves in a specific direction. The integrated model shows that the main drivers of urban flood risk growth in the system are linked to socio-economic and institutional processes. Climate change mainly affects the city externally by increasing flood hazards, while the city itself contributes to flood risk through processes of exposure and social vulnerability. The results show that increasing flood risk and barriers to adaptation in the city are linked to the amplifying feedback loops of path dependency, river engineering measures, urban development, car dependency, the 'levee effect', poverty, urban health and silo-thinking.

The case study demonstrates the usefulness of the qualitative system dynamics modelling approach in developing a shared understanding of the complex social, economic, environmental and political and institutional interactions among multiple drivers of flood risk. Causal loop diagrams can be successfully used to articulate the viscous circles of barriers and lock-in effects of unsustainable development in urban adaptation. However, it should be noted that the model reflects the state of knowledge of the researchers involved in the model-building process and therefore only represents a 'dynamic hypothesis' of the structure and dynamics of the system under consideration. Further work is in progress to place this qualitative system dynamics model in the broader context of decisions support and policy through stakeholder involvement.

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