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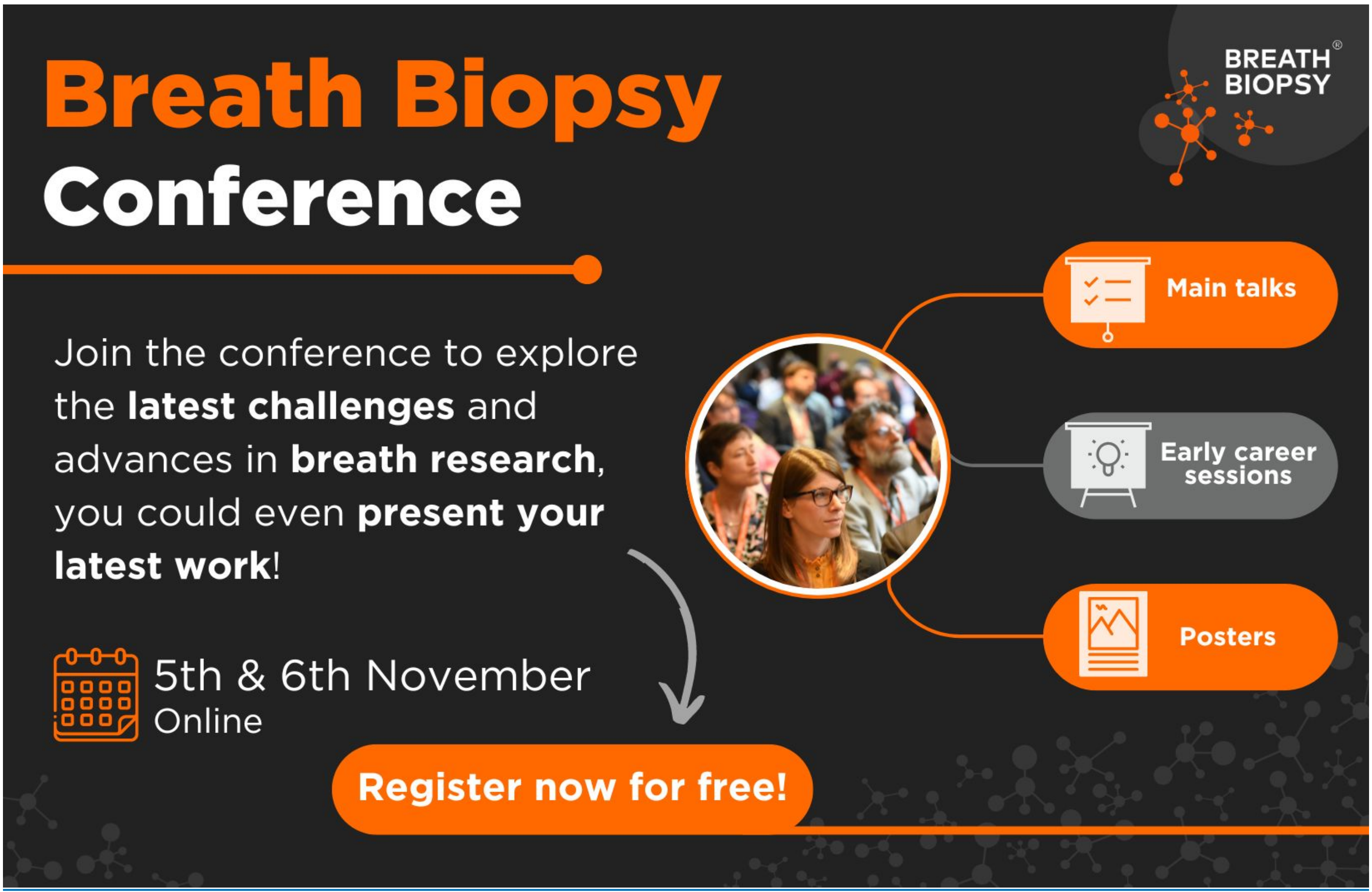
To cite this article: Veronika Zwirglmaier *et al* 2024 *Environ. Res. Lett.* **19** 073003



IOP Publishing Environ. Res. Lett. 19 (2024) 073003 https://doi.org/10.1088/1748-9326/ad536f

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OPEN ACCESS

RECEIVED
1 September 2023

REVISED
26 April 2024

ACCEPTED FOR PUBLICATION
3 June 2024

PUBLISHED
12 June 2024

TOPICAL REVIEW

How suitable are current approaches to simulate flood risk under future urbanization trends?

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Keywords: flood risk, modelling, urbanization, cities

Abstract

Flood risk in urban areas will increase massively under future urbanization and climate change. Urban flood risk models have been increasingly applied to assess impacts of urbanization on flood risk. For this purpose, different methodological approaches have been developed in order to reflect the complexity and dynamics of urban growth. To assess the state-of-the art in the application of flood risk models under urbanization scenarios, we conducted a structured literature review and systematically analyzed 93 publications with 141 case studies. Our review shows that hydrological and hydrodynamic flood models are the most commonly used approaches to simulate flood risk. Future urbanization is mostly considered as urban sprawl through the adjustment of land use maps and roughness parameters. A low number of approaches additionally consider transitions of urban structures and densification processes in their urbanization scenarios. High-resolution physically based flood models have been advanced and are well suited for describing quantifiable processes in data-rich contexts. In regions with limited data, we argue that reducing the level of detail in flood models and increasing the level of detail in urbanization patterns should be considered to improve the quality of flood risk projections under future urbanization. For this purpose, we also call for the development of integrative model structures such as causal network models that have greater explanatory power and enable the processing of qualitative data.

1. Introduction

Urban areas worldwide face significant flood risks that jeopardize lives and cause high economic damages (Alfieri *et al* 2017, Hemmati *et al* 2020). Between 2018 and 2022, for example, flooding caused total losses of US$ 300 billion (Munich 2023). Future projections indicate a drastic increase of risks to urban economies, social and environmental systems as well as physical infrastructure fueled by anthropogenic caused climate change. In addition to climate change, urbanization is a pivotal driver of (past and future) flood risks (Dodman *et al* 2022): Projections indicate a fundamental transformation of land use and land cover and predict that two-thirds of the global population reside in urban areas by 2050 (World Bank Group 2021). Urban sprawl or densification massively change hydrological and hydraulic characteristics of a city, exacerbating flood risks (Feng *et al* 2021). Consequently, the implementation of adaptation strategies becomes inevitable to mitigate adverse impacts and effectively manage flood risks in the future.

The Intergovernmental Panel on Climate Change defines flood risk as the impact of flood hazards on human or ecological systems contingent on their exposure and vulnerability. Risk is shaped by three interconnected components: hazard, exposure and vulnerability (Reisinger *et al* 2020). The employment of modeling techniques has become a prominent tool to comprehend the underlying processes of these three components and project future scenarios (Löwe *et al* 2017). Modeling enables the careful assessment of adaptation-related changes to avoid unintended consequences and to convey inherent uncertainties.

However, urban flood risks assessments are challenging due to the multiple feedbacks and interactions between natural processes and anthropogenic systems across different spatial and temporal scales (Dawson *et al* 2008). To overcome this complexity under limited computational resources, models for urban flood risk assessments are designed to encapsulate the relevant drivers and boundary conditions within clearly defined geographical boundaries for specific targets and environments.

Model-based assessments become even more complex when considering the dynamic evolution of both natural and anthropogenic factors. Therefore, methods used to assess current and future flood risk in urban areas typically require large amounts of data and multiple parameters across temporal and spatial scales that lead to high uncertainties. Furthermore, future scenarios need be considered, including urbanization trends and climate change scenarios. This poses a challenge for many cities around the world as data availability for the current context is already low, and data scarcity hinders the simulation of future conditions for many cities. While many studies have simulated future urban flood risk under climate change (Karamouz *et al* 2011, Zölch *et al* 2017, Ercolani *et al* 2018, Goncalves *et al* 2018, Du *et al* 2019, Cristiano *et al* 2020, Ferguson and Fenner 2020, Ferreira *et al* 2020, Hou *et al* 2020, Vajjarapu *et al* 2020, Costa *et al* 2021, Ertan and Çelik 2021, Cheng *et al* 2022, Gao *et al* 2022), urbanization has been less intensively considered in research.

However, it is already widely recognized that urbanization affects all components of flood risk across scales and in manifold ways, depending on the underlying processes within a city and its adjacent peri-urban areas. This includes city-internal developments, such as the construction of buildings on green open spaces, or densification through the closing of gaps in the building stock, but also city-internal re-developments, like the transitions of urban structure types (e.g. gentrification) (Sakijege and Dakyaga 2022, Wang *et al* 2022). In this regard, it is important to consider not only persisting cities but also peri-urban areas, as these are transition zones, which bridge the urban and the rural environments most likely transition from rural to urban land use. Thus, peri-urban regions are directly linked to the city (UNESCO 2014).

Flood hazard, flood exposure and vulnerability of assets and people are affected from urbanization, which need to be considered in the respective models: For example, urban sprawl leads to an increase of impervious surfaces in the peri-urban region, which results in reduced infiltration and higher discharge rates (Feng *et al* 2021). Therefore, sprawl affects the hazard component of urban flood risk by increasing the frequency and magnitude of floods. Urban densification processes within the city reduce the amount of inner urban retention areas and therefore change the amount of effective rainfall, which is defined as the rainfall that turns into run-off. Urban structure types that are defined as the physical built structures of a city (Lehner and Blaschke 2019) are associated with different hydrological processes (Heiden *et al* 2012, Dodman *et al* 2022). Gentrification therefore impacts the spatial patterns of susceptibility to flooding. A change in urban structures additionally affects the flood hazard through changing roughness parameters and runoff patterns. Especially in cities with unplanned development, drainage infrastructures, which determine the discharge or storage capacity for flood water in the area, largely vary amongst urban structure types (Sakijege and Dakyaga 2022). The same is true for differences in solid waste management, which affect the risks of clogging. Consequently, the distinction of urban structure types is important for and neglecting them would lead to a false representation of the flood hazard (Sakijege and Dakyaga 2022).

The influence of urban sprawl, densification and change of urban structure types on exposure and vulnerability has also already been assessed in a number of studies on urban flood risk. Garschagen and Romero-Lankao (2015) found that the rate of urban sprawl influences the exposure but also coping capacity of a city against climatic hazards, which refers to the readiness to manage disasters. Urban structures in a city can be classified into social, physical and economic vulnerability profiles (e.g. low-rise slum areas may have higher social and physical vulnerability but lower economic vulnerability). Therefore, densification and the change in urban structure types is crucial for a comprehensive assessment of future flood risk under urbanization scenarios. Neglecting the different urbanization characteristics results in an incomplete perception of flood risk and may lead to imbalanced adaptation strategies (Lobo *et al* 2023).

All these aspects have been increasingly explored in recent years using more frequently integrative approaches (Güneralp *et al* 2015, Aich *et al* 2016, Skougaard Kaspersen *et al* 2017, Mustafa *et al* 2018, Chen *et al* 2021, Hemmati *et al* 2021a, Bibi and Kara 2023, García-Ayllón and Franco 2023, Hamdy *et al* 2023, Karutz *et al* 2023, Lazzarin *et al* 2023, Nkonu *et al* 2023). Combined modeling approaches have been used to simulate the growth of new settlements into flood-prone areas or the increasing vulnerability of changing urban structure types (Tam *et al* 2018, Kim and Newman 2020, Tierolf *et al* 2021). These modeling approaches are often intended to support the implementation of more targeted flood adaptation and management plans (Cea and Costabile 2022). Güneralp *et al* (2015) identified global patterns of flood and drought exposure in urban areas by overlaying existing flood maps with maps of urban areas generated with a statistical urban growth model. Hamdy *et al* (2023) used historical urban extents to simulate flood exposure with a hydrological-hydraulic flood modeling approach in Hail City, Saudi Arabia. Lazzarin *et al* (2023) used historical urban maps as input to hydraulic urban flood models for the small city of San Donà di Piave in Italy to assess all three components of risk as well as urban sprawl and densification. Still, many models are challenged to deal with the interdisciplinary complexity of flood risk in rapidly changing urban areas, and often sufficient data are not available to build assessment tools.

Despite being an urgent topic a review on flood risk assessment under future urbanization has not been presented. While there are some recent reviews available that provide an overview of available flood assessment tools urbanization has not been considered. For example, Kumar *et al* (2023) provided an overview of existing flood modeling techniques and their limitations but did not specifically consider urbanization. Li *et al* (2022) reviewed recent studies dealing with flood hazard assessment methods in data-rich urban areas focusing on current time steps. Further reviews analyze urban flood risk assessment without considering how the changes in urban area are represented (Bulti and Abebe 2020, Qi *et al* 2021, Cea and Costabile 2022, Tom *et al* 2022). Therefore, this study provides a comprehensive analysis of current approaches of integrating future urbanization into flood modeling studies and assesses the different levels of detail in the representation of urbanization in urban flood risk modeling. In this study we address the following research questions:

- **Which modeling approaches exist to simulate flood risk under future urbanization and urban change?**
  We develop a classification of the current research landscape and analyze the approaches which are currently used to model flood risk under future urbanization. Based on the results we figure out potential developments to improve the representation of future urbanization in flood risk assessments.
- **How are urbanization scenarios used in flood risk modeling?**
  We analyze current approaches to including future urbanization in flood risk assessments to the modeling community.
- **What is the geographical distribution of the models used?**
  We assess if certain model and scenario types are preferentially applied in certain regions of the world. The assumption behind this question is that models which offer less detail in the processes are more commonly applied in data-scarce environments.
- **Which components of risk (hazard, exposure, vulnerability) are represented by which models?**
  By identifying the components of risk addressed in the studies, we assess the potentials of the models to perform holistic flood risk assessments considering all three components of flood risk (hazard, exposure, vulnerability).

Based on the obtained results of our review, we discuss current approaches and their advantages focusing on the potentials for integrating urbanization into flood models at sufficient level of detail in both components. We also identify the main challenges that currently exist in the research landscape for integrating urbanization modeling into flood risk assessment and suggest potential next steps how to overcome them.

Our study is structured as follows: Chapter 2 describes the design of the screening approach and the methodology of the review. Chapter 3 presents the results in terms of current (i) flood modeling approaches, (ii) urbanization assessments and (iii) mechanisms of coupling flood model and urbanization assessment. In the discussion (Chapter 4), we present the main challenges for current flood modeling approaches, urbanization assessments and combined approaches considering the objective of modeling flood risk in complex urban areas under future developments. Based on the results, we propose solutions in Chapter 5 to address the challenges discussed. The conclusion provides an overview of our main findings and our future recommendations.

2. Data and methods

2.1. Methodology

To obtain a comprehensive overview of current approaches used to integrate urbanization into flood risk modeling, we conducted a systematic search via the Web of Science on 14 July, 2022. We used publications of peer-reviewed journals or internationally acknowledged conferences to account for a high quality of analyzed scientific studies. We applied a systematically selected set of keywords (see table 1).

We restricted our analysis to research articles, review articles and proceeding papers written in English language. We first checked whether it is sufficient to include only peer-reviewed articles found in Web of Science and written in English and to exclude gray literature (e.g. technical reports, governmental documents, research project documentation), other databases, and other languages. As the purpose of this article is to provide an overview of the current research landscape, we decided that this restriction was reasonable. The final search yielded 417 articles between the year 2000 until 2022. We then screened

Table 1. Search terms used in the WOS literature search.

Urbanization	Flood	Risk	Urban context	Model	Future
'Urban growth'	Flood*	Risk	Cit*	Model*	Future
Urbanization		Hazard	Urban	Simulat*	Scenario
Urbanisation		Exposure			
'Urban development'		Vulnerability			

Table 2. Predefined exclusion criteria to evaluate the relevance of the collected studies.

Description of the exclusion criteria	Examples
No consideration of changes in urban area	The focus of the study is not a city but a catchment, where some land is converted to urban area
No assessment of flood risk or a component of flood risk	Urbanization is simulated but flood risk is not assessed by any approach but more the general importance of impacts on flooding are discussed
General assessment of impacts of land use change of flood risk	Flood assessments where the impact of land use transformations is assessed

Table 3. Variables extracted from the publications in a structured way and the type of answer to be given.

Code	Type of answer
Location	Free text
Flood types	Multiple choice with free text options
Considered parameters expressing hazard, exposure and vulnerability results	Multiple choice with free text options
chain (e.g. order of the applied models)	Free text
Coupling of the models	Multiple Choice with free text options
Applied models	Free text
Parameters representing urbanization (e.g. sprawl, densification, structure types)	Multiple Choice with free text options
Consideration of adaptation	Multiple Choice with free text options

the articles according to exclusion criteria listed in table 2. We did not further rate the quality of the included publications—besides only including peer-reviewed publications and conference proceedings to ensure a high scientific standard. Thus, we kept the subjectivity to a minimum. After screening the publications, we obtained a final number of 93 publications that were included in the analyses. The full list of selected studies and a full description of the applied methodology can be found in the supplementary material.

2.2. Data

We carried out a structured content analysis of the selected 93 articles with a set of predefined questions using the online survey tool ScoSci Survey. An overview of the analyzed different thematic areas and the coding scheme is given in table 3.

In the first step of the analysis, we identified the approaches used in each study to assess flooding and urbanization. Secondly, we clustered the methods of how both components—flood and urbanization assessment—were combined and which level of detail was used for flood and urbanization assessment. In the context of flood assessments, level of detail means whether physical processes were modeled or the assessment was based on terrain analysis or historical data. In the context of urbanization assessments, we analyzed which forms of urbanization are considered within the assessments (urban sprawl, urban densification, changes in urban structure types) and refer to it as the level of detail in urbanization. Thirdly, we analyze how far process-based urbanization models were used or if urbanization scenarios follow deterministic rules like the description of master plans or the extrapolation of past trends.

We also investigated the geographical distribution of 141 case studies reported in the 93 studies, in order to assess if certain modelling approaches and certain levels of detail in urbanization representation are clustered among certain countries. For the geographical analysis we used the number of case studies ($n = 141$) rather than the number of publications, as one publication can have several case studies in one country but also in different countries. The results of the described analyses build the foundation of the discussion on current challenges and future potentials for new integrated modeling approaches.

Table 4. Descriptions of the groups of the flood assessment approaches.

	Flood Assessment Approach	Description
Flood model	Hydrological model	Model which simplifies and describes rainfall-runoff processes in equations based on different watershed characteristics (Devia *et al* 2015)
	Hydrodynamic model	Models which use numerical computation techniques to estimate flood routing processes in 1D, 1D/2D, 2D or 3D
	Urban flood model	Hydrodynamic models which explicitly consider urban features influencing flood propagation like subsurface drainage systems, etc
Simplified approach	Cellular Automata	Model based on simple rules to spread water among artificially created grid cells
	Statistical	Models which used past data to learn and predict flooding
	Data aggregation	Approach in which different data of influencing parameters in assembled and combined in a way to get information on the flood situation like indices on flood susceptibility
	GIS-based approach	An approach which uses detailed topographic data to predict the propagation and expansion of flood water in an area
Existing flood map	Existing flood map	Flood map product(s) which are generated in previous research and are not changed within the considered study

3. Results

3.1. Approaches used for flood hazard assessments

We found three main clusters of how flooding is considered in the selected studies, i.e. flood model, simplified approach and existing flood map (table 4): the flood model cluster includes studies that use model approaches based on physical principles. Therefore, all hydrodynamic, hydrological and specific urban flood models are assigned to this cluster accounting for 65% ($n = 60$) of the studies (KC *et al* 2021, Mahato *et al* 2022, Osheen *et al* 2022, Priyambodoho *et al* 2022, Shan *et al* 2022, Zhao *et al* 2022).

One typical example of this category is the study of Khan *et al* (2018), who applied the hydraulic model Mike Flood combined with statistical urbanization scenarios and depth-damage curves. They further used a 1D and 2D modelling approach to account for the subsurface urban drainage system. With this model setup Khan *et al* (2018) analyzed how the impact of the historic flood event in Dhaka, Bangladesh in 2004 changed under an urbanization scenario in the year 2050. Priyambodoho *et al* (2022) assessed the effect of urban development on the flood hazard component in Jakarta, Indonesia. They applied a rainfall-runoff model and a flood inundation model which is based on the equations of Saint-Venant describing the discharge of flood waves. The urbanization scenarios were generated with the cellular automata model SLEUTH, which projects urban growth based on the analysis of historic data on land-use change, transportation and slope. However, the authors had to neglect urban infrastructure within the flood modeling component, as more detailed data than provided by the SLEUTH model would have been required.

The cluster simplified approach includes any kind of data-driven methodology and covers statistical methods, index generation studies, multi criteria analyses, GIS analyses or cellular automata based flood hazard models. 18 studies (19%) used these simplified approaches within the considered literature to assess flooding under urbanization trends (Wolff *et al* 2020, Obiefuna *et al* 2021, Stamellou *et al* 2021, Xu *et al* 2021b). The term simplified approach does not mean that those approaches are less complex or valid, but they do not focus on a precise representation of physical processes in contrast to the cluster flood model. Kaykhosravi *et al* (2020) for example, developed a hydrological–hydraulic index for three Canadian cities, which is based on a set of parameters describing the degree of impervious area. Based on the analysis of different future urbanization scenarios they underlined the demand for a low impact development.

The smallest group forms the cluster existing flood map ($n = 15$, 16%) (Rimal *et al* 2017, Johnson *et al* 2021, Sarica *et al* 2021, Tierolf *et al* 2021, Rifat and Liu 2022). In this cluster, the flood assessment component relies on existing products, e.g. flood

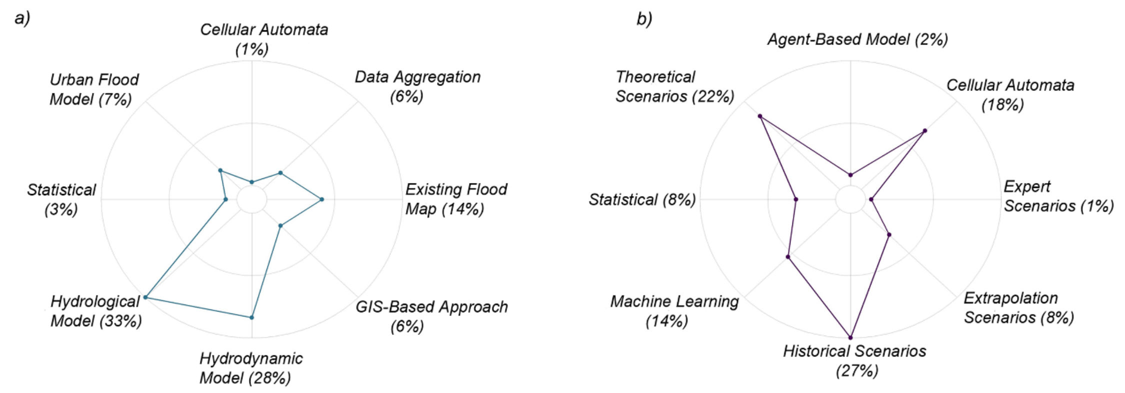

Figure 1. The radar charts show the shares of the categories of (a) flood assessment approaches and (b) urbanization assessment approaches used within the included literature.

extent maps as a baseline for their analysis of flooding under urbanization. Tierolf *et al* (2021) assessed the annual expected damage from flood risk in five South–East Asian countries using flood maps from the study of Dottori *et al* (2016) and overlaid them with urbanization scenarios generated with the CLUMondo land use change model. Furthermore, the authors applied a depth-damage curve to assess the overall expected damage.

The analysis of the applied methodologies shows that hydrological models are the most applied category for assessing flood risk under urbanization scenarios. In contrast, cellular automata-based flood models and statistical methods are the least applied tools (see figure 1(a)). Whereas the three identified clusters flood model, simplified approach and existing flood map are mutually exclusive, different approaches within the subgroups of flood models were combined. For instance, in several studies a hydrological model was combined with a hydrodynamic model to represent the total flood process from run-off generation in the catchment to the final inundation extent (Abdelkarim *et al* 2019, Areu-Rangel *et al* 2019, Beckers *et al* 2013, De Lange and McBean 2017, Feng *et al* 2021, Fu *et al* 2018, Gori *et al* 2019, Hemmati *et al* 2021b, Huang *et al* 2017, Juan *et al* 2020, Mahato *et al* 2022, Nithila Devi *et al* 2019, Priyambodoho *et al* 2022, Sharif *et al* 2016, Zhao *et al* 2022, Zope *et al* 2015).

3.2. Approaches used for urbanization scenarios

Within the urbanization scenarios, we identified two main groups of urbanization projection methods among the included studies (see table 5). The cluster model-based approach covers all methodologies that simulate urbanization in a process-based way based on the underlying drivers of urban growth. 41% of the studies ($n = 39$) projected urbanization patterns by applying models, such as cellular automata models (44%, $n = 17$) (Votsis 2017, Stamellou *et al* 2021, Mena *et al* 2022, Mesta *et al* 2022), machine learning approaches (33%, $n = 13$) (Beshir and Song 2021, Lin *et al* 2020, Rifat and Liu 2022), statistical approaches (18%, $n = 7$) (Khan *et al* 2018, Löwe *et al* 2018, Wang *et al* 2019, Zhao *et al* 2022) or agent-based models (5%, $n = 2$) (Mustafa *et al* 2018, Hemmati *et al* 2021b).

The second cluster deterministic urbanization assessments accounts for 58% ($n = 54$) of the total studies. Deterministic approaches, for instance, cover the methodologies theoretical scenarios, historical scenarios, extrapolation scenarios and expert scenarios. It is remarkable that 48% ($n = 26$) of the studies applying deterministic methods used historical scenarios as base for their urbanization assessment (see figure 1(b)). Historical scenarios refer to scenarios generated by using historical urban extents derived from satellite images or historical land use maps without future projections (Yin *et al* 2015, Zope *et al* 2015, Huang *et al* 2017, Orton *et al* 2020, Xu *et al* 2021b). Theoretical scenarios include those studies evaluating the impact on flood risk by increasing the percentage in impervious urban area within a catchment or within city boundaries (37%, $n = 20$) (Cao *et al* 2020b, Kaykhosravi *et al* 2020, Rosenberger *et al* 2021, Osheen *et al* 2022). Extrapolation scenarios also use historical data, but they additionally extrapolate the observed growth trend to the future (13%, $n = 7$) (Muis *et al* 2015, Areu-Rangel *et al* 2019, Chen *et al* 2021, Daksiya *et al* 2021). One study of the scoped literature developed a scenario based on expert group discussions (Xu *et al* 2020).

The methodologies used in the reviewed literature shows that combined approaches have not yet been applied—neither the approaches across the two clusters were mixed nor the methodologies within their subgroups were combined with one exception: One study used an agent-based and cellular automata model to simulate future urbanization scenarios (Hemmati *et al* 2021b).

Table 5. Descriptions of the groups of urbanization projection approaches.

	Urbanization Scenario Approach	Description
Model-based	Agent-based model	Urbanization simulated with the help of agent-based models, i.e. simulating the development of an urban area based on different agents' actions and decisions
	Cellular automata	Urbanization projected by models based on the cellular automata algorithm
	Machine learning	Urbanization projected by machine learning methods like artificial neural networks
	Statistical	Urbanization predicted by statistical methods, like regression methods
Deterministic	Expert scenarios	Scenarios based on expert opinions, including scenarios generated from focus group discussions, expert workshops or interviews
	Extrapolation scenarios	Scenarios using an observed trend and extrapolate it to future time periods
	Historical scenarios	Scenarios using observed information on urban extent or land use from the past, taken for example from maps or satellite images
	Theoretical scenarios	Scenarios which are based on assumptions and what-if scenarios, for example what is the effect if the urban area increases by x%

3.3. Groups of linking flood and urbanization scenarios

Figure 2 shows, how the three main clusters of flood assessment are linked with types of urbanization scenarios. Alluvial plots were originally introduced to visualize changes over time but are now also used to visualize connections between categorical data. (A detailed figure of existing flood model—urbanization assessment chain is given in the supplementary material).

Four dominant groups can be divided according our analyses: flood models most commonly are linked to deterministic urbanization projections by using the scenarios as input to the flood model, e.g. by applying changed land use maps or by changing respective runoff coefficients (30%, $n = 24$). In this group only urban sprawl was represented as a change in extent of urban area, but densification or a differentiation into urban structure types were not considered. Many studies applied lumped or semi-distributed hydrological models to achieve the discharge produced by a total basin or sub-basins respectively, while considering different urbanization scenarios, represented by the increase in urban area (impervious area) within the catchment. The urban extent serves as input to determine effective rainfall, following different infiltration methods (e.g. SCS-CN, Green and Ampt, Horton). The flood discharge values are then reported as results (Dawod *et al* 2014, Chen *et al* 2015, Akhter and Hewa 2016, Rafiei Emam *et al* 2016, Fu *et al* 2018, Xu *et al* 2020) or further processed in hydraulic models to obtain flood extent maps (Khan *et al* 2018, Areu-Rangel *et al* 2019). Abdelkarim *et al* (2019) used a semi-distributed flood modelling approach to assess flood extent for historical urban extents in Tabuk City, Saudi Arabia. The differentiation of urban area and agricultural area was used to derive CN-numbers, that describe amount of rainfall turning into runoff (effective rainfall). The CN numbers of each subbasin served as input to the HEC-HMS model, resulting in discharge values per subbasin. The discharge values per subbasin are finally used as input to the hydraulic model HEC-RAS to achieve the flood extents in the city. Other studies used spatially distributed hydrological models to compute discharges. This means that processes which influence the effective rainfall, like evapotranspiration or infiltration is represented on raster grid scale and not on basin or sub-basin scale like in lumped or semi-distributed models. For example, Emmanuel *et al* (2018) analyzed the change in discharge at the Bétérou Outlet in Benin under different theoretical future urban growth scenarios. They modified the land-use raster in the hydrological model LISFLOOD which changed especially the infiltration and thus the resulting discharge. While the previous studies considered only the share of impervious areas to estimate the change in infiltration and thus effective rainfall, Juan *et al* (2020) not only considered the altered imperviousness in the hydrological model but also the altered roughness of the area. They used the distributed hydrological model Vflo and the hydraulic model HEC-RAS to simulate flood extents for a historic, current and future urbanization scenario. In addition to urbanization, they evaluate how flood extents change under channelized versus un-channelized conditions.

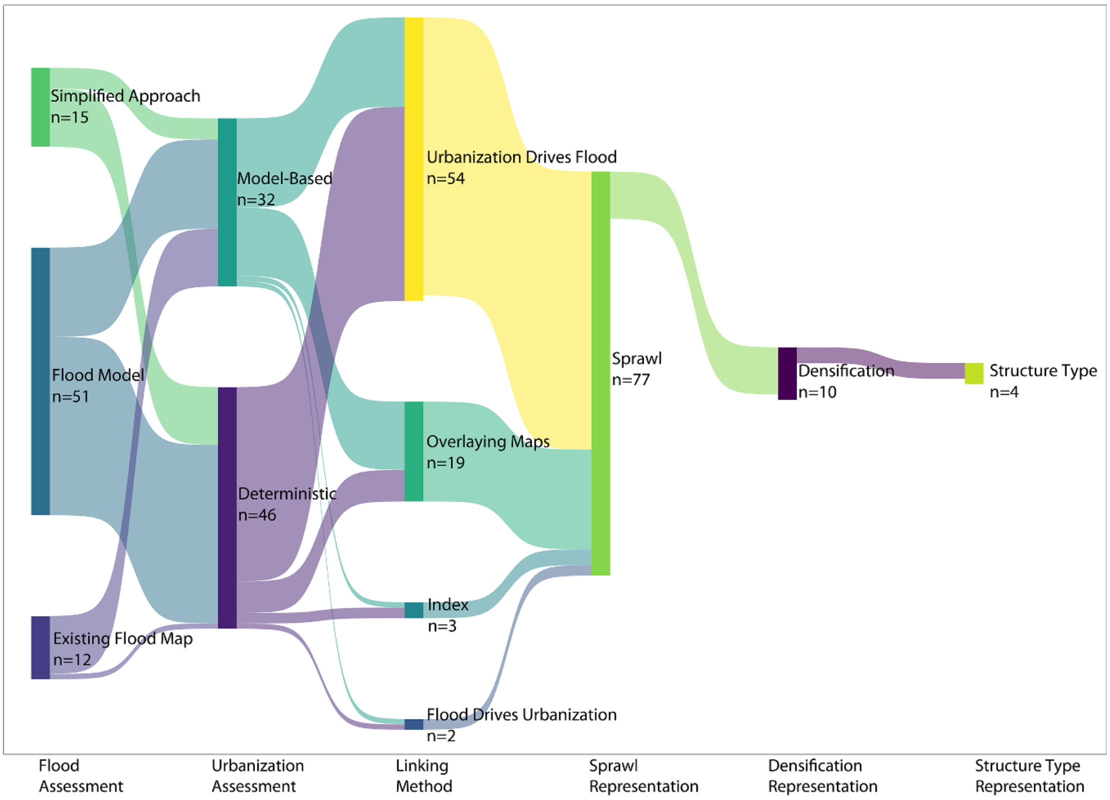

Figure 2. The alluvial plot shows connections between the clusters of flood assessment urbanization assessment approaches, the linking methods and the represented urbanization characteristics. The number of studies included in this plot is n = 78. 15 studies had to be excluded for this analysis because they did now give the required information on the detail in which urbanization is represented.

The second largest group combined flood models and model-based predictions on urban sprawl (16%, $n = 13$). Maps produced by model-based projections of urban growth were overlaid with existing flood maps in 11% ($n = 9$) of the cases.

Group three accounts for 9% ($n = 7$) of the studies: Maps of urban growth produced by model based or deterministic scenarios were used as input to simplified flood simulation approaches without considering densification or different structure types. None of the flood models in the reviewed literature considered the impact of building footprints on flood extents and water depths. However, Cao *et al* (2020a) studied how different building coverage scenarios influence these factors using a simplified approach. They used a cellular automata approach not only to estimate the changed runoff due to changes in pervious area but also the distribution of flood water due to building coverage reporting spatially distributed results and found that the building distribution and coverage largely influences where the flood water accumulates.

Group four represents the most sophisticated class in terms of urbanization assessment and considers densification and/or different structure types apart from urban sprawl (14%, $n = 11$).

A total of 5% ($n = 4$) of the studies of group four used model-based projections for future urbanization either as input to flood models or through the spatial intersection of the produced urbanization maps with existing flood maps ($n = 2$). Mustafa *et al* (2018) applied an agent-based model to simulate densification urbanization scenarios and linked those with a 2D hydrodynamic flood model to assess the impact on flooding in the Wallonia region in Belgium. Zhao and Liu (2020) developed a model framework in order to investigate how risk-adapted changes in land use reduce vulnerability to sea level rise in Bay County, Florida. Therefore, they overlaid maps produced by a cellular automata land use change model with existing sea level rise maps. They considered densification processes and also, they differentiated between commercial, industrial, institutional, residential, transportation and vacant land. Similarly, Song *et al* (2017) employed the SLEUTH cellular automata to assess the implications of various urbanization policies for Bay County, Florida. They intersected maps of future sea level rise with scenarios of future urban structure types (residential, commercial, industrial, institutional, agriculture and conservation) and growth and concluded that a compact development strategy is the most favourable.

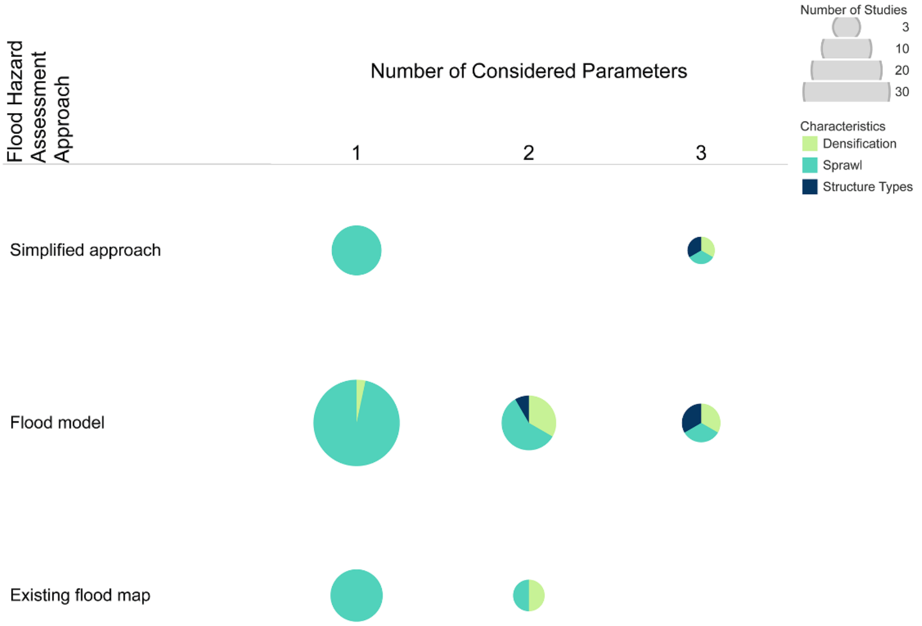

Figure 3. Clustered approaches according to their complexity of integrated urbanization and flood model (numbers according to groups in iii. Groups of modelling). The colors in the pie charts show the share of considered urbanization characteristics per cluster and the size of the pie charts show the number of studies.

Shan *et al* (2022), for instance, used a machine learning based model (FLUS) to simulate future changes of the urban structures in Shanghai, China (residential, industrial, commercial and public service land and transportation land). These results were combined with different RCP climate change scenarios and served as input to a 2D hydrodynamic model to simulate the inundation extent of a storm flood. Shan *et al* (2022) finally assessed the expected annual damage from the simulated exposure maps via depth-damage curves.

Figure 3 shows the clusters the distribution of flood assessment approaches and considered characteristics of urbanization (densification, sprawl and structure types). Urban sprawl is the main urbanization type, which is largely used within the three flood assessment approaches. Only three studies considered all three urbanization characteristics: two used them in flood models ($n = 2$) and one in a simplified approach ($n = 1$). Xu *et al* (2020) simulated surface run-off variations and differentiated between high-density and low-density urban structures in Munich, Germany. They used the physical-based flood model SCS-CN to simulate run-off and a cellular automata model to project urbanization scenarios. (Beckers *et al* 2013) assessed economic damages for different urban structure types by intersecting flood maps produced by a hydrodynamic model with urbanization maps. The study of Chang *et al* (2019) is based on a simplified approach for flood hazard assessment. They authors analyzed the effect of different urbanization forms on coastal flood risk in Vancouver, Canada by with a GIS-based bathtub approach.

3.4. Geographical distribution of assessment approaches

Figure 4 shows frequency of case studies per continent clustered into different assessment approaches, flood assessment approaches, urbanization assessment approaches and their combinations. A strong geographical focus to case studies in the Asian context can be observed ($n = 85$), followed by Europe ($n = 26$) and North America ($n = 21$). We found only few case studies in Africa ($n = 4$) and South America ($n = 2$). Flood modeling approaches are predominant in almost all continents—only in Asia simplified approaches show more applications. In the two South American case studies no flood model was used to assess flooding under urbanization. Analyzing the urbanization approach shows for all regions that deterministic methods were used more frequently than model-based assessments. Flood assessments were mostly combined with urbanization assessments by either using changed urbanization maps as input to flood models or intersecting flood and urbanization maps.

Figure 5 shows a map of the distribution of the case studies and the considered urbanization parameters, i.e. sprawl (purple), densification (turquoise) and different urban structure types (UST, yellow). We found that a dominant share of studies considered urban sprawl without any geographical pattern. Densification was considered by few studies mostly in European and North American cities in i.e. Belgium ($n = 7$) Canada ($n = 1$), Germany ($n = 2$), India ($n = 2$), the UK ($n = 1$) and the USA ($n = 3$), (Beckers *et al* 2013, Zope *et al* 2015, Song

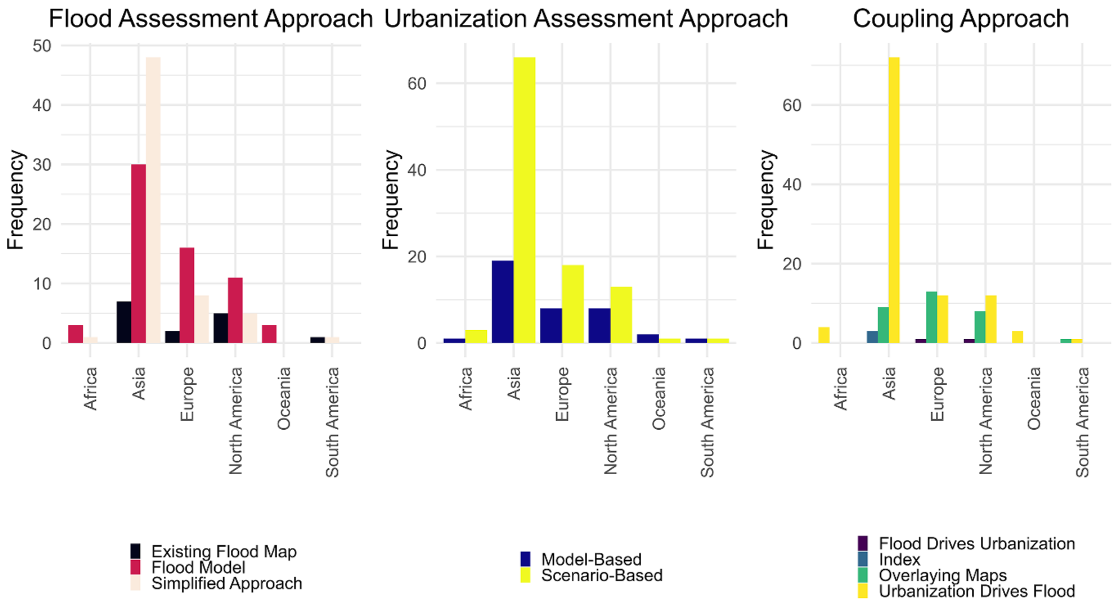

Figure 4. Frequency of Flood assessment approaches, urbanization assessment approaches and coupling approaches per continent.

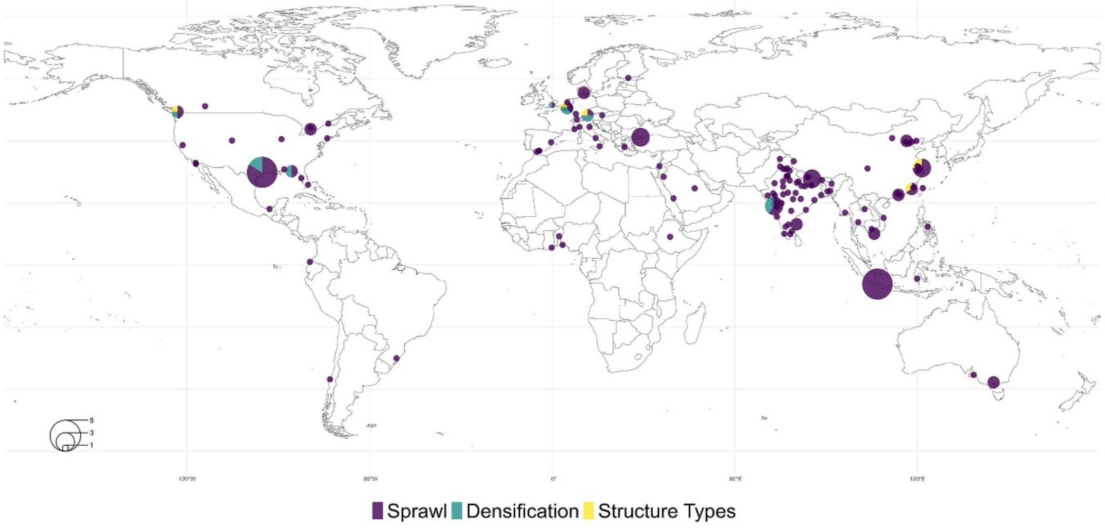

Figure 5. Mapping of case studies, the pie charts illustrate the frequency of different urbanization parameters (sprawl, densification, structure types). The size of the pie charts illustrates the total number of case studies.

et al 2017, Mustafa *et al* 2018, Chang *et al* 2019, Ford *et al* 2019, Juan *et al* 2020, Xu *et al* 2020, Zhao and Liu 2020, Rosenberger *et al* 2021). Urban structure types, however, have been used even less frequently as only six case studies performed in Belgium, China, Canada and Germany, considered them (Beckers *et al* 2013, Chang *et al* 2019, Shan *et al* 2022, Xu *et al* 2020, Xu *et al* 2021a). Beckers *et al* (2013) studied the expected damages by overlaying flood maps with urbanization scenarios and used different urban land uses (residential, industrial, mixed, governmental) as proxy for the impacted value in the Wallon Region, Belgium. In Chang *et al* (2019), future sprawl and densification of residential structures was used to assess exposure of residents towards coastal flooding and earthquakes in Vancouver, Canada. Similarly Shan *et al* (2022) intersected future flood maps with future land-use maps to assess the exposure of different land types in Shanghai, China. Xu *et al* (2020) assessed the surface run-off from high resolution data for different urban structures and the impact on the flood hazard in Munich, Germany under future urbanization scenarios. Overall, the most dominant use of urban structure types in flood risk assessments is to estimate the impacted values of land. However, only one study estimated the differences in the flood generation processes for different urban structure types.

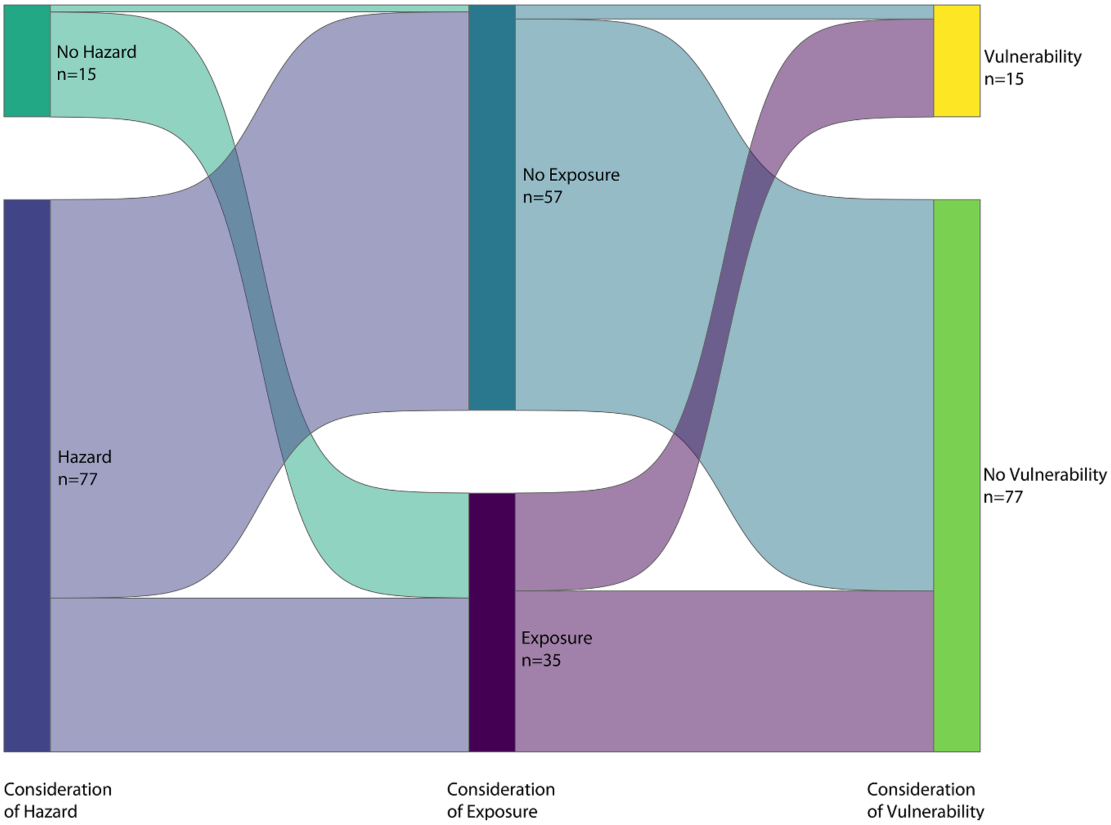

Figure 6. Combinations on considered components of risk, i.e. hazard, exposure and vulnerability, where n reports the total counts of studies considering the parameter within the dataset.

3.5. Consideration of hazard, exposure and vulnerability in assessment combinations

Figure 6 illustrates the considered components of risk—hazard, exposure and vulnerability—within the reviewed studies. It can be seen that most studies evaluated hazard (83%, $n = 77$), while studies evaluating exposure (38%, $n = 35$) and vulnerability (16%, $n = 15$) are largely underrepresented. To assess flood hazard, mainly flood models were used with either model-based ($n = 11$) or deterministic ($n = 33$) urbanization scenarios. Besides the analysis of single flood hazard events, some studies considered multi-hazard events or compound events. Multiple definitions are available for multi-hazard or compound events covering events which co-occur and interact (e.g. high tides and heavy precipitation), several hazards (co-)occurring independently (e.g. earthquake and flood event risk assessments) or one event triggering another (e.g. storm events triggering flooding) (Hochrainer-Stigler *et al* 2023, Stalhandske *et al* 2024). Chang *et al* (2019) analyzed the risk of coastal flooding and earthquake events in Vancouver, Canada under future urbanization. The risk is expressed as deposited sediment as proxy for damage and causalities for flooding and earthquakes respectively. Both hazard types are relevant in Vancouver and are treated as independently occurring events in the study. Ford *et al* (2019) assessed risk from combined storm surge and river flooding under different urban growth scenarios. They simulated urban growth with a CA model and used existing flood modeling results and depth-damage curves to estimate the overall risk. Similarly, Mesta *et al* (2022) used existing pluvial and fluvial flood maps combined with simulated urban growth scenarios from the CA-model Sleuth to generate an Social Vulnerability Index. Mena *et al* (2022) assessed the population vulnerable to landslides and sea level rise by simulating future urban growth with a CA model and overlaying the produced maps with the respective hazard maps resulting from GIS analyses.

Besides the integration of different hazards studies which performed a complete risk assessment, i.e. considering hazard, exposure and vulnerability used flood models combined with model-based urbanization scenarios ($n = 4$) were found in the literature. As an example Löwe *et al* (2018) applied the models MIKE Flood and urban growth and infill projections based on DAnCE4Water to assess the economic damage with depth-damage curves in Melbourne, Australia. Only one study used assessed only vulnerability by applying a cellular automata model to build urban sprawl scenarios and overlaying them with existing flood maps (Mena *et al* 2022). By doing this the authors assessed the change in social vulnerability in Esmeraldas City, Ecuador.

4. Discussion

Our review results show a strong tendency towards the use of physically based flood models and deterministic urbanization scenarios. We conclude that most studies consider changes in flood hazards due to urbanization changes and argue that flood models can be used to describe physical and therefore quantifiable processes of flooding. Further, if the flood hazard assessments are extended by exposure and vulnerability components, flood models are mainly used to assess economic damage—a tangible type of manifested vulnerability, quantifiable in monetary values.

Considering the geographical distributions, flood models are also applied in data-scarce contexts in the Global South. Tom *et al* (2022) reviewed flood modeling approaches for Nairobi, Kenia and concluded that approaches based on remote-sensing data combined with intensive field work are a way forward to overcome the challenges. We also found that most case studies in Asia use simplified approaches. Yet, the high frequency of simplified approaches in Asian case studies can be traced to one publication which applied the same methodology to assess flood risk in 42 different Indian cities with a regression model (Avashia and Garg 2020).

The analysis of urbanization characteristics shows that most studies that consider urban densification and changes in urban structure types besides urban sprawl are performed in data-rich countries. As especially in developing countries the changes in urban pattern within the cities is rapid, we argue that it would be crucial to consider more detailed urban representation in developing, data-scarce contexts.

4.1. Challenges in flood hazard assessment approaches

Models are a popular tool to understand current processes, make predictions, assess future developments and scenarios (Löwe *et al* 2017) or evaluate the impact of different measures which can be implemented. Nevertheless, all models are just a representation of reality and focus on representing the relevant components of reality given a specific purpose in a specific environment. Therefore, a variety of model types are available with different strengths, which makes a careful assessment of suitability for the case to be applied necessary. The review clearly shows that typically flood models like hydrological or hydrodynamic models are used in combination with deterministic urbanization scenarios to assess future situations of urban flood risk. Recently tremendous developments have been made in physical-based hydrological and hydraulic modelling to assess future urban flooding. The applicability of these models is widely acknowledged as they offer great benefits for modeling floods in urban areas. For example, great advances have been made in models representing the subsurface drainage systems and accounting for the interactions of the subsurface and surface flow (Akhter and Hewa 2016, Khan *et al* 2018). An accurate reproduction of these processes is of high importance especially when performing flood hazard assessments in urban areas. Furthermore, hydraulic models are able to represent rapid flow variations and can predict flood extents with a high spatial and temporal accuracy (Teng *et al* 2017). These characteristics make them well suited for flood forecasting, flood wave modeling and detailed flood risk assessments. While there have been plenty of developments in physically-based flood models and their application potentials in urban environments in general (Teng *et al* 2017, Bulti and Abebe 2020, Guo *et al* 2020, Qi *et al* 2021, Cea and Costabile 2022, Mignot and Dewals 2022) our review shows several challenges in their application in the context of future urbanization that can be summarized in five main points:

- Data scarcity
- Uncertainty
- Integration
- Complexity
- Dynamics

These challenges are not to be seen as strictly separated but interconnected. For example, data scarcity is enhanced by an increased complexity of the system to be modeled. In parallel whenever dynamics in a system are considered, the complexity is increased. Complexity itself adds to uncertainty of a modeled system because the representation of the considered processes might be oversimplified (Schröter *et al* 2014). Additionally, data scarcity enhances uncertainty, because with a lack in data which can be used for the calibration or model set-up, results become less robust. In the following sections the challenges and their implications for model users and developers are discussed.

4.2. Data scarcity

One major challenge which needs to be addressed in flood risk modeling is data scarcity. The results of this review show that flood models such as hydrological or hydrodynamic models are most commonly used to assess flood risk under urbanization trends. However, the simulation of flood risk in urban areas using hydrological and/or hydrodynamic models is data intensive (Teng *et al* 2017, Kumar *et al* 2023), which restricts the geographical areas of application (Tom *et al* 2022). In many cases, essential input data sets are not available to represent the complex environment of cities, especially in countries of the global South (Nkwunonwo *et al* 2020). Data can be scarce in several ways: Firstly, a general lack of the amount of data hinders the process of model building, calibration and validation, and the conduction of robust flood risk assessments in the end. In the case of general data scarcity, only limited numbers of observations or measurements are available per site which might not represent the range of values a parameter could take (e.g. discharge measurements). During the calibration and validation phase of a model, a limited amount of data can lead to a less robust model outcome (Huang and Bardossy 2020). Secondly, flood models are often sensitive to the spatial resolution of their input data (Horritt and Bates 2001). For many input parameters, however, distributed data representing the full spatial heterogeneity within a study area is not available, as reported by Priyambodoho *et al* (2022), for example. Thirdly, data might be insufficient due to limited temporal validity. Urban areas are highly dynamic spaces and the required input data can quickly become outdated due to rapid development or changing conditions (e.g. clogging of channels by solid waste changes the drainage capacity) (Kumar *et al* 2023). Fourth, there can be a lack of information regarding a specific parameter, such as in the case of ungauged basins, where no data is available. The continuous trend in recent years towards the use of higher resolutions and more complex models can be observed in this review due to the focus on physically based flood models. The question arises as to how useful this development is for assessments in data-scarce urban environments. More complex models usually do not only tend to require a higher amount of input data (Rosenzweig *et al* 2021), but they also have higher requirements in terms of the temporal validity of the data. For example, topographic data is a crucial input in hydrological and hydrodynamic models in order to assess the flow paths (Hawker *et al* 2018). Typically, studies use static topographic information as input for flood models assessing current and future flood risk (Chen *et al* 2021). However, this information varies especially in rapidly changing urban areas with intensive or unplanned construction activities, even on a small temporal scale, not to mention when projected into the future (Mukesh and Katpatal 2021).

4.3. Integration

The field of flood risk assessment, management and adaptation is experiencing a shift in paradigms moving towards a more integrated and holistic perspective (Vojinović 2015). The review, however, shows that most studies only consider the hazard part of risk in their future scenarios (Cea and Costabile 2022). If all components of risk are represented in a study, the authors usually assess solely economic risks and conduct hazard, exposure and vulnerability assessments individually without considering interdependencies. Therefore, the challenge of data scarcity is amplified when conducting a risk assessment and interconnecting the flood hazard, exposure and vulnerability component.

Additionally, each flood risk component has inherently multiple dimensions to be considered in a risk assessment. In coastal urban areas the co-occurrence of different flood types, such as compound flooding, oftentimes exacerbates the extent and consequences of the occurrence of a singular hazard category (Couasnon *et al* 2020). Thus, scenarios of compound flood events are of high importance for the planning of risk adaptation and management strategies. However, the physical processes underlying these events are very complex which makes their representation in physically-based models a challenge (Moghimi *et al* 2021). Within the reported literature we can see that compound hazards are seldomly considered. In some studies however, multi-hazard risk assessments are performed, yet interactions between the individual hazards are neglected and mainly independent map products are combined to assess damages or vulnerable population (Chang *et al* 2019, Ford *et al* 2019, Feng *et al* 2021, Mena *et al* 2022, Mesta *et al* 2022, Shan *et al* 2022).

Furthermore, the multidimensionality of vulnerability impedes robust risk assessments as well as the development of suitable management and adaptation strategies (Scheuer *et al* 2011). Within the studies which considered all components of risk, vulnerability is usually represented by economic damage through depth damage curves. However, social, ecological, physical and economic dimensions and susceptibilities towards flooding are crucial factors for a comprehensive assessment of future developments (Shan *et al* 2022). This task requires careful analyses and novel methodologies, which extend beyond physical principles or quantitative data, but integrate also knowledge of qualitative character.

The projection of future flood risks requires not only a holistic quantification but also the simulation and integration various adaptation options for the planning of sustainable flood management strategies. Here the review showed that methods which allow the evaluation of soft, non-structural adaptation measures are still under-explored (Kundzewicz 2002, Yin *et al* 2015). Physically based models fed with solely quantitative data are limited in the representation of these dimensions and their interconnections. The integration of all sources, pathways and receptors of flooding is essential to ensure that first the full extent of vulnerability in all dimensions is understood and all consequences are recognized to prevent maladaptation. Thus, new methodologies need to be developed, which are capable of dealing with data of multiple formats to capture relevant dependencies and feedbacks.

4.4. Dynamics

A further challenge in modeling future urban flood risk is dynamics: While working towards integrated assessment and management of flood risk is crucial, it is equally important to consider the various dynamics of the processes influencing flood risk in order to ensure integrated and sustainable adaptation (Kreibich and Sairam 2022, Wetzel *et al* 2022). Dynamics can be referred to as internal dynamics, i.e. the dynamic interactions between flood sources and drivers, pathways and receptors or as future dynamics, i.e. the evolution of (new) flood sources and drivers, pathways and receptors. In our review we found only few studies that address internal and future dynamics as a challenge in flood risk modeling. For example, Shan *et al* (2022) point out as one limitation of their study that the use of depth damage curves, which is a popular tool for assessing physical vulnerability, does not take into account any future dynamics of accelerating urban development. Furthermore, possible scenarios of each component (see challenge of integration) and their dynamic interactions into the future result in a higher complexity of the system to be modeled. To better understand the dynamics and future developments, it would be beneficial to focus on models with explanatory power. Explanatory-based models facilitate the knowledge and understanding of the underlying processes. They further aid in communicating the limitations of a particular approach to practitioners, especially in reflecting on certain dynamics, which cannot (yet) be captured in physically-based models.

4.5. Complexity

Large urban agglomerations are inherently complex environments. Integrating different flood hazard types, social, environmental and physical dimensions, and future dynamics into the simulation of flood risk increases the complexity of the flood risk processes tremendously (Rangari *et al* 2019). However, modeling can only be a simplified representation of the real world, and a careful selection of relevant parameters ensures the validity of modeling results while minimizing complexity. Oftentimes, complexity is already mentioned as a challenge in the reviewed studies: Important system components are often simplified or neglected in the flood model approaches for urban systems. For example, Skougaard Kaspersen *et al* (2015) used a simple flood assessment approach to cover a larger urban area, but their approach neglected the urban drainage system leading to inaccuracies in the assessment of pluvial flooding. Although more detail in models may increase the representation of the real conditions, the increased complexity, the higher number of parameters and the resulting data requirements introduce further uncertainty into the assessments. Therefore, a careful analysis is needed about the components that can be neglected or simplified, and those, which benefit from adding more detail in the modeling approach (see also Chapter Challenges in urbanization scenarios for flood modelling).

4.6. Uncertainty

The studies considered in the review intensively discussed uncertainty in models and future flood assessments under climate change and urban development. Uncertainty in models can arise from several sources (Bates *et al* 2014, Reinstaller *et al* 2022): Firstly, the structure of the model is based on the understanding of the underlying physical, environmental and social processes. Thus, limited process knowledge in both the current and future context and the capability to adequately represent the known processes in a model contribute to uncertainty in results. But also limited computational capacities require a simplified representation of the processes of urban flooding, which introduces uncertainty into the results. Uncertainty can also arise from limited or incomplete data, data of poor quality, or data for parameters that are difficult to measure or quantify (i.e. proxies and their relationship to the actual parameter have to be used). Furthermore, sometimes the actual state of a particular parameter is not known for all time steps of the simulated time period. Both, uncertainty due to incomplete representation of the processes and parameter uncertainty are related in the following way: If the processes are known and represented in a model in high detail, the quality of the model results is increased. However, then more parameters have to be defined and used for the model set up, which usually leads to higher parameter uncertainty (Schreiber *et al* 2014). Thus, the right balance between model complexity and parameter uncertainty needs to be found for each case study. Furthermore, modeling approaches with the capability to incorporate uncertainty assessments should be preferred to assess the robustness of the results and thus enable sustainable adaptation planning in the face of uncertainty. This is especially true for simulating future scenarios of flood risk within the complex environment of cities. Refsgaard *et al* (2007) analyzed the importance of uncertainty assessments during different modeling phases and provided a comprehensive guide how to select appropriate uncertainty assessment approaches based on different modeling purposes.

4.7. Challenges in urbanization scenarios for flood modelling

Our review shows that studies usually focus on the representation of urban sprawl to assess the flood risk. However, a more detailed representation of the different urbanization patterns is essential for the simulation of hydrological and hydraulic processes of flooding and the flood consequences. Densification of an urban area is a popular approach to increase living space without expanding the city's boundaries (Rosenberger *et al* 2021). However, the increase in impervious areas accompanied by reduced infiltration capacities alters flood generation processes and thus needs to be considered when projecting future flood risks in cities. Furthermore, when assessing urban flood risk, it is important to account for the different urban structure types in a city as different physical structures are related to altered flood processes. Therefore, modelers should consider both expansion and transition within a city when projecting flood risk into the future (e.g. the construction of new business districts or slum-upgrading). The review has shown that the studies considering urbanization in this detail are rare and located in data-rich or well-studied geographical regions such as China, Canada and Europe. Based on our analyses we argue, that the lack of data is too great to allow for a detailed representation in many regions of the world. For this reason, it is more reasonable to represent the future development in a city by simply increasing the parameters of urban impervious area. However, different urban structure types ranging from e.g. high-income blocks with high-rise buildings to dense slum areas, have different associated hydrological, hydraulic and social profiles. Knowledge on their distributions has been increasing in recent years due to a rapid progress in the development of remote sensing products (Zhu *et al* 2022). Additionally, recent developments in urbanization modeling make it increasingly possible to project urban morphology change additionally to urban sprawl and get a more comprehensive picture on shape and extent of the future city (Zhao and Liu 2020, Domingo *et al* 2021, Khamchiangta and Dhakal 2021, Xu *et al* 2022). This enables using urban structures as proxies to derive missing data in those environments and help to overcome the problem of data-scarcity in flood models. First steps into this direction could already be seen in our review: Shan *et al* (2022) for instance, differentiated between industrial, residential and commercial urban land use to assess future flood risk in their case study on extreme flooding in Shanghai. In the longer perspective, the representation of the different types of structures should be aimed for, taking into account economic and social factors in addition to building types where appropriate.

4.8. Challenges in coupling flood models and urbanization models

Flood risk under future urbanization involves many feedbacks that need to be considered in a modeling chain. Our review shows that a variety of modeling approaches and coupling mechanisms exists and that there is no commonly used methodology that covers all scales and objectives. We argue that it is essential to be fully aware of the purpose of the assessment and to carefully select an appropriate coupling method for the required level of detail of the model components. This also has recently been discussed in Reimuth *et al* (2024). As an illustration, it may be misleading to intersect current flood maps with projections for future urbanization in order to assess the risk to future buildings. This is because the extent of flooding may change as new urban areas are developed. In such cases, a more appropriate approach might be to use future urbanization maps as input for a flood assessment tool. However, if this step is neglected, a modeling approach may be used that is not optimally designed to answer the question of future risks to buildings. This may lead to poor results as relevant interactions between urbanization and flooding are omitted. If urbanization is a major driver of flood hazard, exposure and vulnerability for the investigated case study, it is essential to take into account the effects of urbanization in the flood model because related processes (infiltration, flow paths, etc) will be massively altered by urban sprawl, urban densification or changes in the characteristics of urban patterns. Intersecting flood maps with urbanization maps might be a first but insufficient step towards a flood risk assessment, as they do not reproduce these variations of flood patterns.

Furthermore, the three mechanisms of urbanization urban sprawl, densification and urban structures change need to be incorporated into dynamic flood risk modeling. It is not sufficient to consider only urban sprawl by increasing the size of the urban extents. Densification within cities and the transition of urban structures lead to varied hydraulic and hydrological characteristics in a catchment. However, most of the studies in our review considered only urban sprawl by using an updated land use map with increased urban extent as input to a flood model and adjusting roughness and infiltration parameters to the values representing urban areas. However, only considering the increase in urban extent by changing the impervious area oversimplifies the process of urbanization. Urban structures vary considerably within a city and this variability is completely neglected when using urban sprawl maps without further subcategorizing the structures in a city. For this reason, flood models are desirably that fully integrate the processes of urbanization and consider the feedbacks between flood generation and urbanization in a better way.

5. Next model generation for future urban flood risk assessments

As discussed in the previous section, modeling future flood risk under urbanization is subject to several challenges. Current approaches largely focus on high-resolution and/or real-time flood forecasts. While these models are widely acknowledged and constant developments take place in the scientific community, we think that other approaches have a likewise potential to face these challenges. Given the high uncertainties associated with future projections and the high and often unobserved data needs in complex urban systems, approaches besides flood models might be well suited for future flood risk assessments under urbanization trends. We call for a further development of the models suited for data-scarce regions regarding the following points:

- Models for urban flood risk projection should move beyond describing flood hazards predominantly with physical equations. Not all processes and systems influencing flood risk can be described in a physical or quantitative manner. Thus, we think adjustable causal models like Bayesian networks could be well suited to integrate and connect different domains in flood risk assessments that may not have a physical basis or lack of quantitative data (Duespohl *et al* 2012). While most process-based models are based on causal links, they are mostly not easily adjustable. Furthermore, within Bayesian networks we can represent system dynamics as the change in one variable is affecting all other variables of the network. Many recent studies have started to apply Bayesian Networks, which is a causal and probabilistic model to describe vulnerabilities of livelihoods (Junquera and Grêt-Regamey 2020), transport vulnerability (De Waal and Joubert 2022) or community resilience (Cai *et al* 2018) in a more integrative way. The broad applicability of these adjustable causal models shows that they can support a better representation of the multidimensionality of vulnerability and adaptation patterns in a flood risk assessment. Qualitative data from expert interviews or participatory stakeholder workshops can be used in Bayesian networks to define the causal links between relevant variables and to inform prior probability distributions, paving the way for quantitative assessments in data-scarce environments. While most other models require quantitative data to define relationships between relevant variables, cause-effect relationships between qualitative and quantitative variables are often well researched in a qualitative manner, but the quantification of the effect size presents a challenge. Kruse *et al* (2024) employed qualitative research methods, specifically expert interviews, to explore the relationship between non-quantifiable sociological factors—such as emotional attachment and internal organizational conflicts—and the adaptive capacity of fishing communities. Although these sociological variables resist direct quantification, the knowledge and perspectives of experts enable the estimation of both the strength and significance of these relationships. Subsequently, these estimations were converted into conditional probabilities using various methodological approaches. Other approaches to translate expert knowledge to conditional probabilities are delineated by Cain (2001), Frank (2015) or Whitney *et al* (2018). This conversion facilitates a more structured and quantitative analysis of the impact of these sociological factors on community resilience, such as demonstrated in Eckel *et al* (2009), Balbi *et al* (2016), Cai *et al* (2023). With these features we think that Bayesian networks are worth to be explored further within future risk assessments.
- Models with greater explanatory power also contribute to a better understanding of the range in future developments and their uncertainties. A concrete example of approaches with these capabilities are Bayesian networks. Bayesian networks can be used for predictive and diagnostic analyses (Duespohl *et al* 2012). For the predictive mode the effect of changes in influencing variables on the outcome is analyzed. This is well suited for the evaluation of future scenarios or management and adaptation options (Sperotto *et al* 2017). The diagnostic mode can help to explain the potential causes of an outcome (Carriger *et al* 2016, Kaikkonen *et al* 2021). For example, if an increased flood risk is observed, it is possible to trace-back the likely reasons for this change within the influencing variables, which is usually not possible in other modeling approaches. The combination of diagnostic and predictive analyses in Bayesian networks permit the explanation of uncertainties from both causes and outcomes, illustrating how specific assumptions about the future or unobserved variables can amplify these uncertainties in risk assessments, especially in data-scarce scenarios. This approach allows for clearer delineation and management of uncertainties as more data become accessible.
- Flood assessment approaches should offer higher flexibility especially regarding the factors and processes included in the assessments. For data-poor regions, models with a less detailed representation of the physical processes should be preferred, as the influencing conditions for these processes remain uncertain, either because of a lack of data for the current situation or because of the high uncertainty in their future development.
- Simulating different scenarios based on various combinations of influencing factors and performing uncertainty assessments in each model component should be inherently feasible and computationally inexpensive. In this way, the full range of future possible developments can be assessed and the main sources of uncertainty identified, which is essential for the planning of robust adaptation measures.
- We argue that urbanization scenarios should include future densification processes and changes in the urban structures in addition to urban sprawl. Considering all forms of urbanization allows for a

holistic representation of urban development. As urban sprawl, urban densification and the changes in urban structure types have impacts on flood hazard, exposure and vulnerability including all forms is crucial for the assessment of future flood risks and potential adaptation options.

- We call for new methodologies that use proxy distributions of plausible values for unobserved parameters to overcome the challenges of data scarcity. Proxy distributions should be thoroughly validated with expert knowledge combined with physical process understanding. Furthermore, proxy distributions should be designed in an updateable format so that the modeling results can be improved as soon as data of sufficient quality become available. We see the use of urban structure types as promising potential representatives for these proxies, especially when combined with other socio-economic data. We argue that, when those proxy distributions are combined with uncertainty assessments, beneficial assessments can be performed even in data-scarce environments (Gaard *et al* 2007). Yet of course the availability of sufficient data is superior to the use of proxy distributions.

Urban structure types can serve as proxies in data-scarce environments, aiding in the spatial differentiation within urban areas. By integrating these types with Bayesian networks constructed from expert and stakeholder inputs, it is possible to define distributions effectively, even in the absence of gauged or quantifiable data or when assessing future scenarios. Yet, up to now this is not done and case studies in rather data-rich environments are the only ones to consider different urban structure types. Furthermore, a trend from single-discipline models which allow the detailed representation of certain physical processes towards approaches which can integrate multiple disciplines would be desirable for the evaluation of integrated flood adaptation strategies and would foster the development of transdisciplinary and potentially transformative adaptation solutions. For the specific case of future flood risk and adaptation pathway under different urbanization scenarios, a possible way could be the development of approaches moving away from high resolution flood hazard modeling to more simplified approaches, while adding more detail in urban development (i.e. density and structure types besides sprawl). While there are promising approaches which consider urban sprawl, densification and changes in urban structure types combined with flood modeling (figure 3), these are mainly applied in data-rich environments to assess economic damage (figure 5) (Beckers *et al* 2013, Xu *et al* 2020). There is also a promising study which applies simplified approach in combination with higher urbanization details (Chang *et al* 2019). Simplified approaches are well suited for the assessment of scenarios without less data demand (Teng *et al* 2017). Thus, we call for more research on combining simplified approaches with urbanization scenarios at higher detail.

6. Conclusion

This study conducted a systematic literature review to assess the current state-of-art in flood risk modelling under future urbanization trends. We found a strong focus on data-intensive and computationally expensive flood modeling techniques, while future urbanization was rarely considered at a higher level of detail. Physically based flood models, including a high level of detail in terms of current urban form, are frequently applied in data-rich countries of the global North to assess changes in flood hazard and economic damage. While the models are well suited for applications in certain geographical regions and the representation of the quantifiable components of risk, their application is challenged in data poor regions.

For these fields of application, we propose to move away from a high-resolution modeling of flood processes towards a simplified approach with extended projections of urbanization by incorporating densification processes and urban structure types (Zwirglmaier and Garschagen 2024). Adding more detail in terms of structure types and their trends not only supports the representation of a more realistic urban environment, but it also has the potential to serve as proxy for characteristics of flood hydrology and the vulnerability of exposed social groups, businesses and infrastructure in data-scarce areas. Such an approach can also serve as a platform for future scenarios which consider development trends in different structure types (e.g. informal settlements vs. high-income neighborhoods).

Additionally, we argue that flood risk assessments can become more integrated by moving away from the physical process description towards causal models. In this way, processes can be incorporated, which are influencing flood risk but cannot be described physically such as findings from social sciences.

We also argue that the resource intensive and data dependent generation and utilization of high-resolution flood maps might not be always needed for initial assessments of flood risk. Rather, priority should be on developing assessment tools which can represent all components of flood risk (hazard, exposure and vulnerability) in order to capture the complex and dynamic interactions between flood generation, urban growth and changing vulnerabilities and therewith increase the practical use and validity of risk modeling in highly dynamic urban contexts. While high resolution and physical-based modeling of flooding is well suited in data and resource rich environments for real time flood forecasting, early warning and detailed infrastructure design planning, more integrative and flexible, albeit less detailed, approaches are needed for assessments of future urban flood risk in environments with strong urbanization trends but challenges in available data. The methodological improvements proposed in this study contribute to the creation a new generation of flood risk models tailored to the highest-risk regions that are often characterized by high urbanization, complex flood risk drivers and a lack of high-quality data.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

The research is part of the research project TRANSCEND funded by the German Federal Ministry of Education and Research (BMBF; Grant No. 01LN1710A1).

Conflict of interest

The authors declare no conflict of interest.

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