International Journal of Disaster Risk Science (2023) 14:782–794
https://doi.org/10.1007/s13753-023-00517-7

www.ijdrs.com
www.springer.com/13753

ARTICLE

An Index-Based Approach to Assess Social Vulnerability for Hamburg, Germany

Malte von Szombathely[4] · Franziska S. Hanf[2] · Janka Bareis[3] · Linda Meier[1] · Jürgen Oßenbrügge[1] · Thomas Pohl[1]

Accepted: 9 October 2023 / Published online: 3 November 2023
© The Author(s) 2023

Abstract

In this study, we set out to develop a new social vulnerability index (SVI). In doing so, we suggest some conceptual improvements that can be made to existing methodical approaches to assessing social vulnerability. To make the entanglement of socio-spatial inequalities visible, we are conducting a small-scale study on heterogeneous urban development in the city of Hamburg, Germany. This kind of high-resolution analysis was not previously available, but is increasingly requested by political decision makers. We can thus show hot spots of social vulnerability (SV) in Hamburg, considering the effects of social welfare, education, and age. In doing so, we defined SV as a contextual concept that follows the recent shift in discourse in line with the Intergovernmental Panel on Climate Change's (IPCC) concepts of risk and vulnerability. Our SVI consists of two subcomponents: sensitivity and coping capacity. Populated areas of Hamburg were identified using satellite information and merged with the social data units of the city. Areas with high SVI are distributed over the entire city, notably in the district of Harburg and the Reiherstieg quarter in Wilhelmsburg near the Elbe, as well as in the densely populated inner city areas of Eimsbüttel and St. Pauli. As a map at a detailed scale, our SVI can be a useful tool to identify areas where the population is most vulnerable to climate-related hazards. We conclude that an enhanced understanding of urban social vulnerability is a prerequisite for urban risk management and urban resilience planning.

Keywords Climate change adaptation · Hamburg · Risk approach · Social vulnerability · Social vulnerability index

1 Introduction

Growing social heterogeneity and inequalities in cities, their drivers, their spatial differentiations, and their consequences for the socio-spatial structure have increasingly become the focus of climate impact research in recent years (Islam and Winkel 2017; Faist 2018; Singer 2018; Kim et al. 2021). Ongoing demographic change, migration flows to cities, and increasingly unequal distribution of economic resources are driving social divisions and polarization within cities (Pratschke and Morlicchio 2012; Tammaru 2015; Tammaru et al. 2021). Urbanization processes generate vulnerability and exposure, which combine with climate-related hazards, driving urban risk and impacts (Mason et al. 2020; Reisinger et al. 2020; Dodman et al. 2022). In addition, urban risks can also result from human responses to climate change (that is, adaptation and mitigation measures) not achieving the intended objectives (Reisinger et al. 2020; Simpson et al. 2021). Especially cities and settlements by the sea are on the frontline of climate change, because they are among those that face the highest climate compounded risks (Glavovic et al. 2022). For this study on social vulnerability, we chose the city of Hamburg, which is unique due to its geographic location and its local specifics—for example, located on the Elbe River and close to the sea and thus subject to the tides; sitting partly below sea level; featuring hinterland rivers; and, due to its size and density, generating its own urban heat island.

✉ Malte von Szombathely
malte.szombathely@uni-hamburg.de

1 Institute for Geography, Center for Earth System Research and Sustainability, Universität Hamburg, 20146 Hamburg, Germany

2 Meteorological Institute, Center for Earth System Research and Sustainability, Universität Hamburg, 20146 Hamburg, Germany

3 Institute for Geography, Universität Hamburg, 20146 Hamburg, Germany

4 Research Unit for Sustainability and Climate Risks, Center for Earth System Research and Sustainability, Universität Hamburg, 20144, Hamburg, Germany

This study developed an index of social vulnerability (SVI) based on two main assumptions. First, vulnerability varies greatly between different population groups. It is therefore important to identify vulnerable groups and to study their (unequal) distribution across the city. Current events, such as the 2021 flood event in the Ahr Valley in western Germany, dramatically demonstrate how, for example, age becomes a predictor of mortality risk in the event of a disaster (Rheinneckar Blog 2021; RND 2021). Second, politicians are demanding research results in order to justify and underpin political decisions. In Germany, changes in intensity and frequency of extreme weather events (for example heavy rainfall, see Poschlod and Ludwig 2021) contribute to the urgency of political action. Yet, for Hamburg there is no comprehensive and high-resolution modeling of vulnerability; this study sought to close this gap.

We thus aimed to spatially reveal high concentrations of social vulnerability in Hamburg, focusing on socioeconomic and demographic characteristics. The index groups the variables that impact social vulnerability into two major categories: (1) sensitivity and (2) coping capacity. We built on the model that has guided (Bouwer 2020) a large number of studies (for example, Füssel 2010; Joakim et al. 2015; Nguyen et al. 2016; Drakes and Tate 2022) since being adopted by the Intergovernmental Panel on Climate Change (IPCC) (McCarthy et al. 2001). We mapped SV and the relationship between its components at a high resolution and analyzed the root causes of SVI patterns in Hamburg, considering a wide range of contextual and historical factors derived from and based upon local knowledge of experts. This discussion serves to evaluate and validate the quantitative results.

The SVI is intended to simplify the complex relationships between various factors shaping social vulnerability. According to Nguyen et al. (2016), it is important to consider how much complexity is required in order to adequately describe a local situation. The simpler the underlying algorithm, the more accessible the results (Balica and Wright 2010). The index developed here was quantified specifically for Hamburg, but refers to a broad base of literature and case studies worldwide. Therefore, the fundamental analyses and arguments in this article may be transferable to other (urban) areas.

The remainder of the article is structured as follows: Section 2 presents our indicator-based approach to social vulnerability. We explain our methodological considerations (Sect. 2.1), and introduce the conceptual framework developed and the selection of variables (Sect. 2.2). The algorithm, data, and material used to calculate the index are described in Sect. 2.3. Section 3 presents the modeled results, including the initial variables (for neighborhood examples) and their aggregation into an index. This index was calculated using small spatial units, intersected with the populated areas of Hamburg and visualized on maps. The results are discussed and summarized both in terms of content and methodology in Sect. 4. Section 5 provides an outlook of future research on this topic.

2 Indicator-Based Approach to Social Vulnerability

Vulnerability was examined in this study by analyzing existing data. This section presents the methodological decisions made and explains the selection of variables.

2.1 Methodological Considerations

Vulnerability indices can help identify and prioritize vulnerable regions, sectors, or population groups (Nguyen et al. 2016) or so-called "hotspots" (Jurgilevich et al. 2017). In general, social vulnerability indexation may address a wide range of potential variables, such as individual characteristics (for example, gender, age, health, education, income), group membership, milieus and social stratification, or social dependencies and networks. Cultural and political aspects are also considered, such as willingness to take risks, sense of community, or trust in the state's ability to act. In addition, especially in cities, there are spatial and temporal dynamics that can be generated by migration patterns, gentrification, or devaluation of neighborhoods. Finally, infrastructural facilities are typically considered, such as hospitals and fire departments, which can be supportive in risk situations or, if they are not available, have to be compensated for (Blaikie et al. 1994; Cutter et al. 2003; Kienberger et al. 2009; Nguyen et al. 2016). From the analysis of current studies on assessing urban vulnerability, we selected those variables that were identified as relevant using the analytical hierarchy process (see Sect. 2.3). Additionally, insights from research about neighborhoods and social areas in cities have been incorporated (see Sect. 2.2).

Methodologically, in index approaches, population-based variables are usually measured and applied relative to the respective population as a whole. This approach has the advantage of uncovering socio-spatial characteristics that point to processes of urban change, like segregation. Yet, when analyzing the extent to which the population is affected by climate-related hazards, the positive effects of social mixing discussed in deprivation studies (Sampson et al. 2002; Beckers et al. 2010; Zamzow and Krahl 2020) do not seem to be relevant: Living in the same neighborhood as households that have a lower sensitivity or a higher coping capacity does not mean an advantage for vulnerable groups per se. In order to make the input variables nevertheless comparable and to take the number of highly vulnerable people adequately into account, we decided to relate the variables to spatial units. Our index thus identifies spatial concentrations of vulnerable groups. However, this goes hand in hand with the fact that the basic population density already has a strong impact on the individual variables (see Sect. 4). With this decision, a later reference to population density becomes obsolete.

2.2 Conceptual Framework and Selection of Variables

Our SVI consists of two components: sensitivity (SVI-S) and coping capacity (SVI-CC). The variables within the components correlate with each other. The components themselves, however, only correlate to a limited extent: Conceptually they point in different directions. They can still overlap, but not necessarily completely. To address this issue, we also analyze sensitivity and coping capacity individually.

When selecting the variables for each component, we opted for an expert-led selection process (see Sect. 2.3). This served, on the one hand, to adequately take into account local knowledge on the ground and, on the other hand, compensated for the lack of data availability (see Sect. 4). Additionally, the variables we chose (Table 1) can be substantiated by the evaluated literature. Reports on recent flood events such as the 2021 flood event in the Ahr Valley (Schlömer et al. 2021) were also considered.

2.2.1 Sensitivity

The key factor in the sensitivity component is the age structure in an area (Cutter et al. 2003; Fekete 2009). Children and elderly singles are defined as particularly vulnerable groups, as they are particularly dependent on external help. They need "physical and psychological assistance during and after disasters" (Kaveckis 2017, p. 182). The restricted mobility of certain population groups leads to greater sensitivity in the event of a disaster (Jodoin et al. 2023).

For example, mainly elderly and disabled people fell victim to the flood disaster in Ahr Valley in western Germany in June 2021 (Rheinneckar Blog 2021; RND 2021) because they could not save themselves (Kosanic et al. 2022). Since this concerns both the age of the affected group and the lack of outside help, the variable *elderly singles* (people older than 65 living alone) was used for modeling SVI. We also argue that older people are potentially doubly disadvantaged if their often already limited health and a low socioeconomic status coincide (Holand et al. 2011).

The age limits for children given in the literature differ. Some studies set the age limit at 5 years (Holand et al. 2011), others at 12 (Preston et al. 2008), or below 14 years (Schröter 2019). For our purposes, the age limit for *children* is set to the mean primary school age of 10 years as children younger than 10 need more assistance and are usually not yet able to correctly classify information about the development of the situation (due to their cognitive and reading skills).

2.2.2 Coping Capacity

The variables *welfare recipients* and *school leavers with no/low educational qualification* were identified as particularly important for the coping capacity component of our model. In the event of a disaster, a lack of financial resources can lead to poor coping ability (Cutter et al. 2003). In Germany, a household's reliance upon social welfare (payments due to Sozialgesetzbuch II) can be used as a proxy for poverty, as eligibility for social welfare is based on insufficient financial resources and ongoing unemployment. In addition, people who receive financial support need additional external help in the event of a disaster (Holand et al. 2011).

The second proxy variable for coping capacity is *school leavers with no/low educational qualification*, as this influences one's ability to improve one's own situation. Access to information and support, for example, is more difficult if one is not sufficiently literate. As no detailed information on the level of education in the total population is available, we identified residents without a (high) school graduation from the last three years. We decided not to simply depict literacy via a possible migration background, as a recent study has shown that this variable does not (any longer) do justice to the problem (Grotlüschen and Buddeberg 2020). Although the higher vulnerability of migrant population groups is indicated by an "inability to understand extreme event-related information due to language problems, prioritization of finding employment and housing, and distrust of authorities" (Cardona et al. 2012, p. 80), language problems are closely related to current levels of education, and some of these can be mapped through school education. This variable is also part of the official socio-spatial monitoring system of the city of Hamburg (Freie und

Table 1 Variables and components of social vulnerability index (SVI)

Component of SVI	Variable	Description
Sensitivity (SVI-S)	C10	Children younger than 10
	O65	Elderly singles over 65 (living alone)
Coping Capacity (SVI-CC)	WR	Welfare recipients
	EDU	School leavers with no/low educational qualification

Hansestadt Hamburg, Behörde für Stadtentwicklung und Wohnen 2021), designed to identify neighborhoods with low social status and to assist in implementing the "social city" policies there. In addition, dependence on social assistance and the level of school qualifications are closely related: "Education is linked to socioeconomic status, with higher educational attainment resulting in greater lifetime earnings. Lower education constrains the ability to understand warning information and access to recovery information" (Cutter et al. 2003, p. 248).

2.3 Material and Algorithm

In selecting proxy variables and aggregating them into a final index, we used a multicriteria decision method—the analytical hierarchy process (AHP)—and based it on local knowledge and expert input. The AHP provides a rational framework for representing and quantifying (or weighting) the various elements (Forman and Gass 2001). This is done specifically by comparing variables in pairs. The AHP process is commonly used for the integration of variables in vulnerability studies (Nasiri et al. 2019; Tascón-González et al. 2020). Here, we used this qualitative method for selecting the proxy variables and for assigning weights to the selected variables. The weighting of variables can have a significant impact on the final result of the index calculation (Reckien 2018). An online tool was used to make this procedure easily and remotely accessible (Goepel 2018).

We began by identifying a total of 56 variables from 22 studies on vulnerability. The initial 56 variables were included in a first AHP model, where they were classified at the first level according to, for example, age, socioeconomic status, and living environment. At the second level, the groups were related to each other. The AHP was carried out by all authors of the study. The results then formed the basis of discussion for the final selection of variables. We identified the variables with the highest weights, and represented some of these using proxies. Based on the final selection of four variables, the AHP was carried out again by all authors of the study to determine the weights of the variables and the subcomponents. The AHP was used with a consistent ratio in each case and a consistent weighting trend, resulting in a very high average AHP group consensus (95.2 %) and a homogeneity of 96.0 %. The weighting of the variables and the components resulting from the AHP process is shown below.

$$\text{SVI} = \frac{(0.5 \times \text{SVI - S}) + (0.5 \times \text{SVI - CC})}{100 \times \text{SVI}_{\text{max}}}, \text{ whereas} \tag{1a}$$

$$\text{SVI-S} = \frac{(0.3 \times \text{C10}) + (0.7 \times \text{O65})}{100 \times \text{SVI-S}_{\text{max}}} \tag{1b}$$

$$\text{SVI-CC} = \frac{(0.5 \times \text{WR}) + (0.5 \times \text{EDU})}{100 \times \text{SVI-CC}_{\text{max}}} \tag{1c}$$

where EDU represents school leavers with low level of education, WR indicates welfare recipients, O65 is elderly singles over 65 (living alone), C10 is children younger than 10, SVI represents social vulnerability index, SVI-S is sensitivity, SVI-CC is coping capacity (lack of coping capacity), and SVI_{max}, $\text{SVI-S}_{\text{max}}$ and $\text{SVI-CC}_{\text{max}}$ refer to the highest value of the respective component.

The data required for calculations and representations were made available by the Statistical Office for Hamburg and Schleswig-Holstein (Statistikamt Nord 2020) and Federal Environment Agency (GeoBasis-DE/BKG 2018). MS Excel 2019 was used to calculate the individual variables.

The variables first had to be transformed individually for the index calculation. Second, to identify settled areas of the city of Hamburg for the calculation of the density of the individual variables (Statistikamt Nord 2020), we used Corine Landcover satellite data (GeoBasis-DE/BKG 2018). Third, in order to be able to offset the different variables (children younger than 10, elderly singles over 65 living alone, welfare recipients, school leavers with no/low educational qualification) with each other, they were standardized (z-transformation). Then the index was recalculated to range from 0 to 100. These standardized variables could then be used to calculate sensitivity (SVI-S), coping capacity (SVI-CC), and social vulnerability (SVI), according to the functions above. The results are visualized in maps (using ArcGIS Pro). They are then discussed and evaluated on the basis of local knowledge in order to validate them, to enable further discussion, and to determine possible interventions.

3 Results

The following section shows the results of our analysis, starting with a visualization of each variable and SVI component (SVI-S and SVI-CC) for three examples to explain differences in detail (Fig. 1). This requires additional information on the context and history of different parts of the city, which is used to interpret the results. Then the comprehensive SVI for Hamburg is introduced and described. A more extensive interpretation follows in Sect. 4.

It is necessary to first take a closer look at the input variables from a smaller-scale perspective to make clear how the variables and components influence the overall SVI. Local hotspots of social disparity and urban injustice become visible with a small-scale perspective on the input variables (elderly singles, children under 10, school leavers with no/low educational qualification, welfare recipients) and the components themselves (sensitivity and coping capacity). As examples, we chose the areas of Eimsbüttel, Reiherstieg/

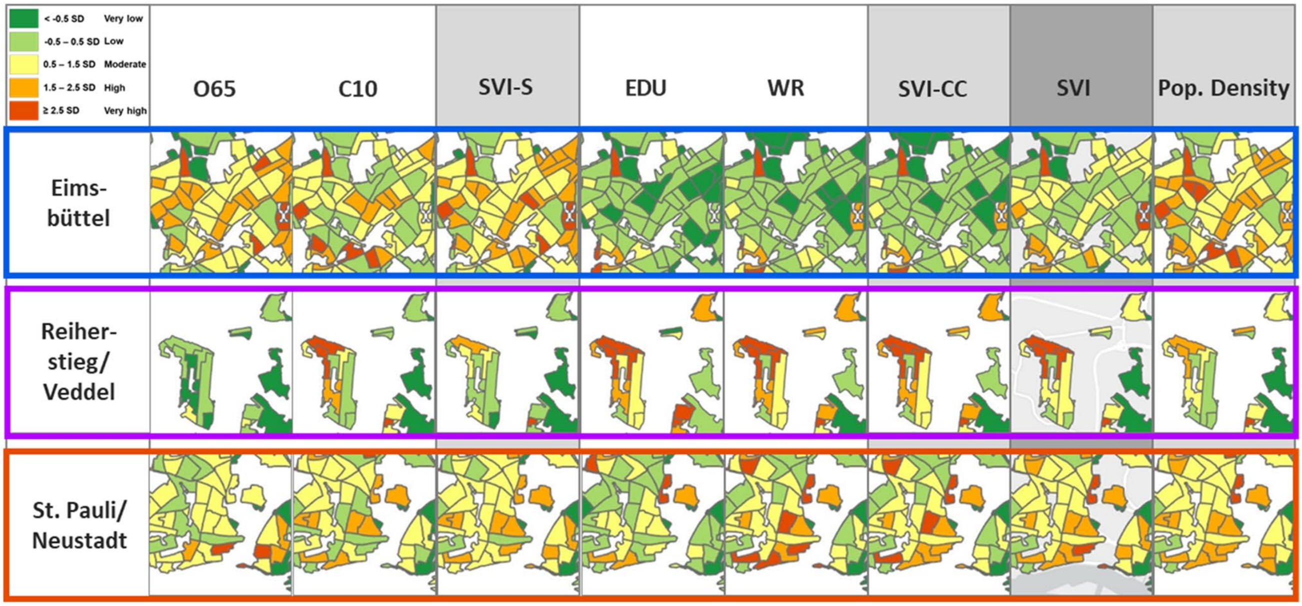

Fig. 1 Neighborhood examples. All colored classes have a width of 1 standard deviation (SD, from the respective mean). Maps in the blue rectangle (Eimsbüttel) show an example of high social vulnerability (SVI) due to high sensitivity (SVI-S), maps in the purple rectangle (Reiherstieg) show high SVI due to the lack of coping capacity (high SVI-CC values), and maps in the orange rectangle (St. Pauli) show high SVI due to high SVI-S and high SVI-CC values (low coping capacity). Individual variables are described in Table 1. Spatial resolution of the social data (Statistikamt Nord 2020) was based on the statistical areas (*Statistische Gebiete*) of the city of Hamburg (Statistikamt Nord 2017). Populated areas and density calculations were based on Corine Landcover (GeoBasis-DE/BKG 2018).

Veddel, and St. Pauli/Neustadt to illustrate the differences in the composition of the SVI and its components. Additionally, we included population density to show how insightful this basic variable is in the case study area of the city of Hamburg (Fig. 1).

The Reiherstieg quarter in Wilhelmsburg is a good example of social deprivation. Here we find comparably low sensitivities (SVI-S) alongside high numbers of school leavers with no/low educational qualifications and welfare recipients, leading to high SVI. Additionally, small-scale differences are revealed, indicating that even at the scale of a city quarter the situation may change from block to block, even building to building, lending a high degree of complexity to the city quarter. Overall, we consider Reiherstieg in Wilhelmsburg and Veddel to be examples where, in particular, the large deviation from the mean value for SVI-CC (more than 2 SD from mean SVI-CC) contributes significantly to high SVI. This peak of the proxy variables for the lack of coping capacity can be found in all socially disadvantaged areas of the city of Hamburg (compare Freie und Hansestadt Hamburg, Behörde für Stadtentwicklung und Wohnen 2021). In order to understand this pattern, however, one has to consider the historical development of residential areas in Hamburg (see discussion in Sect. 4).

Spatial heterogeneity can also be observed in Eimsbüttel. This example offers an illustration of high levels of sensitivity (SVI-S), which have a crucial impact on the overall SVI. The co-occurrence of elderly singles and children below 10 in very dense neighborhoods is a key factor here. In contrast, only two statistical areas in this neighborhood mark very high values for SVI-CC. In this case, social vulnerability is clearly impacted by the sensitivity proxy variables.

St. Pauli/Neustadt, a city quarter between the two historic inner city areas (Altstadt and Altona), is a mixture of the two aforementioned examples. Here, a high level of sensitivity (SVI-S)—due to the different composition of the residents—meets with low coping capacity (that is, high values for SVI-CC). As a result, we see some areas in St. Pauli with the highest overall SVI values.

The overall SVI pattern shows that large areas of Hamburg can be classified as not vulnerable (Fig. 2). Most of these areas are predominantly characterized by low population density. There are some exceptions to this. For example, the Harbour Island Harburg is a relatively new waterfront development that is characterized by childless, young urban professionals with high income and good education, which result in a low SVI even though the density is high. This is also true of a relatively new, high quality housing development in Neue Mitte Altona, where high population density meets a low score of SVI.

The opposite is the case for Neuwiedenthal, where a relatively low population density does not result in a low SVI. Compared to other urban areas, many very sensitive people with low coping capacity live here. Moreover, it is noticeable

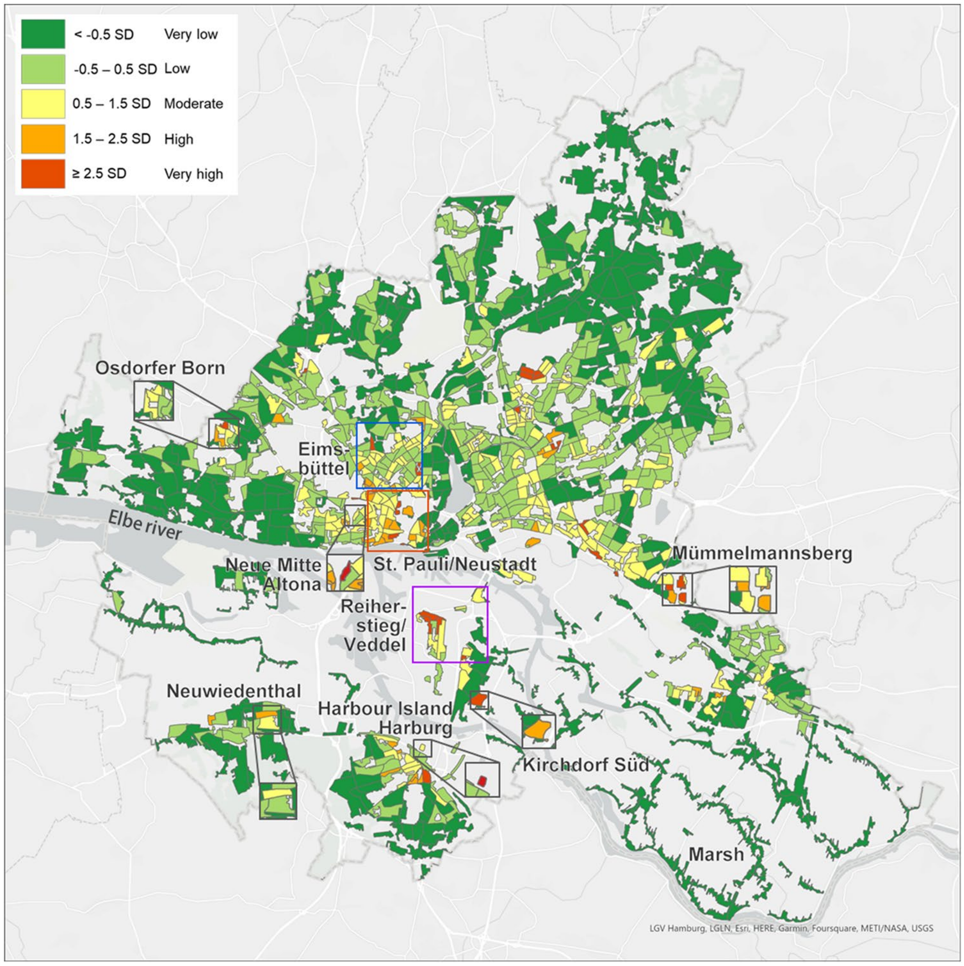

Fig. 2 Social vulnerability index for Hamburg. Spatial resolution of the social data was based on the statistical areas (*Statistische Gebiete*) of the city of Hamburg (Statistikamt Nord 2017). Population data were from the Statistical Office for Hamburg and Schleswig-Holstein (Statistikamt Nord 2020). Populated areas and density calculations were based on Corine Landcover (GeoBasis-DE/BKG 2018). The division of classes was based on standard deviations. Map Zoom-Ins show population density only (grey squares). Blue, orange, and purple squares highlight the neighborhood examples (see Fig. 1).

that most areas along the Elbe River (especially the low-lying marsh) have a moderate or low SVI (Fig. 2).

The spatial distribution of the SVI in Hamburg shows a fragmented distribution of isolated areas that deviate significantly from the mean across the city as a whole (the mean SVI value is 17.09, classified as low) and reveals two important patterns: (1) the population density reflects where quantitative challenges of risk management become apparent; and (2) a closer comparison between SVI and population density points to deviations due to particular influences. Some are related to patterns of socio-spatial inequality, which are associated with coping capacity. Socially disadvantaged parts of the city and areas characterized by large housing estates stand out in this regard. Furthermore, higher scores on the SVI are due to pronounced sensitivities in some parts of the inner city and the outskirts. Yet, interpretation is more difficult, as these sensitivities close to the inner city derive especially from higher shares of older residents living alone. Here, the effects of demographic aging become visible, leading to a reduction in household size and a disproportionate number of single person households in some neighborhoods. When these effects occur together, the combination of social disadvantage and individualization of the elderly increases the SVI score significantly. Furthermore, we note a concentration of sensitive population groups in areas of the city that are typically classified as unproblematic (for example on the basis of income and educational background). This depends on the selection of variables for the sensitivity component—since only age-related variables are considered here, this calculation is not biased by other social, cultural, or economic variables. The decision to calculate the variables in relation to spatial units also contributes to the result. Here, a large number of children and elderly are more prominent factors, especially in very densely populated inner city areas. Low coping capacity, on the other hand, is concentrated in areas that are often identified as socioeconomic hotspots, for example by the social monitoring of the city of Hamburg (Freie und Hansestadt Hamburg, Behörde für Stadtentwicklung und Wohnen 2021). These neighborhoods often suffer from a negative path dependency in terms of image and unemployment rate. Social inequality and the spatial segregation of inequality also lead to an aggregation of low coping capacity.

Figure 3 provides an overview of the main influences of the respective hotspot areas: The map shows whether increased SVI values are primarily due to high SVI-S or SVI-CC. Combined effects can also be identified.

4 Discussion

In this section, the results are first evaluated and discussed. In the second step, the results are also discussed methodically.

4.1 Hotspots: Evaluation and Implications of the Results

The SVI mapping for Hamburg reveals hotspots with high SVI scores. The selected neighborhood examples show how the input variables are reflected in the overall index. The hotspots represent areas with high social vulnerability resulting from unequal distribution and social segregation processes. Focusing on absolute numbers of people, instead of the relative proportions of the population in administrative urban units, produced a picture of the city in which sparsely populated areas are predominantly classified as unproblematic.

The SVI is designed to reveal where high sensitivity and low coping capacity are concentrated, but not why. A valid explanation of SV patterns can only be derived based on a review of historical, qualitative, and quantitative data for individual neighborhoods. This means that in the case of the city of Hamburg, one has to consider the historical construction periods, the impact of disasters, migration waves, and proximity to the port of Hamburg in relation to the prevailing wind direction in order to interpret the results meaningfully. For example, in the case of the Reiherstieg quarter in Wilhelmsburg, the time of construction (Gründerzeit and the 1950s) and the building fabric (for example in terms of apartment size: maximum 3-room apartments) are particularly important and have to be considered when examining population composition (Freie und Hansestadt Hamburg, Behörde für Stadtentwicklung und Umwelt 2004). Additionally, the flood disaster of 1962 in which more than 300 people died throughout Hamburg claimed by far the most victims in this neighborhood; and the damaged buildings were often only provisionally repaired after the flooding

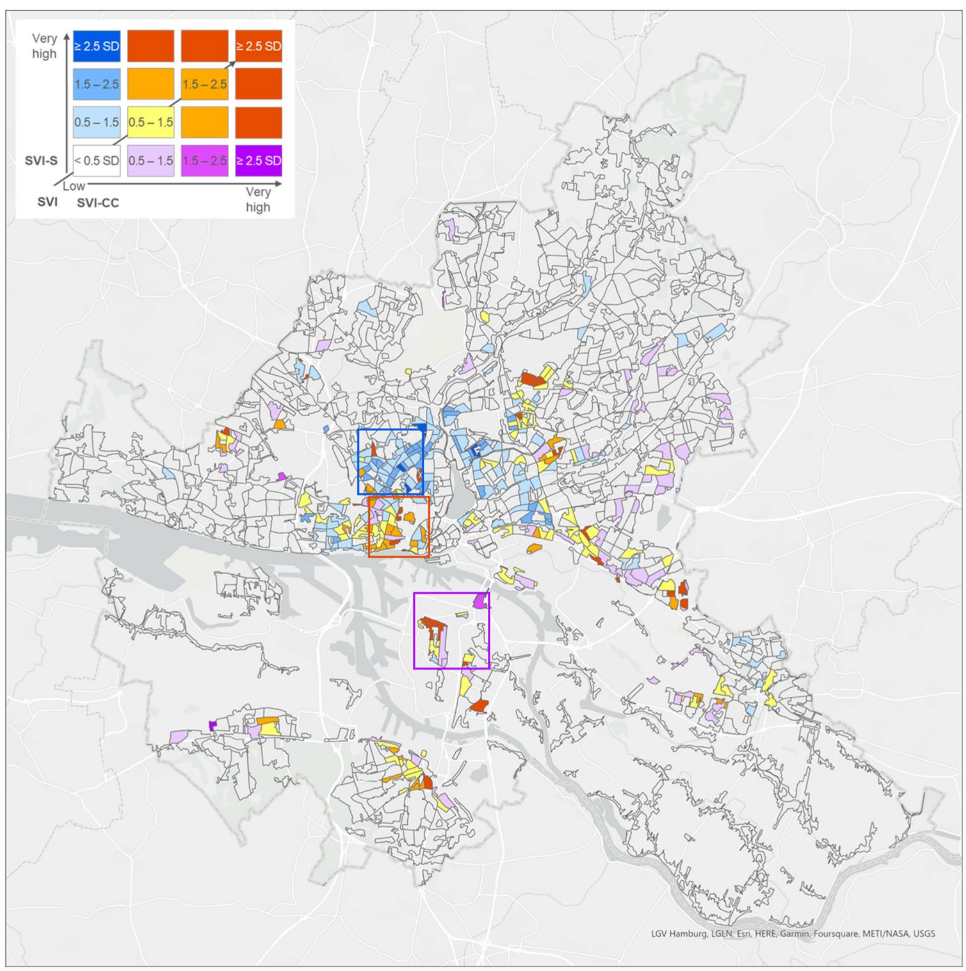

Fig. 3 Hotspots due to high sensitivity (SVI-S) and/or low coping capacity (high SVI-CC values). Resolution of the social data was based on the statistical areas (*Statistische Gebiete*) of the city of Hamburg (Statistikamt Nord 2017). Population data were from the Statistical Office for Hamburg and Schleswig-Holstein (Statistikamt Nord 2020). Populated areas and density calculations were based on Corine Landcover (GeoBasis-DE/BKG 2018). The division of classes was based on standard deviations. Blue, orange, and purple squares show the neighborhood examples (see Fig. 1).

(Paech 2008). The fabric of the buildings and the unfavorable location in the flood hazard area of the tidal Elbe River (Freie und Hansestadt Hamburg, Behörde für Umwelt, Klima, Energie und Agrarwirtschaft 2020) contributed to a negative image for the district, which in turn resulted in a negative social development. This was further reinforced by other urban planning measures (construction of expressways through Wilhelmsburg, see Markert 2008). In order to be successful, adaptation and mitigation strategies must also take these local characteristics into account. Here, educational strategies and empowering the local population are potential strategies that could improve the SVI score.

The relevant parameters used to interpret the results vary from city quarter to city quarter. In Eimsbüttel, for example, the flood of 1962 played no role in the infrastructure that can be observed today. Adequate street width and green inner and rear courtyards are rather attributable to fires (e.g. the Great Fire of 1842) and the resulting changes in building regulations (Schubert 2012, Hanke 2014). As one of the most densely populated areas of Hamburg, Eimsbüttel offers a wide range of cultural, leisure, and everyday activities (Vogelpohl 2010). This mix of living and working with a high population density at the same time has a high degree of continuity, leading to the presence of many elderly residents alongside new families looking for an apartment.

As mentioned above, St. Pauli/Neustadt is a mixture of these two city quarters. Here, housing similar to that in Eimsbüttel meets a very different neighborhood composition. St. Pauli is characterized by residents with various migration backgrounds who found cheap housing in unrenovated *Gründerzeit* buildings in the 1980s—a typical development in major European cities at that time. While the majority of the children also have a migration background, the majority of the elderly singles have been rooted in the neighborhood for decades (Vogelpohl 2010). In addition to this demographic variation, there are the young students who prefer to live in this district due to its proximity to the University of Hamburg and who often contribute to the low coping capacity due to their low level of income and increased demand for housing (Pohl and Wischmann 2014). The leeward location of this district behind the port (relative to the prevailing wind direction) is a historical continuity that is expressed here in the low coping capacity, which in turn is expressed in predominantly small apartment layouts (see Reiherstieg above).

Generally, our analysis draws attention to a specific process of demographic change driving an aging of urban society in parts of the city of Hamburg and thus to an increase in SV. However, local characteristics have to be taken into account when developing new strategies to mitigate the consequences of this urban demographic shift. For example, in St. Pauli, with its relatively steep topography, measures must be designed differently than in Eimsbüttel, where people with restricted mobility can move more easily. A change in the old-age housing situation, for example through shared accommodation for the elderly, could therefore not only have positive effects on public health (Dapp et al. 2014), but also lead to a reduction in SV overall.

It is precisely the identification of areas with high SVI scores that enables a more in-depth analysis of the root causes of SV. There is a connection between our study and the program of the "social city" (Freie und Hansestadt Hamburg, Behörde für Stadtentwicklung und Wohnen 2021), which focuses on areas of Hamburg that have a low SVI-CC in our analysis. Note that our results show a spatiotemporal continuity, that is, neighborhoods with low SVI-CC have hardly changed over decades. Therefore, "spatial traps" (Pohl et al. 2010) of social inequality can also be seen as important indicators of SV.

Socio-spatial inequalities often adversely affect certain social groups, such as elderly people, people with low income, and people with lower educational backgrounds (EEA 2019). Thus, environmental hazards such as flooding not only have a physical impact on urban infrastructure, but also a social impact on those who are most marginalized. In other words, "resilient flood risk governance requires mechanisms to ensure social equity and to address 'unfair' distributional effects" (Driessen et al. 2018, p. 11). The neighborhood examples we chose reveal that SV, as well as coping capacity, sensitivity, and density, are unequally distributed in Hamburg, showing underlying unequal distribution and social segregation processes, which in the long term have a negative effect on the urban system and its inhabitants (Foster et al. 2019).

On a general level, however, the city has responsibilities. First, it can point out hazards and provide the (potentially affected) citizens with the necessary information (for example, Krieger et al. 2013; Freie und Hansestadt Hamburg, Behörde für Umwelt, Klima, Energie und Agrarwirtschaft 2020; Freie und Hansestadt Hamburg, Behörde für Umwelt, Klima, Energie und Agrarwirtschaft 2021). Second, it can increase coping capacity if the city provides targeted subsidies for private homeowners who live in potential hazard areas, in order to strengthen private risk prevention (Mees et al. 2014).

To conclude, the SV concept helps identify hotspots of vulnerable groups that might need additional assistance in case of emergency. Social vulnerability index can also be used for further urban flood risk monitoring, which can guide flood risk communication. For instance, the SVI can be coupled with hazard and exposure data as well as data on socioeconomic losses. A map incorporating data on the structural quality of buildings with the SVI and its underlying sensitivity indicators (young children, elderly singles), alongside a map of flood zones, could help tailor emergency plans within the floodplain to people who would otherwise not reach safe areas on their own. As another example, advance warnings in case of heat waves can be targeted to areas with high SV in the city's heat island, based on age structure and coping capacity. Therefore, working at a detailed scale is worthwhile not only for emergency response, but also for improving prevention planning and community resilience in the long term. Nonetheless, a comprehensive analysis of combining SVI with hazards and exposure maps is beyond the scope of this study.

4.2 Methodological Results and Summary

When comparing the results of the SV analysis with population density, it has been shown that population density can function as a proxy for SVI, despite the heterogeneous settlement structure of the city of Hamburg. However, population density's explanatory power in this regard decreases massively if the segregation of cities increases, whereas in a very mixed, homogeneous city the differences between population density and SVI will only be small. Although Hamburg is structurally very heterogeneous, it is much more mixed overall than is often the case in large cities in the United States, for example. Due to the destruction in the Second World War, there are extensive rows of buildings from the 1950s in the east and south of the city (Freie und Hansestadt Hamburg, Behörde für Bau und Verkehr 2003). Many of the *Gründerzeit* buildings were rebuilt and parts of the city plan were reconfigured to be car-friendly. However, neither the distance to the city center nor the type of building provide reliable information about the social composition of the districts. Our study showed that differences in detail in Hamburg, especially in potential flood hazard areas (compare the Reiherstieg quarter in Wilhelmsburg), are obscured by any analysis that only takes population density into account.

For the aggregation of the factors into a final index, variables are usually summed up, even if there is no intercorrelation between the individual variables or factors (compare for example Tapsell et al. 2002; Preston et al. 2008). This is done even if a factor analysis was previously carried out and the factors determined are orthogonal to each other (for example varimax rotation, see Fekete 2009), although an addition of variables of different dimensions is mathematically invalid (Kaiser 1958). The widely used social vulnerability index SoVI, which was originally developed by Cutter et al. (2003), shares this problematic approach, too. This is the primary methodological reason for using the AHP model for variable selection and weighting in this study. In addition, our SVI is much easier to reproduce.

To summarize, the following points especially characterize our index:

- Using the city of Hamburg as a case study, the SVI reveals the spatial distribution and small-scale variability of social vulnerability, and particularly vulnerable population groups, with high resolution.
- For the calculation of the input variables, the actually populated areas of the city of Hamburg were identified using satellite information. These areas were blended with the survey units of the social data and thus form a unique spatial reference.
- The spatial calculation of the variables and indices derived from methodological considerations show that using population density as a proxy for social vulnerability is appropriate for a rough overview. However, if detailed small-scale urban differences in urban social vulnerability are of interest, the selected variables help to identify hotspot areas.
- We have constructed our index as precisely as necessary and as simply as possible. Despite the simplicity of the index, the proxy variables selected adequately demonstrate the range of the underlying drivers of social vulnerability (social welfare, education, and age).
- The variables chosen are consistent with a variety of studies that have examined social vulnerability to climate-related hazards. They form a basis for climate-related risk analysis for the city of Hamburg.
- Our detailed SVI mapping presents a simple and easily understandable starting point for developing guidance for local flood adaptation and prevention planning as well as emergency planning.

For new urban infrastructure projects, the map locates where special attention should be paid to vulnerable populations to mitigate unequal distribution and dynamics of social segregation. Adaptation measures are necessary to counter the vulnerability of these groups in order to prepare for future climate change. Effectively addressing social vulnerability reduces both the human suffering and economic losses associated with providing social services and public assistance after a disaster (Flanagan et al. 2011; Abebe et al. 2020).

Limitations of this study can be summarized as follows:

- The maps show the current state only and do not include dynamics such as changes in population structure. The SVI can always be recalculated to create a timeline. However, a forecast of demographic developments is only possible on the basis of further assumptions. Such a timeline would be associated with great uncertainties, but is fundamentally conceivable.
- Some variables had to be ignored due to the inaccessibility of data (for example, insurance status) because of the strict data protection regulations in Germany.
- The input variables for coping capacity—*welfare recipients* and *school leavers with no/low educational qualification*—are in a sense country-specific, as such data are

rarely collected in a uniform way within Europe. Therefore, only a comparison to other German cities is strictly possible.

- In this study, local knowledge was incorporated by the expert-guided selection of variables. Therefore, our selection does not claim to be of general validity.
- Our study does not claim to be comparable with current indices with a global scope (Davino et al. 2021), which, however, work with significantly lower spatial resolutions.

5 Conclusion and Outlook

This analysis shows where to take a closer look when discussing the possible effects of, and the people potentially most impacted by, climate-related hazards in the city of Hamburg. Social diversity, inequalities, and segregation processes in cities will continuously gain importance as climate change progresses. Therefore, it is important to continuously focus on SV and its implications for social research and action, focussing on distributional, recognitional, and procedural aspects (Bullard 2001). These perspectives can help us to understand why urban inequalities and very high SVI scores are problematic. For urban transformation and development to be considered sustainable, local hotspots have to be addressed as unjust and unequal distributions have to be solved, including accessible opportunities for participation in the adaptation planning (Shi et al. 2016). In this context, modeling the social vulnerability of urban areas by assessing systemic social issues and barriers can provide an important layer of information and a starting point for urban adaptation and prevention planning (Cook and Swyngedouw 2012; Shi et al. 2016).

Our model of SV offers a clear interface for potentially impactful prognosis: the proxy variables are simple enough to serve as a basis for a prediction of possible future cities, with the help of demographic forecasts (Freie und Hansestadt Hamburg, Behörde für Gesundheit und Verbraucherschutz 2019). In addition, the variable selection allows us to use existing urban development projections (Kaveckis 2017) to calculate future SVIs.

If our results are combined with calculations carried out by the city of Hamburg on potential risk areas in the context of climate-related hazards for coastal and inland cities (for example, flooding, heat stress, air pollution), it is easy to identify areas where there may be a need for action. This means that we are now able to analyze whether potential hazard areas correlate strongly with vulnerable population groups. As a next step, it will be necessary to develop a detailed model of the effects of risks on vulnerable population groups. To fill this gap, further research on this topic will need to be conducted, addressing questions at the nexus of climate-related risk and vulnerability and aiming at a risk model for climate-related hazards. The physical conditions of vulnerability—excluded in the present analysis—must also be included in future investigations. For example, the construction and structural quality of neighborhood housing play a major role in determining whether any existing social vulnerability will actually have an impact in the event of a disaster.

To conclude, further research on vulnerability in cities is highly necessary. First, social diversity and inequalities in cities are predominant and will become even more threatening as urban areas become more and more densely populated. Second, climate-related hazards, such as urban flooding and heat stress, are more present than ever and have major impacts on cities. The intersection of social vulnerability and climate-related hazards must therefore be seen as an important field of research and is of great importance in the current debates of interdisciplinary climate research.

Acknowledgments This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy—EXC 2037 "CLICCS – Climate, Climatic Change, and Society"—Project No. 390683824, contribution to the Center for Earth System Research and Sustainability (CEN) of Universität Hamburg. We thank the Behörde für Umwelt, Klima, Energie und Agrarwirtschaft (BUKEA) for providing data on flooding risks and heavy rains. The Corine Landcover satellite data used in this study were provided by the Federal Environment Agency. We also acknowledge the Geoportal Hamburg for making most of the data used in this study freely available (at https://geoportal-hamburg.de/geo-online/). We thank Klaus D. Goepel for providing a free online tool to calculate AHPs.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Abebe, Y.A., A. Ghorbani, I. Nikolic, N. Manojlovic, A. Gruhn, and Z. Vojinovic. 2020. The role of household adaptation measures in reducing vulnerability to flooding: A coupled agent-based and flood modelling approach. *Hydrology and Earth System Sciences* 24(11): 5329–5354.

Balica, S., and N.G. Wright. 2010. Reducing the complexity of the flood vulnerability index. *Environmental Hazards* 9(4): 321–339.

Beckers, T., K. Birkelbach, J. Hagenah, and U. Rosar. 2010. *Comparative empirical social research (Komparative empirische Sozialforschung)*. Wiesbaden: VS Verlag für Sozialwissenschaften (in German).

Blaikie, P., T. Cannon, I. Davis, and B. Wisner. 1994. *At risk: Natural hazards, people's vulnerability, and disasters*. London: Routledge.

Bouwer, L. 2020. Climate risk information: An essential service for planning. Geesthacht, Germany: Climate Service Center Germany. https://publications.hereon.de/id/39938/. Accessed 13 Oct 2023.

Bullard, R.D. 2001. Environmental justice in the 21st Century. https://uwosh.edu/sirt/wp-content/uploads/sites/86/2017/08/Bullard_Environmental-Justice-in-the-21st-Century.pdf. Accessed 13 Oct 2023.

Cardona, O.D., M.K. van Aalst, J. Birkmann, M. Fordham, G. McGregor, R. Perez, R.S. Pulwarty, E.L.F. Schipper, and B.T. Sinh. 2012. Determinants of risk: Exposure and vulnerability. In *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the Intergovernmental Panel on Climate Change*, ed. C.B. Field, 65–108. Cambridge: Cambridge University Press.

Cook, I.R., and E. Swyngedouw. 2012. Cities, social cohesion and the environment: Towards a future research agenda. *Urban Studies* 49(9): 1959–1979.

Cutter, S.L., B.J. Boruff, and W.L. Shirley. 2003. Social vulnerability to environmental hazards. *Social Science Quarterly* 84(2): 242–261.

Dapp, U., C.E. Minder, J. Anders, S. Golgert, and W. von Renteln-Kruse. 2014. Long-term prediction of changes in health status, frailty, nursing care and mortality in community-dwelling senior citizens – Results from the longitudinal urban cohort ageing study (LUCAS). *BMC Geriatrics* 14: Article 141.

Davino, C., M. Gherghi, S. Sorana, and D. Vistocco. 2021. Measuring social vulnerability in an urban space through multivariate methods and models. *Social Indicators Research* 157(3): 1179–1201.

Dodman, D., B. Hayward, M. Pelling, V. Castan Broto, W. Chow, E. Chu, R. Dawson, L. Khirfan, et al. 2022. Cities, settlements and key infrastructure. In *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, et al., 907–1040. Cambridge, UK: Cambridge University Press.

Drakes, O., and E. Tate. 2022. Social vulnerability in a multi-hazard context: A systematic review. *Environmental Research Letters* 17(3): Article 33001.

Driessen, P., D. Hegger, Z. Kundzewicz, H. van Rijswick, A. Crabbé, C. Larrue, P. Matczak, M. Pettersson, et al. 2018. Governance strategies for improving flood resilience in the face of climate change. *Water* 10(11). https://doi.org/10.3390/w10111595.

EEA (European Environment Agency). 2019. Environmental justice, environmental hazards and the vulnerable in European society (briefing). https://www.eea.europa.eu/publications/unequal-exposure-and-unequal-impacts/environmental-justice-environmental-hazards-and/view. Accessed 14 Oct 2023.

Faist, T. 2018. The socio-natural question: How climate change adds to social inequalities. *Journal of Intercultural Studies* 39(2): 195–206.

Fekete, A. 2009. Validation of a social vulnerability index in context to river-floods in Germany. *Natural Hazards and Earth System Sciences* 9(2): 393–403.

Flanagan, B.E., E.W. Gregory, E.J. Hallisey, J.L. Heitgerd, and B. Lewis. 2011. A social vulnerability index for disaster management. *Journal of Homeland Security and Emergency Management* 8(1). https://doi.org/10.2202/1547-7355.1792.

Forman, E.H., and S.I. Gass. 2001. The analytic hierarchy process – An exposition. *Operations Research* 49(4): 469–486.

Foster, S., R. Leichenko, K.H. Nguyen, R. Blake, H. Kunreuther, M. Madajewicz, E.P. Petkova, and R. Zimmerman et al. 2019. New York City Panel on Climate Change 2019 report chapter 6: Community-based assessments of adaptation and equity. *Annals of the New York Academy of Sciences* 1439(1): 126–173.

Freie und Hansestadt Hamburg, Behörde für Bau und Verkehr. 2003. 50 years of land management in Hamburg: Area management through land consolidation and border regulation (*50 Jahre Bodenordnung in Hamburg: Flächenmanagement Durch Umlegung Und Grenzregelung*). https://epub.sub.uni-hamburg.de/epub/volltexte/2009/3689/pdf/bodenordnung_in_hamburg%20_50_jahre_broschuere.pdf. Accessed 13 Oct 2023 (in German).

Freie und Hansestadt Hamburg, Behörde für Gesundheit und Verbraucherschutz. 2019. Report on the demographic concept Hamburg 2030 (*Bericht Zum Demographiekonzept Hamburg 2030*). https://www.hamburg.de/contentblob/12032286/0880e17d6ef77aab152751b988daf47f/data/download-fortschreibung-demografiekonzept-hamburg2030.pdf. Accessed 13 Oct 2023 (in German).

Freie und Hansestadt Hamburg, Behörde für Stadtentwicklung und Umwelt. 2004. Development perspectives for Reiherstieg and Spreehafen. Leap across the Elbe – Urban renewal in the west (*Entwicklungsperspektiven Reiherstieg Und Spreehafen. Sprung über die Elbe – Stadtumbau West*). https://zukunft-elbinsel.de/wp-content/uploads/2013/08/2004-duesterhoeft_entwicklungsperspektivenreiherstieg-spreehafen.pdf. Accessed 13 Oct 2023 (in German).

Freie und Hansestadt Hamburg, Behörde für Stadtentwicklung und Wohnen (ed.). 2021. Social monitoring and integrated urban development: Report 2021 (*Sozialmonitoring Integrierte Stadtenteicklung: Bericht 2021*). https://www.hamburg.de/contentblob/15711330/727d2c0115b88daaa3514f87297932cb/data/d-sozialmonitoring-bericht-2021.pdf. Accessed 13 Oct 2023 (in German).

Freie und Hansestadt Hamburg, Behörde für Umwelt, Klima, Energie und Agrarwirtschaft. 2020. Accompanying text for flood hazard and flood risk maps for Hamburg (*Begleittext Hochwassergefahren- Und Hochwasserrisikokarten Für Hamburg*). https://www.hamburg.de/contentblob/13535832/49ff87c5193544555c671b8748125c5a/data/d-hh-begleittext-gefahrenrisikokarten-jan2020.pdf. Accessed 13 Oct 2023 (in German).

Freie und Hansestadt Hamburg, Behörde für Umwelt, Klima, Energie und Agrarwirtschaft. 2021. Heavy rainfall alert map (*Starkregenhinweiskarte*). https://www.hamburg.de/starkregenhinweiskarte/. Accessed 13 Oct 2023 (in German).

Füssel, H.-M. 2010. *Review and quantitative analysis of indices of climate change exposure, adaptive capacity, sensitivity, and impacts.* Washington, DC: World Bank. https://openknowledge.worldbank.org/bitstream/10986/9193/1/WDR2010_0004.pdf. Accessed 13 Oct 2023.

GeoBasis-DE/BKG. 2018. CORINE Land Cover 5 Ha, Stand 2018 (CLC5-2018). http://gdz.bkg.bund.de/index.php/default/corine-land-cover-5-ha-stand-2018-clc5-2018.html. Accessed 13 Oct 2023.

Glavovic, B.C., R. Dawson, W. Chow, M. Garschagen, M. Haasnoot, C. Singh, and A. Thomas. 2022. Cross-chapter paper 2: Cities and settlements by the sea. In *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, et al., 2163–2194. Cambridge, UK: Cambridge University Press.

Goepel, K.D. 2018. Implementation of an online software tool for the analytic hierarchy process (AHP-OS). *International Journal of the Analytic Hierarchy Process* 10(3). https://doi.org/10.13033/ijahp.v10i3.590.

Grotlüschen, A., and K. Buddeberg. 2020. LEO 2018: Living with low literacy (*LEO 2018: Leben mit geringer Literalität*). Bielefeld: wbv (in German).

Hanke, C. 2014. *Hamburg's street names tell history: With district walks, maps, photos, and … the latest streets* (*Hamburgs

Straßennamen erzählen Geschichte: Mit Stadtteilrundgängen, Karten, Fotos und … den neuesten Straßen), 5th edn. Aufl. Hamburg: Medien-Verl. Schubert (in German).

Holand, I.S., P. Lujala, and J.K. Rød. 2011. Social vulnerability assessment for Norway: A quantitative approach. *Norsk Geografisk Tidsskrift – Norwegian Journal of Geography* 65(1): 1–17.

Islam, S.N., and J. Winkel. 2017. *Climate change and social inequality working papers.* United Nations Publications 152. New York: UN Department of Economic and Social Affairs (DESA).

Joakim, E.P., L. Mortsch, and G. Oulahen. 2015. Using vulnerability and resilience concepts to advance climate change adaptation. *Environmental Hazards* 14(2): 137–155.

Jodoin, S., A. Buettgen, N. Groce, P. Gurung, C. Kaiser, M. Kett, M. Keogh, S.S. Macanawai, et al. 2023. Nothing about us without us: The urgent need for disability-inclusive climate research. *PLOS Climate* 2(3): Article e0000153.

Jurgilevich, A., A. Räsänen, F. Groundstroem, and S. Juhola. 2017. A systematic review of dynamics in climate risk and vulnerability assessments. *Environmental Research Letters* 12(1): Article 013002.

Kaiser, H.F. 1958. The varimax criterion for analytic rotation in factor analysis. *Psychometrika* 23: 187–200.

Kaveckis, G. 2017. Modeling future population's vulnerability to heat waves in Greater Hamburg. Ph.D. dissertation. Institute of Geography, Universität Hamburg, Hamburg, Germany.

Kienberger, S., S. Lang, and P. Zeil. 2009. Spatial vulnerability units – Expert-based spatial modelling of socio-economic vulnerability in the Salzach catchment, Austria. *Natural Hazards and Earth System Sciences* 9(3): 767–778.

Kim, S.K., M.M. Bennett, T. van Gevelt, and P. Joosse. 2021. Urban agglomeration worsens spatial disparities in climate adaptation. *Scientific Reports* 11(1): Article 8446.

Kosanic, A., J. Petzold, B. Martín-López, and M. Razanajatovo. 2022. An inclusive future: Disabled populations in the context of climate and environmental change. *Current Opinion in Environmental Sustainability* 55: Article 101159.

Krieger, K., A. Kuchenbecker, N. Hüffmeyer, and H.-R. Verworn. 2013. Local effects of global climate change on the urban drainage system of Hamburg. *Water Science and Technology* 68(5): 1107–1113.

Markert, M. 2008. The leap across the Elbe – Wilhelmsburg's path to the center of the city (*Der Sprung über die Elbe – Wilhelmsburgs Weg in die Mitte der Stadt*). 191. Geschichtswerkstatt Wilhelmsburg & Hafen 2008 – Wilhelmsburg.

Mason, D., A. Iida, S. Watanabe, L.P. Jackson, and M. Yokohari. 2020. How urbanization enhanced exposure to climate risks in the Pacific: A case study in the Republic of Palau. *Environmental Research Letters* 15(11): Article 114007.

McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White. 2001. *Climate change 2001: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

Mees, H.L.P., P.P.J. Driessen, and H.A.C. Runhaar. 2014. Legitimate adaptive flood risk governance beyond the dikes: The cases of Hamburg. *Helsinki and Rotterdam. Regional Environmental Change* 14(2): 671–682.

Nasiri, H., M.J.M. Yusof, T.A.M. Ali, and M.K.B. Hussein. 2019. District flood vulnerability index: Urban decision-making tool. *International Journal of Environmental Science and Technology* 16(5): 2249–2258.

Nguyen, T.T., J. Bonetti, K. Rogers, and C.D. Woodroffe. 2016. Indicator-based assessment of climate-change impacts on coasts: A review of concepts, methodological approaches and vulnerability indices. *Ocean & Coastal Management* 123: 18–43.

Paech, F. 2008. The whole stories of the people – The Hamburg flood of 1962 in the consciousness of the Wilhelmsburg population (*Die ganzen menschlichen Geschichten – Die Hamburger Sturmflut von 1962 im Bewusstsein der Wilhelmsburger Bevölkerung*). 161–173. https://content.e-bookshelf.de/media/reading/L-2812425-169e1ca58f.pdf. Accessed 13 Oct 2023.

Pohl, T., and K. Wischmann. 2014. Housing market dynamics and urban political conflicts in Hamburg: A contribution to gentrification research (*Wohnungsmarktdynamik und stadtpolitische Konflikte in Hamburg: ein Beitrag zur Gentrificationforschung*). Mannheim. https://www.ssoar.info/ssoar/bitstream/handle/document/41134/ssoar-europareg-2014-2-pohl_et_al-Wohnungsmarktdynamik_und_stadtpolitische_Konflikte_in.pdf?sequence=1&isAllowed=y&lnkname=ssoar-europareg-2014-2-pohl_et_al-Wohnungsmarktdynamik_und_stadtpolitische_Konflikte_in.pdf. Accessed 13 Oct 2023 (in German).

Pohl, T., F. Giesel, and J. Oßenbrügge. 2010. Suburbia as a spatial trap? – Consequences of demographic and socio-spatial development in major cities using Hamburg as an example (*Suburbia Als „Räumliche Falle"? – Folgen Der Demographischen Und Sozialräumlichen Entwicklung Von Großstädten Am Beispiel Hamburgs*). *Berichte zur Deutschen Landeskunde* 4: 329–348 (in German).

Poschlod, B., and R. Ludwig. 2021. Internal variability and temperature scaling of future sub-daily rainfall return levels over Europe. *Environmental Research Letters* 16: Article 064097.

Pratschke, J., and E. Morlicchio. 2012. Social polarisation, the labour market and economic restructuring in Europe: An urban perspective. *Urban Studies* 49(9): 1891–1907.

Preston, B., T.F. Smith, C. Brooke, R.J. Gorddard, T. Measham, G. Withycombe, B. Beveridge, C. Morrison, et al. 2008. Mapping climate change vulnerability in the Sydney coastal councils group. https://publications.csiro.au/rpr/download?pid=procite:0b6b33c4-90ca-453d-bf77-9480cd047047&dsid=DS1. Accessed 13 Oct 2023.

Reckien, D. 2018. What is in an index? Construction method, data metric, and weighting scheme determine the outcome of composite social vulnerability indices in New York City. *Regional Environmental Change* 18(5): 1439–1451.

Reisinger, A., M. Howden, C. Vera, M. Garschagen, M. Hurlbert, S. Kreibiehl, K.J. Mach, K. Mintenbeck, et al. 2020. The concept of risk in the IPCC Sixth Assessment Report: A summary of cross-working group discussions. https://www.ipcc.ch/site/assets/uploads/2021/01/The-concept-of-risk-in-the-IPCC-Sixth-Assessment-Report.pdf. Accessed 13 Oct 2023.

Rheinneckar Blog. 2021. 106 out of 135 flood victims in the Ahr Valley were over 60 years old: Statement by the Victim Commissioner of the state of Rhineland-Palatinate on the number of victims (*106 Von 135 Opfern Der Flut Im Ahrtal Waren Über 60 Jahre Alt: Angaben Des Opferbeauftragten Des Landes Rheinland-Pfalz Zur Zahl Der Opfer*). *Rheinneckar Blog*, 18 November 2021. https://rheinneckarblog.de/18/106-von-135-opfern-der-flut-im-ahrtal-waren-ueber-60-jahre-alt/162578.html. Accessed 13 Oct 2023 (in German).

RND (Redaktionsnetzwerk Deutschland). 2021. Flood catastrophe in the Ahr Valley: 69 out of the 134 deaths came from Ahrweiler (*Flutkatastrophe Im Ahrtal: 69 Der 134 Toten Stammten Aus Ahrweiler*). *Redaktions Netzwerk Deutschland*, 18 November 2021. https://www.rnd.de/panorama/hochwasser-im-ahrtal-das-juengste-todesopfer-war-vier-jahre-alt-das-aelteste-97-T3FPN5OE76AAWKGLCY6EV5USSI.html. Accessed 8 Oct 2023 (in German).

Sampson, R.J., J.D. Morenoff, and T. Gannon-Rowley. 2002. Assessing "neighborhood effects": Social processes and new directions in research. *Annual Review of Sociology* 28(1): 443–478.

Schlömer, O., J. Giesel, and M. Lindinger. 2021. Déjà-Vu of the catastrophe (*Déjà-Vu Der Katastrophe*). *Frankfurter Allgemeine*

Zeitung, 5 August 2021. https://www.faz.net/aktuell/gesellschaft/ungluecke/flutkatastrophe-im-ahrtal-neue-erkenntnisse-zum-hochwasser-17470847.html. Accessed 13 Oct 2023 (in German).
Schröter, K. 2019. *Improved flood risk assessment*. Habilitationsschrift: Mathematisch-Naturwissenschaftlichen Fakultät, Universität Potsdam, Germany.
Schubert, D. 2012. The Great Fire of Hamburg, 1842: From Catastrophe to Reform. In *Flammable Cities: Urban Conflagration and the Making of the Modern World*, ed. G. Bankoff, U. Lübken, and J. Sand. Madison, University of Wisconsin.
Shi, L., E. Chu, I. Anguelovski, A. Aylett, J. Debats, K. Goh, T. Schenk, and K.C. Seto et al. 2016. Roadmap towards justice in urban climate adaptation research. *Nature Climate Change* 6(2): 131–137.
Simpson, N.P., K.J. Mach, A. Constable, J. Hess, R. Hogarth, M. Howden, J. Lawrence, and R.J. Lempert et al. 2021. A framework for complex climate change risk assessment. *One Earth* 4(4): 489–501.
Singer, M. 2018. *Climate change and social inequality: The health and social costs of global warming*. London: Routledge.
Statistikamt Nord. 2017. Statistical areas in Hamburg (*Statistische Gebiete in Hamburg*). https://metaver.de/trefferanzeige?docuuid=DB93B23B-D3F1-4460-8C62-DD1961893767&plugid=/ingrid-group:ige-iplug-hmdk.metaver&docid=DB93B23B-D3F1-4460-8C62-DD1961893767. Accessed 7 Oct 2023 (in German).
Statistikamt Nord. 2020. Customer file 2020 (*Kundendatei 2020*). Obtainable from the authors.
Tammaru, T. 2015. *Socio-economic segregation in European capital cities*. London: Routledge.
Tammaru, T., A. Sinitsyna, A. Akhavizadegan, M. van Ham, S. Marcińczak, and S. Musterd. 2021. Income inequality and residential segregation in European cities. In *Urban inequality and segregation in Europe and China: Towards a new dialogue*, 1st edn, ed. G. Pryce, Y.P. Wang, Y. Chen, J. Shan, and H. Wei, 39–54. Cham: Springer.
Tapsell, S.M., E.C. Penning-Rowsell, S.M. Tunstall, and T.L. Wilson. 2002. Vulnerability to flooding: Health and social dimensions. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences* 360(1796): 1511–1525.
Tascón-González, L., M. Ferrer-Julià, M. Ruiz, and E. García-Meléndez. 2020. Social vulnerability assessment for flood risk analysis. *Water* 12(2): Article 558.
Vogelpohl, A. 2010. The reproduction of urban diversity (*Die Reproduktion urbaner Vielfalt*). In *Times and spaces of the city: Theory and practice (Zeiten und Räume der Stadt: Theorie und Praxis)*, ed. D. Läpple, U. Mückenberger, and J. Oßenbrügge, 91–108. Opladen, Farmington Hills, MI: Verlag Barbara Budrich (in German).
Zamzow, B., and A. Krahl. 2020. Living in disadvantaged neighborhoods (*Wohnen in benachteiligten Stadtteilen*). In *Handbook of housing sociology (Handbuch Wohnsoziologie)*, ed. F. Eckardt, and S. Meier, 313–325. Wiesbaden: Springer (in German).