Regional flood impact assessment for Kiel and Eckernförde, Germany

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1. INTRODUCTION

Hydro-meteorological natural hazards greatly impact coastal zones around the globe. Cyclones and consequent floods, dikes overtopping and erosion affect not only coastal ecosystems, but cause immense social and economic losses. Recent and historical data expose the vulnerability of coastal systems to low-frequency and high-intensity events. Atlantic storms together with tropical typhoons in Asia caused tremendous loss of life and economic damage. Hurricane Katrina in 2005 caused $81 billion damage in the United States itself and took about 1500 lives (Beven-II, Avila, Blake et al., 2008). Typhoon Yolanda in 2013 was one of the strongest tropical cyclones ever recorded and devastated South East Asian countries, killing at least 6300 people in the Philippines alone and took over a thousand missing (Lagmay, Agaton, Bahala et al., 2015). Additionally, a related issue is climate change which will likely affect the number (Lambert & Fyfe, 2006) and magnitude of storms (McGranahan, Balk, & Anderson, 2007; Ranger, Reeder, & Lowe, 2013). In terms of the global changes, the mean sea level is assumed to rise in a range of 0.52m to 0.98m by 2100, as assessed in the 5th IPCC report (IPCC, 2013). As a result, some areas will be flooded more frequently in the future. Such conditions indicate the importance of developing strategies which would help to lower upcoming risks.

Europe has been developing the flood control polices with an emphasis on events with 100 years return period, therefore most of the coastal protection was designed within this threshold (Hofstede, 2008a; Merz, Kreibich, Schwarze et al., 2010). In the meantime, low-frequency high-intensity events demonstrate how fragile the coastal communities might be. The international community is eager to develop a common tool for the assessment of the potential damage, in this domain the European Union project Resilience-Increasing Strategies for Coasts – toolkit (RISC-KIT) has been launched. The project’s objective is to “develop methods, tools and management approaches to reduce risk and increase resilience to low-frequency, high-impact hydro-meteorological events in the coastal zone” (Van Dongeren, Ciavola, Viavattene et al., 2014, p. 2).

The German Baltic Sea coast is an important center of economic development of the region. Its maritime activities are an important sector which encompasses transport industry, shipbuilding, marine and coastal tourism business. The region has had developed certain flood defense traditions during the past centuries (Hofstede, 2008b). However, the 1989 storm surge showed that for instance the marinas around Kiel Fjord and elsewhere in the Western Baltic area were not designed for such heavy events (Martinez, 2014).

For this reason, the area was chosen by RISC-KIT project among other European “hotspots” in order to have a profound insight on various conditions. The current research will be dealing with the impact assessment tool (software) and its application on the area of the German Baltic Sea coast, in particular on the coastal municipalities of Schleswig-Holstein state.
1.1 **Fundamental background**

Coasts have always been an attractive place to live and do business. The borderline between sea and land brings a lot of benefits, such as marine transportation, abundant natural biological and mineral resources, and fertile deltaic soils. These and other peculiarities have been inducing people to settle closer to the seas. With the growth of the global population the amount of people migrating to the coasts has increased dramatically in past century (Neumann, Vafeidis, Zimmermann et al., 2015). The accumulation of the assets is a natural trend in such conditions. Certain businesses which export goods using vessels as the means of transportation are likely to be located on the coasts in the vicinity of ports.

Nowadays this trend is clearly visible as the 10% of global population lives in the low elevated coastal zones (plains with elevation less than 10 meters above sea level). Hence, such areas are potentially vulnerable to different natural hazards. These events might have different origin and generally can be grouped as meteorological (different types of storms) and geophysical (tsunami, earthquakes, etc.), hydrological (floods) and climatological (extreme temperature conditions) (Kron, 2013). According to a statistical database most devastating in terms of monetary losses are storms (Munich Re, 2016). The inclusion of direct and indirect damage makes the losses even bigger.

The increasing risk of the floods and the growing socio-economic development on the coastal zones creates additional pressure on the ecosystems and communities (McGranahan et al., 2007). Low frequency high-magnitude events may immobilize vast areas and large cities, causing life losses and monetary damage, making settlements exposed to natural disasters. As the future tendency indicates the increasing flood risks in coastal communities it is important to re-assess the risk reduction measures. In addition ecosystem-based mitigation solutions are becoming more acceptable in terms of effectiveness, environment protection ideas and costs-efficiency.

High-magnitude weather related events are occurring around the globe; however they only become disasters when human lives are affected and economic damage is observed (Kron, 2013). There are numerous definitions of what risk is; scientists from different fields would interpret it differently. In current research risk is defined after Helm (1996) and is a “product of probability of the event and its consequences” (Helm, 1996, p. 10). The consequences are to be considered as the product of vulnerability and exposure of the population and assets.

The risk reduction measures for moderate events may cause the higher risk for extreme events. Protection measures such as dikes or levees designed for moderate events (for most countries it is 100 years return period), lead to further economic development and give the population a misleading sense of security in the areas behind the coastal defense. Often such conditions cause immense damage in case of extreme events, and indicate that communities are not prepared to the rare extreme weather events and therefore the losses are becoming catastrophic.

Exposed assets such as ports, marinas and ship-building facilities can’t be fully protected by traditional coastal defense measures; therefore they are normally at a higher risk. Thus, these structures should be more resilient to natural hazards in terms of engineering solutions (Kron, 2013). Furthermore, coasts are also attractive for tourists and businesses connected to it, which
depending on location have a seasonal character. On regional scale, the assessment of the imposed risks on tourist activities and infrastructure is a necessary instrument for economic development.

Risk assessment is a complex process which demands the participation of specialists from different disciplines, decision-makers and stakeholders. International organizations put efforts in developing regulations and methodology for risk reduction. Hyogo Frame Work of Action of the United Nations Office for Disaster Risk Reduction and European Union (EU) Floods Directive contribute to the increase of the resilience to natural disasters; however, they are not specific in the light of coastal floods and related multi-hazards (dike overtopping, breaching, coastal erosion). Additionally, the assessment is contributing to the understanding of river floods, whereas the methodology on the storm surge and flash flood is distorted. Although the EU Flood Directive proclaims the need of an early-warning system (EWS), it is not adapted with equal importance throughout EU (Van Dongeren et al., 2014).

The EU-funded RISC-KIT project was developed as a tool to encompass all the issues and features related to the risks reduction and resilience increase to the coastal flooding extreme events. It is dealing with a wide range of aspects related to the methodological background, instruments development, their implementation and results; and is assessing 11 study cases in Europe and one in Bangladesh. An asset of RISC-KIT is that it includes a close collaboration with stakeholders and population in the results evaluation, which corresponds to the principles of integrated coastal zone management (Van Dongeren et al., 2014).

This thesis contributes to the implementation of the Coastal Risk Assessment Framework (CRAF) tool which will allow assessing the coastal impacts on the regional scale on one of the project’s study cases – an area around Kiel. The research will be dealing with the outputs of the earlier work on CRAF Phase 1, where the study area of about 150 km was assessed and hotspots were selected. The evaluation of the coastal vulnerability index was done on a larger scale in order to identify possible hotspots at a higher flood risk. At that stage rather simple modelling techniques were applied on hazard, land use, transport exposure and economic activities assessment. CRAF Phase 2 deals with the hotspots selected in Phase 1, performing a more detailed impact assessment and determining which single hotspot is at the highest risk by using a model which was specifically developed for this purpose within RISC-KIT project. The methods and specific instruments of such assessment are pre-defined by the project’s instructions but were modified according to the peculiarities of the study case.

1.2 Study area

The study area of the research lies in the northernmost state of Germany, Schleswig-Holstein, and is bordered by the Baltic Sea. Previously, CRAF Phase 1 embraced the section with stretches of about 150 km between the towns Heiligenhafen and Kappeln (Figure 1). The assessment procedure showed the areas with the highest impact scores and this research takes into consideration such coastline. Figure 1 displays the selected study region and this is the area of coastal municipalities between Barkelsby and Wisch. This regional boundary is used in this research for the comparison of hotspots. The hotspots are smaller areas within the region, where
the flood risk is higher. The results of CRAF 1 investigation pointed on two obvious hotspots in the area: Kiel fjord and Eckernförde bight, therefore it was decided to study it further in the current research.

![Study area and coastal indices](image)

Figure 1: Overlook on the study region. Large-scale map displays the position of the study area within the Baltic Sea and neighbouring countries. Smaller-scale map is a closer look to primary and selected areas. Coastal index file is produced by G.Seiß, Bundesanstalt für Wasserbau.

Morphologically, the coast in the study area originates from the Holocene epoch, which is characterized by fjords that evolved into semi-enclosed inlets that were later cut off from the sea by peninsulas and became spits or islands (Hofstede, 2008b). Such sand spits can be clearly observed along the coast, where the inlet area is today a built-in land. The topography is mainly represented by low-lying coastal areas (below 10 meters), which elevate hinterland reaching 10-40 meters above mean-sea level; maximum altitudes are close to 80 meters and located deeper inland (Figure 2). Some parts of the coast alter steeply within just several meters from the shore, which is particularly pronounced in Schwedeneck and within most of Kiel municipality. The remaining coast is rather gradual and in some places lies even below mean sea-level (e.g. Wendtorf and Wisch). A similar pattern is also typical for the inner tip of Kiel bight: low coast stretches there for up to 1 kilometer inland on the western shore. The town of Eckernförde is mainly elevated for only up to 5 meters above sea-level and is exposed to the storm waters.
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The mean water levels are mostly defined by the meteorological conditions rather than tidal activity, which usually does not exceed several centimeters (Soomere & Healy, 2008). The low pressure systems with atmospheric fronts bring gale-force winds which result in the high sea levels; the maximum points of the water levels are usually observed in the bights exposed to the northeasterly winds. Together with the inflows from the North Sea, the water level may increase in the larger area at the same time and in rare occasions produce extreme values along the coast. Normally, the distribution of the levels through the coastline is rather uneven. The highest water levels registered at two gauge stations along the study area give an overview of the surge magnitudes (Figure 3). The other events would produce a storm surge of slightly more than 2 meters. In cases with the dominant northeasterly winds the storm surge may last for many hours and cause vast damage (Sztobryn, Stigge, Wielbińska et al., 2005).

Figure 2: Digital Terrain Model (DTM) with elevation above mean sea-level for the study region with municipalities’ boundaries. (BKG, 2012), processed by G.Seiß, Bundesanstalt für Wasserbau.
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The highest recorded values reached up to 3.15m above sea level during the 1872 storm (WSB, 2015), causing in total 271 deaths (from it 31 deaths in Schleswig-Holstein alone). Eckernförde is reported to be the most damaged settlement on the German Baltic during that event; it is estimated that 78 households were completely destroyed and 138 were highly damaged with over 100 families losing their homes. Kiel area also suffered from the flood: 33 Hectares of the land were inundated, including 13 streets and about 340 land parcels (Geckeler, n.d.). Many houses and most of the harbor infrastructure were heavily damaged. Some archive documents describe that one of villages in the region was completely destroyed within a few hours ("Historische Sturmfluten," 2005).

The next devastating event occurred in 1904 on New Year’s Eve (2.62 meters maximum water levels); it was remarkable in that it flooded a large part of Kiel city such as the old city center (Altstadt), Andreas-Gayk street, and the present shopping area up to Kleiner Kiel Lake (Figure 5). Inundation caused damage to the harbor area and coastal roads causing their obstruction (Geckeler, n.d.).

However, less intense events brought even more damage, for instance one of earlier observed storm surges struck the German Baltic coast in October 1625 causing immense destruction to fishery and agriculture, and taking about 9100 lives in the Baltic region ("Historische Sturmfluten," 2005).

One of the latest and well-documented floods occurred in 1989, which was rather an outlier in the general statistics of high water levels, as it was the only storm surge which reached such high marks (1.73 meters) in the summer time, in August. The season was one of the main reasons for vast damage, as the coast of Schleswig-Holstein is one of Germany’s significant tourists’ destinations. At that time, marinas along the coast were occupied by pleasure boats and different tourist infrastructure and once the storm hit the coast, most of them were damaged or lost. This was especially prominent in Wendtorf marina, where the insurance claims for damaged vessels reached 25 million € (Buhr, 1990). Other settlements along the coast, such as Schönberg,
Kalifornien, Eckernförde, Laboe, Kiel and other experienced roads closure, coastal infrastructure and vessel destruction (Figure 4).

Figure 4: Kiellinie after the 1989 flood, Kiel (Sävert, n.d.).

Modern coastal defense is represented by sea dikes, protecting the low-lying densely populated coastline along over 60 kilometers, including some areas within the study spots of the research, such as Wendtorf and Wisch (Hofstede, 2004). Additionally, groyne fields protect the coast from erosion, e.g. near Wendtorf. The first attempts to defend the communities and economies on the German Baltic coast against high water could be observed in 16th century. After the highest ever recorded storm surge of almost 3.5 meters above sea level hit the German Baltic coast in 1872 (Sävert, n.d.), it turned out that old structures weren’t sufficient to withstand high-magnitude events. The storm caused hundreds of fatalities and huge economic losses. Since then governments took the initiative to develop and implement the system of the flood-defense structures and measures, providing a master plan and involving the public sector (Hofstede, 2008b). Nowadays, the program Integrated Coastal Defense Management in Schleswig-Holstein adopted as the master plan in order to protect from the hydrodynamic stresses for the further decades. This plan includes strategies of coastal protection against floods in regard to future challenges (Hofstede, 2004).

The local picture shows that the area to the south of Eckernförde is protected by dikes. The Kiel area is well adapted to the moderate storm surge events, however a closer look at the specific parts of the protection or the assets located there and reconsideration of their vulnerability to the extreme events is needed.

The selected hotspots are generally characterized by the strong connections to the numerous marine activities. The study region is known for its transportation, tourism and shipbuilding sectors. The summer season is characterized by the increased amount of domestic and international tourists which make the investigation area an important touristic center in Schleswig-Holstein. The exact hotspot boundaries are generated after the inundation maps are analyzed and usually repeat the inundation extent hinterland. Therefore, the hotspot’s outline would change according to the
inundation depth modeled. First of all, the land use of the coastal area defined in CRAFT Phase 1 and extended inlands were evaluated in order to analyze the socio-economic interconnections.

1.2.1 Hotspot Kiel

The population of Kiel is over 243 000 inhabitants (Statistikamt Nord, 2016), which makes it the largest city in Schleswig-Holstein. In addition it is the capital of this federal state and therefore has important administrative and socio-economic functions. The hotspot area, however, is not the whole city but a coastal area to the west of the fjord (Figure 5). It stretches along the fjord from the navy base in the north until the main train in the south.

![Figure 5: Map of hotspot Kiel with landmarks.](image)

The southern and northern parts of the city are connected with several roads. Some of them, such as Kiellinie and Düstenbrooker Weg streets lie right on the coast and parallel to it. They link the center of Kiel with the residential area in the north of the city. These streets are characterized by the high concentration of assets represented by expensive residential properties, hotels, restaurants and yacht clubs. The Kiel Institute for the World Economy and the world’s largest National Library of Economics is located on the edge between Kiellinie and Düstenbrooker Weg streets.

The sea side promenade, called Kiellinie is a part of Kiel which consists of pedestrian paths and roads. The southern part is exclusively pedestrian and includes a promenade, a marina, bars and restaurants, museums, businesses and is connected by roads to the rest of the city.

Marinas occupy a large portion of the Kiellinie and makes it an attractive area for local visitors and tourists. During the winter time the marinas are empty of boats, and some restaurants are
closed, but the summer time is a high season for the boat owners and small tourist businesses. The marina accommodates several sports clubs and the buildings of the marine research center GEOMAR. Once a year a huge international sailing event takes place in Kiel, then the marina gets occupied by boats and the promenade turns into a fair ground. Kiel Week is a sailing event and is the largest festival in Northern Europe, which takes place every June and was expected to accommodate over three million guests in 2016 ("From Kiel to the World," 2016). It contributes significantly to the regional income, touristic development and attractiveness.

Furthermore, the harbor of Kiel accommodates three international ferry terminals for passenger (cruise) ships and ferries (Hofstede, 2004). Among the exposed in the hotspot are Ostseekai and Schwedenkai. These are ferry terminals which serve connections daily, bringing a considerable income to the regional economy. Ostseekai hosts large cruise liners in the summer season from April until October, while Schwedenkai is a terminal for regular daily ferries which connect Göteborg, Sweden with Kiel all year around ("Fährabfahrten. Port of Kiel ", 2016).

The large University Hospital of Kiel, administrative buildings as the state parliament, the main train and bus stations, botanical gardens and different businesses such as shopping and entertainment areas (between the streets Holstenstraße and Kaistraße) are located further inland. The lake Kleiner Kiel is divided in two parts by a bridge and is connected to Bootshafen and the sea with a canal. The area around the lake is represented by parks, cultural center, offices, restaurants and residential district, banks and City Hall.

1.2.2 Hotspot Eckernförde

Eckernförde is located on the tip of a cognominal bight and stretches between the Baltic Sea and Windebyer Noor (Figure 6). The northern border of the hotspot is Vogelsang street (until it turns north). The southern border of the hotspot is a Kurpark green zone. The area has previously experienced extreme flood events, e.g. in 1872 (WSB, 2015), now some parts of the city are protected with dikes.
Figure 6: Map of hotspot Eckernförde with landmarks.

Administratively it belongs to the Rendsburg-Eckernförde region and forms the individual municipality of Eckernförde. The hotspot can be characterized as a center of economic activities of the municipality, and the population of the town is about 22 000 (Statistikamt Nord, 2016). The area is pronounced by the marina, business and residential areas including promenade, bars, restaurants, hotels and shopping zones, this part of the town (to the east from the street of Reeperbahn) is a built-in area. South of the city center stretches along a sandy beach with an adjacent residential area. These beaches attract numerous tourists during the summer season. From the side of the lake, the area is represented by the industrial sites and train station. Unlike Kiel, Eckernförde has some natural ecosystems; fresh water marshes occupy a large portion of the hotspot. They neighbor with a private gardens sector.
This study area is a transport center where several roads connect northern and southern parts of the city. These links are Reeperbahn and adjacent Riesebyer streets, which are important for the municipality as they connect not only southern and northern parts of town but also neighboring municipalities. The disruption of such a link affects commuters from the whole region, as the alternative way leads around the lake and lasts longer. The intersection of B76 road with Reeperbahn serves about 19,500 vehicles each day (Die Bundesanstalt für Straßenwesen, 2011), this would bring additional pressure to the alternative paths and cause traffic congestions. In addition, there are railroads and a train station situated west of the town center.

1.3 Research question

The issues related to the higher magnitude of the natural hazards in the study area may have serious consequences on the coastal values. It is estimated, that about 15.44 billion € are concentrated on the flood prone areas of Schleswig-Holstein Baltic coast in the form of assets. Moreover, about 92,000 people reside there and are at potential risk of flooding (Hofstede, 2008c). The overview of previous extreme events in the area have shown that despite the certain level of adaptation, high magnitude-low frequency events may cause vast damage. In addition, the low probability of such events tempts people to move closer to the coast and develop businesses concentrating more assets in potentially exposed areas. Previously conducted interviews showed that local people underestimate the potential risks from flooding (Martinez, 2014).

Due to this effect which is observed in the study area, one of main goals of this investigation is the assessment of direct impacts associated with residential properties, businesses, transport network and risk to life. Furthermore, the disruption of the transport network and household displacement will be analyzed. In order to investigate the resilience of the communities the financial recovery mechanisms will be researched. For this reason, a storm event with the return period of 200 years was studied as an example of an extreme event.

It should be noted that such complex analysis has not been conducted in the study area previously. To address above mentioned tasks the objectives of the research are the following:

1. Collect, process and analyze the corresponding geodatabase for hazard and impact assessments.
2. Evaluate the impact indicators which will be used for the assessment according to the peculiarities of the German Baltic coastal area from physiographic and socio-economic perspectives.
3. Perform potential impact assessment for direct and indirect damage by applying impact assessment model.
4. Apply multi-criteria analysis (MCA) in order to rank the hotspots.
5. Select the hotspot based on the model outputs for the further investigation.
2. MATERIALS AND METHODS

The impact assessment tool used in this research is the INtegrated DisRupttion Assessment model (INDRA). It is built on the freeware NetLogo platform (Wilensky, 1999) and has an open code, thus can be modified and changed by the user. The tool was produced within the RISC-KIT project by Flood Hazard Research Centre (Middlesex University – London) partners and is available at the RISC-KIT website (Viavattene, Jimenez, Owen et al., 2015).

The tool considers direct and indirect impacts of flood hazards: inundation, erosion and overwash. The assessment is on regional scale and performed in order to estimate the losses of a specific hotspot compared to the whole region. The application of INDRA requires the users to follow multiple specific conditions, however once they are set, the model is ready to be run. The interface consists of 4 main units: input files, a map of the study area, results section represented by histograms and a multi-criteria analysis menu (Table 1) (Viavattene et al., 2015).

Table 1: Structure of INDRA interface.

<table>
<thead>
<tr>
<th>Input files</th>
<th>The map of the study area</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Obligatory (case study boundary, flood inundation/erosion/overwash map, landuse shapefile, descriptive text files)</td>
<td>Used for the basic representation of the hazard, receptors and impacts</td>
</tr>
<tr>
<td>- Optional, according to the peculiarities of each study case, (transport network, utilities, business supply chain). Such flexibility allows the users to adopt the model to the specific conditions. The thresholds for all impact scores in INDRA are written into the descriptive text files called “CHT_forINDRA.txt”, “Insur_forINDRA.txt”</td>
<td></td>
</tr>
<tr>
<td>Results</td>
<td>MCA</td>
</tr>
<tr>
<td>- Histograms within interface</td>
<td>- Assignment of weights to each impacted category (transport, properties, etc.)</td>
</tr>
<tr>
<td>- Output files in the root folder.</td>
<td>- Calculated MCA scores.</td>
</tr>
</tbody>
</table>

The input files were processed in ESRI ArcGIS 10.3.1 environment (ESRI, 2015). The chapters below discuss hazard and impact assessment methods used in this research in detail, giving the theoretical background based on the literature review and the development of the parameters for INDRA application.

2.1 Hazard assessment

The basic boundary which identifies the hotspot in the regional assessment is the maps of a hazard, which is inputted and run separately for each hotspot.
The INDRA model requires the inundation map to be introduced in the polygon shapefile format using specific field names. The hazard intensities of each polygon are represented by inundation depth, depth-velocity product, flood duration and wave height. For this reason the data provided by the Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein (LKNM-SH) upon request was processed in a way that the requirements are fulfilled (MELUR, 2016b). The inundation maps were produced by LKNM-SH in order to satisfy the requirements of the European Flood Directive. The current approach uses such maps developed for each hotspot; their probability is 1 to 200 years. Both hotspots have slightly different maximum inundation depths (Table 2), so the damage is computed using the event approach (a specific simulated event, not a uniform inundation depth). This difference is explained by local hydrodynamic characteristics, bathymetry and wind directions variations (MELUR, 2016b).

Table 2: Modeled water levels for hotspots. Adopted from (MELUR, 2016b).

<table>
<thead>
<tr>
<th>Place</th>
<th>Water level above mean sea level, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiel</td>
<td>260</td>
</tr>
<tr>
<td>Eckernförde</td>
<td>245</td>
</tr>
</tbody>
</table>

The delivered grid files had the cell size 1*1 meters, such high resolution gives an opportunity to capture the inundation on a realistic scale giving more details. However the computational capacity didn’t allow using it. The model calculates the damage on cell by cell order, therefore, the resolution was decreased to 10*10 meters, some details were lost and the receptors which would fall in the inundation extent were not in there anymore, and vice versa. For the sake of simplicity it is assumed that this operation is reasonable as the initial number of grids for Eckernförde hotspot is on average 1.5 million and the one used in INDRA about 7000. The changes in the receptors’ amount are negligible in the scale of the research.

Certain editing was done to the original inundation maps; in the area of Kiel city center 3 spots of about 5-6 cells each had values of 3 to 28 meters of inundation. Extensive field research proved that such holes do not exist in reality, so these pixels were given the value of the deepest inundation of the neighboring cells.

The next step was the transformation of the grid file into polygon shapefile and further modifications of the attributes. As mentioned above the attribute table must contain the data on the inundation, depth-velocity product, duration and wave height. The first one, inundation, was already included into the maps provided by the LKNM-SH (MELUR, 2016b). The other parameters were obtained from the experts interview (Dr. G. Seiß,” Bundesanstalt für Wasserbau”, personal communication, June 15, 2016) and it is assumed that the velocity of the flow during the storm event would not be higher than 1m/s. So the attribute table was populated with the formula \(1 \times \text{inundation depth}\). The geomorphological conditions of the area are heterogeneous, so this is rather a rough assumption. The flood can last for many hours, the rigid value used in our study case is 48 hours for all storms on all hotspots. The wave height parameter is not applied in our case, so it was populated with zeros. These assumptions were made as the modeled hazard maps with the above mentioned parameters were not available; however it is considered that the
produced file is sufficient for the research. Better results can be obtained by running a complex 1-2D hydrodynamic model for each hotspot and each modeled water level. However, this voluminous task is outside the scope of the current master thesis.

2.2 Impact assessment

2.2.1 Direct impact assessment

Direct impact assessment estimates the losses caused by a hazard directly on receptors. Among them is flood damage to structures and transport networks, total collapse of buildings, inventory damage, erosion of agricultural soils, damage to livestock, negative effects on ecosystems, lives losses, etc. (Merz et al., 2010). The impact is mainly attributed to the depth damage parameters, exposure of the receptors, the type of hazard and its intensity, as well as coastal protection systems.

The current research is using an approach delivered within the project; the assessment has a comparative character, so no monetary losses are introduced. Instead, the definitions of the impact scales are: none, low, medium, high and very high. The indicators within the model are given five-scale ranges and require us to provide the four thresholds for the receptors (Viavattene et al., 2015). Certain indicators and parameters are already produced by the model developers but are adapted and modified in this study. Here the thesis is focused on the:

- Direct damage to buildings
- Risk to life
- Direct damage to roads

This chapter describes the input file development and the direct impact parameters within them.

2.2.2 Land use data and land use type

The studied region stretches between the municipalities Barkelsby and Wisch. The hotspots are selected in the previous research by Seiß (2014) and by the cooperation with stakeholders (Martinez, 2014). As mentioned before they are: the western part of Kiel fjord and the central parts of Eckernförde town.

One of the key files for the tool is the landuse point shapefile; it encompasses the information about the spatial location of the receptors (buildings, landuse types and infrastructure) and their attributes. The spatial information is a crucial aspect; additionally its attributes include the basics for the direct and indirect impact assessment. The file was produced using the open source databases, the information provided by the statistical agencies, stakeholder`s interview and surveys. In total, there were 3 local citizens (and coastal scientists) interviewed over a period from May to July. They have contributed on different levels, mostly for validation of the receptors classification and providing an insight on the exterior view of the buildings within the region.

Two datasets were evaluated in order to create the input file for INDRA, those are the Open Street Map (OSM) (OpenStreetMap, 2016) and Coordination of Information on the Environment (CORINE) data (EEA, 2013).
The OSM data was represented as two separated polygon shapefiles: Buildings and Landuse. The data for the whole region was derived from those two datasets; however the hotspots were assessed more precisely: the survey for Kiel and expert knowledge for Eckernförde (only the hotspot area, not the whole municipality). The missing receptors where digitized using the ArcGIS tool and classified with high precision. Such details are significant for the hotspots, as they will be further processed in the INDRA tool, where the exact spatial location is of high importance, while the areas outside the hotspots will be grouped and united, and therefore the location doesn’t play a role. The detailed data on hotspots and the OSM building file were merged in one, so the further operations are done with the polygon shapefiles which overlay with the boundaries of the study region (coastal municipalities).

An important part of the work on the buildings shapefile is to give the proper class to the buildings. This study uses generic classification for most of areas outside the hotspots (households, businesses). This study includes other types of buildings (public, military, etc), however the assumption was made to classify them as “businesses”. Their number is minimal compared to other classes (especially residential), so it doesn’t affect the regional indicators. Nevertheless, it was decided to include them in order to reflect such parameter as Risk to life. Further on, all non-residential properties are referred as “businesses”.

Then, the buildings were assigned with a respective type according to the Landuse file. First, the Landuse file with the “commercial” attributes was intersected with the corresponding Buildings (spatially) and was given the “commercial” type for buildings. The total number of buildings is over 58 000, so this method was implemented but the further corrections were done to the whole region. Some of the OSM attributes indicate the type of the buildings or the name of the businesses (i.e. restaurant “Seehund”), and in such cases the buildings obtained type according to the indicating attributes.

Most of buildings which weren’t possible to assess with a land use file were given a value according to amenity type (café=commercial, hotel=commercial, church=public, hospital=public etc.) provided within the OSM database.

One of the issues with open geodatabase is that the files might contain errors or be incomplete. The comparison of the statistical data retrieved from Statistikamt Nord on the amount of residential properties and the estimated number of residential buildings in geographical information systems (GIS) shapefile revealed the inaccuracy in the OSM database (Statistikamt Nord, 2016). Some very small villages are not represented in GIS shapefile or, vice versa, some buildings assigned as residential in reality have another type (business or other).

The overall number of the residential buildings in the shapefile is larger than in data retrieved from Statistikamt Nord by 14%. The comparison was done in order to validate the results obtained in GIS. It detected that in most municipalities the estimated amount was very similar to statistical data, but in some cases the difference is rather large (i.e. Strande, Wendtorf municipalities). The overall difference is mainly attributed to the city of Kiel, where the statistical data is over 6500 units lower than GIS data. Nevertheless, this difference was used to correct the amount for each municipality; as there were the buildings with no type or sign which class they belong to, they were distributed between commercial and residential according the table data. For instance, the
buildings with no class in Wendtorf municipality were given the class “residential”, as the number of residential buildings in the shapefile is fewer than in the statistical data. Therefore, the difference was smoothed. Importantly, the number of households in the hotspots is correct. All buildings within hotspots were given the elevation above ground values in meters; the counting point was the actual entrance of the building (above stairs or foundation).

The other part of the work was performed for the Landuse file (buildings excluded). While CORINE shapefile covers the whole area of the region, the OSM has gaps. The final file was obtained by the combination of the CORINE and OSM datasets on landuse. The top layer is the OSM and the underlying one is CORINE. This was done in order to produce the file which covers the whole region, and additionally OSM files were observed to contain more details. The landuse classes were optimized with the classification of the OSM and requirements of the model.

Then, the total area in sq. km was calculated for each receptor and the polygons were converted to point shapefile. Buildings and Landuse files merged and the number of the receptors outside the hotspots with same attributes aggregated. The parameters for direct and indirect impact assessment described in the sections below were included in the attribute table of the final Landuse file upon their completion.

### 2.2.3 Flood Depth damage to buildings

Floods contribute to one third of all economic losses caused by natural disasters around the globe. The calculation of the damage is an important attribute of effective flood risk management, however the uncertainty associated with hazard characteristics and quantification of the elements at risks is relatively high (Gerl, Bochow, & Kreibich, 2014). The most common approach to evaluate the direct damage to the buildings is the depth-damage functions; they enable the users to estimate the monetary or relative damage according to the inundation depth.

Currently, methods to assess direct economic losses due to coastal flooding in Europe are generally the same as those applied to river floods (BMVBS, 2012; Huizinga, 2007; Koks, Bočkarjova, Moel et al., 2015; Reese & Markau, 2002). However, unlike riverine flooding, storm surges contains distinct hazard characteristics (flood water velocities), and such differences may lead to considerably higher damage (Nadal, Zapata, Pagan et al., 2009). According to FEMA, “only highly engineered, massive structural elements are capable of withstanding breaking wave forces” (FEMA, 2011, pp. 8-24). Furthermore, it can be expected that the presence of salt water will induce different damaging processes compared to fresh water. Nevertheless, this study elicits some of German river and coastal flood damage models in order to select the one which fits our study best. Application of those models (Emshergenossenschaft Hydrotec, 2004; Reese, Markau, & Sterr, 2002) requires detailed information, so for the sake of simplicity, the flood damage functions developed by Huizinga within the JRC-Institute for Environment and Sustainability (Huizinga, 2007) is adopted. It was selected among other as it contains the information on the different buildings types and is based on the inundation depth only, which is important for the INDRA application and doesn’t require a detailed survey. The study uses the depth-damage curves for two building types (residential and commercial). Such simplification is done as certain assumptions were made while deriving the building types.
As these functions were developed based on the river floods the curves are adopted by comparing the damage factor of different receptors. It is important to mention that the research uses the curves in order to investigate the relation between curves, not the absolute values.

Figure 7: Depth-damage function for residential and commercial buildings. Adopted from (Huizinga, 2007).

The four vulnerability thresholds for INDRA were generated according to the research based on the findings of Penning-Rowsell (Viavattene et al., 2015), Kelman (2004) (Kelman & Spence, 2004) and chosen depth-damage functions. This approach allows using the principles of the coastal flood impact on the buildings in combination with the damage curves developed specifically for Germany.

First of all, it should be mentioned that the thresholds represent a certain impact. The character of the damage to the buildings and inventory is a main parameter. Table 3 is adopted from the Library and gives an overview of the damage character used for the development of thresholds.

<table>
<thead>
<tr>
<th>Impact</th>
<th>Threshold</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>1</td>
<td>Minor damage to flooring, carpets and some superficial damage to household inventory items. Mainly drying and cleaning required</td>
</tr>
<tr>
<td>Medium</td>
<td>2</td>
<td>More household inventory items damaged, Building fabric severely damaged. Items likely to need replacement</td>
</tr>
<tr>
<td>High</td>
<td>3</td>
<td>Building foundations can be undermined with some partial building collapse</td>
</tr>
<tr>
<td>Very high</td>
<td>4</td>
<td>Damage is associated with a building collapse</td>
</tr>
</tbody>
</table>

The model considers the flood depth so the task was to assign thresholds of the degree of the structural and content destruction. It is assumed that the flood depth is 0-0.35 meters and is
restricted to insignificant damage, the items require drying and cleaning only (Threshold 1), while over 0.35 meters inundation brings certain damage not only to the flooring but also to the contents of residential buildings (Threshold 2) and the damaged items would need replacement. Flood depth of over 0.9 meters causes high damage, the structural and material integrity is not stable anymore, which eventually leads to building collapse (Kelman & Spence, 2004). The study takes a value of 1m for the Threshold 3, assuming that the buildings in the area have high standards of construction and are maintained at a proper level. The threshold 4 is not used in the residential and commercial damage assessment as it is considered as a building collapse and thus represented as an individual parameter (Table 4).

Table 4: Impact thresholds for residential and commercial buildings.

<table>
<thead>
<tr>
<th>Land use types</th>
<th>Hazard Intensity</th>
<th>Threshold1</th>
<th>Threshold2</th>
<th>Threshold3</th>
<th>Threshold4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>flood depth</td>
<td>0</td>
<td>0.35</td>
<td>1</td>
<td>9999</td>
</tr>
<tr>
<td>Commerce</td>
<td>flood depth</td>
<td>0</td>
<td>0.2</td>
<td>0.8</td>
<td>9999</td>
</tr>
</tbody>
</table>

Similar logic was applied to the commercial buildings; however it was decided to lower the thresholds due to inventory; it is considered that the values of the trade and industrial content might be higher. Such a tendency can be also observed in the depth-damage curves by Huizinga in Figure 7 (Huizinga, 2007). It displays that the damage factor for commercial buildings at different inundation depths is higher than residential. It is assumed that moderate damage would be observed with inundation of over 0.2 meters (Threshold 2) and the content of different commercial properties is more valuable than the one in private households. Such assumption is also applied for the Threshold 3 which is 0.8 meters. This research suggests that at this boundary most inventory is damaged and the expenses for the structural repair may increase.

2.2.4 Building collapse

When the flood depth increases, the peak pressure around the buildings increases exponentially causing serious destruction to the buildings and in some cases collapse (Kelman & Spence, 2004). Building collapse threatens not only assets but also human lives; therefore it is important to take it into consideration. The INDRA model is designed to calculate this parameter and the Library provides generic values for the calculations (Owen et al., 2016). It uses the flood-depth velocity product and is able to calculate this parameter separately for different building types. The first two thresholds point to the absence of building collapse with low and moderate impact, but when the depth velocity product increases to 3 meters, moderate structural damage (windows and doors are completely destroyed, the structure feels minor damage) is expected. After flood depth-velocity reaches 7 meters or more, total building collapse is expected, the house can no longer be repaired in the future (Table 5).
Table 5: Impact thresholds for building collapse. Adopted from (Viavattene et al., 2015).

<table>
<thead>
<tr>
<th>Land use types</th>
<th>Hazard Intensity</th>
<th>Threshold1</th>
<th>Threshold2</th>
<th>Threshold3</th>
<th>Threshold4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>flood depth-velocity</td>
<td>9999</td>
<td>9999</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Commerce</td>
<td>flood depth-velocity</td>
<td>9999</td>
<td>9999</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

The majority of the buildings in the study area are not expected to collapse due to the low maximum inundation depth and low vulnerability. The exceptions are the small buildings such as harbor info centers, toilets, and small kiosks. This study uses the same thresholds for the different building types.

2.2.5 Risk to life

The mortality rate has risen along with the increase of the frequency of flood events. The attempts to predict the fatalities were mainly focused on the large scale events, or the defence breach; however various hazard characteristics and specific conditions of the study areas may bring large uncertainties to this approach (Jonkman, Vrijling, & Vrouwenvelder, 2008). There is a large amount of factors which influence the rates of life losses during flood events; many factors may cause the fatalities and the underlying processes stay uncertain. Some models were developed based on the coastal and river foods, and cases of dam breaking. Further overview of models is mostly selected from the literature research of Jonkman (Jonkman, Vrijling, et al., 2008). Mizutani (1985) was one of the first who investigated the relationship between mortality rates and flood depth on the coasts (Jonkman, Vrijling, et al., 2008). Other researchers such as Duiser (1989), Jonkman (2002) and Boyd (2005) would also relate the factor of the storm surge height and the number of people affected, considering further parameters such as rapidly rising water levels, social vulnerability, flood velocity, etc. (Boyd, Levitan, & van Heerden, 2005; Jonkman, Van Gelder, & Vrijling, 2002; Jonkman, Vrijling, et al., 2008). Moreover, the role of the early warning and leading evacuation time has been included in the methods as one of the most important factors, for instance Jonkman’s (2002) model would take into consideration the area characteristics (population density, landuse, warning and emergency assistance) (Jonkman et al., 2002). Waarts (1992) proposed the method which is based on the warning and evacuation and flood flow velocities (Jonkman, Vrijling, et al., 2008). The Penning-Rowsell (2005) model identifies hazard characteristics, people’s vulnerability and area vulnerability as three main components, and furthermore the suggested method is later validated with the observed data and the modeled results match well (Penning-Rowsell, Floyd, Ramsbottom et al., 2005).

The time for evacuation is particularly important for the models which describe the dam break and consequent losses of life; Brown and Graham (1988) pointed out the importance of the time available for evacuation and its relationship to the size of population at risk (Brown & Graham, 1988). A slightly different approach was suggested by Zhai (2006), where he relates the fatalities to the amount of inundated buildings basing on the empirical studies of Japanese study case (Zhai, Fukuzono, & Ikeda, 2006). Some previous investigations were focused on the life losses from the point of the labour loss/disruption; such a method allows calculating the economic losses but not the degree of injuries and fatalities in terms of the social vulnerability (Koks et al., 2015).
As the literature review exposed, the range of the factors which influence the larger mortality rate during and after the flood event is vast. Among such factors could be added time when the flood arrives, extreme hazard conditions (high depth, waves, velocity, strong winds, etc.), mitigation measures and social and behavioural patterns of the local population. The estimation of the life losses and injuries rate is a complex task, however the assessment is a very important part of the risk evaluation (Viavattene et al., 2015). This research uses the method adopted from the FLOODsite project, which is based on the Source-Pathway-Receptor approach and considers damage and losses to people (risk to life) (Priest, Tapsell, Penning-Rowsell et al., 2008). It is produced based on the data collected in Europe, the normalisation and validation of the parameters among them, and has resulted in the formula where:

\[
Risk \text{ to Life in Europe} = f(F, Ex, Pv, -M)
\]

Where F is the depth-velocity product, Ex is the exposure to the hazard (the possibility to find shelter and escape from direct contact with the hazard, as well as structural vulnerability of the shelter), Pv is the vulnerability of the local population and M is mitigation measures (early warning system, evacuation plans, etc) (Viavattene et al., 2015).

This approach has been tested in different European countries and showed a significant robustness and flexibility at different geographical scales. The parameters of the function are accessible in most of European countries and they do not require a sophisticated analysis, which means it is easy to apply and the assessment can be performed on national or local levels (Priest et al., 2008).

**Evaluation within INDRA**

INDRA uses a simplified matrix where only the risk scale is represented in the output. This means that the nature of the area is divided by 4 thresholds and according to the depth-velocity product obtains the rate of vulnerability of the area (Table 6) (Owen et al., 2016; Priest et al., 2008).

**Table 6: Impact thresholds for nature of the area parameter. Source (Owen et al., 2016).**

<table>
<thead>
<tr>
<th>Nature of the area</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth/Velocity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;0.25 m²s⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25-0.50 m²s⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50-1.10 m²s⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.10-7 m²s⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;7 m²s⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Detailed classification helps to assess the risk to life parameter. By assessing the structural features of the buildings it was possible to give the vulnerability rate. Three classes taken from the Library developed by Priest et al (2007) (Priest, Wilson, Tapsell et al., 2007) and adopted to the current study (Table 7).
Table 7: Nature of area classes. Source (Owen et al., 2016).

<table>
<thead>
<tr>
<th>Nature of the Area</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N0</td>
<td>No vulnerability</td>
</tr>
<tr>
<td></td>
<td>Buildings: not used</td>
</tr>
<tr>
<td></td>
<td>Landuse: areas where people are not expected to appear</td>
</tr>
<tr>
<td>N1</td>
<td>Low vulnerability</td>
</tr>
<tr>
<td></td>
<td>Buildings: multi-storey apartments and masonry concrete and brick properties</td>
</tr>
<tr>
<td></td>
<td>Landuse: not used</td>
</tr>
<tr>
<td>N2</td>
<td>Medium vulnerability</td>
</tr>
<tr>
<td></td>
<td>Buildings: Typical residential area with mixed types of properties</td>
</tr>
<tr>
<td></td>
<td>Landuse: urban open spaces (parks, streets), high possibility to find a shelter</td>
</tr>
<tr>
<td>N3</td>
<td>High vulnerability</td>
</tr>
<tr>
<td></td>
<td>Buildings: campsites, bungalows and poorly constructed properties</td>
</tr>
<tr>
<td></td>
<td>Landuse: open spaces outside settlements, low possibility to find a shelter</td>
</tr>
</tbody>
</table>

The assignment of the nature of the area was performed using Google Earth (Google Inc., 2015) images and Google maps (Google Inc., n.d.); in addition, the hotspots have a better assessment quality owing to the field survey and as mentioned above, stakeholders’ participation. Each receptor in the hotspots was assessed individually; the buildings outside the hotspots were grouped and given the Nature of the Area according to the Google images and basic knowledge about the local building patterns. Generally, nature of the area classes were distributed according to several parameters, their basics are displayed in Table 7. The buildings which have more than 2 storeys and are made of brick, concrete or glass were given value N1. Figure 8 displays the most common type of building within the Kiel area with category N1. The amount of small old buildings within Kiel city center is minimal; most of structures were completely renovated or newly built after World War 2.

While in Eckernförde the picture is different, as it didn’t suffer as much during the war, there are numerous old buildings, and the majority of them obtained a value of N2, as they might be more vulnerable to flood waters. In Eckernförde a large number of the buildings in the city center have a ground floor + living attic (Figure 9), so it was decided to give them the value of N2. An additional factor which supported this decision was the age of buildings and number of storeys. As it is shown in Figure 9, some receptors have more than 2 storeys but in regard to their age (the field research showed that some of them are from the 16th century) they were given N2 value.
Figure 8: Typical building type in the city center of Kiel.

Figure 9: Typical building types in the old town of Eckernförde.
The remaining buildings were assigned the value N3. Those are small structures such as kiosks and other one-storey buildings mostly located on the coast and within marinas. However, outside the hotspots there are camping sites, where the structures could be characterized as poorly constructed (one-storey, wooden buildings). Overall, their number compared to N1 and N2 receptors is much smaller.

Some municipalities’ receptors inside and outside the hotspots were later validated with stakeholders in terms of the structural vulnerability and the results of this cooperation proved that the classification approach used was valid and sufficient for the case study. The vulnerability of the landuse classes is also used in the risk to life indicator. Therefore, the different landuse types and the open urban spaces were distributed between three categories with certain modifications. N3 was assigned to the agricultural lands, and natural ecosystems, as there is a lack of shelter in case of the flood event. N2 was given to the open urban spaces, as there is a possibility to find a shelter during the storm. N1 and N0 were not used in this study case.

The next step was aimed at the identification of disaster risk reduction (DRR) measures in the area, and after the evaluation of the sources (BSH, 2016; MELUR, 2016a; MRLLT-SH, 2012) it was concluded that the most appropriate was “Flood warning with sufficient lead time”. There is no information available on evacuation plans and most probably they do not exist on regional level. However, the warning system for flood events and storms is well-developed and publicly available through all types of mass-media. Additionally, authorities provide the suggestions on how to behave during natural hazards. The thresholds were then adopted from the Library (Owen et al., 2016) and written into attributing text file “CHT_ForINDRA.txt” (Table 8).

Table 8: Impact thresholds for Risk to life. Adopted from (Viavattene et al., 2015).

<table>
<thead>
<tr>
<th>Risk to life type</th>
<th>Code Hazard Thresholds</th>
<th>threshold_1</th>
<th>threshold_2</th>
<th>threshold_3</th>
<th>threshold_4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk to life for Low</td>
<td>N1_flood-depth velocity</td>
<td>0</td>
<td>1.1</td>
<td>9999</td>
<td>7</td>
</tr>
<tr>
<td>Risk to life for Medium</td>
<td>N2_flood-depth velocity</td>
<td>0</td>
<td>0.5</td>
<td>1.1</td>
<td>7</td>
</tr>
<tr>
<td>Risk to life for High</td>
<td>N3_flood-depth velocity</td>
<td>0</td>
<td>0.25</td>
<td>0.5</td>
<td>7</td>
</tr>
</tbody>
</table>

The thresholds indicate that for the qualitative groups, for instance for the N1, flood-depth velocity of more than 0m²/s means the risk is low, 1.1m²/s suggests medium risk to life, the value of 9999 means that the threshold for high risk is not specified (non-existent) and when the flood-depth velocity increases to more than 7 m²/s the risk to life is extreme. The other values of the vulnerability site (N2, N3) are interpreted correspondingly. Depth-velocity value is taken from the hazard map and the calculations are performed automatically by the model.

Then, the model calculates the **Regionalized Risk to Life indicator** using the following equation:

\[
I_{RtL} = \frac{\sum_{i=0}^{n}(S_i \times RtL_i)}{\sum_{i=0}^{n}(S_i \times 4)}
\]  
(2)
Where: $I_{\text{RtL}}$ is risk to life indicator, $n$ is the number of landuse receptors, $S_i$ is the surface area of $i$; $\text{RtL}_i$ is the risk to life score of area $i$ and 4 is the highest score of risk to life matrix (Viavattene et al., 2015).

2.3 **Indirect impact assessment**

Direct impacts caused by floods can in certain cases trigger indirect impacts and be reflected in the socio-economic and natural processes. The indirect losses are linked with certain disruption of normal (pre-event) processes and are visible after the flood (days, months or years). The extent of these disruptions can be dramatic for the regional and national economies. Indirect damage after Hurricane Katrina were calculated as 28 billion US $, therefore, their assessment is of immense significance (Merz et al., 2010).

In order to assess indirect damage there have been models developed for the estimation of indirect economic losses, among them are computable general equilibrium models or input-output (Ujeyl & Rose, 2015). Koks’ model allows computing both direct and indirect economic losses using the production losses functions and hybrid input-output models to evaluate the recovery of the economy (Koks et al., 2015). The current study is focused on the evaluation of the transport disruption which may lead to serious economic losses for the businesses located inside and far outside of the hazarded area.

In contrast to tangible losses impacts caused on communities from the social point of view are evaluated as well. The disaster events are responsible for the social dislocation which in turn may cause instabilities in settlements (Twigger-Ross, 2005). The ability to recover quickly is an important parameter which increases the resilience of the affected population.

Thus, to estimate the indirect damage for the study case the following impact indicators are considered:

- household displacement
- household/business financial recovery
- regional transport disruption

There are no monetary losses estimated, the assessment is done in the same manner as for direct impacts. The five scale range of impacts from non to very high require us to provide 4 thresholds. The ranking of the hotspots can be done using indirect impacts. The following chapters contain the development of the thresholds and associated input files for INDRA.

2.3.1 **Household Displacement**

The damage caused by hazards directly on properties or landuse may trigger further impacts. The building damage or collapse is a reason for its inhabitants to seek a temporary or permanent accommodation outside their usual place of residence. The disastrous event followed by household displacement attributes to stress and disturbances for the affected individuals and inside entire communities (Viavattene et al., 2015). This effect was described by Sims (Sims, Medd, Mort et al., 2009) and Lamond (Lamond, Joseph, & Proverbs, 2015). A long term psychological impact and deterioration of mental health in flooded households has been observed in post-event
communities. Thus, it is considered that household displacement indicator is one of important factors which determine the resilience of the communities which is why it is included in the INDRA model.

The associated distress of the displaced people is deeply connected to the recovery mechanisms of the households and communities, for instance, the existence of insurance or compensation scheme and time when they could be obtained. In addition, studies showed that the longer the people stay outside their homes, the more likely they are to have mental health issues (Lamond et al., 2015). For INDRA it is assumed that “the longer the duration of time a household is in alternative accommodation the more severe the disruption of the household (Viavattene et al., 2015, p. 58). The simplified Regionalized Household Displacement Indicator is developed within the project and includes the scale of impact magnitudes.

Each scale is generated from the duration of the household displacement and a description of the associated impact (low, moderate, high and very high). The displacement is related to both, direct (flood depth damage, building collapse) and indirect impacts. Due to inaccessibility of the insurance records, and the lack of survey data on the displacement, the study uses the generic values produced within RISC-KIT project for the UK study case, based on the insurance data analysis (Viavattene et al., 2015). Each impact scale (low, medium, high and very high) is assigned with the values in percentile reflecting the amount of the households displaced and their weight described in Table 9. In that study, the weights were calculated separately for each direct impact score by multiplying the amount of displaced households (percent) with the impact score (0-5) and then aggregating the outcomes within each direct impact type. The computation for these generic values was adopted from the Guidance (Viavattene et al., 2015). Consequently, the scores for other impacts are calculated in the same way and Table 10 displays the final scores for damaged buildings (not collapsed).

Table 9: Weights for different displacement types. Adopted from (Viavattene et al., 2015).

<table>
<thead>
<tr>
<th>Type of displacement</th>
<th>Displacement weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Households are not displaced</td>
<td>0</td>
</tr>
<tr>
<td>Households are displaced for up to 1 month</td>
<td>1</td>
</tr>
<tr>
<td>Short-term displacement (1-3 months)</td>
<td>2</td>
</tr>
<tr>
<td>Medium-term displacement (3-12 months)</td>
<td>3</td>
</tr>
<tr>
<td>Long-lasting displacement (&gt;12 months)</td>
<td>4</td>
</tr>
<tr>
<td>Household never returns to the original property</td>
<td>5</td>
</tr>
</tbody>
</table>
### Table 10: Thresholds for direct damage impact on households. Adopted from (Viavattene et al., 2015).

<table>
<thead>
<tr>
<th>Direct damage impact on household</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Very high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household displacement score</td>
<td>0</td>
<td>1.9</td>
<td>2.7</td>
<td>9999</td>
</tr>
</tbody>
</table>

Building collapse displacement score are also generic Table 11. They are calculated independently because the construction takes longer than cleaning or minor repair (Viavattene et al., 2015).

### Table 11: Thresholds for direct damage impact on household in case of building collapse. Adopted from (Viavattene et al., 2015).

<table>
<thead>
<tr>
<th>Direct damage impact on household</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Very high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household displacement score</td>
<td>9999</td>
<td>9999</td>
<td>2.62</td>
<td>5</td>
</tr>
</tbody>
</table>

The scores are then included in the “CHT_ForINDRA.txt” (INDRA input). The **Regionalized Household Displacement indicator** is then computed by model using the following formula:

\[
I_{Hd} = \frac{\sum_{i=0}^{n} H_{di}}{\sum_{i=0}^{n} 5}
\]  

(3)

Where \(n\) is for the number of residential properties in the region, \(H_d\) is a Household displacement score, and 5 is a maximum score (Viavattene et al., 2015).

### 2.3.2 Financial recovery

Among the adaptive measures the financial recovery plays an important role, it identifies how fast the households and businesses would come back to the pre-disaster state. The recovery mechanisms may have a form of insurance payments, governmental compensations, charity, tax relief, etc. (Viavattene et al., 2015). In most countries private insurances have a voluntary character and express the eagerness of the people to protect themselves against hazards (Kreibich, Bouwer, & Schwarze, 2015). However, it might be also at local or national levels, building a complex net between stakeholders and government (Fan & Davlasheridze, 2015). In all cases the resilience of the individuals and communities depends on the availability and character of the financial recovery mechanisms in the country. Efficient flood risk management requires the evaluation of the existing measures, their effectiveness and extent. This study is aimed to identify the financial recovery mechanisms using a simplified approach, where the larger the extent of the financial support, the faster the recovery (Viavattene et al., 2015).

**Households**

According to the German insurance policies no private households (residential properties) can be insured against coastal floods (Lange, 2011). However, the additional research showed that the market of such insurance has a tendency to develop and in some cases elementary insurances
(Elementarversicherung) include the storm surge cover. The literature review based on the previous flood loss investigation during the river floods in 2002 and 2006 in Eastern and Central Germany (Kreibich, Seifert, Thieken et al., 2011; Thieken, Bessel, Kienzler et al., 2016; Thieken, Kreibich, Müller et al., 2007; Thieken, Petrow, Kreibich et al., 2006) displayed that certain compensation scheme and donations took place before. The specific summary giving an insight on the river floods, might be useful in the current research. The properties situated in the river flood prone areas can be insured (voluntarily) and the type of insurance depends on the return period of floods in a particular area. After the 2002 flood (1000 years return period), the damage were extreme and the government made a decision to compensate losses to insured and non-insured households. The rate of the compensation reached in some cases 80-100% (Thieken et al., 2006). The 2006 flood showed that population and businesses were more prepared and less compensation was paid by the government (Kreibich et al., 2011). Unlike the river floods, coastal floods may have a different financial recovery picture, moreover Schleswig-Holstein state, which is responsible for the disaster risk reduction measures at the study case may not have a capacity to compensate the losses in the same high level.

In addition, the 2002 event was linked to a specific political situation in the country (Eastern Germany redevelopment program and upcoming parliament elections), so very high compensations could have been attributed to such conditions. As the Federal Law prohibits paying any compensation for flood damage (Viavattene et al., 2015), the future disastrous events might not be compensated, unless they are classified as “catastrophic”. The current investigation is based on the extreme event scenario and therefore the previous research is taken into account recognizing regional differences.

INDRA evaluates a scale of financial recovery impacts from 1 (full recovery) to 5 (very low recovery); the scores are provided by the Library and are unified for all study cases (Table 12) (Viavattene et al., 2015). It also requires the users to select a certain type of financial recovery developed as a matrix with the recovery type and magnitude of the direct impact. Then, the properties were assigned a category of the direct impact (low, medium, high, very high). The distribution is another important parameter developed within the current study, which points to the number of receptors under each recovery mechanism.

Based on the review of previous research (Thieken et al., 2006), insurance market surveying and expert assumption the following recovery mechanisms were selected from the Guidance (Viavattene et al., 2015) and are displayed in Table 12.

**Table 12: Financial recovery mechanisms for households, distribution of mechanisms within the region and impact scores (adopted from (Viavattene et al., 2015)).**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Households</td>
<td>NoIScomp Households with no insurance, but which are able to access a small/medium amount of government compensation</td>
<td>30</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
1. **Household with no insurance, but a small/medium amount of governmental compensation is provided.** About 30% might rely on certain governmental compensation. In our case it is assumed that the event is catastrophic and governmental compensations and donations might take place. However, not as high compensation as it was observed after the 2002 river flood (Thieken et al., 2006).

2. **Household with no insurance, but resident is self-insured.** The number of self-insured properties reflects the ability of households to assist themselves in the recovery process. This assumption is based on economic data: most of affected households are situated in urban areas which are characterized by higher GDP rates over Schleswig-Holstein state (Statistikamt Nord, 2016) and might have savings to recover after a flood; therefore, 30% are assigned to this category.

3. **Household with no insurance.** It is assumed that 9% of residential properties in the affected region have no insurance and might have a very limited ability to recover after an extreme event.

4. **Household with partial insurance.** As was mentioned before, there is an insurance company which has recently started providing coastal flood insurances. The expert interview (W. Goeken, “Itzehoer Versicherungen”, personal communication, July 28, 2016) revealed the market penetration of storm surge insurances about 1% in the area.

5. **Household with no insurance but large degree of governmental compensation.** Some households may receive higher compensation and it is assumed to be about 30%.

The decision to assign above mentioned categories was made due to the extreme event considered in the study, so there might be a case when the event is called “catastrophic” and governmental compensation would take place to a certain extent. As there is no data from the recovery mechanisms from the previous events in the study area and the previous research is based on river floods it was decided to distribute the compensation equally between large and small/medium. The thresholds are included into text file “Insur_forINDRA.txt”.

**Businesses**

From the expert interviews (W. Goeken, Prof. H. Sterr, personal communication, July 2016) it became clear that it is not possible to obtain data on the types of recovery mechanisms for businesses, so assumptions must be made. At the moment it is known that there is no compensation.
schemes developed to recover after flooding and generally, the decision on the degree of compensation takes a long time to be made. The larger companies and manufactures in the region can expect help from the government, but it is not guaranteed. By the businesses all non-residential buildings are taken into account. In this case due to data inaccessibility a rough assumption had to be made combining worst and best case scenarios (Table 13). The impact scores are adopted from the Guidance (Viavattene et al., 2015).

Table 13: Financial recovery mechanisms for businesses, distribution of mechanisms within the region and impact scores (adopted from (Viavattene et al., 2015)).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-residential</td>
<td>NoI Business with no insurance/self-insured smaller-to-medium sized business.</td>
<td>50</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Non-residential</td>
<td>BPartI Fully insured businesses</td>
<td>50</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

1. **Businesses with no insurance/self-insured smaller-to-medium sized business** are 50% of non-residential properties. A large portion of non-residential properties in the study area are shops, restaurants, bars, small hotels, etc, which triggered our decision to assign worst case scenario based on the business size using expert knowledge and the GIS data.

2. **Fully insured businesses** are 50%. The possibility to access literature or surveys on business properties financial recovery was very limited; however it is assumed that the best case scenario would be based on the lower impact scores, which are attributed to the full insurance. It is important to mention that the current research admits the fact that there are no insurance policies given to the coastal non-residential properties against storm surge. Nevertheless, this mechanism is chosen in order to reflect the financial recovery impact scores (Viavattene et al., 2015). This choice is also related to the building types which were assigned earlier, they include public and military properties which most likely will be compensated from governmental funds.

The impact scores for both, business and households are calculated the same way: each impact score (low, medium, high and very high) is assigned with the values in percentile reflecting the number of receptors with a certain recovery mechanism and their weight (Viavattene et al., 2015). This data is written into the text file “Insur_forINDRA.txt” and read within the model. The financial recovery score is the reflection of the recovery mechanism and the hazard impact on properties. In case of a very high hazard impact (Table 13) the business recovery score is an aggregation of the products of distribution and the impact score:

\[ 0.50 \times 5 + 0.50 \times 2 = 3.5 \]
The Business Financial Recovery Score for a particular receptor equals 3.5. The same operation is done for the Households on each receptor according to the hazard impact and the type of recovery mechanism. Further procedures are performed within INDRA.

**Regionalized Business/Household Financial Recovery indicator** is computed inside the model in the following manner:

\[
I_{fr} = \frac{\sum_{i=0}^{n} f_{r_i}}{\sum_{i=0}^{n} 5}
\]

Where \( n \) is all businesses/households in the region, \( fr \) is financial recovery score, and 5 is the maximum of business/household financial recovery score for each business/household property. Correspondingly, the outputs are generated separately for each hotspot producing business and household financial recovery indicators (Viavattene et al., 2015).

### 2.3.3 Transport Disruption

The overall resilience of a community, as well as individual units cannot be assessed without taking into account links and connections between them. Extreme events may cause direct and indirect damage to roads, bridges, and contingent infrastructure. The direct damage is considered in a similar way as flood depth damage to buildings, by accounting the direct response of the road fabric and road structures to the hazard. Moreover, a certain level of inundation may lead to road closure, which in turn results in traffic congestions and further inaccessibility of destinations. There are other reasons of road disruption, such as wind speed, flow velocity, precipitation rates and others, but their assessment is rather complex and demands a very detailed observation (Li, Ozbay, & Bartin, 2015).

The specific character of the transport networks is that it may disturb the receptors located far outside the hazarded areas, in our case hotspots. The disruption of such networks affects both, private and business sector. The factors that disrupt transport system include a wide array of parameters, such as occurrence time, the placement of the vehicles during the event, the costs connected to the travel time and demand-supply chains of a particular area (Viavattene et al., 2015). In economic terms the delays in delivery of certain goods may cause additional costs.

During the Irene and Sandy hurricanes in 2012 (US) a high number of traffic accidents happened due to the inaccessibility of coastal roads. The alternative roads were overloaded which resulted in 100 mile long traffic jams of the evacuees´ vehicles (Li et al., 2015). A river flood in Germany in 2013 resulted in closure and obstruction of numerous streets in regions such as Braunschweig and Hannover, Dresden, Leipzig and others, including federal motorways. This affected the transport connections on the national scale. While most of the links were cleared within days, some parts of the roads had limited use for over 8 weeks after the flood event (Thieken et al., 2016).

Consequently, transportation disruption is one of the key parameters which should be abided in the impact assessment in order to reflect a full picture of possible damage. There is a certain amount of tools designed for the evaluation of the indirect impacts on transport networks; however they were rather complex and relied on the measurement of the associated financial losses. Some were focused on specific components, for instance accessibility loss index suggested by Sohn or capacity reliability index described by Chen et al (Chen, Yang, Lo et al., 2002; Sohn, 2006).
A simplified approach for INDRA was developed within the project in order to perform a relatively simple but sufficient evaluation of the indirect impacts of transport disruption. It is based on the extensive analysis of the existing techniques and called Weighted Disconnection (WD) and Time Lengthening (TL) Indicator (WDTL), taking into account nodes (junctions) and links (roads). The evaluation of the nodes and links is described in detail below.

The main idea is to calculate the connectivity and time ratio before and after the occurrence of the event. INDRA calculates the indicator in the following way:

\[
WDTL = \frac{WD_2}{WD_1} \times \frac{TL_1}{TL_2}
\]

(6)

Where indices 1 and 2 signify the correspondence to pre- and post-event indicators. Further specifications can be found in the Guideline (Viavattene et al., 2015).

The Regionalized Transport Disruption indicator is computed according to the simulation time in days (which can be changed in the model interface) and reflects the readiness of the road in terms of the repair works in relation to time. In this case the amount of simulation days should not be very high as the road is a system which doesn’t always depend on seasonality (i.e. touristic seasons) but is used regularly. In order to see the disruption in the long term, the INDRA simulation time in days is set as 1, 2, 7 and 30 days. It is aimed to show how the MCA scores change according to the simulation day’s number in order to have a better insight into the disruption. The Disruption Indicator is a value between 0 and 1, where 0 identifies no disruption and 1 is for complete accessibility loss. The longer the simulation time is, the lower the Indicator (disruption factor) and vice versa (Viavattene et al., 2015).

**INDRA input file development**

The location of the flooded area for both hotspots is characterized by the marinas which are used for various purposes: sport activities, transport, leisure centers, etc. For this reason there are road networks which connect the harbors with the other parts of the city. The train station and tracks in both hotspots are considered not inundated and not included in the analysis. For regional transport systems in the affected areas different types of connections are involved—among the largest are the tertiary and secondary roads (according to OSM). Certain information input is required in order to run INDRA; the transport network should be represented as a polyline shapefile; each polyline represents a road as an “intersection” to another. Each intersection or node should be analyzed in order to provide attributes on importance of the nodes that are considered as the beginning and end of a road (Viavattene et al., 2015).

First, the OSM data was analyzed. The current shapefile is the digitized polylines taken from the OSM file; all edges were snapped and assigned with an alphabetical order (i.e. A-FA). The roads which lie in tunnels or bridges over or under other roads were not intersected in such cases. The next step was the development of a common algorithm for defining the nodes´ importance. In current thesis, the main parameters used in the classification are municipality size and proximity to critical infrastructure (“locations”), such as hospitals, train stations, ferry terminals, marinas and harbors, airports, etc. It was decided to calculate the final score as a mean value of parameters, where 0 identifies the lowest importance (unimportance). For this reason municipality size is given
4 classes (1-4) based on the fact that there is no 0 population density at any of the administrative units.

1. Municipality size. The statistical data on the population of the municipalities (Statistikamt Nord, 2016) was combined together with the area of the municipalities in order to receive the density value. Then, the obtained population density data was put in 4 classes using the Natural Breaks (Jenks) method. The lowest density class was assigned value 1, correspondingly values 2-4 were assigned to higher classes.

2. Locations. This parameter was taken in order to identify the existence of important infrastructure points such as marinas, ports, train stations, hospitals, ferry terminals and airports. The data from Google Earth, Google Maps and OSM were used in order to identify these important points. The buffer zone of 1000m was built around each intersection in order to identify the proximity of the junctions to the critical infrastructure. The critical infrastructure was edited manually according to the data from Google Earth and the OSM basemap in ArcGIS. Then, the number of infrastructure points was joined spatially with the buffers, which is how the number of points per buffer was derived. Later the tables were joined in order to assign indices to the vertices. Here, the places with 2 locations in the 1000m vicinity were given the value of 2. The rest – correspondingly.

3. The overall importance of nodes was a mean value of two above mentioned parameters. For the direct damage assessment the vulnerability thresholds should be applied. The roads structure has distinct characteristics and therefore should be assessed differently. Here, the flood depth of over 0.3 meters is attributed to the impact which leads to road (Table 14) (Viavattene et al., 2015).

Table 14: Impact thresholds for roads. Adopted from (Viavattene et al., 2015).

<table>
<thead>
<tr>
<th>Land use types</th>
<th>Hazard Intensity</th>
<th>Threshold1</th>
<th>Threshold2</th>
<th>Threshold3</th>
<th>Threshold4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roads</td>
<td>Flood depth</td>
<td>0.3</td>
<td>9999</td>
<td>9999</td>
<td>9999</td>
</tr>
</tbody>
</table>

The calculation of the transport network disruption requires the data on the amount of time that the road is not accessible. Basically, this is represented as the repair time for the related hazard magnitude. This value is based on the assumption that there is no extensive contamination (large debris) on the roads but, some cleaning is required. Table 15 represents the value inputted to the “CHT_ForINDRA.txt” file.

Table 15: Recovery thresholds for roads. Adopted from (Viavattene et al., 2015).

<table>
<thead>
<tr>
<th>Land use types</th>
<th>Recovery</th>
<th>Threshold1</th>
<th>Threshold2</th>
<th>Threshold3</th>
<th>Threshold4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roads</td>
<td>Repair time</td>
<td>2</td>
<td>9999</td>
<td>9999</td>
<td>9999</td>
</tr>
</tbody>
</table>
2.4 Multi-criteria analysis

Risk management decisions are complex and often based on various parameters, such as tangible and intangible values. In order to retrieve a certain solution both values have to be weighted in a way that financial (i.e. direct damage to receptors) and non-financial indicators (i.e. risk to life, household displacement) could be compared (Hajkowicz & Higgins, 2008). MCA is a method that is able to deal with such cases; it gives an opportunity to analyze the criteria, choose, rank or sort a set of options (Greco, Figueira, & Ehrgott, 2005). A vast amount of research in environmental sciences and in particular water and flood risk management rely on the MCA methods. In particular, Raaijmakers (2008), Meyer (2009) and Papaioannou (2015) successfully applied the GIS-based spatial MCA for assessing flood risks and decision making, with the participation of stake-holders. (Meyer, Scheuer, & Haase, 2009; Papaioannou, Vasiliades, & Loukas, 2015; Raaijmakers, Krywkow, & van der Veen, 2008).

Thus, it is chosen to assist in the process of hotspot ranking within INDRA and for the purpose of the current research the weighted summation approach of Howard was selected among many others (Howard, 1991). It is relatively simple in application, can be understood by the different stakeholder groups, and hence provides transparency to the selection process (Viavattene et al., 2015). The method is based on the multiple Regional indicators which have been transformed into a scale from 0 to 1 (where 1 represents maximum disruption), then it is multiplied by the weight and aggregated to derive a total MCA score. The ranking of the hotspots in this research is performed using MCA by comparing those scores. The calculation algorithms are included in the INDRA environment, while the evaluation criteria and their weight is the responsibility of users. It gives the flexibility to select the indicators considering the peculiarity of the specific region (Viavattene et al., 2015). In the current study case they are:

- household displacement,
- household financial recovery,
- risk to life,
- business financial recovery,
- regional transport service disruption

The computation methods of Regional indicators are described in respective chapters above. The weights are assigned using multiple options but each run’s weight always equals in sum 100%. The final MCA score is calculated as sum of all indicators. The interface of the model displays the MCA separated in two boxes: in one of them the user inputs weights and in another enquires the results of the analysis.

The scope of this study doesn’t include stakeholder participation, which is why the selection of most realistic weighting combinations (scenarios) based on expert knowledge will be used. This study analyzes different scenarios on how the situation may unfold and assigned weights are subjective. First, the weights were assigned by generating all possible combinations where intervals of weights are 5 and maximum weight is 50 (3246 scenarios in total). The combinations will be filtered according to most realistic weight assignments based on the analysis of INDRA results.
3. RESULTS

3.1 General overview

The impact assessment and the hotspots ranking is the main objective of the research. By performing an extensive data collection and analysis this thesis aims to the receptor-based direct and indirect impact assessment and provides transport system disruption outcomes. It is apparent that both hotspots reveal a certain impact which may pose danger to the lives and health of local population and cause considerable economic losses. In addition, the flooding of the roads triggers transport disruption and increases traffic flows in the areas outside the hotspots.

First, the obtained and formatted inundation maps are shown in Figure 10, and they represent the inundation extent in both hotspots.

![Inundation in Kiel (A) and Eckernförde (B)](image)

Figure 10: Inundation extent in hotspot Kiel (A) and hotspot Eckernförde (B).

It is estimated, than the inundation extent in Eckernförde is virtually twice as large as in Kiel (0.536 km² and 1.008 km² correspondingly). These figures include the water surfaces of Kleiner Kiel Lake and parts of Windebyer Noor. The results are attributed to the local topography, as mentioned in Chapter 1.2, Eckernförde is characterized by rather flat lands with the dominant elevation ranges between 0-2 meters, and therefore, despite lower storm surge height the inundation extent is wider. This is especially pronounced in the western part of the town, which is mostly occupied by ecosystems, however there are industrial sites and private gardens.
RESULTS

In Kiel on the other hand, the terrain is rather steep and the low lying lands below 2 meters are typical within a much smaller area (mostly around Kleiner Kiel Lake). Modeled inundation in Kiel in most of the area is below 1.5 meters. Another distinctive characteristic for this hotspot is the inundation, which stretches over the entire western coast of the inner fjord but, at the same time, is very narrow. On average, the flood plain width in that part is 20-30 meters and hardly reaches 100 meters inland in certain places.

In general, Table 16 represents general outcomes of INDRA, overall, the number of exposed receptors within two hotspots is unequal; there are 4 times more receptors in Eckernförde than in Kiel. Importantly, the number of residential properties is 10 times bigger in Eckernförde, whereas ecosystem and open urban spaces are defined by the area rather than receptors number. The extent of both is considerably larger in Eckernförde than in Kiel.

Table 16: Receptors in both hotspots.

<table>
<thead>
<tr>
<th>Receptor type</th>
<th>Kiel</th>
<th>Eckernförde</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential buildings</td>
<td>33</td>
<td>339</td>
</tr>
<tr>
<td>Non-residential buildings</td>
<td>112</td>
<td>158</td>
</tr>
<tr>
<td>Open urban spaces</td>
<td>16 (0.36 km²)</td>
<td>100 (0.6 km²)</td>
</tr>
<tr>
<td>Ecosystems</td>
<td>0</td>
<td>45 (0.26 km²)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>161</strong></td>
<td><strong>642</strong></td>
</tr>
</tbody>
</table>

All characteristics about each impact scale for different impact parameters are based on the Guidance document for CRAF (Viavattene et al., 2015). INDRA allowed using the direct impact scale presented earlier; it means that the results will be introduced in categories:

Table 17: Categories of impacts in INDRA.

<table>
<thead>
<tr>
<th>0</th>
<th>No impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low impact</td>
</tr>
<tr>
<td>2</td>
<td>Medium impact</td>
</tr>
<tr>
<td>3</td>
<td>High impact</td>
</tr>
<tr>
<td>4</td>
<td>Extreme impact</td>
</tr>
</tbody>
</table>

The following chapter presents the outcomes of the model and a regional picture of the associated impacts. As was mentioned in Chapter 2, the two hotspots are assessed separately, so this chapter is structured as follows: first, the impact assessment results for the Kiel hotspot, then the outcomes for Eckernförde. The MCA and final ranking are described at the end for both hotspots.
3.2  **Kiel hotspot**

3.2.1  **Direct impacts (buildings and transport)**

The analysis includes all points located within a hotspot. It means that there are all types of buildings and landuse receptors. In the case of Kiel, the only landuse type is open urban spaces; however, the model doesn’t calculate direct impacts for landuse and gives them value 0. Therefore, the buildings with no impact and open urban spaces are reflected in the same way. If the building has an impact category of 0 (17% of total amount of residential and non-residential buildings within the hotspot), it is explained by the higher elevation of the building compared to the flood depth, for instance, when the foundation is elevated and there are stairs which lead to the ground floor entrance. The map displays the outcomes of the model; in order to have a better representation the results are shown only for the hotspot.

As can be seen in Table 16, half of all buildings obtained category 2 (72 building receptors), which represents damage to household items, building fabric damage and most likely items would need to be replaced. 18% (27 buildings) in the hotspot might experience partial collapse (category 3). Most of those receptors are one-storey buildings around Kleiner Kiel Lake or kiosks on Kiellinie; however some of them are stores and cafes in the shopping area. Nevertheless, the stores might not experience partial collapse to a large extent, because the threshold for the commercial receptors was higher, so it is assumed that the inventory and content would suffer most of the damage, therefore they fall into category 3. The remaining 27 receptors (15%) fall into category 1; this goes for minor damage and mostly leads to the flooring and inventory damage. As expected, no building would collapse (category 4).

Spatially, it is observed that most receptors are located in the central part of Kiel (marked with a rectangular in Figure 11) due to specific inundation extent. Most buildings in this area are businesses (shops, bars, cafes, etc.) and only some of them, mostly centered around Kleiner Kiel Lake, are residential. The northern part of the hotspot is characterized by a narrow line of inundation plain; however, it still reaches some buildings. Those are kiosks, bars and buildings which are a part of the infrastructure of Kiel marina and only few residential buildings.
RESULTS

Figure 11: Direct impact on buildings and inundation extent, Kiel.

Transport

The model assigns direct impact scores according to the inundation depth. The outputs of the INDRA model show that there are 3 links that are impacted by flood. Remaining roads within the hotspot are not impacted. In the case of Kiel this is a road which leads from the north to the south of the city and connects residential areas with the city center. Basically, it is a continuous line but within INDRA it was divided into 3 parts, the underlying reason being the intersections (junctions) which were highlighted due to their different importance and maximum speed. So, one road is Kiellinie and Düstenbrooker Weg, the other two are Wall and Kai Streets (Figure 12).

Concerning the scores, impacts on all links are low; this is explained by the thresholds which were described in Chapter 2.3.3. As was mentioned there, only one threshold was used for the transport network, where the inundation of 30 centimeters causes restrictions of the use of a road. Hence, according to the model outputs the links with impact scale 1 are not used for the time period of 4 days (during the event and 2 days after). Impacted links are the only ones which lead to ferry terminals and in the case of the modeled event these become inaccessible. Therefore, the closure of Wall street and Kai streets can be critical for the coastal businesses.
3.2.2 Risk to life

This parameter was calculated based on the flood depth-velocity product and receptor type (Nature of the Area). Here, all types are included: open urban spaces and buildings, and percentages are represented from the total amount of receptors within the hotspot. From the sum of 161 receptors in the hotspot, 15 are under none and 116 are under very low risk to life (10 and 74% respectively). These figures show the degree to which people are exposed during the flood: very low risk means that despite a certain water level people are very much likely to stay safe and in this type of area where they are, shelter can be found. Only elderly people, children or the disabled may be impacted by flooding.

There are 24 receptors under the moderate risk to life, which is about 13% of all receptors within the hotspot. In this case, the degree would depend on the type of the building/landuse (Nature of the Area) they are in and vulnerability of groups of people. In most of cases, the exposed people are in direct danger when they stay outside or are in highly vulnerable buildings (huts, campsites, mobile homes, poorly constructed properties). According to the Guidance (Viavattene et al., 2015),
in cases where people are located in multi-storey concrete or brick properties the risk to their lives would depend on the behavior (i.e. if people decide to go outside or not).

Only 4 buildings pose a higher risk of injuries and fatalities. They are small kiosks on Kiellinie (Figure 13) that might be highly damaged during the flood event and the chance of injuries and fatalities is relatively high. Buildings situated next to each other on Kiellinie are at high risk due to high depth-velocity values in those places. The other two places in the same category are open urban spaces along Kiellinie, where the hazard characteristics, such as flow velocity, are rather intense.

The total area of open urban spaces is about 0.36 km² and is represented by 16 dots (receptors). Only on 0.007 km² is there high risk to life, and those are small polygons on Kiellinie, where the hazard intensities are rather high. In these areas people are exposed to direct danger, but it is rather unlikely that there would be people outside during the storm. An area of over 0.06 km² may pose a moderate danger to the exposed population; there are open areas on the tip of the bight and central parts of the city, where the shopping streets are. The remaining open spaces (0.3 km²) can be characterized as less dangerous for most of the people, but vulnerable groups are still at risk of injury. According to Priest et al (2007) (Priest et al., 2007), the safety of such individuals would depend on their behavior, and most likely they would be able to find shelter in the surrounding buildings.

Figure 13: Risk to life and inundation extent, Kiel.
3.2.3 Household displacement

Household displacement score outputs showed that as much as 47% of households (16 private properties) will experience no displacement; however 41% (14 private properties) would have to leave their usual places of residence for the period of 1-3 months, which would not leave a negative impact on the community. In the meantime, only 12% (4 private properties) would experience a mid-term displacement which lasts 3-12 months. Such a long time brings negative consequences to the community associated with the rebuilding process and the stress of being away from home.

Figure 14 represents the spatial pattern of displacement scores. Those receptors which experience medium-term displacement (orange dots) are located within the areas with higher inundation depth and are characterized by greater direct damage.

As recorded in Table 16, the overall number of residential properties within the hotspot is 33, which is rather negligible on the regional and local scale. This fact and evidence from outputs presented in Figure 14 display a minimal household displacement in Kiel.

Figure 14: Household displacement and inundation extent, Kiel.

3.2.4 Financial recovery

This parameter represents the recovery mechanisms of private households and businesses. As outlined in Chapter 2.3.2, scores depend on the direct impact and distribution of the receptors within particular recovery mechanisms. The impact scores were based on logic that the higher the impact the higher the financial damage is. Additionally, it should be reminded that all non-
residential properties are assumed as businesses while calculating the financial recovery parameter.

The outputs show that 6 receptors, which is 17% of all households, will have a full recovery after the flood. This means that the impact is low and residential properties would have no or few adverse impacts, mostly basic cleaning and drying of the household contents. Less than a half of all households within the hotspot would recover within a year. Fewer residential receptors (only 4 households) would expect partial financial recovery which would be expected after more than a year. It can be observed in Figure 15 that the households which would experience long duration partial recovery are the same as would experience medium-term displacement as shown in Figure 14.

![Financial recovery of residential properties, Kiel](image)

**Figure 15: Financial recovery of residential properties and inundation extent, Kiel.**

Medium duration recovery is attributed to as much as 74 non-residential receptors, which is over 66% of all non-residential receptors. About 23 receptors (21% of non-residential properties within the hotspot) would experience partial recovery which might take over a year. This result is linked to high financial damage caused to the buildings. At the same time there are no business receptors in the hotspot that would experience a low degree or full financial recovery. A certain degree of recovery (partial with medium and long duration) among businesses was possible in the worst and best case scenarios which were assigned earlier. This fact is also attributed to the absence of other types of recovery mechanisms (full, low, very low). Figure 16 displays spatial distribution and exposes the dependence of the inundation depth on the recovery. As most of businesses are located
within city center, it is shown that most buildings with long duration partial recovery are concentrated in that area.

Figure 16: Financial recovery of non-residential properties and inundation extent, Kiel.

Due to the fact that the direct impact level was zero for some buildings (higher elevation of structure compared to the ground level), they would not be affected by flooding, which means that financial recovery is not applicable. About 30% of residential and 13% of non-residential receptors are, therefore, not included in the maps.

3.3 Eckernförde hotspot

3.3.1 Direct impacts (buildings and transport)

As discussed previously, despite lower inundation depth the extent of the flood in Eckernförde is larger than in Kiel and a bigger area is exposed to inundation depth of more than 2 meters. Overall, the concentration of assets (receptors) within the Eckernförde inundation area is higher and more diverse than in Kiel.

The landuse types here are represented by natural ecosystems and open urban areas (23% of receptors) and they all fall into category 0 and are further excluded from the impact on buildings analysis. The same category (16% of buildings) is for the buildings whose entrances are above ground level (Figure 9). As most of the buildings in the city center are rather old, which is typical
for this region, the ground floor is elevated above the ground. The results show that as many as 161 receptors (32% of buildings) belong to category 1 (minor damage) and almost 200 (40%) to category 2 (inventory and buildings structure damage). The remaining receptors could experience higher damage (category 3), such as partial collapse and loss of inventory. Those are mostly industrial one-storey buildings, lower elevated stores in the commercial district or small kiosks and bars on the coast. No buildings would experience collapse.

As can be observed in Figure 17, the receptors with a high impact score (category 3) are concentrated in the western part of the town and as mentioned above they are industrial structures (usually one- or two-storey). That area is also characterized by higher inundation depths and, therefore, is attributed to higher impacts. The receptors with none, low and moderate impact are distributed over the flood plain rather randomly, pointing to a higher concentration of exposed receptors along the narrow part of the bight and down Reeperbahn street. This is an area with mixed-type properties, such as residential, businesses, public and cultural.

Figure 17: Direct impact on buildings and inundation extent, Eckernförde.

Transport

INDRA outputs for direct impact on transport network (displayed in Figure 18) show that there are links which get inundated during the modeled flood event: Reeperbahn, Vogelsang, B76 and the road which connects Vogelsang and B76. Moreover, B76 is divided in two parts (northern and southern) and thus, the total number of impacted streets is 5. The impact scores for all of them are low with a recovery time of 4 days. This assumption is identical to the one made for direct impact on roads in Kiel. The links which get flooded during the modeled event are crucial for the region,
as they connect neighboring municipalities. On local scale these roads are of high importance as they link different parts of Eckernförde and lead to the train station, the marina, industrial sites and other crucial locations.

![Figure 18: Direct impact on roads and inundation extent, Eckernförde.](image)

### 3.3.2 Risk to life

The values obtained from INDRA show that there is a higher risk to life in this hotspot compared to Kiel: all receptors (buildings and ecosystems) may pose a certain level of risk of injuries or fatalities. Figure 19 shows that the majority of exposed buildings are located within the central parts of Eckernförde, where low risk to life (green dots) would be expected. Low risk is attributed to as many as 347 receptors, which is 70% of the total amount of buildings within the hotspot. Those are the buildings of different purpose (residential or business). 25% or 125 receptors are under moderate risk to life and can be observed within the eastern part of the town, where the industrial site is. Some of them are also located within the town center and are characterized by higher values of flood depth (the area close to the tip of Eckernförde Bight). Only 25 buildings within the hotspot would be places of high risk to human lives; those are mostly old one-storey buildings, which are distributed over the north-western part of the town. There, people are exposed to flood waters and consequent danger: however, in this case risk would depend on people’s behavior rather than hazard.
RESULTS

Figure 19: Risk to life (buildings) and inundation extent, Eckernförde.

Open urban spaces and ecosystem types are assessed according to the depth-velocity values and the ability to find a shelter (Figure 20). For instance, most of the open urban spaces are less vulnerable, as there is a chance to hide in surrounding buildings. Figure 20 shows that a considerable number of such spaces (green dots) are distributed over the eastern part and pose low risk. In other words, people who are looking for a place to hide there would be able to do so. It is estimated that there is about 0.19 km² of such area. The exception is vulnerable groups of people (the elderly, children, etc.); they could be in direct danger. Moderate risk threatens 31 receptors (yellow dots), which is about 0.06 km² and is attributed to open urban spaces and marshes. There, safety would mostly depend on the behavior of people, and vulnerable groups are in direct danger from flood waters.

High risk to life is more distinct to the ecosystems in the western part of the city (0.43 km²), where fresh-water marshes are (Figure 20); there is no shelter and in case of a flood event the people may not find a place to hide. There the risk would depend also on behaviors and the vulnerability of those individuals. The inundation is rather higher there (over 1-1.5 meters), so people who are there during the flood event are in direct danger.
3.3.3 Household displacement

As it is shown in Table 16, the amount of displaced households in Eckernförde is larger than in Kiel. In Eckernförde about 31% (104 private properties) will experience short-term displacement for 1-3 month. During this time the affected families will reside in alternative accommodation and the sense of community will not be lost. Such displacement doesn’t impact the societal ties and after the event will return to normal. However, 14 properties will be damaged to the degree that the inhabitants would be required to leave them for up to a year. According to the Displacement Matrix (Viavattene et al., 2015) the associated stress will affect the displaced people with the continuous repairs and the negative feeling of being away from home. Most of displaced properties are located along Reeperbahn street and in the vicinity of the tip of Eckernförde Bight (Figure 21). Such concentration indicates the issues related to the distress of post-disaster communities (neighborhoods) as some households will be displaced for a rather long time compared to others.

At the same time, as many as 221 households (over 65% of the total) would experience no displacement due to the modest hazard parameters.
3.3.4 Financial recovery

Unlike the Kiel hotspot, the distribution of the receptors of recovery mechanisms is different for households and businesses. The reason is that the amount of exposed households Eckernförde is significantly higher (Table 16). As many as 47% of households (161 receptors) in the hotspot might have a full recovery, while 31% of private properties (104 receptors) would have partial recovery with medium duration. Partial recovery which would take over a year to receive would have only 14 households.

Spatially, the recovery mechanism is linked to the impact magnitude. The higher the inundation the higher the damage is. This statement underlines the distribution of receptors with partial long and low recovery – they are, to a certain extent, located in the areas with higher inundation, hence higher damage (Figure 22). As mentioned previously, these areas are the neighborhoods along Reeperbahn and the tip of the Bight. Correspondingly, the receptors with full recovery are more likely to be located in the areas with lower inundation.

As outlined in Chapter 2.3.2, the recovery mechanism for each receptor varies upon the hazard impact and distribution of the receptors within each mechanism. Therefore, another reason for such results is the number of buildings with compensation, insurance or neither. In the earlier stage of the research, it was assumed that the households would rely on governmental compensation (small/medium or large) or be self-insured (meaning they dispose of their own funds or savings for the recovery). This explains that 47% will recover fast after the event. From the
other side, according to the model, only 4% would have certain difficulties in recovering. Despite high direct damage, they additionally might have no insurance or limited access to compensation.

Figure 22: Financial recovery of residential properties and inundation extent, Eckernförde.

In the case of non-residential receptors, the background methodology has different principles. By assigning the combination of best and worst case scenarios over the region, the outcomes indicated that about 60% (95 receptors) would need many months to recover. The last option would also mean that certain businesses could be shrunk. The produced results show that as many as 29% (45 receptors) would have a lower capacity to recover; the businesses might shrink due to severe direct impacts and attain certain recovery after one year or more. As was assumed, the businesses include all non-residential properties including industries, it can be seen in Figure 23 that the lower recovery capacity is typical for more damaged structures within the industrial site in the western part of Eckernförde. The other 60% of non-residential receptors are distributed over the eastern part of the town, which is due to the lower inundation.
3.4 Multi-Criteria Analysis and hotspots ranking

As described in Chapter 2.4, MCA is an instrument that ranks hotspots by giving indicators specific weights; the scores vary between 0 and 1, where 1 means a critical impact of the indicator and its severe consequences. The resulted indicators for each hotspot are shown in Figure 24.
Figure 24: MCA indicators for two hotspots and different simulation days’ number.

The table illustrates a pattern, where the number of days influences transport indicators and shows that more or less significant scores are produced when the simulation duration equals 1 day. So, the most impact is expected within 1 day after the event and drops considerably over 30 days. It is explained by the dependence of transport disruption on the amount of simulated days. 24 hours after the flood event it is expected that the disruption is much higher, as there was not enough time for the system to recover. A week and a month after the event, the degree of disruption drops, meaning that the network returns to pre-disaster state. Additionally, the graph displays that this same indicator is more impacted than others, and less pronounced than transport is the business financial recovery indicator.

In order to compare the scores, previously described scenarios were filtered leaving those, where weight of transport disruption is 30, 35 or 40 and risk to life weights are higher than 20 but lower than 35. It was decided to make this assumption to show the high importance of transport disruption and risk to life indicators and trying not to overestimate their significance. This logic is based on the importance of human lives compared to household displacement and financial recovery. At the same time it is estimated that regional importance of transport network is slightly higher, in particular in Eckernförde. The reason for this is roads in Eckernförde which have a remarkable regional importance. It connects not only parts of the town, but also neighboring municipalities from both sides of Eckernförde. Yet, the selection of the conditions is subjective and may vary in a real situation.
By doing this, it was found that MCA scores for Kiel and Eckernförde are distributed in such a way that the highest score for Kiel is 0.0483 and the lowest score for Eckernförde is 0.0477 (Figure 25). The scenarios where MCA is higher in Kiel are all characterized by higher weights for transport disruption in Kiel; however it is assumed that these options are unrealistic. This lets us conclude that for all possible combinations of indicators for remaining scenarios (592) MCA scores are higher in Eckernförde than in Kiel.

![MCA scores](image)

**Figure 25: MCA scores for two hotspots for selected combinations.**

Yet, the differences are in the order of 0.001´s and are considered as minimal. This can be explained by the total number of exposed receptors; this consequently affects all other indicators such as direct impacts, risk to life, household displacement, etc. The research showed that the Eckernförde hotspot reveals more significant impacts compared to Kiel on the regional scale. At the same time, it should be noted that MCA scores are very low and don’t exceed 0.068, meaning that regional flood impacts are minimal. These results nevertheless suggest that further improvement of data quality and extensive analysis of the used parameters may provide useful input for the complex impact assessment modelling.
4. DISCUSSION

4.1 Evaluation of impact assessment outputs

The approach used in this study required to define thresholds for each impact indicator identifying low, medium, high and extreme impacts. In turn, the thresholds of each indicator were given concrete characteristics of impact degree. Therefore, the assessment of direct losses in the current study is based on relative damage, and presents consistent outcomes. As mentioned above, the hazard parameters and the structural vulnerability of buildings are the reason for the dominance of none, low and moderate damage in Kiel and Eckernförde (about 81 and 90% respectively). This means that the majority of buildings in both hotspots would require only cleaning or inventory replacement. Due to low flood-depth velocity values and the types of structures, there are no buildings which would experience total collapse. It should be noted, that as many as 50% of receptors in Kiel would suffer moderate impacts and would require certain maintenance on building fabric materials and inventory items. In Eckernförde this figure is close to 32%. In earlier studies it can be observed that certain patterns are in line with the current research. For instance, in terms of the direct (monetary) damage, in Kiel the areas with most impact correlate spatially well with the findings of Reese et al (Reese et al., 2002).

The current thesis gives an additional insight on the indirect damage, risk to life and household displacement on the receptors level. These indicators are of particular theoretical and practical importance. Assessment of the areas where human lives are in particular direct danger can be useful in emergency situations. Risk to life is especially pronounced in fresh-water marshes, some parts of old town in Eckernförde and in small structures located on Kiellinie (Figure 20). Yet, mortality and injury rates due to floods depend on numerous factors; this approach relies on hazard characteristics and vulnerability of ecosystems/buildings.

The findings on the hotspots reveals that household displacement, although not catastrophic, still might pose negative impacts to certain areas, in particular some older buildings around Kleiner Kiel Lake and the most damaged buildings of the old town in Eckernförde. Most of the displaced households are concentrated in a specific part of town (see above); however, it is suggested that there will be no significant distress on the community, rather on local and individual level.

An important component of a resilient household or business is access to financial aid (insurance, compensation, humanitarian aid, etc.). The analysis displayed that weaker recovery abilities of households are expected in Eckernförde; meanwhile in Kiel it is more typical for businesses. Proportionally, the estimates of the receptors with low and partial recovery with long duration are larger in Kiel. Moreover, MCA showed that the Business Financial Recovery indicator has a considerable significance compared to most indicators.

Eventually, the most significant compared to others is the Transport Regional Disruption indicator. The principle of the application was to measure weighted disconnection and time lengthening between nodes (road intersections). The MCA performed for the main streets in Eckernförde and Kiel showed that the scores in the same scenarios are higher in Eckernförde.
The results of the model exposed that the streets Wall and Kaistraße in Kiel get inundated almost completely, while in the case of another link, it is only the northern part which is represented by Kiellinie (Figure 12). As was mentioned in Chapter 2.3.3, only larger roads were included in the assessment, so the outputs show the whole road Kiellinie and Düstenbrooker Weg as one, as there are no large intersections between. Thus, it should be noted that despite the absence of inundation on Düstenbrooker Weg, it is assumed as a single link with Kiellinie and, consequently, impacted. It is essential to point out that in a real situation the picture might look differently, as the drivers might select other alternative paths via small local roads avoiding inundated parts of Kiellinie and still use Düstenbrooker Weg. This aspect is especially complex in the case of urbanized zones with developed road network as in Kiel.

The same effect is observed in results for Eckernförde, where some roads such as Vogelsang and B76 are partly inundated. This is a similar effect which was observed on the roads in Kiel. The assessment is done only for larger roads excluding local paths. Hence, the impact is shown for each road regardless of the extent of inundation within it. In reality the impact might be lower in non-inundated parts.

It is necessary to point out that the significance of the Reeperbahn and Flensburger streets in Eckernförde is eminent. Most of the area between Eckernförde bight and Windebyer Noor gets inundated during extreme storm and the use of the roads might be limited or restricted. Moreover, the train station linked by Reeperbahn to the other parts of town can become inaccessible for a period of time. In addition, the field research and further analysis displayed that these roads are important not only to Eckernförde town but to neighboring municipalities, as is the road links Kiel with coastal municipalities to the north-west (direction Flensburg). Therefore, the disruption of these links is considered as critical.

Meanwhile, the importance of the links in Kiel seems to be not as high, but due to the size of the city and the landmarks located there they are considered important. The roads within this hotspot don’t link municipalities and are mostly used by the local population. Affected roads link the city center with other districts. As it was observed, most of the areas in the city center are small or medium businesses such as shops, restaurants, banks, offices, etc. Inundation may affect the logistics of Ostseekai and Schwedenkai international ferry terminals. Daily, Schwedenkai serves ferries and Ostseekai large cruise ships in the summertime ("Fährabfahrten. Port of Kiel ", 2016). Consequently, transport disruption on roads leading to ferry terminals causes indirect economic losses to the terminal, and therefore it is assumed that these roads are of high importance as there are no alternative ways leading there.

All the factors considered indicate the significance of the transport network within studied hotspots and are clearly reflected in the INDRA outputs. From the perspective of the regional impact, transport disruption in Eckernförde hotspot is higher than in Kiel.
4.2 **Evaluation of multi-criteria analysis**

The MCA method, which is considered to be very effective, is based on the estimation of the relative importance of indicators and prioritizes them. (Van Herwijnen, n.d.). MCA is expected to present applicative outputs when the weights are discussed within interest groups (local citizens, stakeholders, politicians, decision-makers, scientists, etc.) for each hotspot individually. This task is outside the scope of the thesis; therefore the final weights assignment was performed by eliminating the least realistic combinations relying on expert knowledge about the study region and the results of impact assessment. The weights are given in the range from 0 to 100, where their sum always equals 100. After assigning these weights it was concluded that Eckernförde is more impacted than Kiel in terms of the considered indicators for 592 combinations. Importantly, the magnitude scores are not significant; hence the overall impacts of extreme floods on hotspots in the scale of the whole region seem to be very low.

Despite broad eliciting of MCA combinations, it is expected that interested groups might assign different weights and the ranking might look different. Here, most realistic scenarios were generated from the expert point of view after doing field research and processing the data. Nevertheless, it is important to point out that the final MCA scores for all possible combinations are low, which signifies low impacts on the hotspots on regional scale, but considerable on the local level.

To sum up, the outcomes are explained by several factors: the hazard extent in Eckernförde is larger than in Kiel, although maximum inundation depth is higher in Kiel. Therefore, the number of exposed buildings in Eckernförde is 4 times larger and the regional impact of transport disruption is extensive. Thus, the outcomes of MCA are realistic and are justified by the performed investigation.

4.3 **Limitations**

Due to the amount of uncertainty in modeling techniques and input parameters/data properties there are always the options of result interpretation. The degree to which the outcomes can be used further in research or management decisions should be discussed. This sub-chapter presents the limitations and issues connected to the input data and model applications used in the thesis.

Quality of data directly influences research outcomes. Data collection was one of the first and most complex steps towards the impact assessment and was performed on the highest level of detail in agreement with the scope of the thesis.

Firstly, this research used the hazard maps provided by the LKNM-SH. Generally, the limitations are related to the quality of the data in terms of the hydrodynamic model chosen and Digital Terrain Model. There were obvious errors detected concerning inundation depth which were corrected according to field research. An important matter was the resolution; as the model assesses receptors for each inundation cell (a polygon with the same inundation depth) it was necessary to reduce the
DISCUSSION

number of cells. For this purpose the resolution was changed from 1*1 meter to 10*10 meters, which is positively reflected on the computation time but presumably posed less than perfect accuracy to the flood extent. Other hazard characteristics such as duration of the flood event and depth-velocity product were assigned based on the broad-brush approach. A detailed hazard assessment using the hydrodynamic models will deliver more accurate hazard map. Nevertheless, it is considered sufficient for the scope of this study.

Secondly, the analysis of the limitations related to the impact assessment is voluminous due to the amount of used data. For the sake of efficiency it was decided to assign the quality scores and related limitations to them as following:

4  No data available, based on multiple assumptions

3  No data available/poor data, use of generic data but likely not representative. New data will be required.

2  No data available/poor data use of generic data but representative enough. New data will be required.

1  Data available but with known deficiencies. Improvements may enhance results in the future, overall sufficient for the research

Table 18 presents the quality scores for data used in the research, related limitations and possible ways to improve the quality of the data.

Table 18: Review of data limitations and possible improvements.

<table>
<thead>
<tr>
<th>Score</th>
<th>Data type</th>
<th>Main source</th>
<th>Related limitations</th>
<th>Ways of improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Business insurance / compensation schemes</td>
<td>(Thieken et al., 2006) expert interviews (see Chapter 2.3.2)</td>
<td>Directly affects the Financial recovery indicator. The assumption made within the research based on the combination of best and worst case scenarios may give a mistaken picture of the real situation due to the large geographical area presented and the diversity of businesses within it.</td>
<td>Extensive survey on the businesses at flood risk and their recovery capacity</td>
</tr>
<tr>
<td>4</td>
<td>Household compensation schemes</td>
<td>(Thieken et al., 2007; Thieken et al., 2006), expert interview (see Chapter 2.3.1)</td>
<td>Directly affects the Financial recovery indicator. Gives wrong insight on the distribution of the recovery characteristics.</td>
<td>Extensive survey and analysis of similar events on the German Coast of the Northern and Baltic Seas.</td>
</tr>
</tbody>
</table>
DISCUSSION

| 3 | Household displacement distribution | Generic data (Viavattene et al., 2015) | The quantitative distribution of the displaced households during past events and the related outcomes on individuals and society influences the Household Displacement indicator. The generic data based on the research made on UK insurance data most likely doesn’t comply with regional peculiarities. This affects the Households Displacement Indicator, which may bring limitations to the outputs. | Extensive research on the previous extreme flood events occurred on the coast of the Baltic and Northern Seas in Germany. |
| 2 | Depth-damage functions | (Huizinga, 2007) | The limitations of this choice are mostly related to the over/underestimation of the real direct damage to buildings and roads. | Extensive field research on the buildings, cadastral maps would allow using other functions and produce more detailed assessment. |
| 2 | Type of buildings | OSM, Google Earth, Google Maps, statistical data, field research | Affects most of indicators except of Risk to Life and Transport. The amount and spatial location of two main groups (households and businesses) has a very significant influence on the Displacement and Financial Recovery indicators. The inconsistency with the real picture leads to incorrect outcomes to a large extent. | Analysis of detailed cadastral maps, including other types of buildings |
| 1 | Type of landuse | OSM, Google Earth, Google Maps, field research | Affects Risk to Life indicator. The wrong landuse type might be reflected on the nature of the Area parameter (See Chapter 2.2.2). | Analysis of detailed cadastral maps and splitting the area in smaller polygons based on districts/streets or any geometrical polygons in order to obtain clear boundaries of the Risk to Life spatial extent. |
| 1 | Transport network | OSM, Google Earth, Google Maps, field research | Affects direct impacts on transport and Disruption Indicators. The spatial location isn’t an issue but the analysis of the importance of the nodes is essential. The incorrect data affects the degree of impacts. | Analysis of traffic flow will give a better insight into the nodes importance. |

As the table shows most of the data can or has to be improved to get a better insight on the situation within the region. However, parameters such as transport and land use type are rather sufficient. For instance, the landuse type for the current study case is limited to open urban spaces and freshwater marshes and influences only one indicator. The character of the hotspots allows certain errors in the extent and spatial location as it is represented as urban zones and main landuse type is open urban areas. A significant source of possible limitations is an assumption that all non-residential
DISCUSSION

buildings are classified as businesses. This may lead to the errors related to the Financial Recovery for businesses by over- or underestimating their resilience. Transport assessment can be improved with some additional data, although for the current research it is rather sufficient. Remaining inputs (financial recovery, displacement) have to be refined by very detailed analysis and the access to complex data. Conversely, such data is usually restricted from public use due to administrative regulations.

In terms of the INDRA application, this study implements the approach which allows quantifying impacts by assigning categories, not the absolute values. Therefore, the source of errors and limitations may lie in the selected thresholds and input files. In order to improve results of the assessment it can be valuable to include more receptor types. Field research suggested that there are other building types within the hotspots such as administrative (ministries, governorates), public (hospitals, museums, libraries, etc.), police stations, and other; their assessment is of great theoretical and practical importance.

To have a complete picture of the indirect impacts it is suggested that future work includes the disruptions related to the demand-supply chains of large businesses located within hotspots (i.e. international ferry terminals). Previous studies described significant economic losses of business and industries due to extreme floods (Jonkman, Bockarjova, Kok et al., 2008; Koks et al., 2015; Merz et al., 2010).

4.4 Implications of INDRA outputs

The focus of the study was predominantly on the production of inputs for the model, which included the collection of voluminous geodatabase, data processing and formatting and interpretation of model outcomes. The outcomes provide a detailed insight on the direct and indirect impacts in hotspots.

The results can be used by a range of end-users: municipalities, flood managers, insurance companies, decision makers, stakeholders, etc. For instance, the identification of areas with higher risk to life gives a large potential to the urban developers, decision makers and possibly to evacuation teams by providing an overlook on the areas where more danger to human lives could be expected. Yet, it should be noted, that the indicator can be further improved by providing the analysis of the location of main vulnerability groups within hotspots.

Based on the outcomes of the model it is assumed that despite low regional importance, the number of buildings which would demand a certain form of recovery after a flood event is still high. The analysis of financial recovery mechanisms in the region demonstrated that market penetration of storm surge insurance is minimal (less than 1%), together with unclear compensation schemes it becomes evident that the majority of receptors might experience difficulties in recovering after extreme flood events. With this study it is suggested that there is a need to promote storm surge insurance within the region in both the private and business sectors.
Another implication of this study can be found in the outcomes of the Regional Transport Disruption indicator. It is believed that it may serve responsible institutions to evaluate and address weak spots of regional transport systems in the view of flood hazards and related consequences.

The strength of the impact assessment methodology and the INDRA model in particular is that it gives an opportunity to estimate and evaluate diverse impact indicators and compare them. Impact assessment and obtained indicator values can be used to perform patulous MCA involving interested groups. Selection of the most impacted hotspots is of high importance for flood managers and decision-makers, as it allows better resource allocation. Also, selected hotspot can be further analyzed on a micro-scale and assist the development of flood mitigation and protection measures. Despite recommended improvements of input data and parameters, overall, INDRA showed that the results are applicative. It is hoped that this work will stimulate further research on the complex regional impact assessment on the German Baltic coast.
5. CONCLUSION

It is well-observed that extreme flood events bring considerable destruction to coastal communities. The estimates of damage increases when direct and indirect losses are both considered in the assessment. This study applied the INDRA tool which is designed to estimate and compare not only tangible but also intangible losses such as risk to life, recovery mechanisms and household displacement. The tool required an extensive collection of data through comprehensive literature review, field research, expert and stakeholder interviews. A created voluminous database was then later processed and formatted by applying various algorithms and methods in order to be inputted into INDRA. MCA was performed in order to compare hotspots of current study on the regional scale and detect which impact indicators influence results the most. The focus was on two pre-selected hotspots of flood risk, where direct and indirect impacts from 200 years flood were assessed and analyzed in terms of relative importance to the region. The hotspots are the towns of Kiel and Eckernförde, urban areas with a high concentration of people and assets, which previously experienced extreme flood events.

From the performed investigation it was found out that modeled flood differently impacts Kiel and Eckernförde. From one side, direct and indirect damage was estimated and illustrated. From the other side, overall impact level for both hotspots was analyzed. The results produced by MCA show that the scores of direct and indirect damage for identical scenarios and their combination are slightly higher in Eckernförde than in Kiel. Transport disruption is a compelling element in the performed regional impact assessment and demonstrated immense weight. Extreme events may pose significant direct and indirect impacts on the coastal roads, ob structing not only the access to important landmarks such as hospitals, train stations, harbors, etc. but also to contiguous municipalities. Yet, the analysis showed that other impact indicators are rather of local importance and would not cause vast damage on a regional scale. Nonetheless, the study suggests, that these effects should not be underestimated in terms of losses.

Conducted research exposed weak points in view of extreme floods; despite the high importance of insurability and compensation schemes in terms of financial recovery; they are rather unstated on the Baltic coast of Schleswig-Holstein. Financial recovery mechanisms of businesses are of particular importance and should be further investigated. Moreover, the previous research (Martinez, 2014) showed that potential impacts from extreme flood events in the study area are underestimated by the coastal population. This especially becomes critical in light of possible future shifts in extreme flood magnitudes and probabilities due to climate change (Hallegatte, Ranger, Mestre et al., 2011). For this reason, explicit impact assessment should contribute to the reduction of exposure of population and assets to extreme events. Additionally, the model used demonstrated flexibility to adapt the input parameters to any case study peculiarities and provided a large spectrum of possible improvements.

The findings of this study confirm that there is a need in the extensive impact assessment on the German Baltic coast from the perspective of economic, social and human losses from low-probability high-intensity events. Future work should consider additional indicator, such as
regional business disruption, which was beyond the scope of this study but of a remarkable significance.
6. REFERENCES


REFERENCES

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Declaration

Herewith, I declare that this thesis has been completed independently and unaided and that no other sources other than the ones given here have been used.

The submitted written version of this work is the same as the one electronically saved and submitted on CD.

Furthermore, I declare that this work has never been submitted at any other time and anywhere else as a final thesis.

Date  Signature