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Climate change vulnerability and possible adaptation measures in cities – the case of Hamburg

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Abstract

The vulnerability index presented in this paper is a tool to measure the vulnerability of different city areas related to flooding. The index is applied to the boroughs of the City of Hamburg. The city faces three different kinds of flood risks: storm surges, inland flooding and heavy rainfall. The presented index provides a basis for decision making about where to support or initiate appropriate adaptation measures. It is based on data from official statistics. Thus, it can easily be transferred to other regions and additional information can easily be added.

Keywords: Storm surges, inland flooding, heavy rain, social vulnerability, economic vulnerability

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Content

1. Introduction

The city of Hamburg is located 100 km upstream of the Elbe estuary. The Hamburg harbour is the largest seaport in Germany, which makes the city a centre of trade, transport and services as well as an important industrial site in Germany. The city area comprises 755 km^2 – nearly half of the area is at risk of storm floods. Climate change poses a great challenge to the city. Besides an expected increase in storm surge heights, there are the risks from inland flooding due to more heavy rainfall events and river floods.

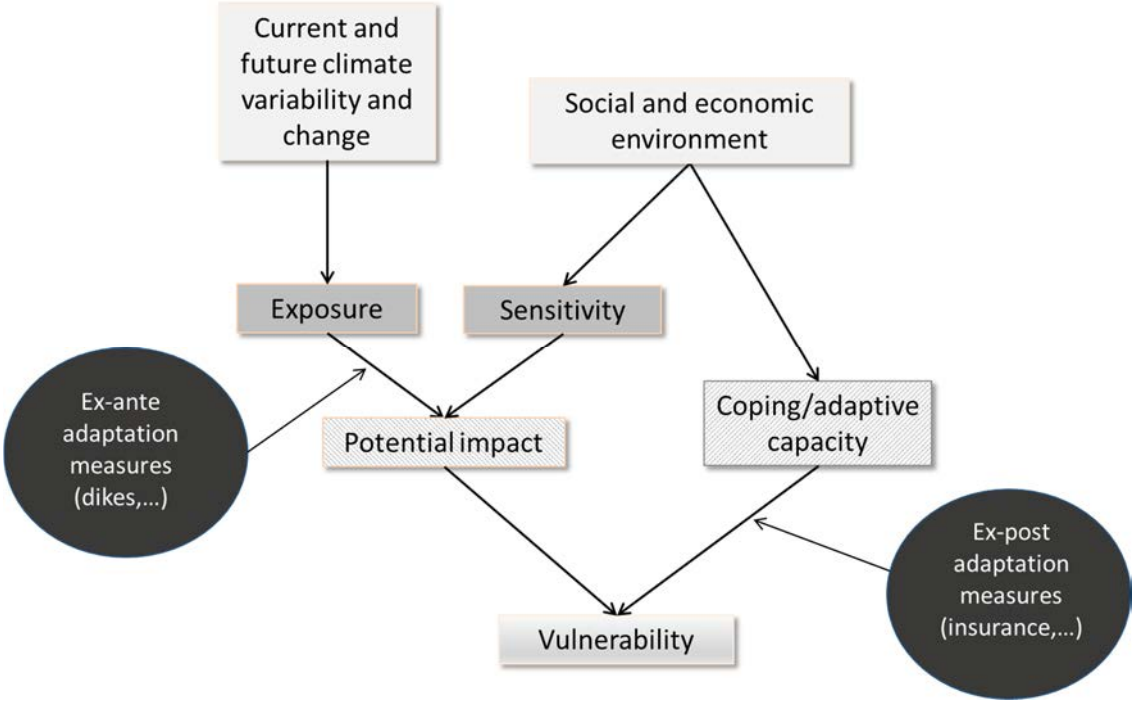
The high residential and commercial damage potential makes adaptation to the expected risks necessary. However, city districts or boroughs differ substantially by their vulnerability to climate change. In general, the degree of vulnerability of a system depends on three factors (IPCC 2007):

- the exposure to climatic changes,
- the sensitivity, depending on socio-economic (and cultural) factors,
- and the coping and adaptive capacity.

For the development of the vulnerability index for the boroughs of Hamburg we take all three factors of vulnerability – exposure, sensitivity, and coping/adaptive capacity – into account. A graphical representation of our methodical approach can be found in Figure 1.[1]

[1] This procedure is based on the approach recommended in the Vulnerability Sourcebook of the Federal Ministry of Economic Cooperation and Development (2014).

Figure 1 Methodical approach



Source: Based on Federal Ministry for Economic Cooperation and Development 2014.

In our paper, the systems under investigation are regions, firms and households. Ecosystems are not considered here. The question is which areas face the highest vulnerability, either because they are more directly exposed to flood hazards in the future, have a higher sensitivity due to their social and economic structures or have a lower coping and adaptive capacity.

The vulnerability index presented here is a tool to identify the most vulnerable areas in a city and show the reasons for their vulnerability. This provides the necessary basis for decision making about where to support or initiate adaptation measures to climate change. The index is based on data from official statistics. Thus, it can easily be transferred to other regions and additional information can easily be added.

The development of the vulnerability index is in some parts very similar to the social vulnerability assessment of Koks et al. (2015) for the city of Rotterdam, Netherlands. However, it has been developed independently – demonstrating even more the need of such an index. There are also some clear differences in the construction of the index on the one hand and the influencing factors on the other hand.

The paper is structured as follows. Section 2 provides an overview of the regional structure of the Free and Hanseatic City of Hamburg including selected economic and residential aspects in order to derive their sensitivity and coping capacity. In a second step, we try to identify the sensitivity of each borough, which is influenced by the social and economic structures (section 3). In section 4 the exposure index is developed, followed by the sensitivity index in the fifth section, and the coping and capacity index in the sixth section. The three indices are then combined into the vulnerability index which shows the relative vulnerability of the boroughs of Hamburg (section 7). Section 8 concludes and gives some suggestions for future research.

2. Spatial, economic and residential structures

2.1 Hamburg's administrative regions and their spatial structure

The City of Hamburg is divided into seven boroughs ('Bezirke')[2] (Figure 2).

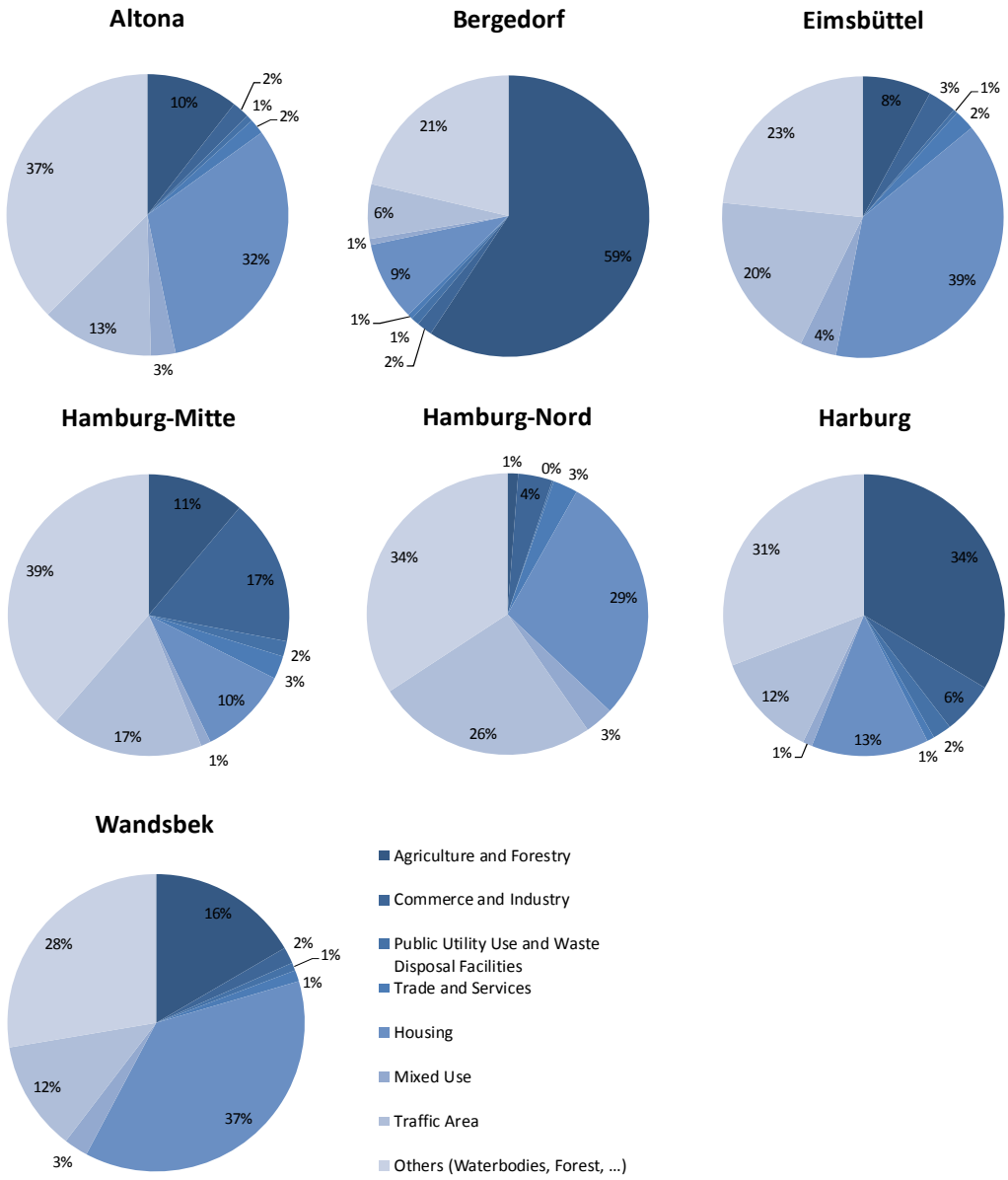
Figure 2 Subdivisions in the City of Hamburg

Source: Wikimedia Commons 2012.

One quarter of the land area of Hamburg is used for agricultural purposes. Around 20% are used for housing and 12% is covered by traffic area, such as streets (65%), train stations (12%) or airport ground (6%). Only 8% of the whole city area is used for Commerce and Industry (6%) and Trade and Services (2%). A closer look into the single boroughs shows considerable differences in land use. In the core city (Hamburg-Mitte) the share used for service, commercial and industrial purposes is comparatively high (19%), while other districts, such as Bergedorf, are characterized by large agricultural areas (Figure 3). The highest traffic infrastructure density is observed in Hamburg-Nord, where the airport is located.

[2] They are subdivided into 104 urban districts ('Stadtteile'). The borough offices carry out local administrative tasks, whereas the urban districts constitute geographic and statistic subdivisions.

Figure 3 Land use classes in the City of Hamburg 2011



Sources: LGV 2012a; Calculations HWWI.

The natural landscape of the City of Hamburg is characterized by the river Elbe and its distributaries Alster and Bille. Furthermore, several watercourses flow from the adjacent federal states Schleswig-Holstein and Lower Saxony into the city area and there is a multitude of waterbodies in the marsh areas (LSBG 2009).[3]

[3] A comprehensive description of the natural landscape of the city is given in LSBG (2009).

2.2 Economic structure

The land use structures indicate the different economic structures in the boroughs of Hamburg. A combined analysis of various data sources provides a picture of the spatial distribution of economic activity and the corresponding assets in the city area.

Table 1 presents the share of each borough in each land use class. It shows that Hamburg-Mitte can be regarded as the center of economic activity. Here, 57% of Hamburg's land used for commercial and industrial purposes is located, not least because 62% of Hamburg's harbour area can be found in its districts south of the Elbe. Around one-third of the 462 larger manufacturing firms (with more than 20 employees) are based in Hamburg-Mitte with 40% of the employees in manufacturing (Table 2). Furthermore, the central city accounts for one third of the land used for Trade and Services (Table 1).

Table 1 Spatial distribution of the different land use classes in the City of Hamburg 2011

			Share of districts in the different land use classes							
No.	ALKIS code	Sectors	Altona	Bergedorf	Eimsbüttel	Hamburg-Mitte	Hamburg-Nord	Harburg	Wandsbek	City of Hamburg
			%							
1	0270	Agriculture and Forestry	4.4	49.0	2.1	8.5	0.4	22.5	13.1	**100.0**
2	0170	Commerce and Industry	3.7	6.5	3.9	56.5	5.4	17.7	6.3	**100.0**
3	0250-0260	Public Utility Use and Waste Disposal Facilities	6.3	16.6	2.6	28.6	1.3	30.4	14.2	**100.0**
4	0140	Trade and Services	11.7	7.8	10.1	31.9	13.9	9.2	15.5	**100.0**
		Total land area	**10.3**	**20.5**	**6.6**	**18.8**	**7.6**	**16.6**	**19.5**	**100.0**

Sources: LGV 2012a; Calculations HWWI.

Table 2 Spatial distribution of firms with 20 and more employees in Hamburg 2009

		Share of firms with focus on...				
Borough	**Manufacturing firms**	**Industrial goods**	**Intermediate goods**	**Consumer goods**	**Energy and durable goods**	**Estimated Number of employess in manufacturing**
	absolute	%				absolute
Altona	-	32	-	32	-	6,504
Bergedorf	24	50	-	17	-	-
Eimsbüttel	-	32	-	33	-	-
Hamburg-Mitte	150	40	38	-	-	33,091
Hamburg-Nord	-	50	12	32	-	13,111
Harburg	52		42	13	-	9,451
Wandsbek	63	50	-	-	-	6,535
Total	**462**	**40**	**30**	**25**	**5**	**81,463**

Sources: Statistical Office of Hamburg and Schleswig-Holstein 2011; Presentation HWWI.

Other boroughs, such as Bergedorf (49%) and Harburg (23%), are characterized by a relatively large shares of agricultural land. Furthermore, Harburg comprises about one third of the land used for Public Utility and Waste Disposal Facilities and 18% of the land used for commercial and industrial purposes.

Less economic activity can be found in the smaller districts Eimsbüttel, Altona and Hamburg-Nord which account for 24% of the land area. However, 35% of the land used for trade and service activities is located here. Furthermore, in Hamburg-Nord 16% of the employees in the larger manufacturing find their workplace in Hamburg-Mitte in 2009 (Table 2).

However, a closer look into the firm structure in Hamburg reveals that firms with 20 and more employees represent only a small part of the total number of firms, not only in manufacturing but also in the service sector. More than 90% of the firms employ between 0 and 9 people (Table A1).

2.3 Residential structure

The residential structures differ substantially between the boroughs of Hamburg. In general, the land in the north of the Elbe is a more intensely used for residential building than the land in the southern part (Table 3).

Table 3 Land area and residential assets in the boroughs of Hamburg, 2011

	Total land area		Residential building area		Residential	Private
Borough	m^2	%	m^2	%	buildings	cars
Altona	142,275,361	18.8	14,767,418	9.1	36,045	84,657
Bergedorf	77,929,894	10.3	24,749,749	15.3	20,705	45,933
Eimsbüttel	49,816,765	6.6	19,449,803	12.0	30,529	87,381
Hamburg-Mitte	57,768,712	7.6	16,666,714	10.3	23,897	72,149
Hamburg-Nord	147,541,717	19.5	54,982,186	34.0	30,206	93,322
Harburg	154,758,540	20.5	14,064,364	8.7	24,650	51,462
Wandsbek	125,213,714	16.6	16,871,794	10.4	74,809	163,842
City of Hamburg	**755,304,703**	**100.0**	**161,552,028**	**100.0**	**240,841**	**598,746**

Source: LGV 2012b.

The highest population densities of nearly 5,000 persons per km^2 are observed in Eimsbüttel and Hamburg-Mitte (Table 4). They account for 14% of the total land area but for 22% of the general residential building area (Table 3).

The lowest population densities are observed in the largest borough, Bergedorf, (773 persons per km^2) and Harburg (1,224 persons per km^2). The second largest borough, Wandsbek, has the largest population with more than 413,000 inhabitants and accounts for 34% of the residential building area in Hamburg (Table 3).

On average, 17.4% of the household are households with children. Thereby, the shares vary between 23% in Bergedorf and12.9% in Hamburg-Nord (Table 4).

The average income per person subject to income tax varies drastically between the boroughs. The highest average income is observed in Altona (49,139 euros). In contrast, a person in Hamburg-Mitte earns on average only half of this income.

Table 4 Population structure in the boroughs of Hamburg, 2011

Borough	Population	Population density (persons/km²)	Persons aged 65 and over (% of pop.)	Persons in receipt of benefit (% of pop.)	Income per person	Private households	Households with childen (% of house.)
Altona	253,735	3,220	18.5	9.5	49,139	140,338	19.1
Bergedorf	121,053	783	18.7	10.7	29,685	58,712	23.0
Eimsbüttel	247,477	4,989	19.3	6.6	39,427	146,415	15.7
Hamburg-Mitte	285,936	2,021	14.9	18.2	23,358	160,268	16.7
Hamburg-Nord	284,891	4,955	17.3	7.6	37,872	183,083	12.9
Harburg	153,404	1,224	19.7	13	27,602	79,936	19.8
Wandsbek	413,521	2,800	22.4	9.2	37,014	216,688	19.5
City of Hamburg	**1,760,017**	**2,331**	**18.9**	**10.5**	**35,887**	**985,440**	**17.4**

Source: Statistical Office of Hamburg and Schleswig-Holstein 2013.

3. Climate change induced flood risks

3.1 Storm surges

The focus of the present paper is on the risks of extreme weather events, especially storm surges, river floods and heavy precipitation. These events have in common that potential damages occur because of flooding. However, the hazard sources differ and hence the respective areas under risk.

Although the protection level in Hamburg is very high, there is a risk for areas located directly at the Elbe of being flooded during a storm surge. The blue marked areas in Figure 4 show the land affected by storm floods. Nearly half of the area of Hamburg is declared as flood prone. These areas would be flooded if there were no flood control measures. 327,000 people and 165,000 workplaces are located here as well as stored goods and commodities amounting to more than 10 billion Euros (Behörde für Inneres und Sport Hamburg 2012, p. 2).

While the harbour is tide-exposed, the urban areas are protected from flooding by dykes, sluices and flood barriers. The dyke heights are between mean sea level +7.60m and +9.25m.

In the future climate change might influence flood heights and frequencies. Due to effects of a changing storminess and global mean sea level rise, the mean maximum water level during a stormy season are expected to rise by 20 cm ± 5 cm in Hamburg until 2030 (relative to 1980-90 levels). Until the end of the century, the increase is expected to sum up to even 60 cm ± 20 cm (von Storch et al. 2008). Therefore, the Senat adopted new design water levels of flood protection in Hamburg in 2012. The levels are increased by 80 cm from NN +7.30 m to NN +8.10 m at the level of St. Pauli.

Figure 4 Flood prone areas

Note: The blue areas would be flooded during a storm flood if there was no flood protection. The red lines are the flood control lines.
Source: Ministry of the Interior and Sport Hamburg (2012), p. 4.

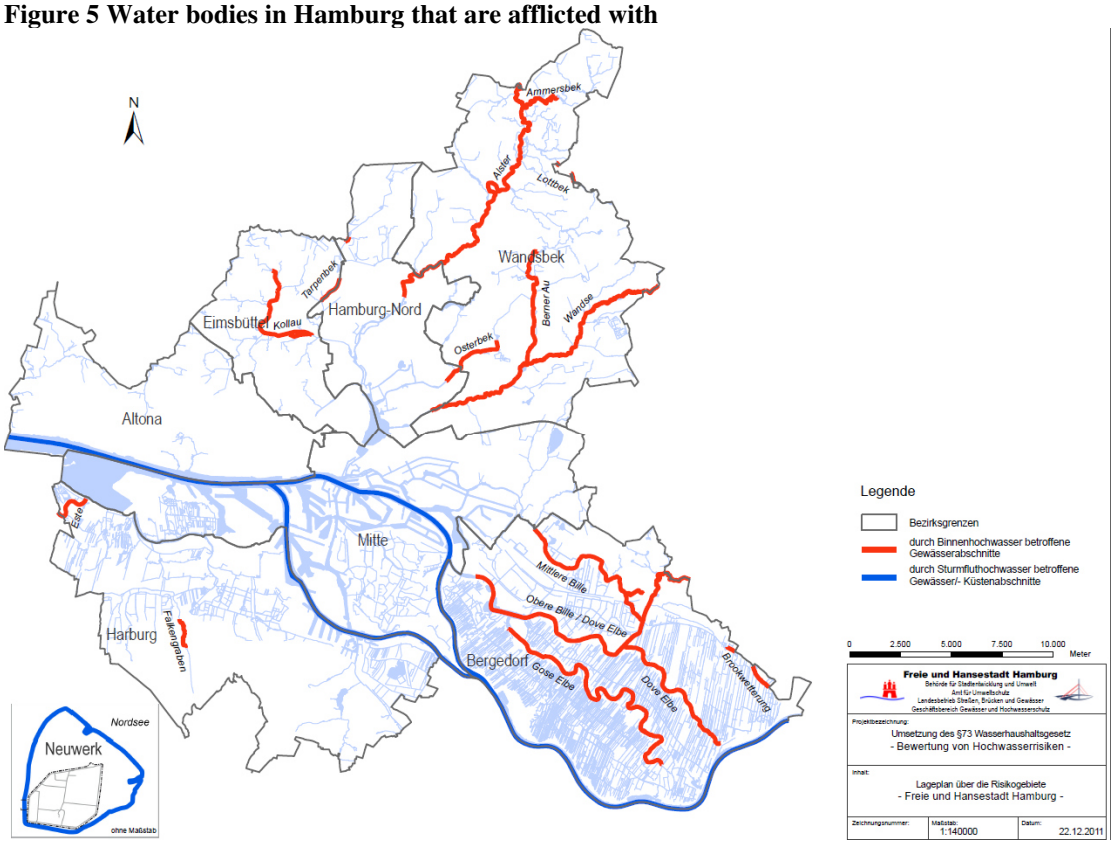
3.2 Inland flooding

Due to the numerous water bodies in Hamburg, there is also a risk of inland flood events. The affected water bodies in Hamburg are marked by red lines in Figure 5. High risks, i.e. high probability of occurrence and significant expected damages from flooding, are ascribed to Alster, Wandse, Berner Au, Osterbek and Ammersbek mainly located in the borough Wandsbek. Part of the Alster is also located in Hamburg-Nord as well as the creek Tarpenbek. The latter is located at the border to Eimsbüttel. Here, the creek Kollau is another stream affected by flood risks.

In the southern part of Hamburg, Bergedorf faces the risk of flooding due to the rivers Mittlere Bille, Obere Bille, Dove Elbe, Gose Elbe and the creek Brookewetterung. In Harburg, there are the Este and the Falkengraben.

Under the European Directive on flood risk management, the City of Hamburg published flood hazard and flood risk maps for each of the above mentioned water bodies in Hamburg at the end of the year 2013. These maps show the extent of potential flood events and the adversely affected areas including the number of potentially affected inhabitants for three different occurrence probabilities – low (return period of 200 years), medium (return period of 100 years), and high (return period of 10 years) (Ministry of Environment and Energy Hamburg 2015).

Figure 5 Water bodies in Hamburg that are afflicted with



Source: Ministry for Urban Development and Environment Hamburg (2011).

3.3 Heavy rain

In contrast to flooding that emanate from water bodies, the localization of pluvial flood is more uncertain. Although in the north and the north-east part of the city, there are areas with higher precipitation, which is due to the high density in these areas (LSBG 2009), heavy precipitation events can also occur in other parts of the city.

Climate projections for Hamburg show that – depending on the underlying emission scenario – a shift of precipitation from the summer into the winter months is expected (Table 5). In total, a 10% increase in the yearly precipitation level is expected.

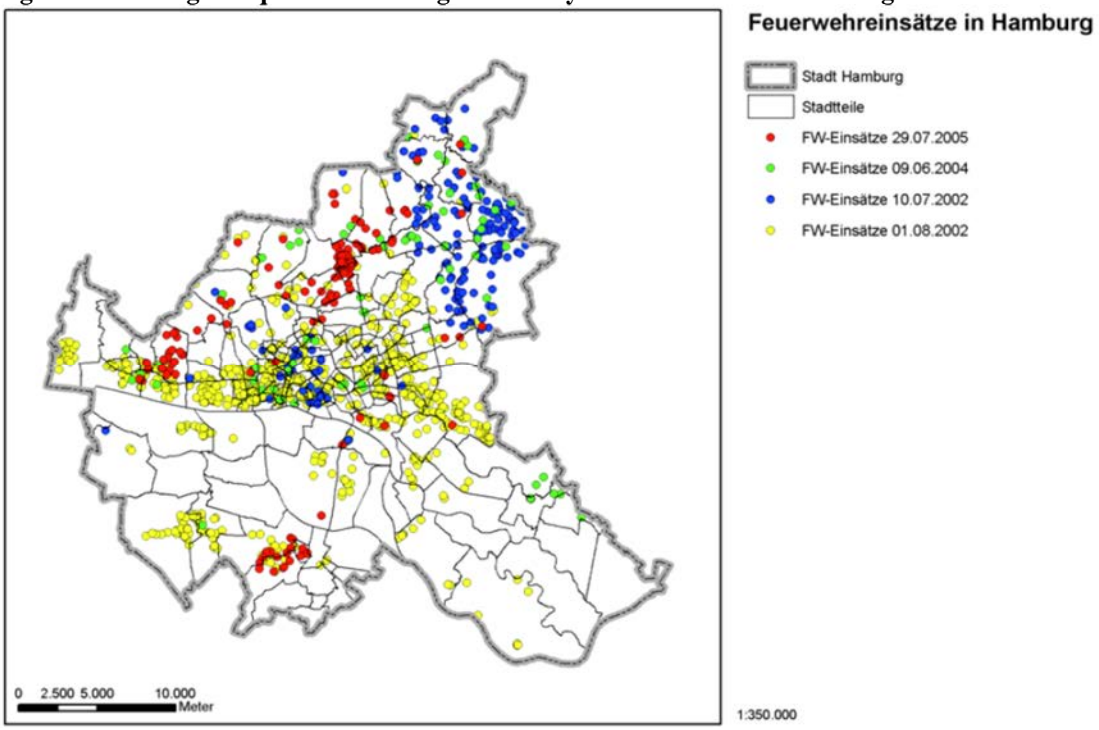
Table 5 Change in precipitation in the City of Hamburg

Year	Summer precipitation	Winter precipitation
Until 2050	-15 to -25%	13 to 20%
Until 2100	-30 to -40%	28 to 53%

Source: Kruse 2011.

The high flood damage potential becomes apparent from Figure 6. It highlights the fire brigade operations during heavy rainfall events in 2002, 2004 and 2005 in Hamburg. Most of the operations were in residential areas due to flooded basements.

Figure 6 Fire brigade operations during four heavy rainfall events in Hamburg



Source: URBAS (2008).

4. Risk Exposure

In the first step, we analyze the exposure of the boroughs of Hamburg against the described different flood hazards under the current situation and under the assumption that climate change will increase the severity and frequency of flood events. We define exposure as the assets and values located in flood-prone areas according to the IPCC (2012). From the different hazard maps the relative exposure against storm floods, inland flooding and heavy rainfall are assessed. From these maps we estimate the share of land that would be flooded during each of the three hazard types in the boroughs of Hamburg. These shares represent the weights used for the different indicators.

We create an index ranging between zero to seven (for seven boroughs) for the exposure against water related hazards, which itself consists of three sub-indices for each of the three types of hazards. Thereby, the sub-indices are generated by using several indicators, which represent the economic and residential exposure.

From the different hazard maps the relative exposure against storm floods, inland flooding and heavy rainfall is assessed. We estimate the share of land in each borough that would be flooded during each of the three hazard types. These shares represent the weights used for the different indicators. In case that a borough does not show any exposure against one of these hazards, the weight and consequently the indicator is set to zero.

The value of the sub-indices and the exposure index for each borough then result from the mean of the different indicator values. Thus, the indices shows the relative exposure of the boroughs.

4.2.1 Residential exposure

The residential exposure sub-index for the boroughs of Hamburg consists of several components. We have no detailed information about the houses and other assets located in the flood plain areas. Therefore, we have to use indicators. These indicators are the number of residential buildings, the residential building area in qm and the number of private cars (Table 5).

4.2.1.1 Storm surges

Table 6 represents the estimated share of land in each borough that would be flooded during a severe storm surge with low probability, i.e. water level St. Pauli 7.30 m above sea level and simultaneous failure of all flood protection systems. The whole of Hamburg-Mitte and large parts of the southern boroughs, Bergedorf and Harburg,

would be flooded during such an event. The northernmost borough Wandsbek would not be affected by flood waters. Here, therefore, the weight equals zero (Table 8).

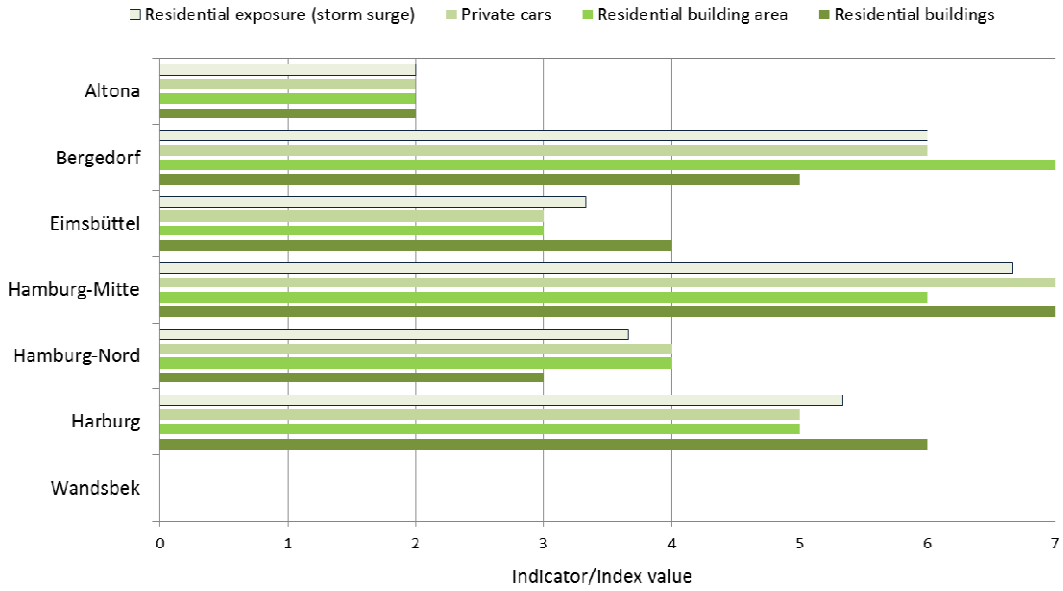
Table 6 Storm flood weights[4]

Borough	Weight
Altona	0.1
Bergedorf	0.9
Eimsbüttel	0.2
Hamburg-Mitte	1
Hamburg-Nord	0.2
Harburg	0.8
Wandsbek	0

Source: Own estimates.

Figure 7 shows the results for the residential exposure against storm surges. Compared to the other boroughs, Hamburg-Mitte shows the highest estimated amount of residential assets and values located in flood-plain areas, followed by Bergedorf and Harburg.

Figure 7 Residential exposure against storm surges



[4] At this stage of our research we had to work with own estimates of the storm flood weights, as information about the share of flooded land area during a severe flood in each borough is not easily accessible.

4.2.1.2 Inland flooding

Information about the potential number of people adversely affected by a one in 200 years inland flood event is provided by the flood risk maps for the City of Hamburg. The share of this number in the total population of the respective borough gives the inland flood weight presented in Table 7.

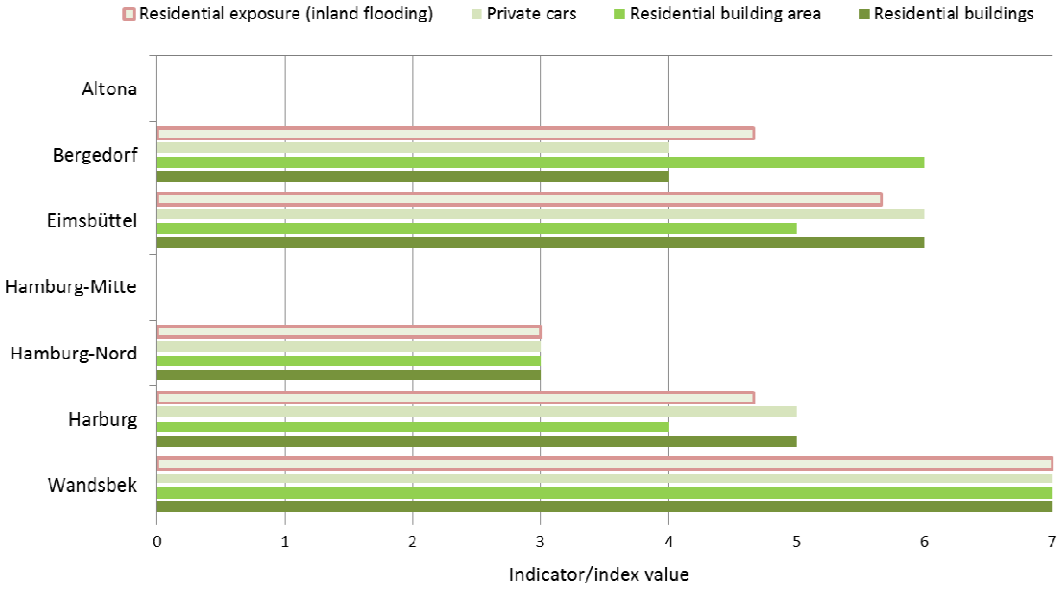
Table 7 Inland flooding weights

Borough	Population	People in flood plain areas	Weight
Altona	253,735	0	0.000
Bergedorf	121,053	480	0.004
Eimsbüttel	247,477	910	0.004
Hamburg-Mitte	285,936	0	0.000
Hamburg-Nord	284,891	170	0.001
Harburg	153,404	600	0.004
Wandsbek	413,521	3340	0.008

Sources: Statistical Office of Hamburg and Schleswig-Holstein, 2013; Ministry of Environment and Energy Hamburg 2015; own estimates.

The boroughs Altona and Hamburg-Mitte are not affected by inland flooding as no rivers or other water bodies with the risk of flooding are located here. In contrast, in Wandsbek a high amount of assets and values is estimated to be located in flood-plain areas, especially in the catchment areas of the rivers Alster and Berner Au (Figure 8).

Figure 8 Residential exposure against inland flooding



4.2.1.3 Heavy rainfall

The weights for the heavy rainfall are the most difficult to assess, as in principal all parts of Hamburg could be affected by such an event. However, according to the fire brigade operations during four heavy rainfall events in Hamburg (Figure 6) we determined heavy rainfall weights presented in Table 8.

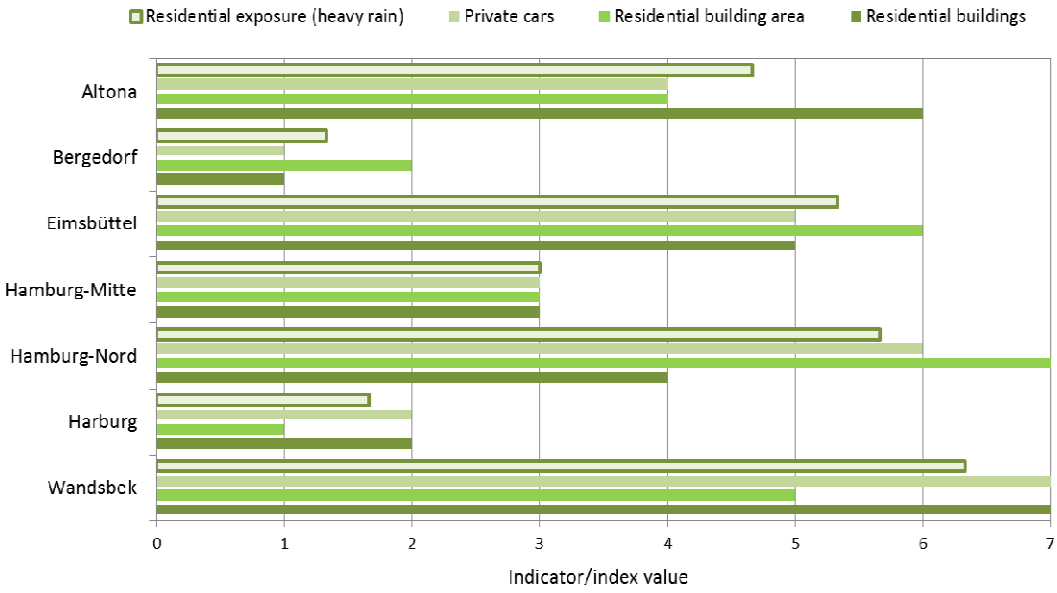
Table 8 Heavy rainfall weights

Borough	Weight
Altona	1.0
Bergedorf	0.3
Eimsbüttel	1.0
Hamburg-Mitte	0.8
Hamburg-Nord	1.0
Harburg	0.4
Wandsbek	1.0

Source: own estimates.

The highest amount of residential assets and values exposed to heavy rainfall are estimated to be located in Wandsbek. But also in Hamburg-Nord, Eimsbüttel, and Altona exposure against heavy rainfall events is high (Figure 9).

Figure 9 Residential exposure against heavy rainfall



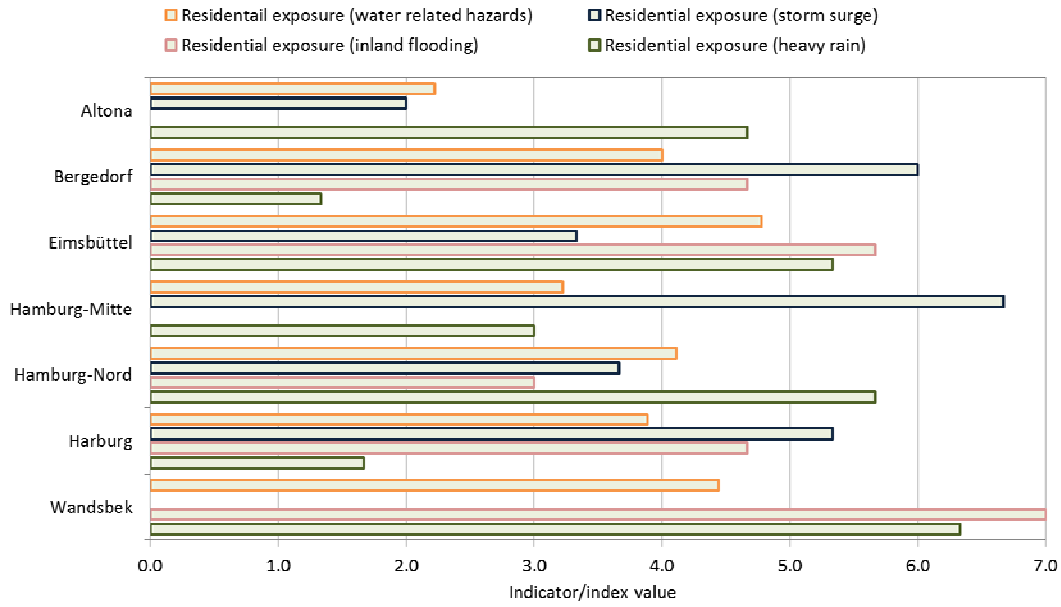
4.2.1.4 Residential exposure against water related hazards

The three indices of residential exposure against storm surges, inland flooding, and heavy rainfall are combined into the sub-index of residential exposure, which will later enter the vulnerability index.

The results show that Eimsbüttel shows the highest relative residential exposure against water related hazards, although looking at each hazard type separately it is in no event

the borough with the highest exposure. In contrast, Wandsbek is the borough with the highest exposure against inland flooding and heavy rainfall, but the fact that is not affected by storm surges reduces its overall residential exposure. The lowest amount of residential assets and values is estimated to be located in Altona, although it shows a relatively high exposure to heavy rain (Figure 10).

Figure 10 Sub-index residential exposure



4.2.2 Economic exposure

The assessment of the economic exposure in each borough is carried out similar to the residential exposure assessment. We use different indictors for the amount of economic assets in the boroughs and apply the same weights as for the residential exposure in order to identify those assets located in flood plain areas. The indicators we use are the estimated densities of fixed assets for each sector (agriculture, manufacturing, public utility use and waste disposal, services), i.e. the amount of fixed assets per qkm.

In order to get an idea about the asset values that correspond to the economic activities, the amount of gross fixed assets for the City of Hamburg is distributed among the different boroughs according to their share in each land use class from Table 1.

In 2011, the total value of the assets in the city amounted to 357 billion euros. Thereby, buildings constituted the largest part of asset values (66%) in the service sector, while in manufacturing and construction machinery and equipment summed up to 75% (Table 9).

Table 9 Gross fixed assets in Hamburg, 2011

No.	WZ08-Code	Sector	Gross fixed assets in Hamburg: Total	Machinery and Equipment	Buildings
			Million Euro		
1	A	Agriculture, Forestry and Fishing	1,538	419	1,119
2	C	Manufacturing and Construction	17,223	12,831	4,360
3	D-E	Electricity, Gas, Steam and Air Conditioning Supply; Water Supply; Sewerage, Waste Management and Remediation Activities	11,042	1,856	9,217
4	G-T	Services	326,704	110,888	215,817
		Sum	**356,507**	**125,993**	**230,514**

Sources: VGRdL 2011; Calculations HWWI.

Table 10 shows the results of the estimated gross fixed assets in the boroughs of Hamburg. The estimation shows that there is a spatial concentration of fixed assets in Hamburg-Mitte. Although the borough accounts for only 19% of the land area, 33% of the total gross fixed assets are located here. The largest amount is attributed to the service sector. But the borough also comprises 57% of the fixed assets in Hamburg belonging to manufacturing and construction mainly because of the harbor industry. In the other boroughs the shares in gross fixed assets vary from 8% in Bergedorf to 15% in Wandsbek.

Table 10 Estimated gross fixed assets in the boroughs of Hamburg, 2011

No.	ALKIS code	WZ08-Code	Sector	Estimated total gross fixed assets: Altona	Bergedorf	Eimsbüttel	Hamburg-Mitte	Hamburg-Nord	Harburg	Wandsbek	City of Hamburg
				Million Euro							
1	0270	A	Agriculture,	68	754	32	131	6	346	201	**1,538**
2	0170	C	Manufacturing;	637	1,125	673	9,734	931	3,043	1,081	**17,223**
3	0250-0260	D-E	Public Utility Use and Waste Disposal	693	1,829	285	3,159	145	3,360	1,571	**11,042**
4	0140	G-T	Services	38,064	25,492	32,851	104,167	45,361	30,058	50,712	**326,704**
			Sum	**39,461**	**29,200**	**33,841**	**117,191**	**46,442**	**36,807**	**53,565**	**356,507**

Sources: LGV 2012a; VGRdL 2011; Calculations HWWI.

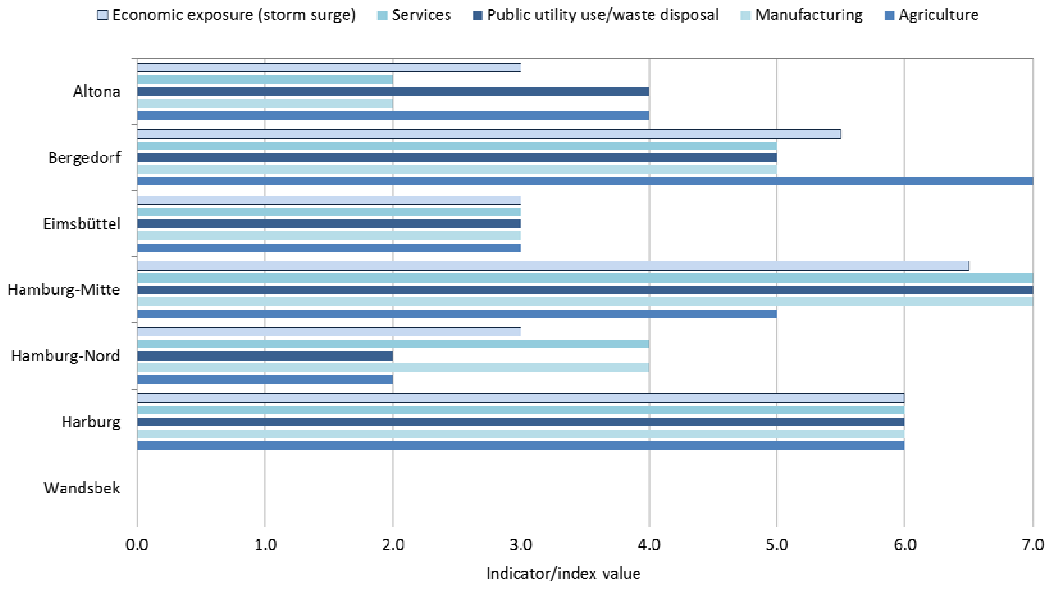
4.2.2.1 Storm surges

In order to compare the economic exposure against storm surges in the boroughs, the estimated gross fixed assets per sector are weighted by the share of land area that would be flooded in each borough during a severe storm flood. The weight is the same as for residential exposure against storm surges (Table 8).

Figure 11 shows that Hamburg-Mitte is the borough with the highest economic exposure against storm surges in Hamburg. This originates from the high amount of fixed assets (Table 10) on the one hand and the very high share of land that would be flooded during a severe storm surge (Figure 4). However, a detailed look into the sub-indicators illustrates that the highest exposure of the agricultural sectors is observed for

Bergedorf followed by the borough Harburg. These boroughs are characterized by comparatively large areas of agricultural use and are among boroughs with the largest flood prone areas.

Figure 11 Economic exposure against storm surges

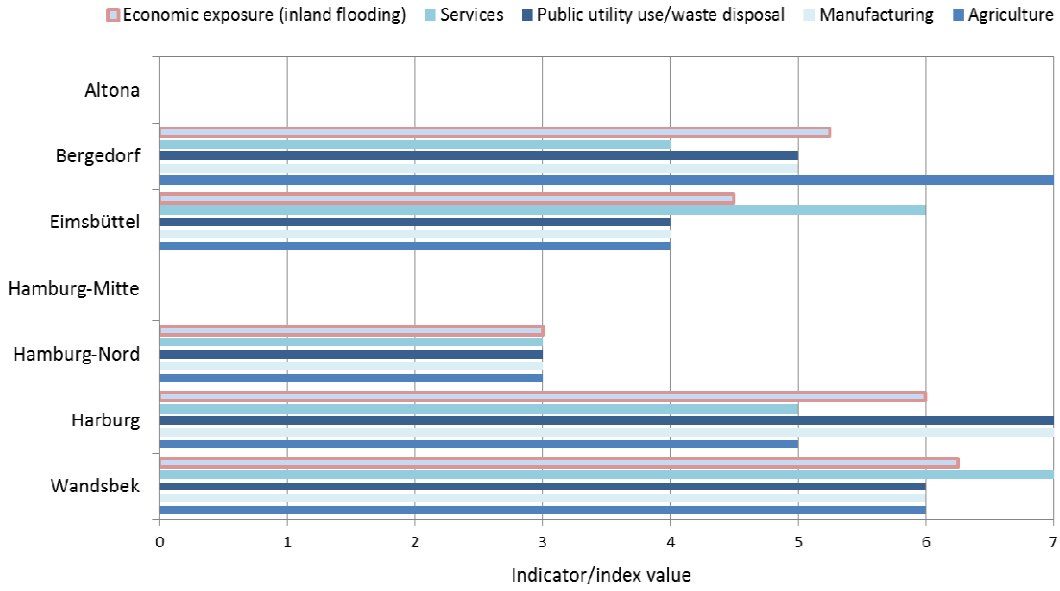


4.2.2.2 Inland flooding

For inland flooding the same weights as for the residential exposure against inland flooding are used because of a lack of more specific information, e.g. about the number of firms affected by inland flooding.

The highest economic exposure is found to be in Wandsbek and Harburg due to the estimated relatively high amount of fixed assets in the service sector (Wandsbek) and manufacturing and public utility use and waste disposal (Harburg) (Figure 12).

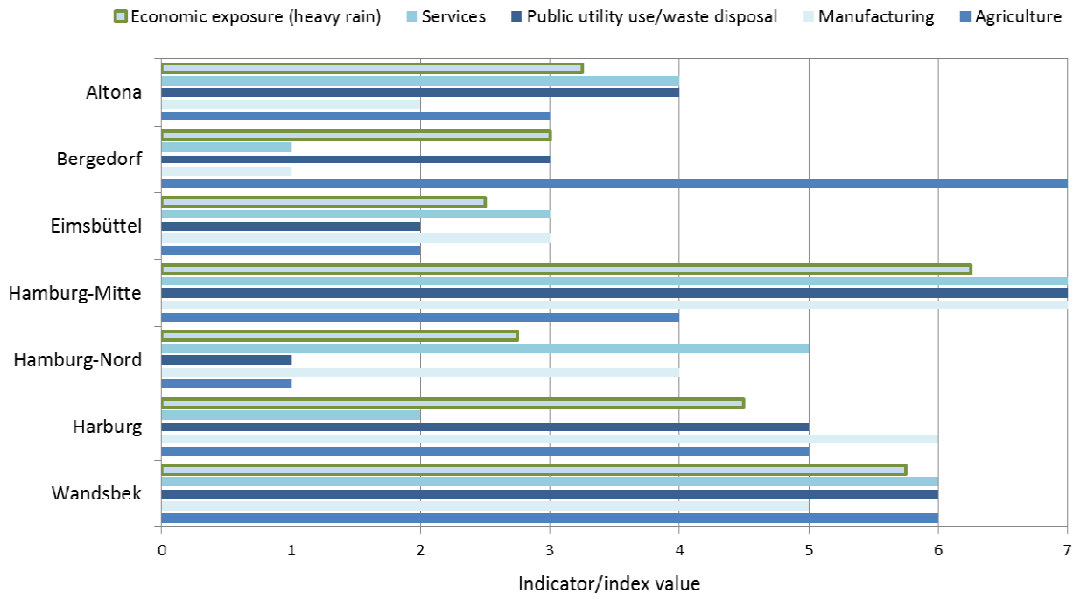
Figure 12 Economic exposure against inland flooding



4.2.2.3 Heavy rainfall

As for the other indices, we use the same weights for heavy rainfall as for the residential exposure index. The combination with the estimated assets in the boroughs results in the estimates of relative economic exposure of the boroughs against heavy rainfall presented in Figure 13. Here, Hamburg-Mitte shows the highest values in three of the four indicators.

Figure 13 Economic exposure against heavy rainfall

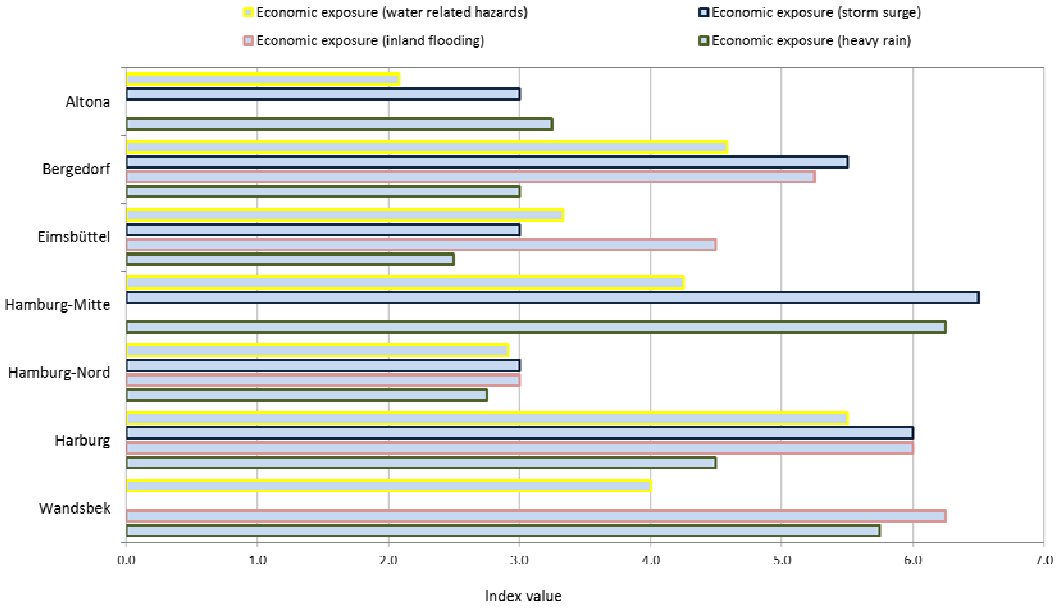


4.2.2.4 Economic exposure against water related hazards

The combination the indices of economic exposure against storm surges, inland flooding, and heavy rainfall leads to the sub-index of the overall economic exposure against water related hazards presented in Figure 14.

Harburg, where also large parts of the harbour of Hamburg are located, shows the highest relative economic exposure against water related hazards. In contrast, it is estimated that the lowest amount of economic assets in areas with the risk of flooding is located in Altona.

Figure 14 Economic exposure sub-index

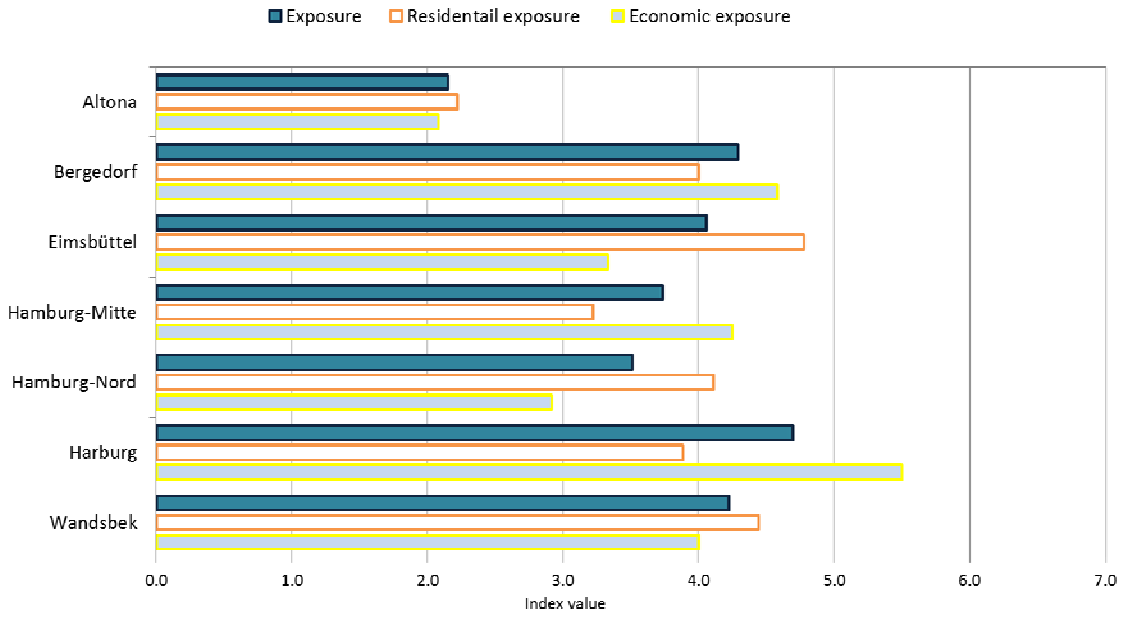


4.2.3 The Exposure Index

The exposure index presented in Figure 15 summarizes the results of the indicator based assessment. The index is generated as the mean value of the residential and the economic exposure indices.

As a result, the highest exposure against water related hazards is found in Harburg. Especially the economic exposure is high in this borough compared to other parts of the city. On the contrary, the borough Altona shows the lowest exposure.

Figure 15 Exposure index against water related hazards



5. Sensitivity

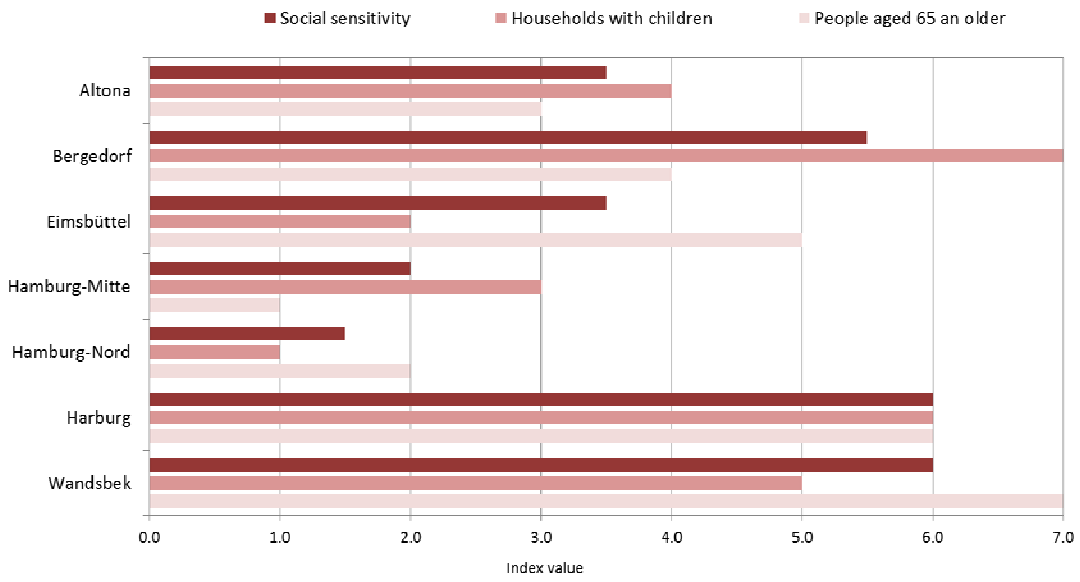
5.1 Social Sensitivity

The sensitivity of people or households can vary within a city or region not only because households are differently exposed to flooding but also because of different household structures. For elderly people and households with children, for example, it takes more time to evacuate in case of emergency. Elderly people often also need external support during evacuation. Furthermore, people older than 65 years tend to have a weaker social network than working age people. This is why elderly people are ascribed with a higher susceptibility than younger people. These are the results from a large household survey in flood risk areas in the cities Cologne and Dresden (Birkmann et al. 2011). They find that evacuation time and the ability to be evacuated represent very well the sensitivity of household.

Following Birkmann et al. (2011) we use two indicators that represent the social sensitivity within each borough: the share of people older than 65 years in total population, and the share of all households with children. According to these shares the boroughs are ranked from one to seven. Thereby, on refers to a low share of elderly people or households with children, respectively, and thus, a low social sensitivity.

The highest social sensitivity according to these indicators is observed in the northern borough Wandsbek and the southern borough Harburg, followed by Bergedorf in the eastern part of Hamburg (Figure 15). Here, the share of households with children is comparatively high, which suggest that evacuation time of these household in case of an emergency is relatively high. Hamburg-Mitte and Hamburg-Nord, in contrast, are characterized by different social structures which is assumed to be able to react more rapidly in case of flooding.

Figure 16 Social sensitivity sub-index



5.2 Economic Sensitivity

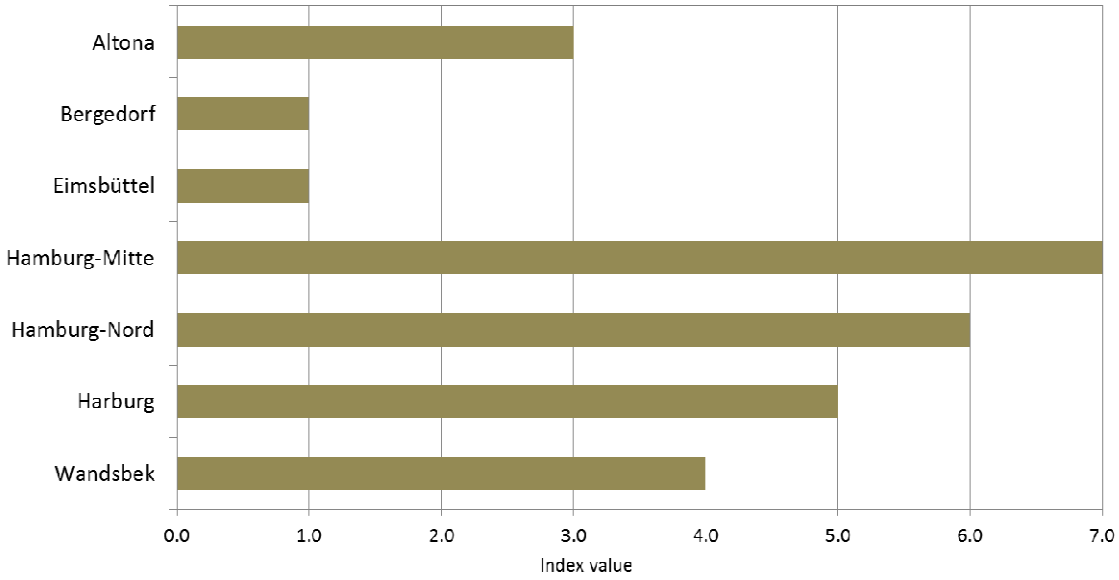
Different factors are influencing the sensitivity of a firm. The sector affiliation is one of them. Manufacturing firms, for example, tend to depend more on intermediate products than service firms. Transports that rely on infrastructure, like streets, railway, shipping or internet, are always exposed to the risk of an interruption of these facilities. This means, firms can be indirectly affected when supply difficulties occur – either because the supplying firms are damaged and cannot deliver the required intermediate goods or infrastructure is damaged and supply chains are interrupted (Frei/Kowalewski 2013).

Following the assumption that manufacturing firms face a higher risk of being indirectly affected by flooding, one would have to use the share of manufacturing firms in all firms in each borough as an indicator for economic sensitivity. However, this information is not available. Thus, we use the number of employees in manufacturing in each borough best possible indicator according to Table 2.[5] The results for the economic sensitivity sub-index are presented in Figure 17.

The highest economic sensitivity is observed for Hamburg-Mitte, followed by Hamburg-Nord. Here, most of the manufacturing firms are located, which makes these boroughs susceptible to indirect flood impacts.

[5] The number of employees in manufacturing in Bergedorf and Eimsbüttel are estimated to amount to 6,386.

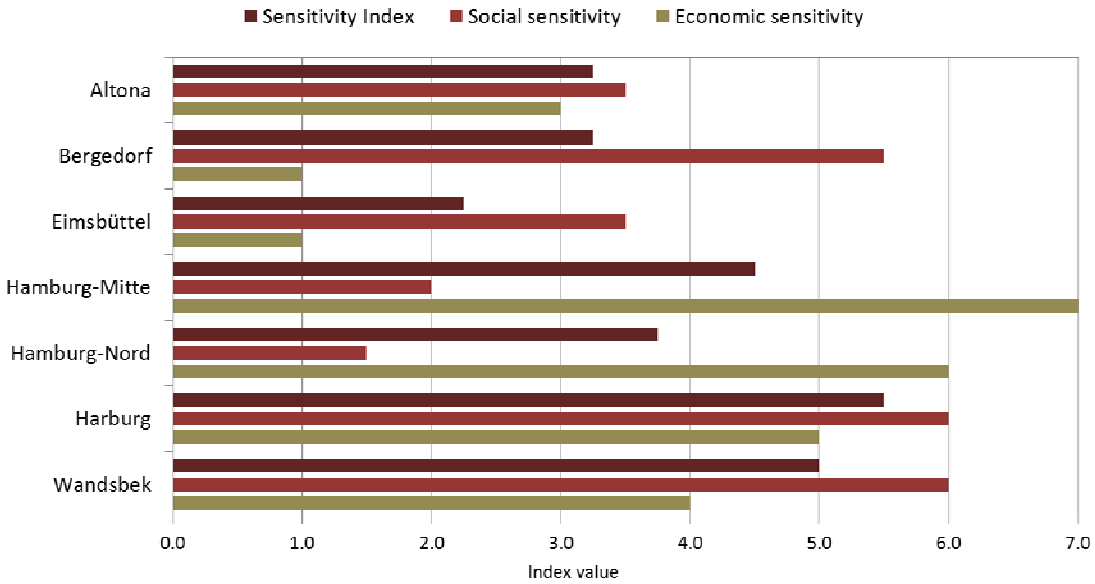
Figure 17 Economic sensitivity index



5.3 The Sensitivity Index

The sensitivity index for the boroughs of Hamburg is a combination of the social and economic sensitivity sub-indices. Again, the mean value of the sub-indices is calculated, which then represents the overall relative sensitivity of the boroughs.

The sensitivity index shows that the social and economic structure in Harburg makes this borough highly sensitive compared to the other boroughs. In contrast, the lowest sensitivity is observed for Eimsbüttel.

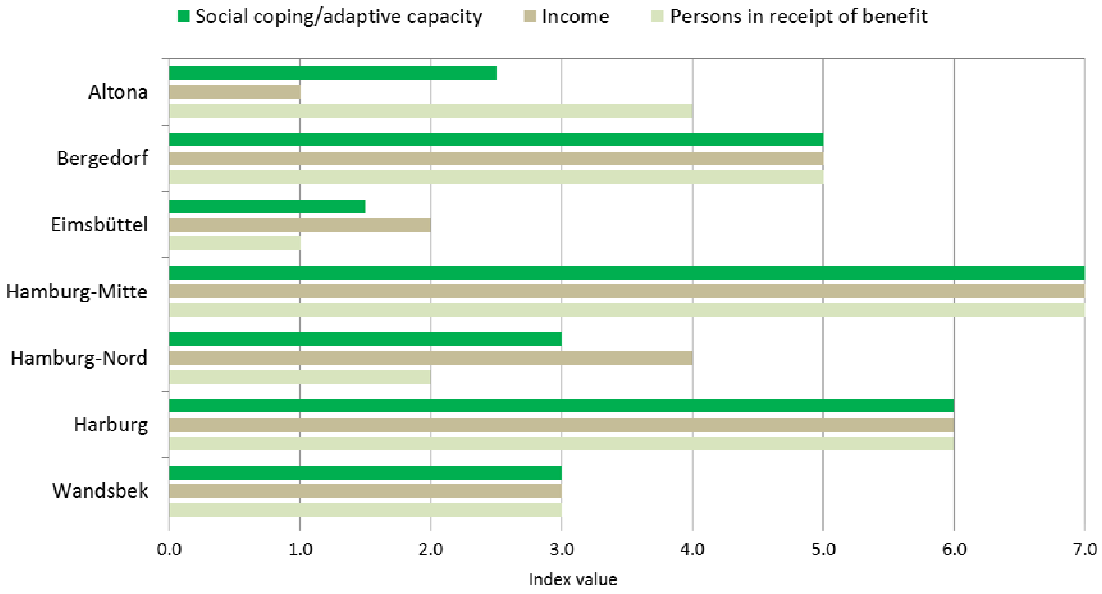


6. Coping and Adaptive Capacity

6.1 Social coping and adaptive capacity

The assessment of the social coping and adaptive capacity again follows the findings of Birkmann et al. (2011). We use the average income of people living in one borough as a proxy for their ability to take prevention measure before and to deal with damages after the flood. In addition, we use the share of persons in receipt of benefit (Hartz IV) in the total population of each borough as a second indicator (Figure 18).

Figure 18 Social coping capacity



Note: A high value means low income, high share of persons in receipt of benefit and low social coping and adaptive capacity.

6.2 Economic coping and adaptive capacity

A driver of a firm's coping and adaptive capacity is the business size. Research on the business level has shown that small firms develop differently after major natural disasters (e.g. earthquakes, flooding) than larger ones. This is because of special characteristics, which tend to make it more difficult for small firms to deal with disaster impacts and force them to stay closed for longer time periods than larger firms (e.g. Tierney 1997; Wasileski et al. 2011). For example, it has been shown that small firms undertake less preparedness and adaptation measures and they have generally less resources to draw on in disaster situations (Webb et al. 1999).

Data about the distribution of firm within the city of Hamburg is not available from official statistics and it is up to this stage of our research not possible to get such data from other sources. Therefore, we cannot consider economic coping and adaptive capacities in the present index.

7. The combined vulnerability index

Combined, exposure and sensitivity give an idea about the potential impacts. In combination with the coping and adaptive capacities of the economy and the people living in the boroughs, which is analyzed in the third step, the relative vulnerability of each borough in the city of Hamburg is assessed.

For the assessment of the relative vulnerability of the boroughs of Hamburg against water related hazards, a joint vulnerability index is constructed. Exposure, susceptibility, and coping and adaptive capacity are the three indices that are combined to represent vulnerability. The aspects we cover are again presented as an overview in Figure 19. As all of the three indices should be given equal weight in the vulnerability assessment, each index is ranked again from one to seven. The value of the vulnerability index for each borough is then given by the mean of the positions in the rankings.

Figure 19 Aspects of the vulnerability assessment

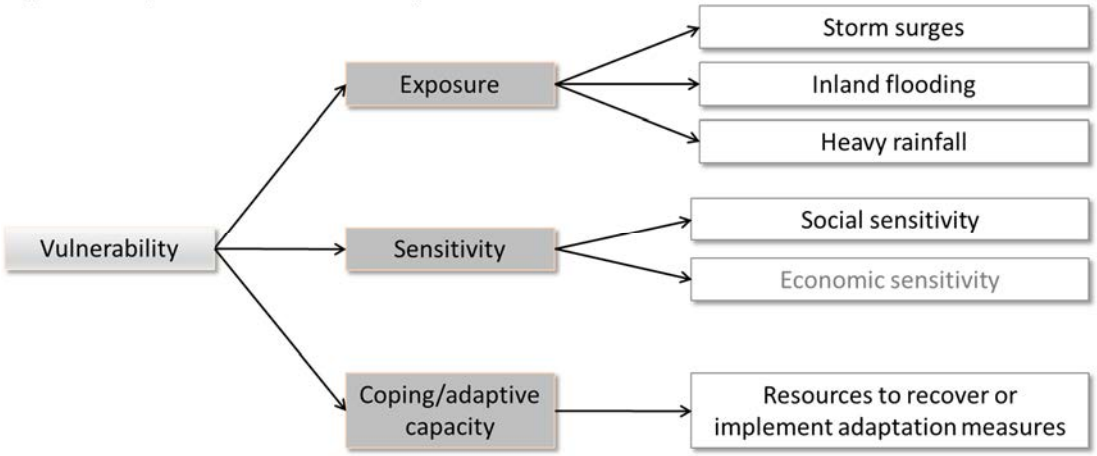
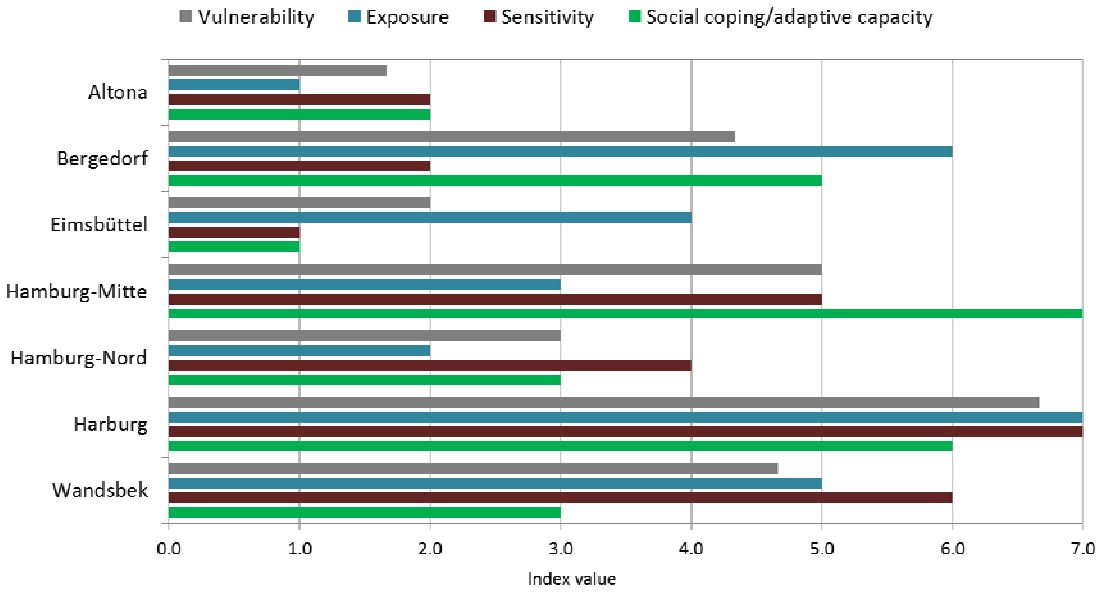


Figure 20 shows the combined vulnerability index for each borough. A low value is positive and represents a relatively low vulnerability of the respective borough. Comparison within the city shows that, given the available information, especially Harburg is vulnerable against water related extreme events. Its vulnerability mainly results from the relatively high amount of fixed assets that are exposed to flooding as well as a high social sensitivity.

The lowest vulnerability is observed in Altona. It has a relatively low exposure as it merely exposed to inland flooding and only slightly affected by storm flood. In addition this borough shows the second lowest sensitivity and the second highest coping and adaptive capacity due to the high income of people living in this borough. The highest coping capacity and the lowest sensitivity is ascribed to Eimsbüttel. Thus, it is expected that the borough with the highest residential exposure and also a high amount of economic assets in flood plain areas is able to prepare for and deal with flood damages and is thus less vulnerable than other boroughs.

Figure 20 Vulnerability index for the boroughs of Hamburg



8. Conclusion and Outlook

The vulnerability index presented here comprises all three factors of vulnerability: exposure, sensitivity, and coping and adaptive capacity. It is a tool to identify the most vulnerable areas in a city and shows the reasons for their vulnerability. This provides the necessary basis for decision making about where to support or initiate adaptation measures to climate change. The index is applied to the boroughs of the city of Hamburg. However, as it is based on data from official statistics, it can easily be transferred to other regions and additional information can easily be added.

In this paper, we analyzed which areas in Hamburg face the highest vulnerability, either because they are more directly exposed to flood hazards in the future, have a higher sensitivity due to their social and economic structures or have a lower coping and adaptive capacity.

We found that Hamburg-Harburg, a borough south of the Elbe river, has the highest vulnerability to climate change. Especially the economic exposure against inland flooding and storm surges is high compared to the other boroughs in Hamburg. Large parts of the harbor are located here and there is a high sensitivity of both households and firms. The share of households with children and the share of people aged 65 and older are relatively high. It is assumed that these groups need more time to evacuate in case of emergency. Elderly people often also need external support during evacuation. The local economy is classified as relatively sensitive because a lot of manufacturing firms are located here. It is assumed that these firms face a relatively high risk of being affected by indirect flood impacts like disruptions of supply chains. Furthermore, the residential coping and adaptive capacities in Harburg turn out to be low because of the high share of low income households and people in receipt of benefit. In the end, in consideration of all aspects the borough has the highest vulnerability against climate change regarding water related hazards.

The lowest vulnerability is found for Altona. It is only exposed against heavy rainfall events and the social structure suggests a low sensitivity while high capacities exist in order to cope with and adapt to such hazards. Relatively low vulnerability indices are further assigned to Eimsbüttel and Hamburg-Nord.

The presented index considers social and economic aspects as far as data could be gathered from official statistics. However, more spatially explicit demographic and economic data would be desirable in order to increase the accuracy of the vulnerability index. Future work on this index will therefore focus on the collection of data from other sources. In the present form, the vulnerability index can easily be replicated for other regions in Germany and more explicit or additional data can be used to expand it. Future research will also focus on more accurate weights for the share of land that would be flooded during flood events and on the application of different methods for the construction of the index (e.g. the methods of Frei/Kowalewski 2013 and Koks et al. 2015).

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Appendix

Table A1 Firm structure in the City of Hamburg 2009 (without Agriculture, Forestry and Fishing)

WZ08-code	Sector (WZ2008)	Firm size by number of employees: 0 to 9	10 to 49	50 to 249	>249	Total
		Number of firms				
C	**Manufacturing and Construction**	**8,756**	**1,110**	**226**	**73**	**10,165**
	Mining	9	3	0	1	13
	Manufacturing	2,919	540	162	66	3,687
	Construction	5,828	567	64	6	6,465
D-E	**Public Utility Use and Waste Disposal Facilities**	**347**	**62**	**23**	**8**	**440**
	Electricity Supply	216	13	11	4	244
	Water Supply	131	49	12	4	196
G-T	**Services**	**85,599**	**6,729**	**1,658**	**362**	**94,348**
	Wholesale and Retail Trade; Repair of Motor Vehicles	17,198	1,633	345	83	19,259
	Transport, Storage	5,528	732	192	45	6,497
	Hotels and Restaurant	5,189	473	74	7	5,743
	Information and Communication	5,914	542	146	26	6,628
	Financial Intermediation	2,033	230	85	38	2,386
	Real estate	7,813	152	27	2	7,994
	freelance, scientific and technical services	18,923	1,097	212	28	20,260
	Other business services	4,471	575	259	54	5,359
	Education	1,710	194	48	13	1,965
	Health and social work	5,104	703	170	46	6,023
	Art, entertainment, recreation	5,000	99	38	6	5,143
	Other services	6,716	299	62	14	7,091
	Sum	**180,648**	**14,692**	**3,588**	**813**	**199,741**

Source: Federal Statistical Office 2012.

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- Real Estate and Asset Markets.

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