DMI report WP311 - Data driven climate change adaptation Part B: National and local scale flood modelling as a basis for damage cost assessments

Final scientific report of the 2020 National Centre for Climate Research Work Package 3.1.1, Data-driven climate service (part B)

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Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Larsen, M. A. D., Karamitilios, G., Halsnæs, K., & Halsnæs, K. (2021). *DMI report WP311 - Data driven climate change adaptation Part B: National and local scale flood modelling as a basis for damage cost assessments: Final scientific report of the 2020 National Centre for Climate Research Work Package 3.1.1, Data-driven climate service (part B)*.

The Danish
Meteorological
Institute

DMI report WP311 - Data driven climate change adaptation Part B: National and local scale flood modelling as a basis for damage cost assessments

Final scientific report of the 2020 National Centre for Climate Research Work Package 3.1.1, Data-driven climate service (part B)

DMI Report
15 January 2021

By Morten Andreas Dahl Larsen (DTU), Giorgios Karamitilios (DTU), Mads Lykke Dømgaard (DTU) and Kirsten Halsnæs (DTU)

Colophon

Serial title	DMI Report
Title	DMI report WP311 - Data driven climate change adaptation Part B: National and local scale flood modelling as a basis for damage cost assessments
Subtitle	Final scientific report of the 2020 National Centre for Climate Research Work Package 3.1.1, Data-driven climate service (part B)
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Other contributors	[Other contributors]
Responsible institution	Danish Meteorological Institute
Language	English
Keywords	[Text]
URL	https://www.dmi.dk/publikationer/
Digital ISBN	[Insert ISBN]
ISSN	[Insert ISSN]
Version	15 January 2021
Website	www.dmi.dk
Copyright	DMI

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https://www.dmi.dk/publikationer/

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1 Abstract (ENG)

In light of climate change, which will inflict not only sea-level rise but potentially also more forceful extreme winds for some regions, there is a pressing need to assess the magnitude and occurrence statistics of future storm surges and their resulting impacts in terms of affected economic assets. This study employs different combinations of existing climate projection scenarios, return period statistics, future periods and sea-level rise assumptions to depict resulting damages from storm surges on a national scale and shown here per municipality. The methodology employs two tracks: 1) based on insurance payouts from previous storm surge events and 2) based on sales price information (postal code based). Further, the resulting damage assessment effects of using static sea-level rise, as for the national scale analysis, as opposed to a dynamical storm surge model, which is assumed as a more correct approach, is analyzed and discussed.

In general and as expected, there is a positive correlation between the extremeness of the scenarios employed and time into the future and the resulting damages. The results from the mildest to the most extreme scenarios span +5000 to +9000 flooded buildings for the single-most flooded municipality alone. The insurance based methodology assumes equal payouts between regions whereas the sales price estimates are dominated by areas with higher property values such as the capital region. As also expected, the damages resulting from the dynamical storm surge modelling result in a reduced flood area compared to the static sea-level rise due to the underlying assumptions on duration.

2 Resume (DK)

Klimaændringer vil medføre en stigning af havspejlet samt potentielt kraftigere vinde for visse regioner i Danmark, hvilket i særdeleshed nødvendiggør analyser af forventede stormfloder for de kommende årtier og de dertilhørende sårbare områder og kommuner samt de resulterende forventede skadesomkostninger. Dette studie benytter forskellige kombinationer af klimascenarier, sammenhængen mellem den forventede frekvens og størrelse på ekstreme hændelser, perioder og antagelser for havspejlsstigninger til at beregne forventede økonomiske omkostninger på national skala – her vist på kommunalt niveau. Studiet benytter to spor til udregningen af skader: 1) baseret på forsikringsudbetalinger, udregnet på basis af tidligere hændelser, og 2) baseret på lokale salgspriser (pr. postnummer). Desuden vises og diskuteres forskellen i den beregnede stormflodshændelse imellem brug af en statisk havspejlsstigning, som for den nationale analyse, og dynamisk modellering, hvoraf den sidstnævnte antages mest korrekt.

Som forventet er der en positiv korrelation mellem hvor ekstremt et scenario der forventes og de resulterende skader. Spændet imellem det mildeste og det mest ekstreme scenario går fra +5000 til +9000 oversvømmede huse for den hårdest ramte kommune alene. Skadesfunktionerne baseret på forsikringsudbetalinger antager ensartethed imellem regioner i Danmark hvorimod resultaterne fra analysen baseret på salgspriser domineres af områder med høje huspriser såsom hovedstadsområdet. Som også forventet ses et lavere oversvømmelsesniveau ved brug af den dynamiske model, som forventes mere korrekt, modsat brugen af dynamisk havspejlsstigning, hvilket hænger sammen med antagelser omkring stormflodens varighed.

3 Introduction

The Danish National Centre for Climate Research (Nationalt Center for Klimaforskning, NCKF) has completed its first year in 2020. It has been a source of funding for the Danish Meteorological Institute and collaborators for climate change related research during this year. The 18 work packages fall under four general themes:

- Arctic and Antarctic Research
- Climate change in the near future
- Use of climate data
- Support for the IPCC

This report falls under theme no. four., and has been developed by *the Technical University of Denmark* (DTU Management) by contract of DMI

Climate change is expected to imply increasing coastal flooding hazards in Denmark in terms of the frequency of storm surge events, enforced in magnitude by sea-level rise, and the consequences on flooded assets. Coping strategies in terms of climate change adaptation are important in reducing the flooding risks, and in order to plan adaptation options efficiently very detailed knowledge about the local of flooding risk prone areas, and the assets at risk in these areas, as a basis for planning very specific adaptation options, should be located.

This report is developing detailed flooding scenarios for the Danish coastline including projections of flooded areas, which have been geographically overlayed in GIS with detailed information about buildings allocated in the areas. Danish studies, which have assessed costal damages of flooding, have concluded that damages on buildings make up a large component of total flooding costs, and the results of the study therefore provide very essential information about, where adaptation options should be located along the Danish coastline.

Further, the report addresses the issues of scale in both spatial and temporal terms. Spatially, by analyzing both national and local scale results and temporally by analyzing the effect of employing either static or dynamic storm surge models. The focus for this work is the extent of flooded assets in terms of areal extent and the number of flooded buildings, which have been addressed within the specific classes of private houses, industry, holiday houses, garages, culture and supply. Adjacent studies (not shown here) address the monetary assets which are at risk using methodologies which have been developed in the COHERENT project (COHERENT, 2020).

4 Methodology

2.1 General approach

This study combines flooding scenarios based on climate data, sea level etc. with hydrological flood modelling and calculates resulting flooded assets on a national and local scale. Figure 1 shows a flow chart providing a general overview of the three different analysis frameworks used in this study.

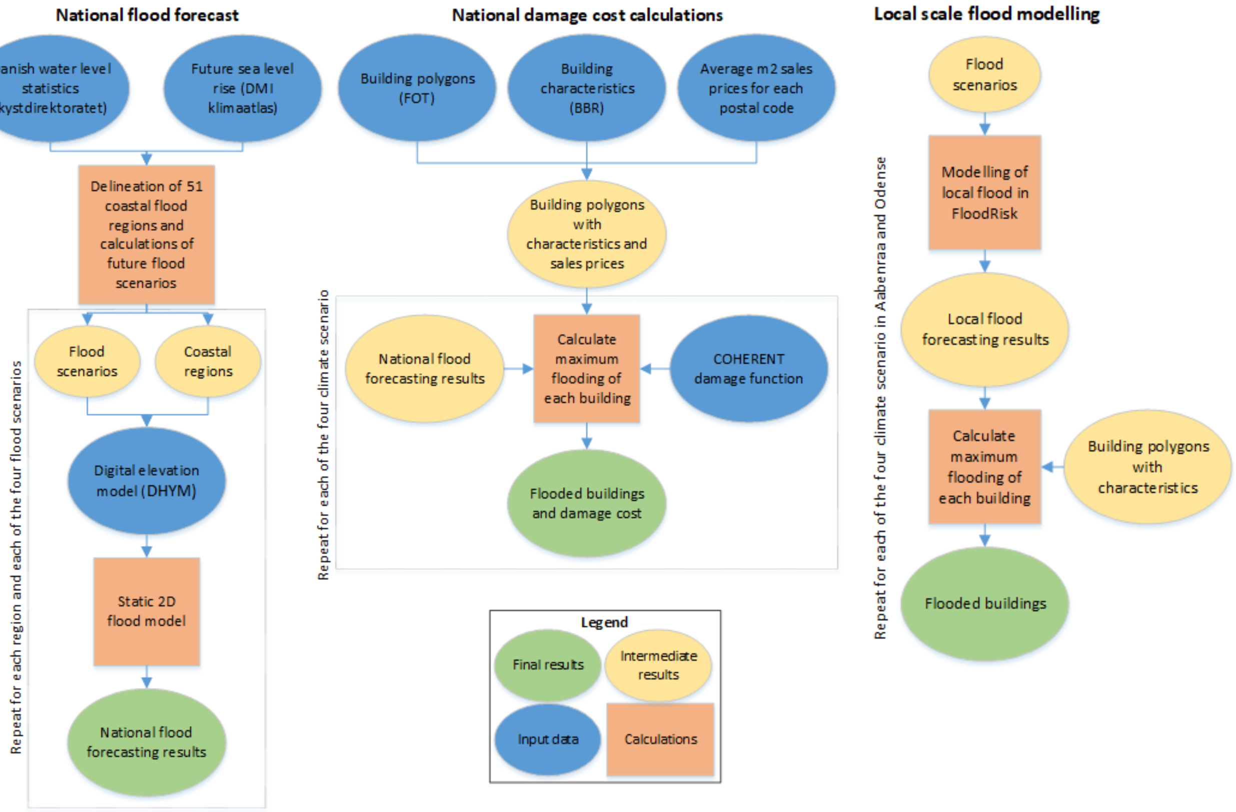


Figure 1: Flow diagram of the general analysis framework for 1) the national flood forecast, 2) the national damage cost calculations, and 3) the local scale flood modelling.

The *national flood forecasts* are based on water level statistic from The Danish Coastal Authority (Kystdirektoratet, 2018), future sea level estimates from DMI (DMI, 2020a) and The Danish Hydrological Elevation Model (DHYM) from Kortforsyningen (Kortforsyningen, 2020). First, the data on the water level statics and future sea level rise were combined and studied to delineate the Danish coastline into regions of similar flooding characteristics (51 regions in total) as well as determine the four future flooding scenarios, which have been selected for this report.

Next, a 2D static flood model was applied to the DHYM for each of the 51 coastal regions and four scenarios to estimate the flooding. Finally, the 51 flood results of each scenario were combined for a National forecasting map. See section 2.2 for an in-depth description of the methodology.

The *national damage cost calculations* determines the economic damages of all residential buildings within three categories (i) flooded private houses, (ii) apartments and (iii) holiday houses in Denmark for each of the four flood scenarios calculated in the national flood forecasting. The spatial footprint of all buildings were acquired from Kortforsyningen (Kortforsyningen, 2020) and combined with The Central Register of Buildings and Dwellings (BBR, 2020) for information on building characteristics (usage, size etc.).

The economic damages were calculated using two different approaches:

a. The first approaches uses the potential sales price of each house, estimated from statistics of the mean price per m^2 in each postal area from 2015-2020 (Finansdanmark, 2020).
b. The second approach uses the COHERENT damage cost model (COHERENT, 2019), which is based on insurance payments from the Danish Storm Council (The Danish Storm Council, 2020) from 2013-2017.

See section 2.3-2.4 for an in-depth description of the methodology

Finally, a *local scale flood model* analysis was carried out for two case areas, Aabenraa and Odense, to study the differences between using a static and dynamic flood model. For the static flood model we use locale results from the national flood forecast, whereas the dynamic flood is modelled using the FloodRisk tool from DHI (DHI, 2020). The results are depicted in terms of flooded area (e.g. m^2) and no. of flooded buildings (incl. sub-components of industry, holiday houses etc.) as local damage cost assessments are a part of the COHERENT project (COHERENT, 2020) and will be published at a later stage. See section 2.5 for an in-depth description of the local scale methodology.

2.2 National flood forecasting

Danish sea levels are monitored continuously by a network of 67 gauge stations placed along the coastline and in harbors (figure 2). Several stations have been collecting measurements for more than 100 years, whereas others were set up within the last 20 years. Based on these historical time series, The Danish Coastal Authority have developed individual water level statistics for each of the stations providing the recurrence intervals or return periods (RP) (Kystdirektoratet, 2019).

Figure 2: Placement of the 67 gauge stations in Denmark. The red values next to the station name indicates the water level causing a 100-year flood event. Source: (Kystdirektoratet, 2019).

Figure 3 shows an example of a water level statistic for Copenhagen Harbor, with the 20, 50 and 100-year return period (RPs) intervals marked. RP levels describe the magnitude of an event, meaning that according to historical data, a 100-year storm would statistically occur, on average, every 100 years. The red lines show the 95% confidence interval of the water level statistics and, as evident in figure 3, the results contain significant uncertainties as the 100-year event is in the interval of 144-177 cm. It is also evident that the uncertainty is positively correlated with the severity of the extreme events due to curve fitting of a small number of high-magnitude events and extrapolation for high RP-levels.

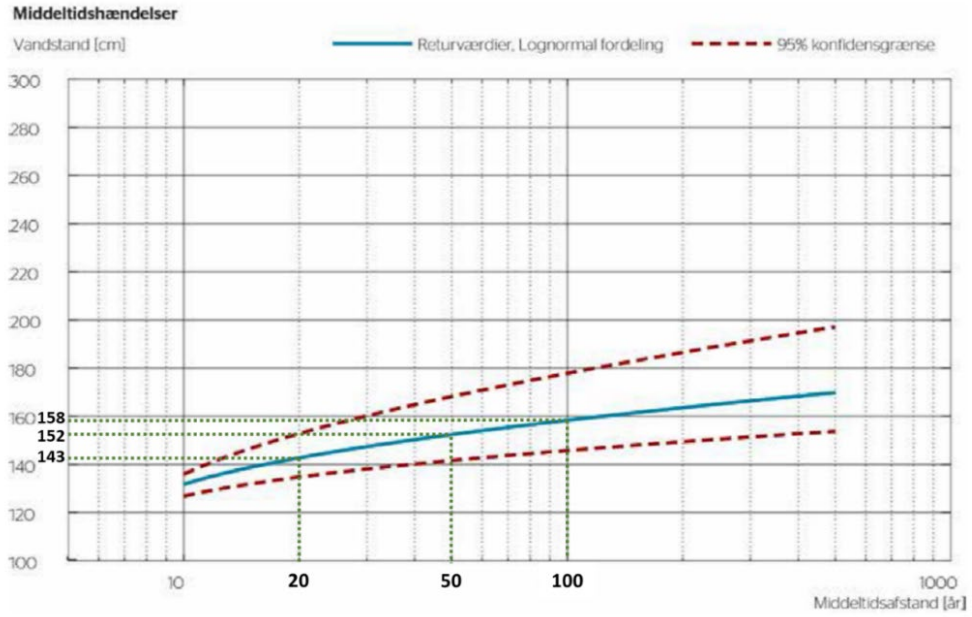


Figure 3: Water level statistics for gauge station in Copenhagen Harbor. Source: (Kystdirektoratet, 2019).

Throughout Denmark, there are substantial geographically determined differences in the water level seen for a specific RP level. For example, in Western Jutland near Ribe, an RP100 event corresponds to an increased water level of 488 cm above the mean sea level, whereas just 111 cm is seen for an RP100 event in Ringkøbing (figure 2). Thus, to assess flood risk at the national scale for similar RP-levels, Denmark has been divided into 51 regions covering all coastlines including inner seas (figure 4). This division is mainly performed by simply dividing into halfway points between neighboring gauging stations. However, in some situations where the specific coastal morphology such as fjord/open-sea boundaries, spits and barriers made this approach non-feasible, expert knowledge was used in the process of assessing borders between regions of similar return period sea levels. In regions where two or more gauge stations are located, the mean water level is used. Each of the 51 regions are studied separately calculating the following four flooding events:

1. 50 RP flooding in 2041-2070 RCP4.5 Mean (19cm sea level rise (SLR))
2. 100 RP flooding in 2041-2070 RCP4.5 Mean (19cm SLR)
3. 100 RP flooding in 2041-2070 RCP8.5 Mean (25cm SLR)
4. 100 RP flooding in 2071-2100 RCP85 90% percentile (97cm SLR)

To simulate future flooding under various scenarios, as represented by the IPCC RCP scenarios RCP4.5 and RCP8.5 (IPCC, 2014), the national mean sea level rise based on the DMI Klimaatlas were added (DMI, 2020b) to the individual present day RP flood levels of each of the 51 regions.

The scenarios used in this report encompass 30-year periods, as it is a standard approach in climatology to omit natural variability: 2041-70 and 2071-2100 and these longer-term periods are also in line with the associated uncertainty in the occurrence of extremes. Regarding the selection of scenarios for the study, three out four flooding scenarios reflect a near-future period, the 2041-2070 period, since the assets, which are potentially flooded, will show larger changes looking further into the future. One scenario, the most extreme RP100_RCP8.5_2071-2100_90th, however addresses the far future.

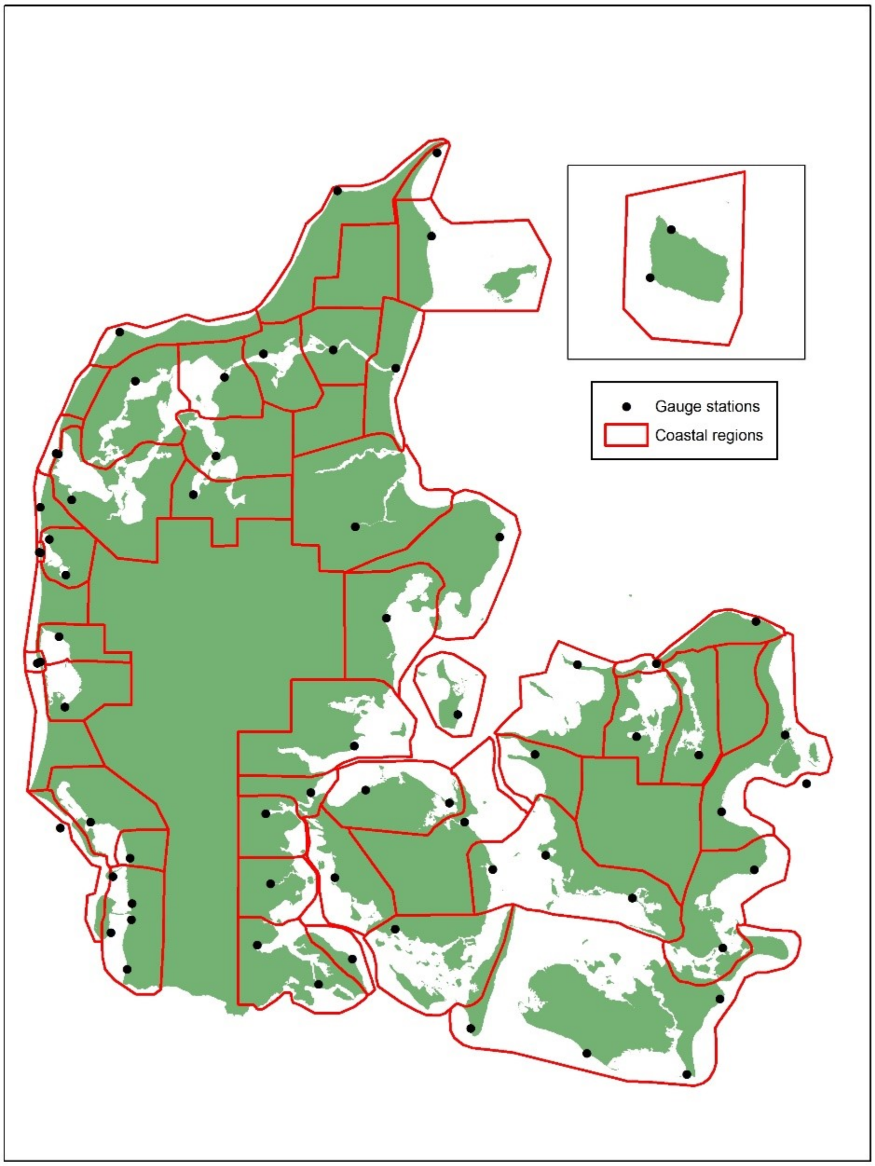


Figure 4: Map showing the 51 coastal regions used for the nation scale analysis (see methodology).

To determine the extent of the flooding as a function of storm RP-statistics and projected sea level rise, a simple static 2D surface flood model framework was used based on the DHYM sea rise elevation model downloaded from the database of Styrelsen for Dataforsyning og Effektivisering (SDFE) (SDFE, 2019) entitled Kortforsyningen (Kortforsyningen, 2020). The original elevation model has a pixel size of 0.4 m but was aggregated to 4 m resolution to balance operational simulation times. After pixel resampling, all hydrological corrections such as stream crossings under roads and piped streams were detected and burned into the DEM to ensure that these waterways are not overlooked during the aggregation process. Furthermore, all protective infrastructure such as floodgates and sluices were assumed closed (and functional) during the flood simulations, as would be the case during a storm surge. The flood simulations were conducted by raising the sea level to match the water level for each of the four flooding scenarios for each region. Only areas that are directly connected to the sea are considered being flooded. Water that enters one coastal region is enabled to run into adjacent regions, as seen in figure 5. Groundwater interactions that might occur during longer-term increase in sea-levels are overlooked, which is assumed realistic for the shorter-term wind-induced storm surges in focus here.

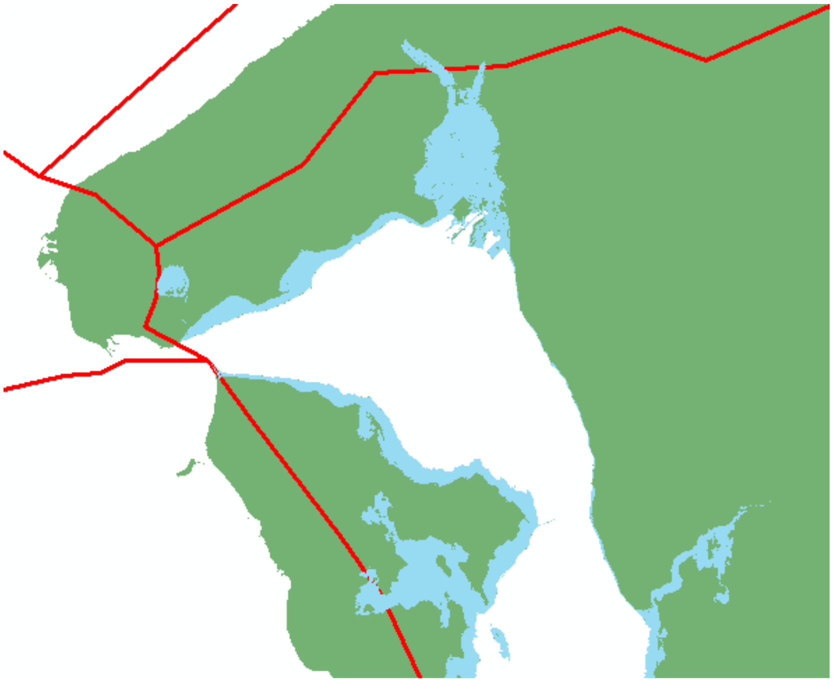


Figure 5: Example of flooding from one region propagating into an adjacent region.

2.3 Estimation of economic damages

The economic damages are estimated in two ways:

a) The potential sales prices of the flooded houses, based on the average m^2 price of houses in each postal code and the size of the building. This analysis includes only private building incl. apartments.
b) The potential insurance payout calculated using the COHERENT damage cost model (COHERENT, 2020), which is based on actual insurance data from The Danish Storm council. This analysis includes all the components of private houses (incl. permanent housing, holiday houses and apartments).

2.3.1 Sales price damage cost model

The website of Finansdanmark (Finansdanmark, 2020) offers the possibility to download the actual selling price of properties per m^2 at postcode level. The archive has data from 1992 and the properties for residential buildings are divided into three categories: apartments (ejerlejlighed), single or attached houses (parcel-/rækkehus), and vacation houses (fritidshus). Moreover, it is possible to retrieve the prices of the properties per m^2 at municipal (kommune), areal (Landsdel), and regional (Region) levels. In this study, the mean value of the actual sales prices from 2015 until the first half of 2020, for each of the three types of buildings, was used. In some cases where there were no data in postcode level, the prices on the municipal level were used, followed by the areal and regional if there was no data in the previous levels. The number of m^2 sales price per postcode multiplied by the number of building's total m^2 in order to estimate the sale price of the flooded buildings.

2.3.2 Insurance based damage cost model

The COHERENT damage cost model is developed as a part of the COHERENT project (COHERENT, 2020). It is a GIS based damage cost model, which enables the user to calculate damages related to coastal flooding of ten different sectors (buildings, industry and private business, public services, transport, health, critical infrastructure, ecosystems and biodiversity, recreational values, agriculture and forestry and tourism). As the focus of this report is on the economic damages of flooded houses, the following section will only describe the damage cost calculation for the building sector with a particular focus on private houses and holiday houses.

The main component in the COHERENT building damage cost model is a variety of different damage functions. Damage functions describe a correlation between one or more independent variables and the cost of the flooding. As the damage cost can vary depending on the building type, there is a need for a specific damage function for each building type. Figure 6 shows the damage cost function for private houses and holiday houses used in the COHERENT building damage cost model. The damage cost functions are based on data obtained from The Danish

Storm council (The Danish Storm Council, 2020), which contains information on all insurance payouts from storm surges at addressee level from 2013-2017. The dataset consist of insurance claims from 1075 holiday houses and 906 private houses caused by six different storm, with the majority originating from the Bodil storm in December 2013. For each of the private- and holiday houses the nearest gauge stations were identified and the peak water level during the storm based on the national water level statics (Kystdirektoratet, 2019). Next, the storm surge was simulated (using a static 2D flood model, similar to what is described in section 2.2) which enabled us to identify the water level surrounding each flooded building. Hence, the damage functions were constructed (figure 6) showing the correlation between the water depth and the absolute damages in DKK. These two damage cost functions will be used in the following sections to calculate the insurance cost of flooded houses.

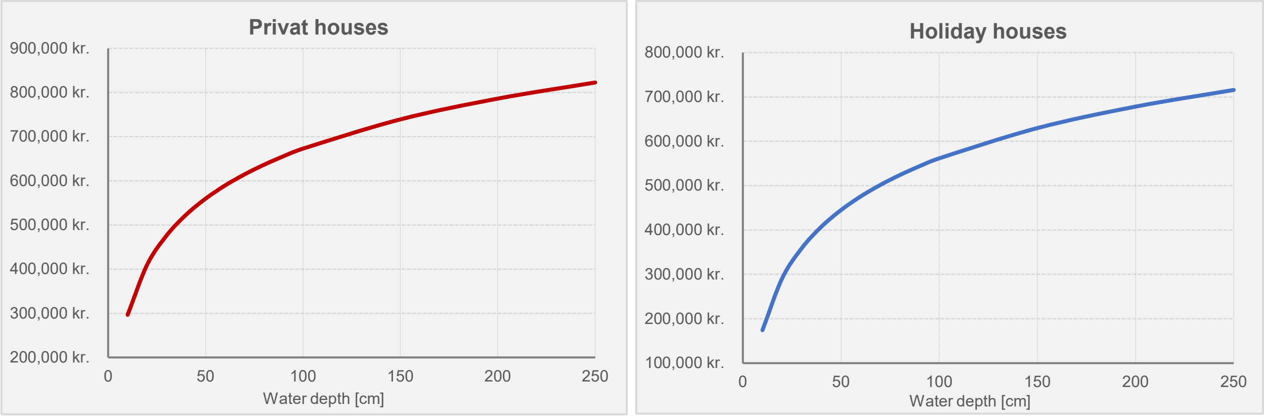


Figure 6: Damage cost function for private houses (left) and holiday houses (right), describing the correlation between the water depth and the absolute cost in DKK.

2.3.3 National Scale damage cost calculations

2.3.3.1 Data collection

For the calculations on the total insurance payout as caused by flooding at a national level (only private housing at the national scale) four datasets were needed:

1. Information about the buildings' location, type, and the number of square meters (m^2).
2. Information about m^2 price per postcode in Denmark.
3. Geographical information for the municipalities and postcode areas in Denmark.
4. Static model flood scenarios (four are used here – see above).

2.3.3.2 Buildings dataset

The dataset of buildings was retrieved from Kortforsyningen website (Kortforsyningen, 2020). The dataset contained information about all buildings in Denmark but does not include specific and detailed information. However, it was possible to add more information to the dataset as an id field (BYGN_UUID) is included. This id number were then used to extract more information for each building via the website Danmarks addressers Web API (DAWA) (DAWA, 2020).

The extra information for buildings added in the dataset of kortforsyningen includes: a) a code, which refers to the type of the building, and b) the total building area sum of the floor area without basement area and area of the attic. The areas are measured using the gross floor area (the outside of the outer walls) (BBR, 2020).

The buildings dataset in this study was updated only for the flooded buildings.

2.3.3.3 Dataset with m^2 price per postcode in Denmark

The sales price were calculated using the mean price per m^2 for each postcode from 2015 until the first half of 2020. The calculations were made only for residential buildings falling in three (3) categories: a) houses b) apartments and c) holiday houses.

2.3.4.4 Municipalities and postal code area shapefile

As the building and sale price dataset do not contain any geographical information about the municipalities or postcode areas, it was necessary to retrieve a dataset with geographical information about them. In the next steps, these datasets were joined together. Both municipalities and postcode area datasets were downloaded from Kortforsyningen website (Kortforsyningen, 2020).

2.4 Analysis and work flow

The first part of the analysis was to transform the primary data (figure 7). To spare computational time the data were divided by municipality and every process was run for each municipality separately. The buildings for each municipality were extracted from the national dataset, in separate files and the next step was to join spatial the dataset with the m^2 prices per postcode. The results of the first analysis include a dataset for each municipality with information about buildings location and m^2 sales price for each building.

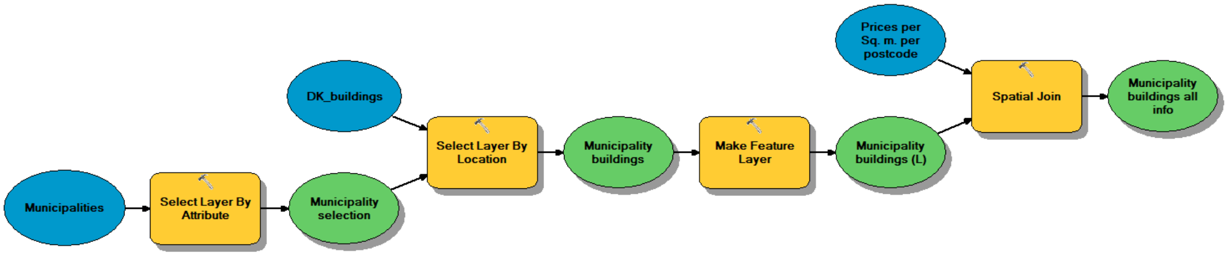


Figure 6: Stages to transform primary data.

In the second step of the analysis, the dataset from the previous step was used, adding a new field, which would show in a later stage if the building was flooded or not for a specific flood scenario. To again save computational time, the file that includes the water level of each flood scenario at a national level was extracted for each municipality separately. Using the file with the water level and the buildings for each municipality the next step was to combine these two datasets. More specifically, the maximum value of the water at the building level were extracted and saved with the information on the buildings dataset. Every building that had a water level attached to it was considered as flooded while the rest not flooded for the specific scenario (figure 8).

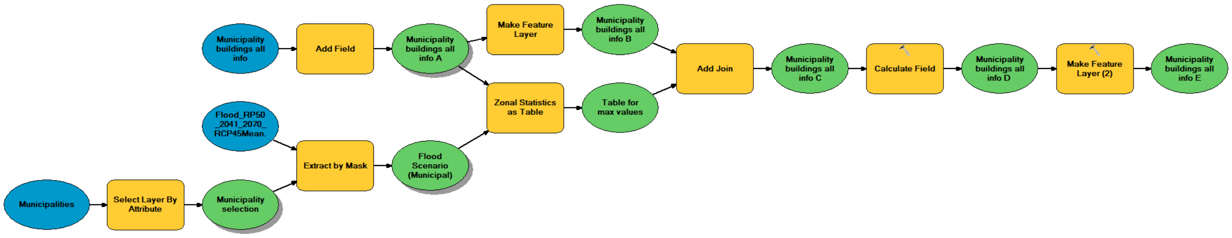
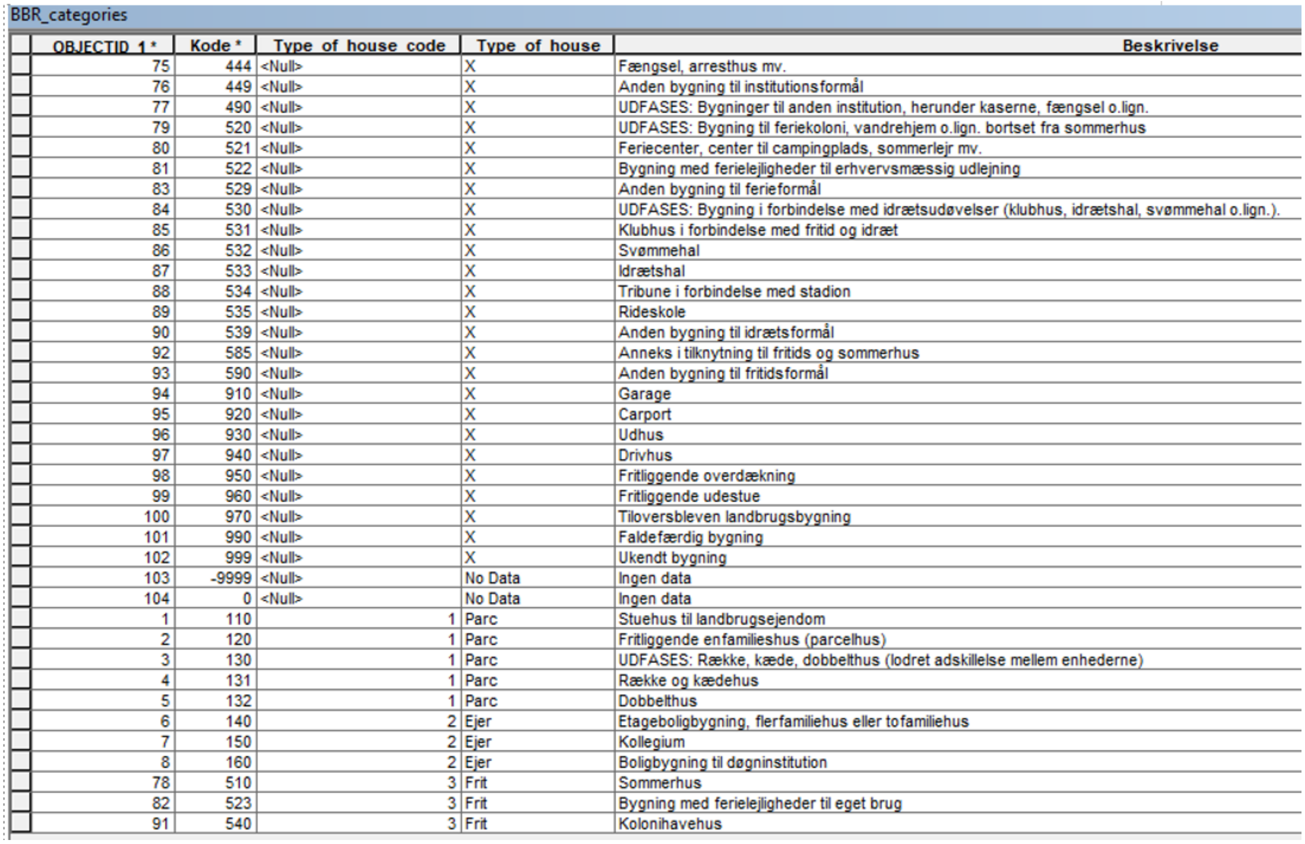


Figure 7: Model for creating flooded buildings dataset for each scenario.

The next step was to add more information about the flooded buildings from the DAWA website using the unique id code. For each building, information about the code, which refers to the type and use of each building (figure 9), and the total gross floor area of them in m^2, was added. Then, the datasets were joined with a table that describes the codes of each building with more details. In this table, a separation was also made between the types of houses (figure 9). The separation of residential houses into three types (apartments (“Ejer”), single or attached houses (“Parc”), and vacation houses (“Frit”) was used in the next step of the analysis.



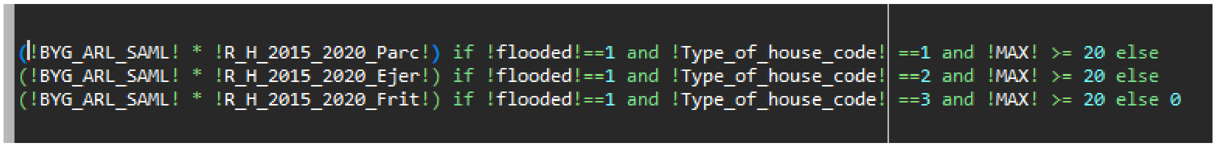
BBR_categories

	OBJECTID_1 *	Kode *	Type_of_house_code	Type_of_house	Beskrivelse
☐	75	444	<Null>	X	Fængsel, arresthus mv.
☐	76	449	<Null>	X	Anden bygning til institutionsformål
☐	77	490	<Null>	X	UDFASES: Bygninger til anden institution, herunder kaserne, fængsel o.lign.
☐	79	520	<Null>	X	UDFASES: Bygning til feriekoloni, vandrehjem o.lign. bortset fra sommerhus
☐	80	521	<Null>	X	Feriecenter, center til campingplads, sommerlejr mv.
☐	81	522	<Null>	X	Bygning med ferielejligheder til erhvervsmæssig udlejning
☐	83	529	<Null>	X	Anden bygning til ferieformål
☐	84	530	<Null>	X	UDFASES: Bygning i forbindelse med idrætsudøvelser (klubhus, idrætshal, svømmehal o.lign.).
☐	85	531	<Null>	X	Klubhus i forbindelse med fritid og idræt
☐	86	532	<Null>	X	Svømmehal
☐	87	533	<Null>	X	Idrætshal
☐	88	534	<Null>	X	Tribune i forbindelse med stadion
☐	89	535	<Null>	X	Rideskole
☐	90	539	<Null>	X	Anden bygning til idrætsformål
☐	92	585	<Null>	X	Anneks i tilknytning til fritids og sommerhus
☐	93	590	<Null>	X	Anden bygning til fritidsformål
☐	94	910	<Null>	X	Garage
☐	95	920	<Null>	X	Carport
☐	96	930	<Null>	X	Udhus
☐	97	940	<Null>	X	Drivhus
☐	98	950	<Null>	X	Fritliggende overdækning
☐	99	960	<Null>	X	Fritliggende udestue
☐	100	970	<Null>	X	Tiloversbleven landbrugsbygning
☐	101	990	<Null>	X	Faldefærdig bygning
☐	102	999	<Null>	X	Ukendt bygning
☐	103	-9999	<Null>	No Data	Ingen data
☐	104	0	<Null>	No Data	Ingen data
☐	1	110	1	Parc	Stuehus til landbrugsejendom
☐	2	120	1	Parc	Fritliggende enfamilieshus (parcelhus)
☐	3	130	1	Parc	UDFASES: Række, kæde, dobbelthus (lodret adskillelse mellem enhederne)
☐	4	131	1	Parc	Række og kædehus
☐	5	132	1	Parc	Dobbelthus
☐	6	140	2	Ejer	Etageboligbygning, flerfamiliehus eller tofamiliehus
☐	7	150	2	Ejer	Kollegium
☐	8	160	2	Ejer	Boligbygning til døgninstitution
☐	78	510	3	Frit	Sommerhus
☐	82	523	3	Frit	Bygning med ferielejligheder til eget brug
☐	91	540	3	Frit	Kolonihavehus

Figure 8: Sample of BBR categories table with the type of residential houses.

The final step of the analysis was to estimate the economic damages of the buildings. The damages are calculated by using two methods (see section 2.3.1 and 2.3.2): a) the sale price for each building and b) the potential insurance payout (COHERENT, 2020). In both methods, the calculations take into account only flooded buildings with a water level of 20 cm or higher assuming that all buildings have a threshold of 20 cm (i.e. the building socket height).

In the first method, the total number of gross m^2 of each flooded building was multiplied by the price of m^2. The calculations were made only for flooded buildings with a water level of more than 20 cm. Moreover, the prices per m^2 were depending on the type of building (figure 10).



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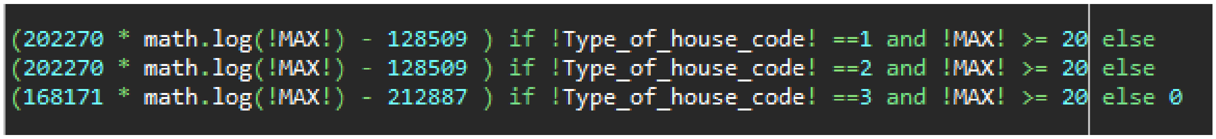
(!BYG_ARL_SAML! * !R_H_2015_2020_Parc!) if !flooded!==1 and !Type_of_house_code! ==1 and !MAX! >= 20 else
(!BYG_ARL_SAML! * !R_H_2015_2020_Ejer!) if !flooded!==1 and !Type_of_house_code! ==2 and !MAX! >= 20 else
(!BYG_ARL_SAML! * !R_H_2015_2020_Frit!) if !flooded!==1 and !Type_of_house_code! ==3 and !MAX! >= 20 else 0
```

Figure 9: Expression for calculation of buildings' economic damages using the sale price.

In the second method, the logarithm of the maximum water level value that attaches to each building was used. As can be seen from the expression (figure 11), the calculations are the same for houses and apartments but differ for vacation houses. The calculations were made for flooded buildings with more than 20 cm of water level.



```
(202270 * math.log(!MAX!) - 128509 ) if !Type_of_house_code! ==1 and !MAX! >= 20 else
(202270 * math.log(!MAX!) - 128509 ) if !Type_of_house_code! ==2 and !MAX! >= 20 else
(168171 * math.log(!MAX!) - 212887 ) if !Type_of_house_code! ==3 and !MAX! >= 20 else 0
```

Figure 10: Expression for calculation of buildings' economic damages using the potential insurance payout.

The final datasets contain information about the sale price for each flooded building and the potential insurance payout for each flood scenario. In this final stage of the study, the separate datasets for each municipality were merged, with a result of a dataset containing information about the sale price and the insurance payout, for every flood scenario at a national level.

2.5 Local scale flood modelling

2.5.1 Dynamic vs. static flooding

As described in section 2, our national flood scenario is based on a simple static 2D flood modelling approach. The static model has its limitations, and in the following, the static and dynamic modelling results were compared in order to assess differences of the two approaches in terms of magnitude and location of flooding and related consequences. Based on the literature, the static flood models are expected have a tendency to overestimate the flooded area (Ramirez et al., 2016) as the water is able to reach the furthest inland depressions connected to the sea, i.e. resembling a storm surge with a very long duration. To assess the consequences of using a static flood model compared to a dynamic model two local case studies were performed, one in Aabenraa and one in Odense (figure 12). The dynamic flood is modelled using the DHI FloodRisk tool (DHI, 2020) which is based on the DHI MIKE flood tool, with a storm duration set to 33 hours and a peak water level of 2 hours from hours 17-19.

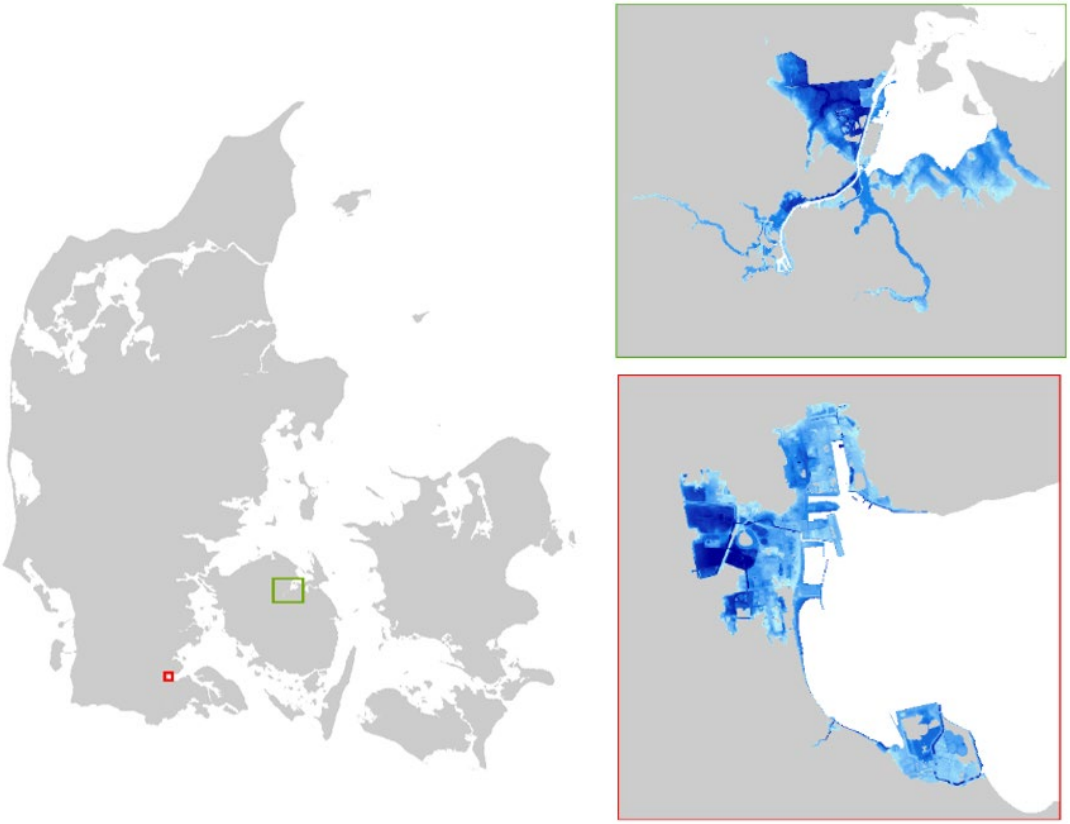


Figure 11: Case study areas. Green: Odense, Red: Aabenraa

5 Results and discussion

3.1 National Scale results

The results in in this section shows the results from the two damage cost approaches applied in this report:

a) The COHERENT damage function (COHERENT, 2020), based on insurance payouts as a function of flood level, is applied to all flooded buildings (from now on referred to as the damage function) per km^2 for each scenario, and
b) Flooded assets based on average m^2 sales prices per postal code.

Additionally, and using the same two damage cost approaches, the following was calculated: a) the number of flooded buildings, and b) the average price per flooded buildings. All calculations were made for the four projected flooding scenarios, which also form the division into sections below (from low to high flooding).

3.1.1 RP50_RCP4.5_2041-2070

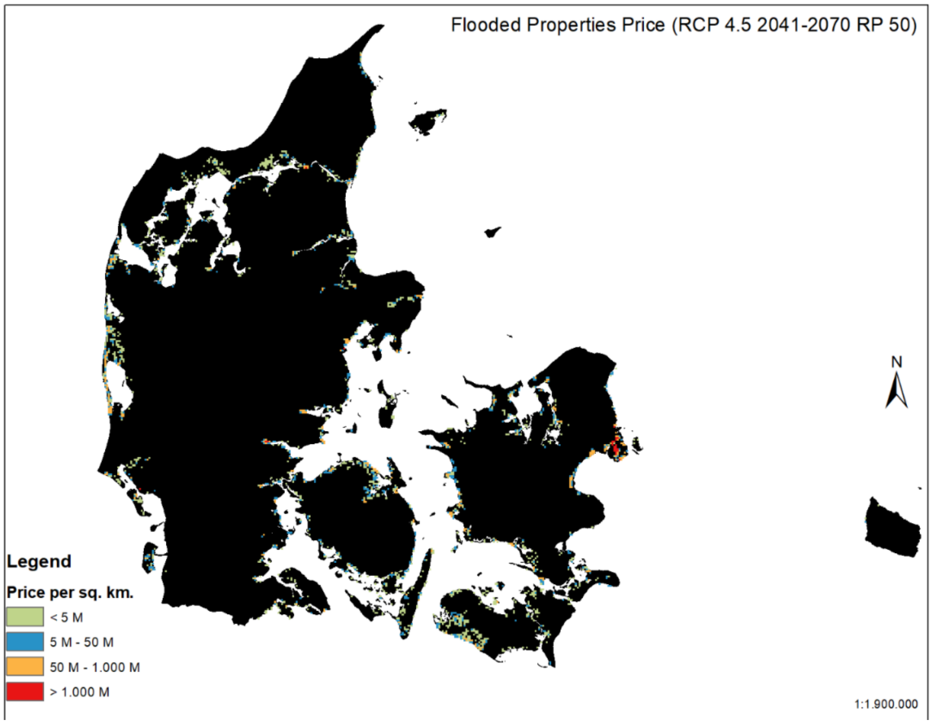


Figure 12: Sales prices of flooded properties per km² for the RP50_RCP4.5_2041-2070 flood scenario.

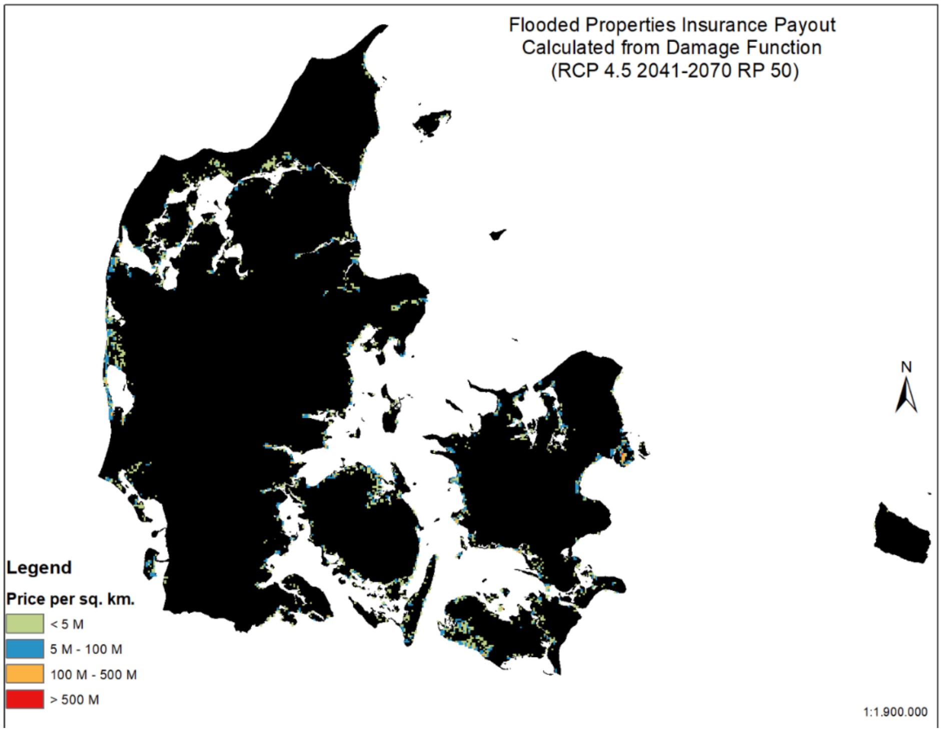


Figure 13: Insurance payout for flooded properties per km² for the RP50_RCP4.5_2041-2070 flood scenario.

The first flood scenario is the RP50_RCP4.5_2041-2070. Figure 13 illustrates the total sale price for all flooded buildings per km^2 in Denmark and figure 14 shows the total insurance payout for flooded building per km^2. In general, areas with sales prices above 1.000 mio. DKK/km^2 are located mostly in Copenhagen area and mainly in Amager. For the Insurance payout, the highest values (100 – 500 mio. DKK/km^2) are located in Amager only. Lolland and Ringkøbing-Skjern is seen to have the largest areas with flooded building in this scenario. The majority of flooded areas have an insurance payout reaching 100 mio. DKK/km^2 maximum while northern Jutland have a price smaller than 5 mio. DKK/km^2 in total insurance payout.

Figures 15 and 17 show the number of flooded properties and price per building for each of the two damage cost methods respectively while figures 16 and 18 depict the information on a geographically distributed level. Municipalities that are not seen in figures 15 and 17 had no flooded properties or lacked information on building type.

Ringkøbing-Skjern, Tårnby, and Lolland have the largest number of flooded buildings but the average sale price per building is generally low compared to other municipalities. Municipalities with high average price per building but relative low number of flooded buildings are Copenhagen, Aarhus, Gentofte, Horsens, Esbjerg, Vejle, and Lyngby-Taarbæk. More specifically, the average price per flooded building is more than 5 mio. DKK in these municipalities (figure 16). According to this flooding scenario, areas with a large number of flooded buildings do not necessarily have a high damage cost per building. As the damage function is dependent on the water level and the type of the building, municipalities such as Skive and Morsø will have bigger economic damages despite low average sales prices per building.

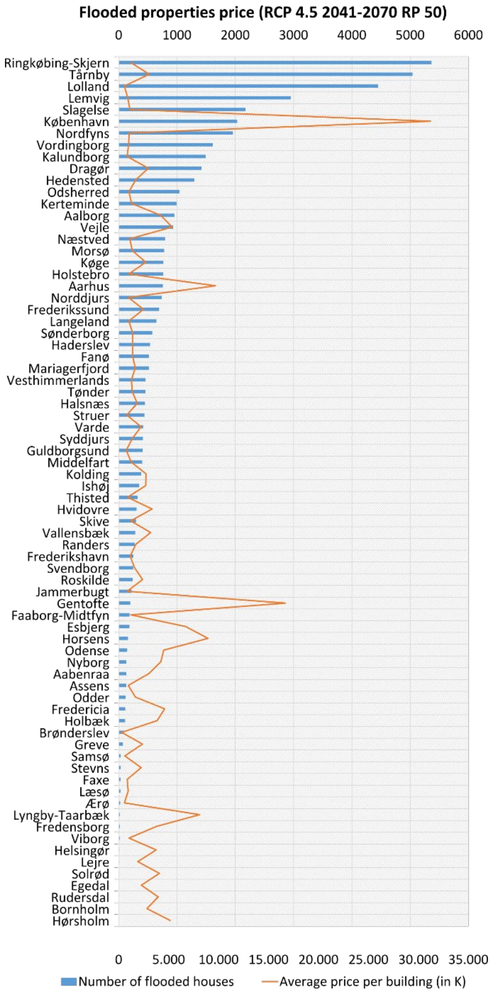


Figure 14: The number of flooded properties and the mean cost per building based on sales prices, per municipality for the RP50_RCP4.5_2041-2070 flood scenario.

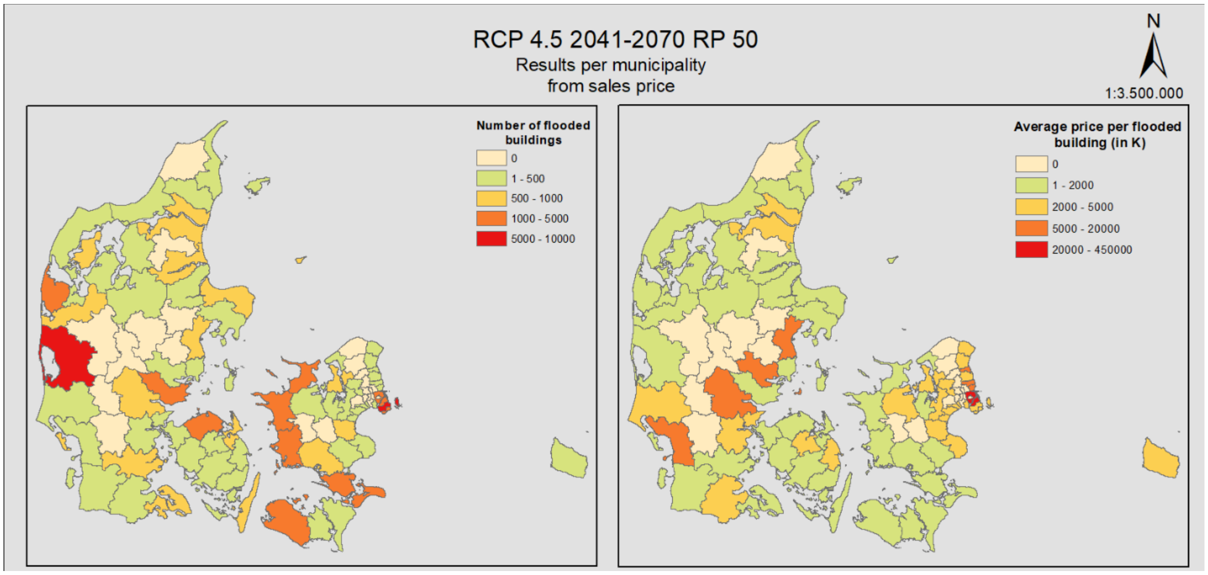


Figure 15: As for figure 15, but distributed.

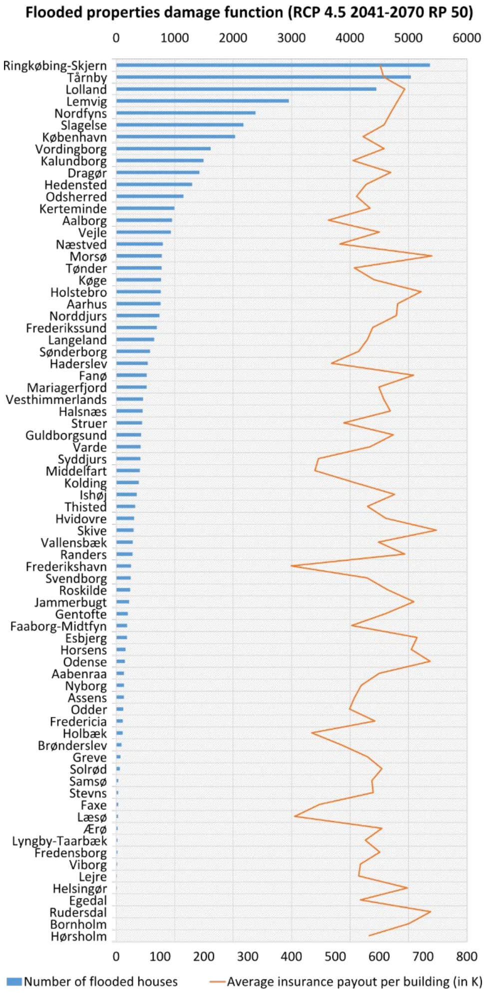


Figure 16: The number of flooded properties and the mean cost per building based on the insurance payout, per municipality for the RP50_RCP4.5_2041-2070 flood scenario.

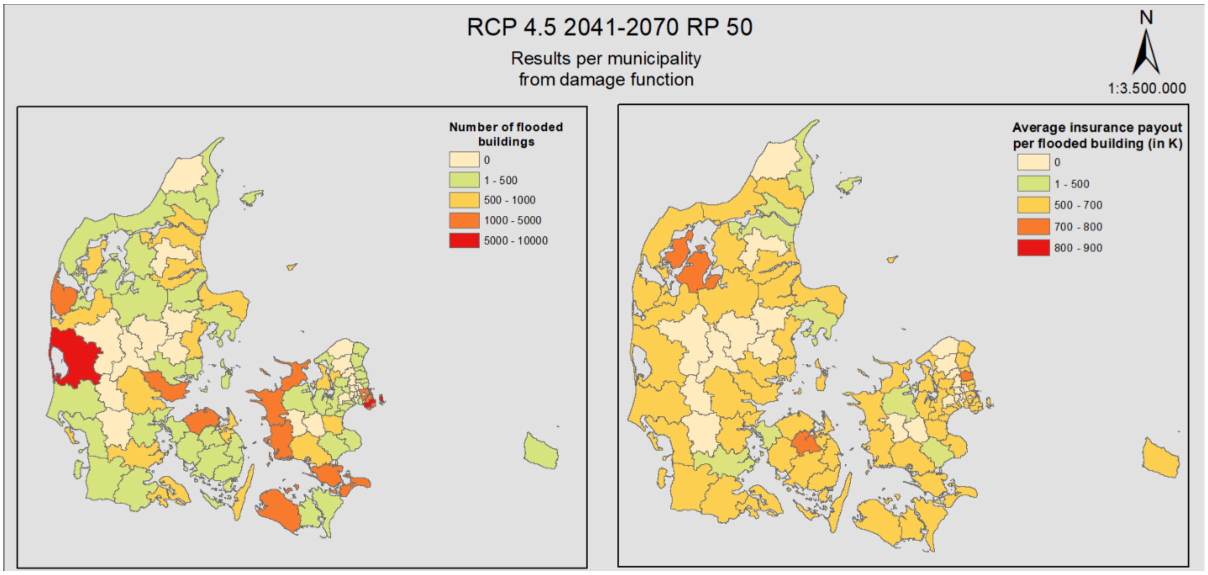


Figure 17: As for figure 17, but distributed.

3.1.2. RP100_RCP4.5_2041-2070

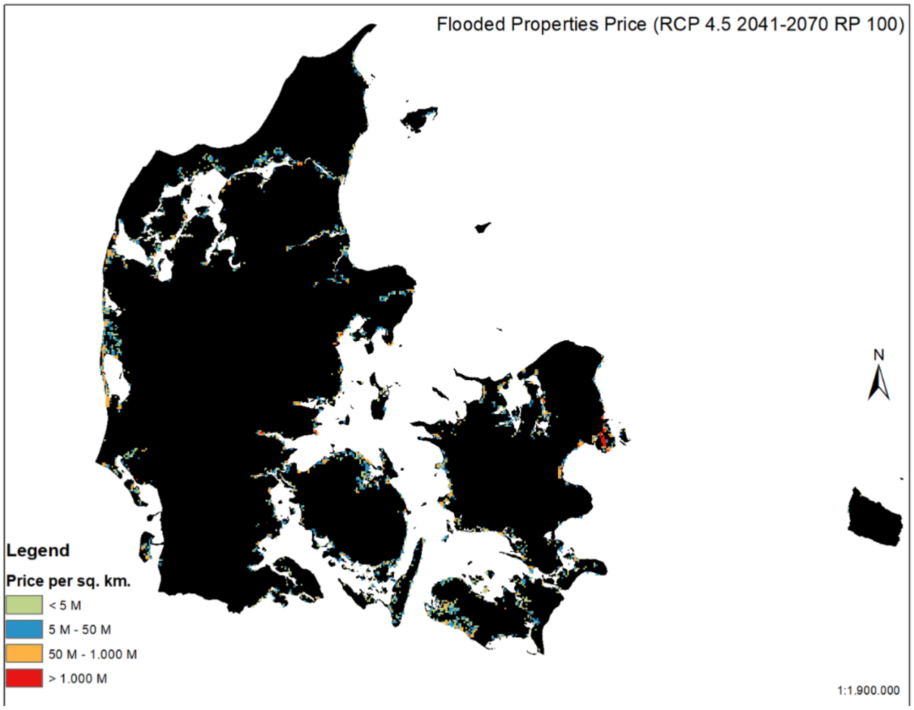


Figure 18: Sales prices of flooded properties per km^2 for the RP100_RCP4.5_2041-2070 flood scenario.

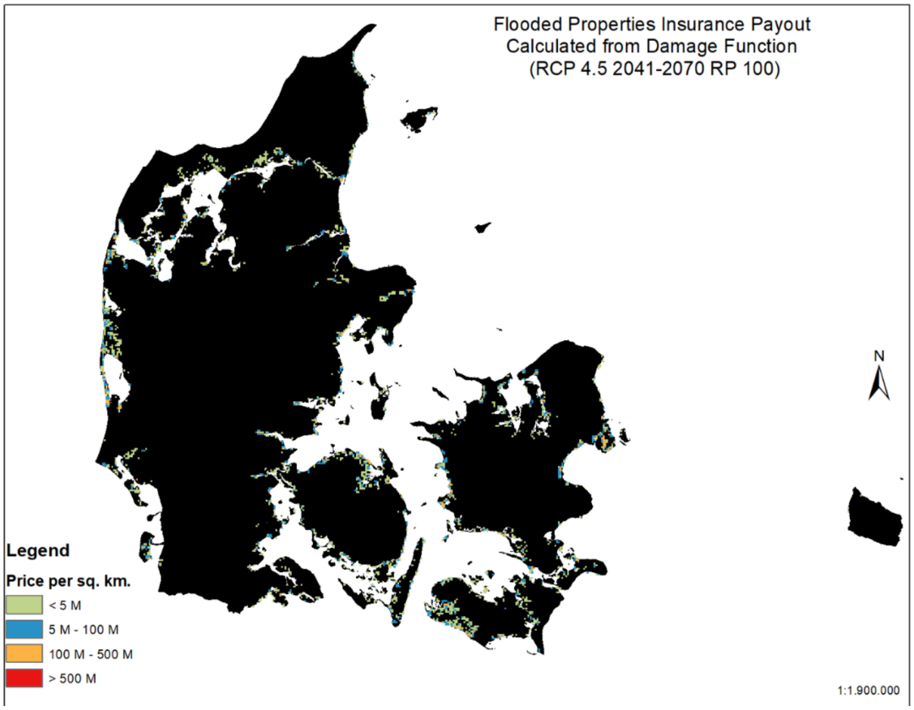


Figure 19: Insurance payout for flooded properties per km^2 for theRP100_RCP4.5_2041-2070 flood scenario.

According to the RP100_RCP4.5_2041-2070 flood scenario, the results show (figure 19) that the sales prices of flooded buildings are mostly in the 5 – 50 mio. DKK/km^2 range while the insurance payout is mostly less than 5 mio. DKK/km^2 (figure 20). Flooded areas with sales prices higher than 1.000 mio. DKK/km^2 outside of Copenhagen area are seen in Aalborg and on the western and eastern coasts of Jutland. However, high insurance payouts from flooded buildings (100 – 500 mio. DKK/km^2) are generally observed in Amager. Relative large areas of Lolland, Ringkøbing-Skjern, Køge, and western Zealand have total sales prices of flooded buildings in the 50 – 1.000 mio. DKK/km^2 range and an insurance payout less than 5 mio. DKK/km^2.

As for the previous scenario, Ringkøbing-Skjern, Tårnby and Lolland have the highest total number of flooded buildings (figure 21). More specifically, Tårnby and Ringkøbing-Skjern have 5.000 to 10.000 flooded buildings while Copenhagen, municipalities in western Zealand, municipalities located in the northern part of Odense fjord, Lemvig, Hedensted and Aalborg municipalities have 1.000 – 5.000 flooded buildings (figure 22). As in the previous flood scenario, the highest average sale prices per flooded building are observed in Copenhagen and Gentofte, and now additionally in Rudersdal. Copenhagen has the highest average sales price per flooded building (more than 20 mio. DKK), which is also related to a higher share of apartment buildings. The municipalities located in the coastal area north of Copenhagen have high average prices per flooded buildings (5 – 20 mio. DKK) even though the number of flooded buildings is low. The same range of values are seen for Aarhus, Odense, Esbjerg, Vejle and Horsens municipalities. According to the insurance payout results, the highest values of the insurance payout per building are in Odense, Esbjerg, Skive and Morsø municipality (700 – 800K DKK) and the lowest values are in Læsø and Frederikshavn municipalities (figure 23). The majority of the municipalities have a range of average insurance payout of flooded building, between 500K and 700K DKK (figure 24).

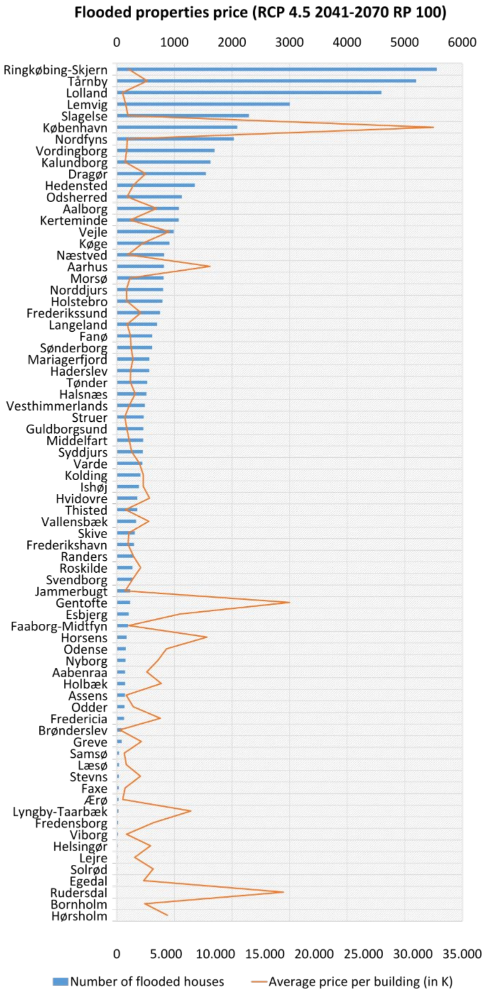


Figure 20: The number of flooded properties and the mean cost per building based on sales prices, per municipality for the RP100_RCP4.5_2041-2070 flood scenario.

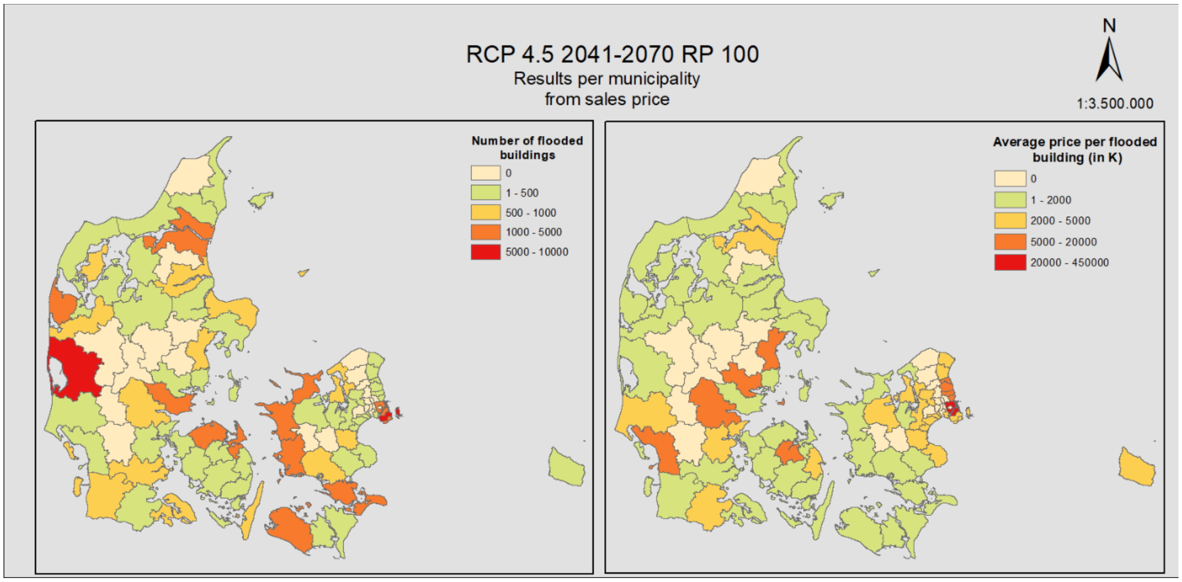


Figure 21: As for figure 21, but distributed.

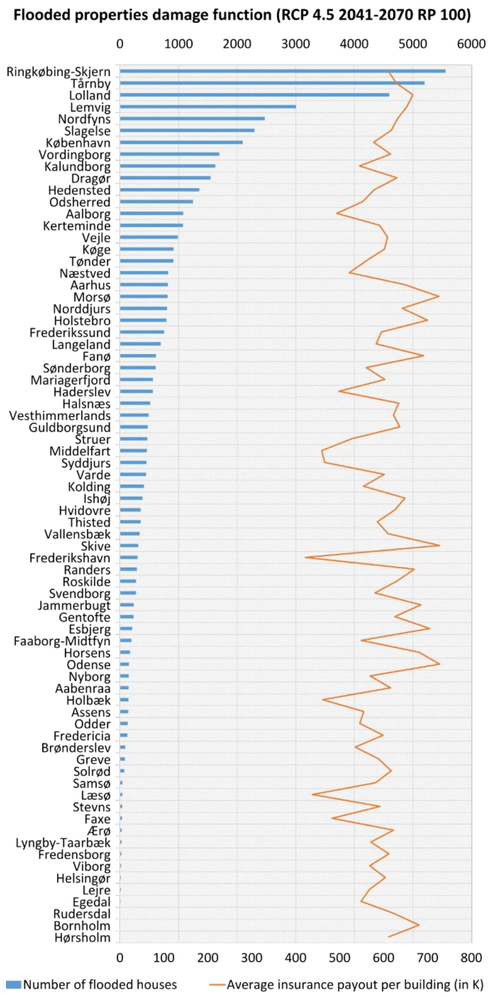


Figure 22: The number of flooded properties and the mean cost per building based on the insurance payout, per municipality for the RP100_RCP4.5_2041-2070 flood scenario.

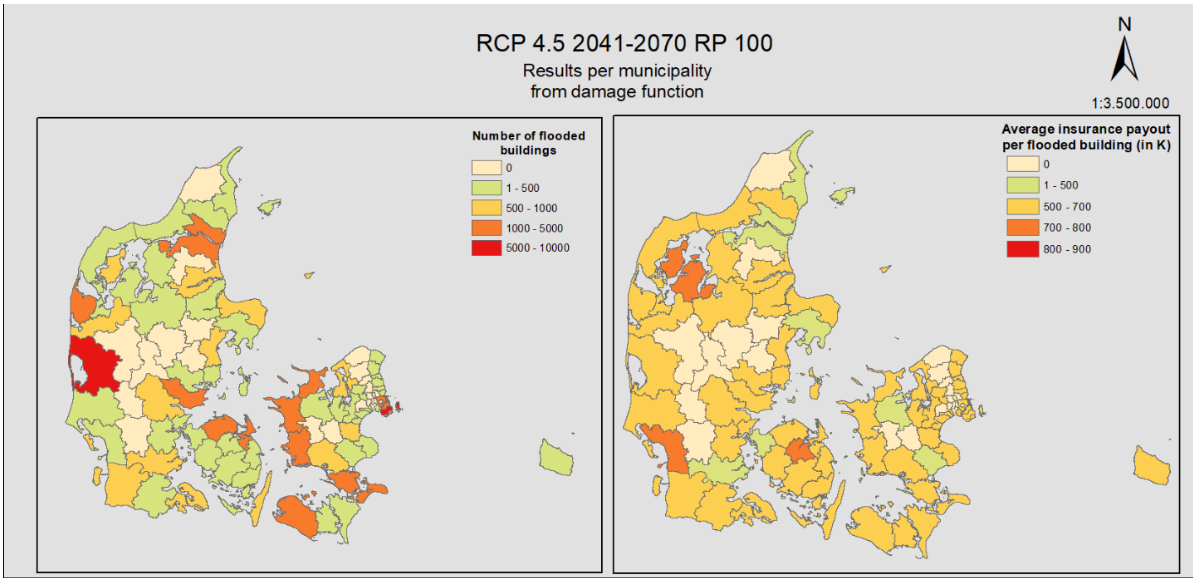


Figure 23: As for figure 23, but distributed.

3.1.3 RP100_RCP8.5_2041-2070

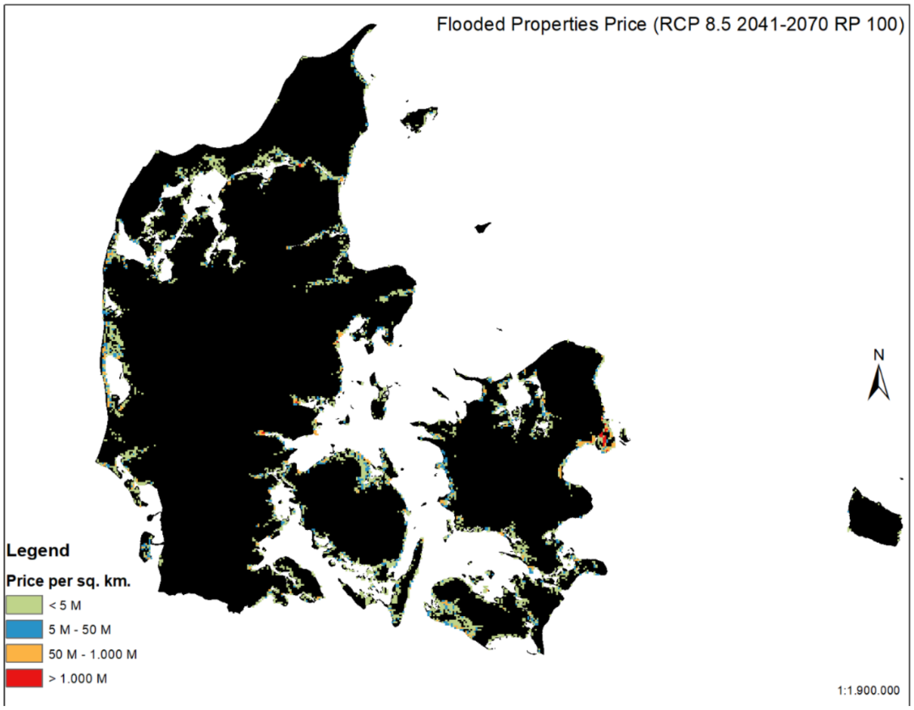


Figure 24: Sales prices of flooded properties per km^2 for the RP100_RCP8.5_2041-2070 flood scenario.

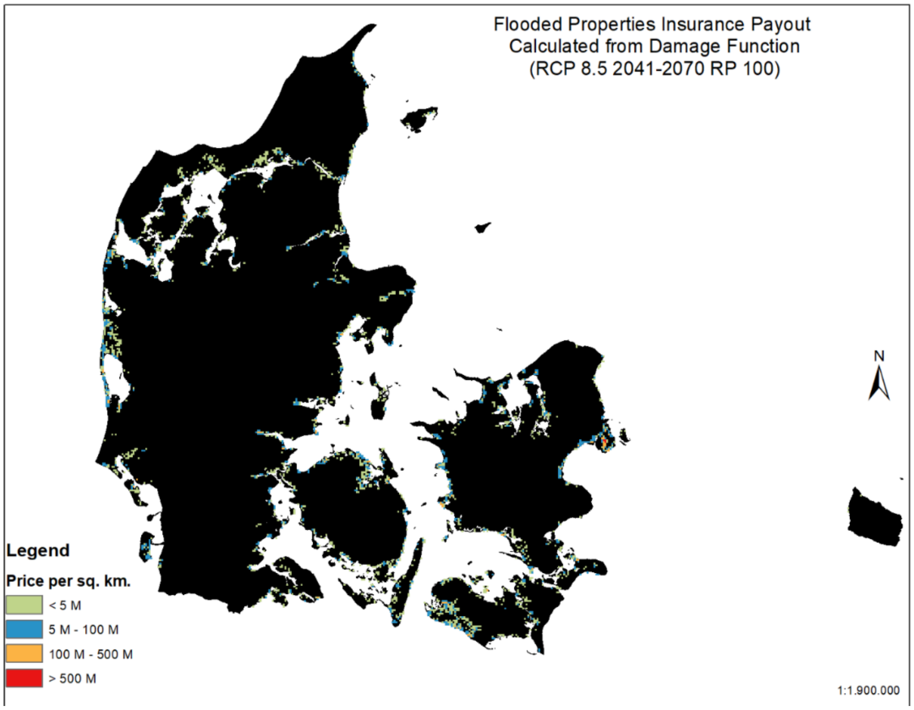


Figure 25. Insurance payout for flooded properties per km^2 for the RP100_RCP8.5_2041-2070 flood scenario.

For the RP100_RCP8.5_2041-2070 flooding scenario, larger areas on the west coast of Jutland, northern Jutland, north Fyn, Lolland and south Zealand have areas with flooded buildings, typically with damages below 5 mio DKK/km^2 (figures 25 and 26). Areas with sales prices of more than 1000 mio. DKK/km^2 are observed, in areas with larger cities on the east coast of Jutland and in the Copenhagen area while high insurance payouts (more than 500 mio. DKK/km^2) are observed in areas in Amager.

In the third flooding scenario, Lolland, Tårnby and Ringkøbing-Skjern each have more than 5.000 residential buildings flooded. However, Copenhagen, Rudersdal and Gentofte municipalities have the highest values in the average price per building (figure 27), while high values are observed also in the municipalities of Aarhus, Horsens, Esbjerg, Odense, Helsingør and Lyngby-Taarbæk (figure 28). The number of flooded buildings is smaller in the majority of the northern municipalities of Copenhagen, but the average sale price per building is relative high especially for the eastern municipalities. On the other hand, in Lolland, Falster and western parts of Zealand, the average sale price is lower even though the number of flooded buildings is high. This is the case also in Ringkøbing-Skjern municipality where there are almost 6.000 residential buildings flooded but with an average price per flooded building not exceeding 2 mio. DKK. As for the insurance payout, the majority of municipalities in Denmark have a value between 500K and 700K DKK (figure 29). The lowest payout per building (around 300K DKK) is observed in Gribskov municipality and the highest (around 730 DKK) at Morsø. Municipalities with a high insurance payout per building are Odense, Esbjerg, Horsens, Holstebro, Skive and Morsø (figure 30).

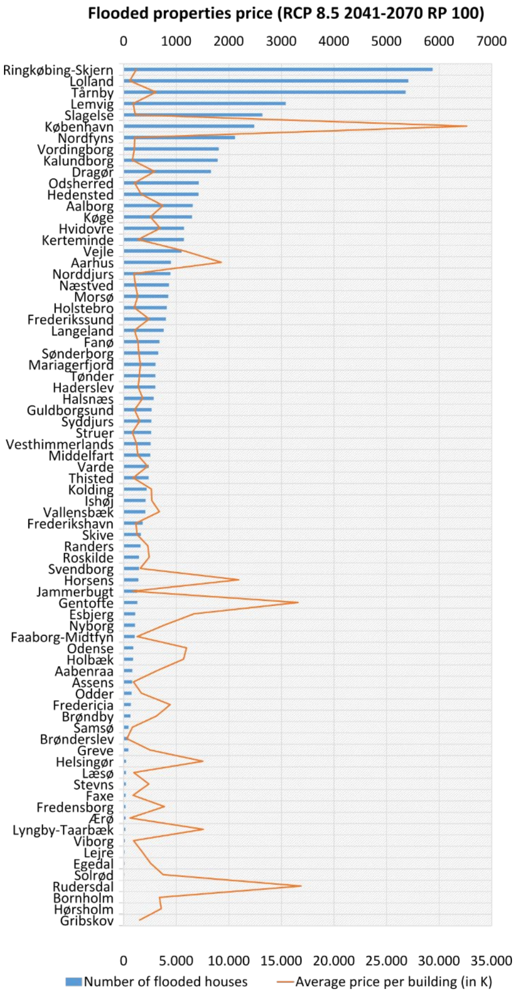


Figure 26: The number of flooded properties and the mean cost per building based on sales prices, per municipality for the RP100_RCP8.5_2041-2070 flood scenario.

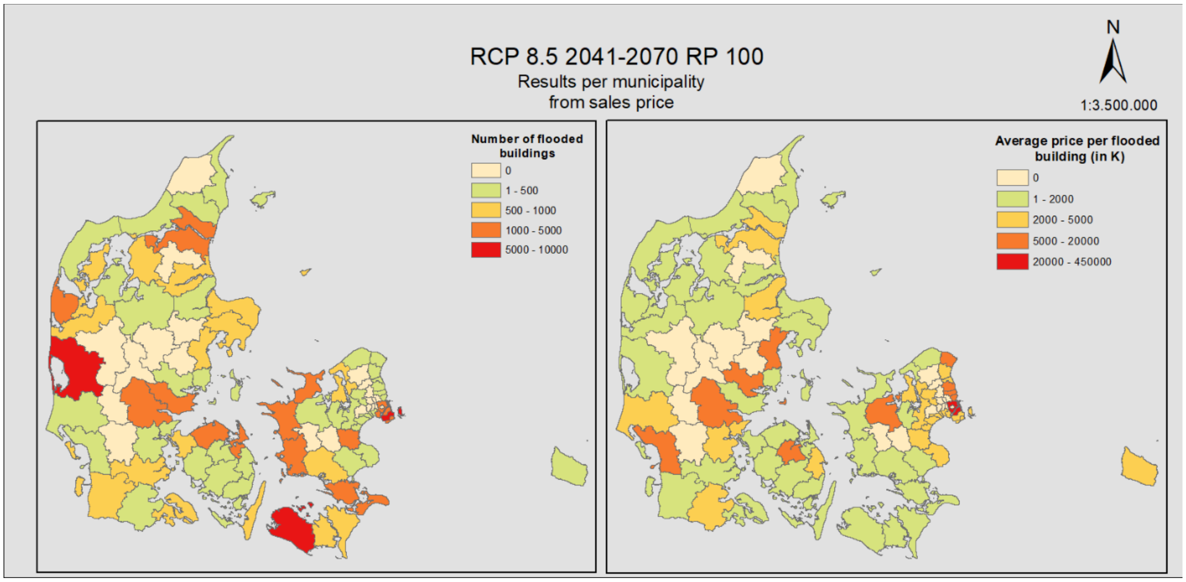


Figure 27: As for figure 27, but distributed.

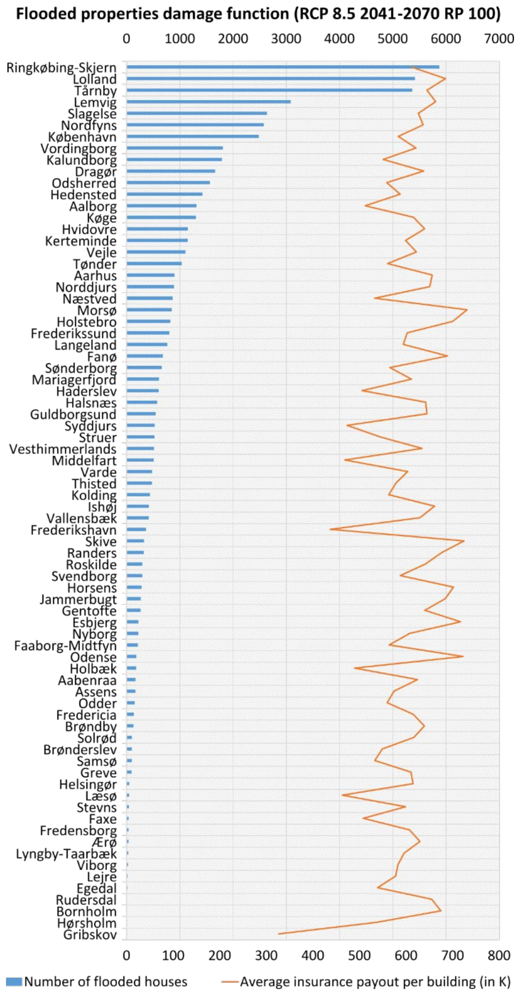


Figure 28: The number of flooded properties and the mean cost per building based on the insurance payout, per municipality for the RP100_RCP8.5_2041-2070 flood scenario.

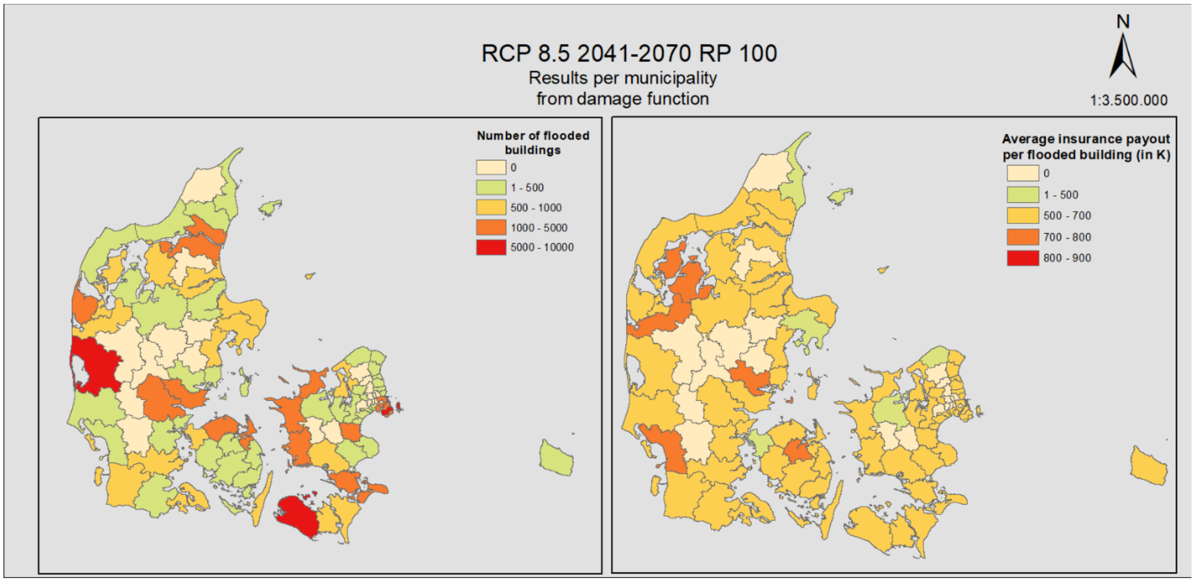


Figure 29: As for figure 29, but distributed.

3.1.4 RP100_RCP8.5_2071-2100_90th

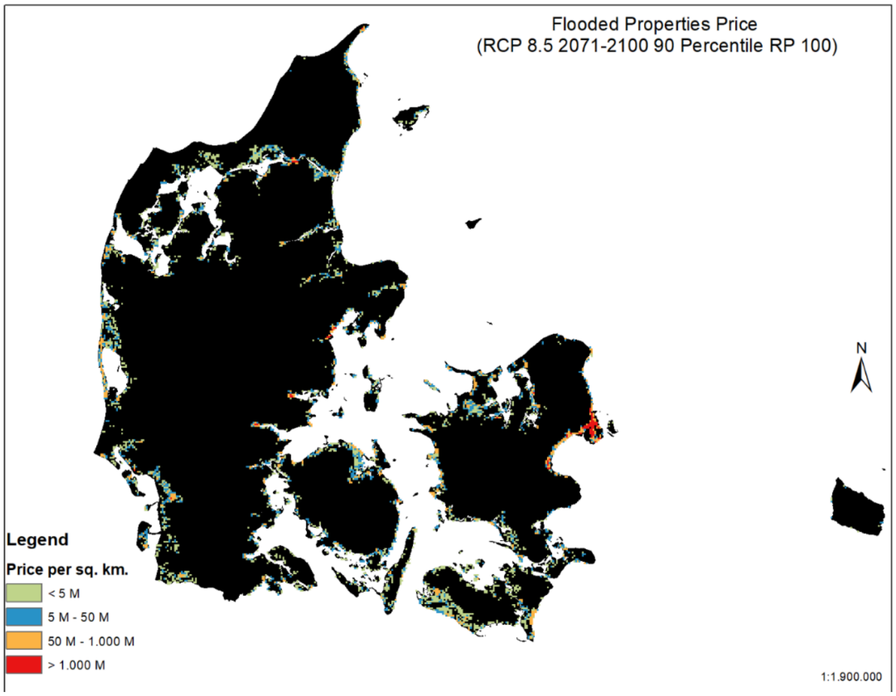


Figure 30: Sales prices of flooded properties per km² for the RP100_RCP8.5_2071-2100_90th flood scenario.

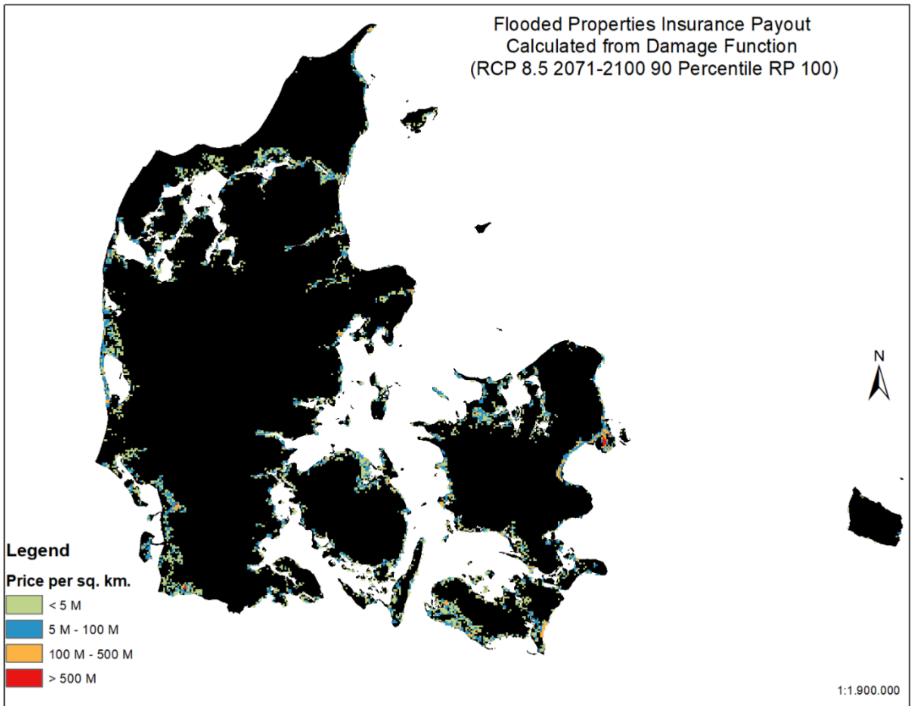


Figure 31: Insurance payout for flooded properties per km² for the RP100_RCP8.5_2071-2100_90th flood scenario.

For the most severe flooding scenario addressed in this report (RP100_RCP8.5_2071-2100_90th), larger areas with flooded residential buildings are seen in Lolland, close to Odense and Isefjord, the west coast of Jutland and areas close to Aalborg. The same applies for the coastal areas close to Copenhagen and Amager (figure 31). The sales prices of flooded buildings per km^2 are higher mostly close to Copenhagen and in smaller areas in eastern Jutland around larger cities such as Aarhus, Vejle and Horsens. High insurance payouts are also seen in Amager (more than 500 mio. DKK/km^2) (figure 32). Many areas in Køge bugt and some areas on Falster have relative large (100 – 500 mio. DKK/km^2) insurance payouts for flooded buildings. Also, the coastal areas of western Jutland, Lolland and the fjords seem to have large areas with a 5 – 100 mio. DKK/km^2 insurance payout.

For this severe flooding scenario, the highest number of flooded buildings are located in Copenhagen, Guldborgsund, Lolland, Ringkøbing-Skjern, and Tårnby municipalities (figure 33). Many of the coastal municipalities have more than 1.000 residential flooded buildings each (figure 34). Despite the large number of flooded buildings, the average price per flooded building in the majority of the municipalities of Denmark is in the relative lower range of 1 – 2.000K DKK. Municipalities with high values (more than 5.000K DKK) of average price per flooded buildings include Copenhagen, Aarhus, Horsens, Vejle and the majority of coastal municipalities north of Copenhagen. In this scenario, municipalities of Copenhagen and Guldborgsund have the highest total number of flooded buildings (slightly bigger than 9.000) (figure 35). The average payout per building, with few exceptions, seems to be very close to 700K DKK in all municipalities in Denmark. The municipalities of Tønder and Esbjerg have the highest average insurance payout per building (800K – 900K DKK) (figure 36). Compared to Copenhagen, the average payout is higher in municipalities among Jutland and some regional municipalities of Copenhagen.

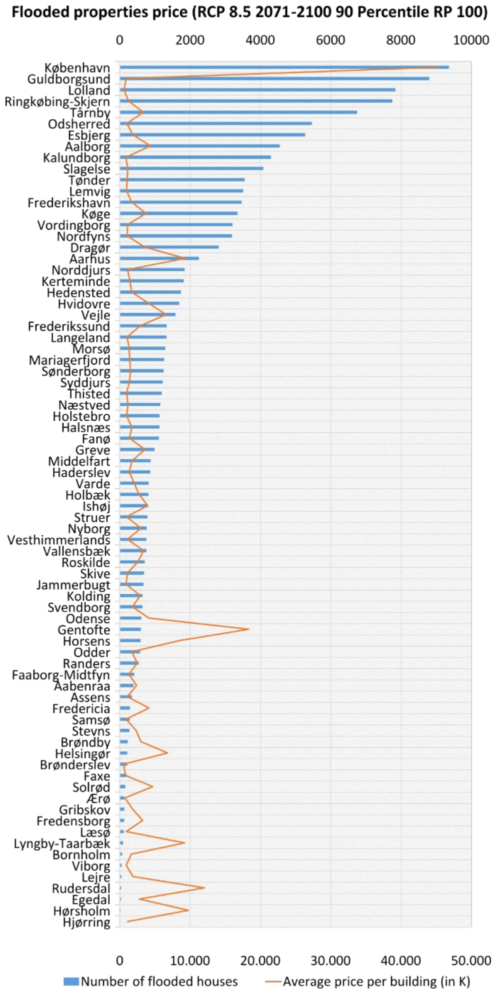


Figure 32: The number of flooded properties and the mean cost per building based on sales prices, per municipality for the RP100_RCP8.5_2071-2100_90th flood scenario.

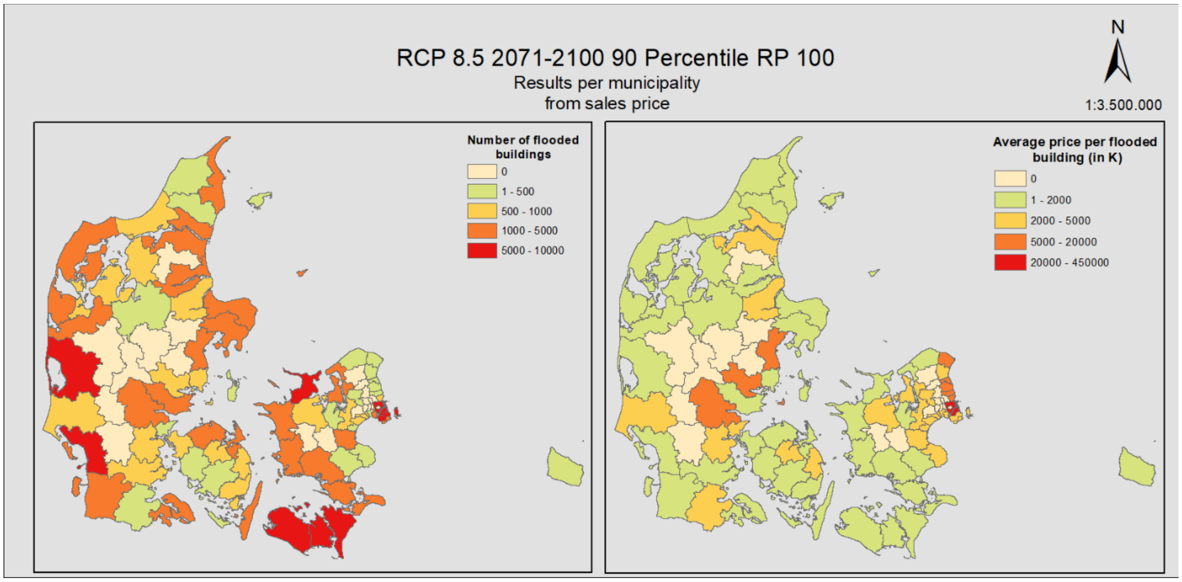


Figure 33: As for figure 33, but distributed.

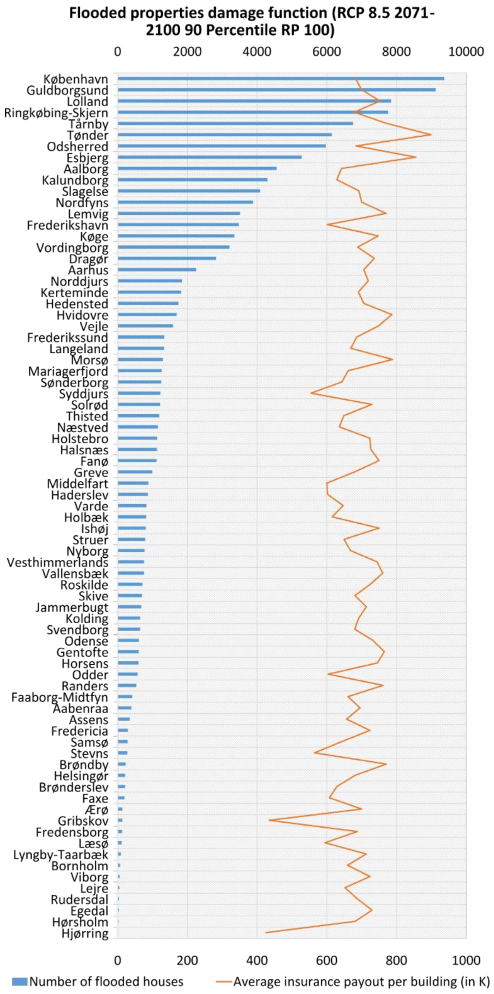


Figure 34: The number of flooded properties and the mean cost per building based on the insurance payout, per municipality for the RP100_RCP8.5_2071-2100_90th flood scenario.

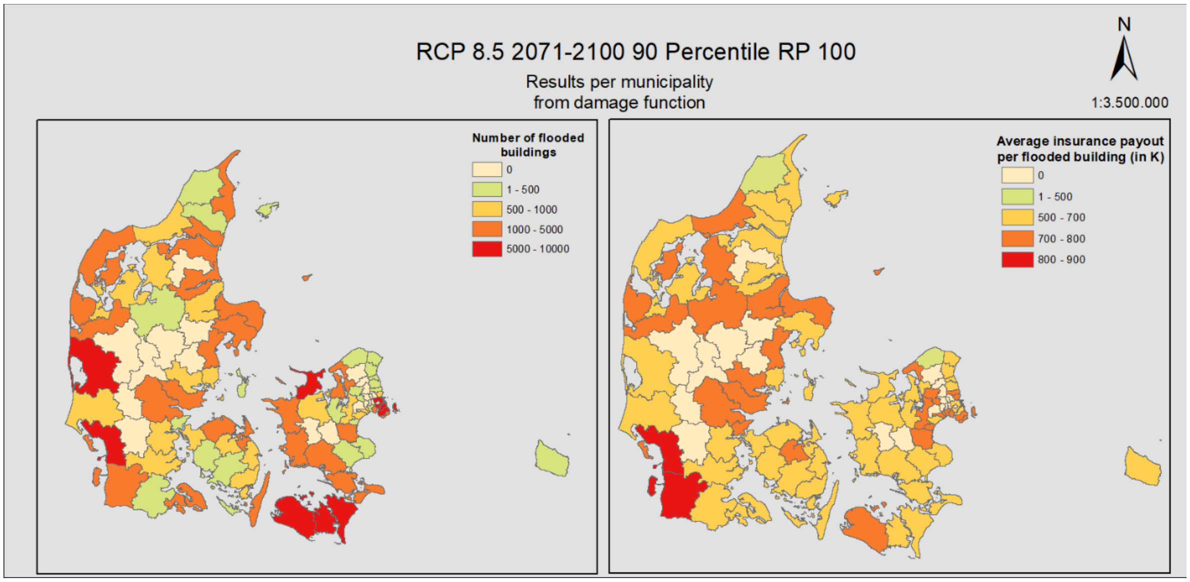


Figure 35: As for figure 35, but distributed.

3.2 Local scale results

3.2.1 Aabenraa

Figure 37 shows the total flooded area for the dynamic and static model for the four different scenarios in Aabenraa. For the highest scenario, the static model estimates the flooded area to be just 11% larger than the dynamic whereas the difference is 183% for scenario 3, 252% for scenario 2, and 309% for scenario 1 (table 1).

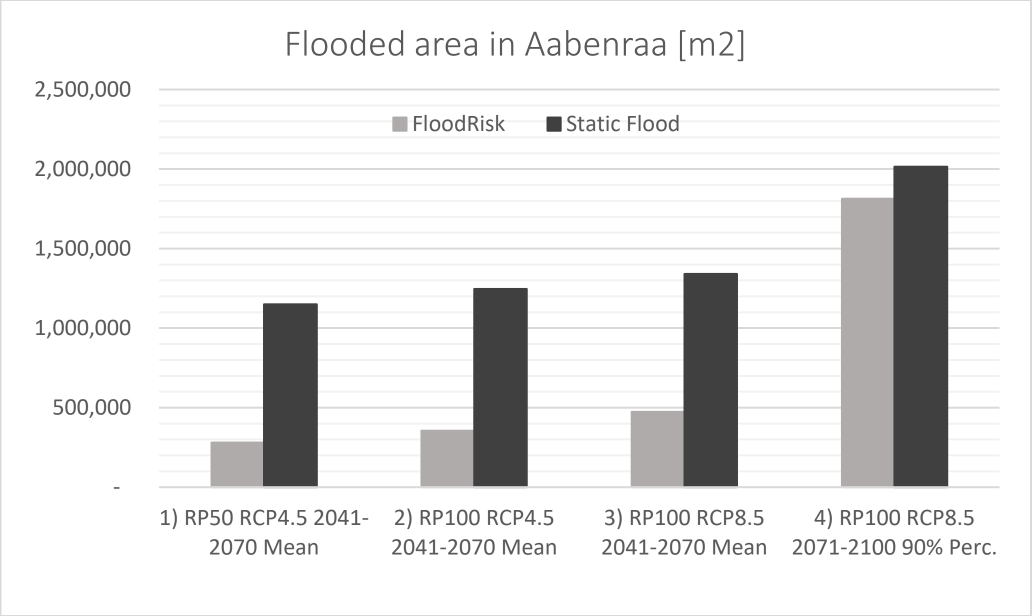


Figure 36: Flooded area (m2) in Aabenraa of the four climate scenarios for both a dynamic (FloodRisk, (DHI, 2020)) and static flood model

Figure 38 A-D show the spatial distribution of the flooded area of the RP100_RCP8.5_2071-2100_90th and RP100_RCP8.5_2041-2070 scenarios for the dynamic and static flood model, respectively. It resembles figure 37, as the models present an almost identical results in the highest scenario (Figure 38B and Figure 38D) whereas there is an extremely large difference between figure 38A and figure 38C. In both static model scenarios and the dynamic RP100_RCP8.5_2071-2100_90th scenario (figure 38A, figure 38B and figure 38D), the water reaches the main western road, which acts as a natural water barrier protecting the city behind it. In the dynamic RP100_RCP8.5_2041-2070 scenario, the water is not able to reach this border due to the storm duration (figure 38C), but is mainly flooding the harbor and industry area in the northern part of the city.

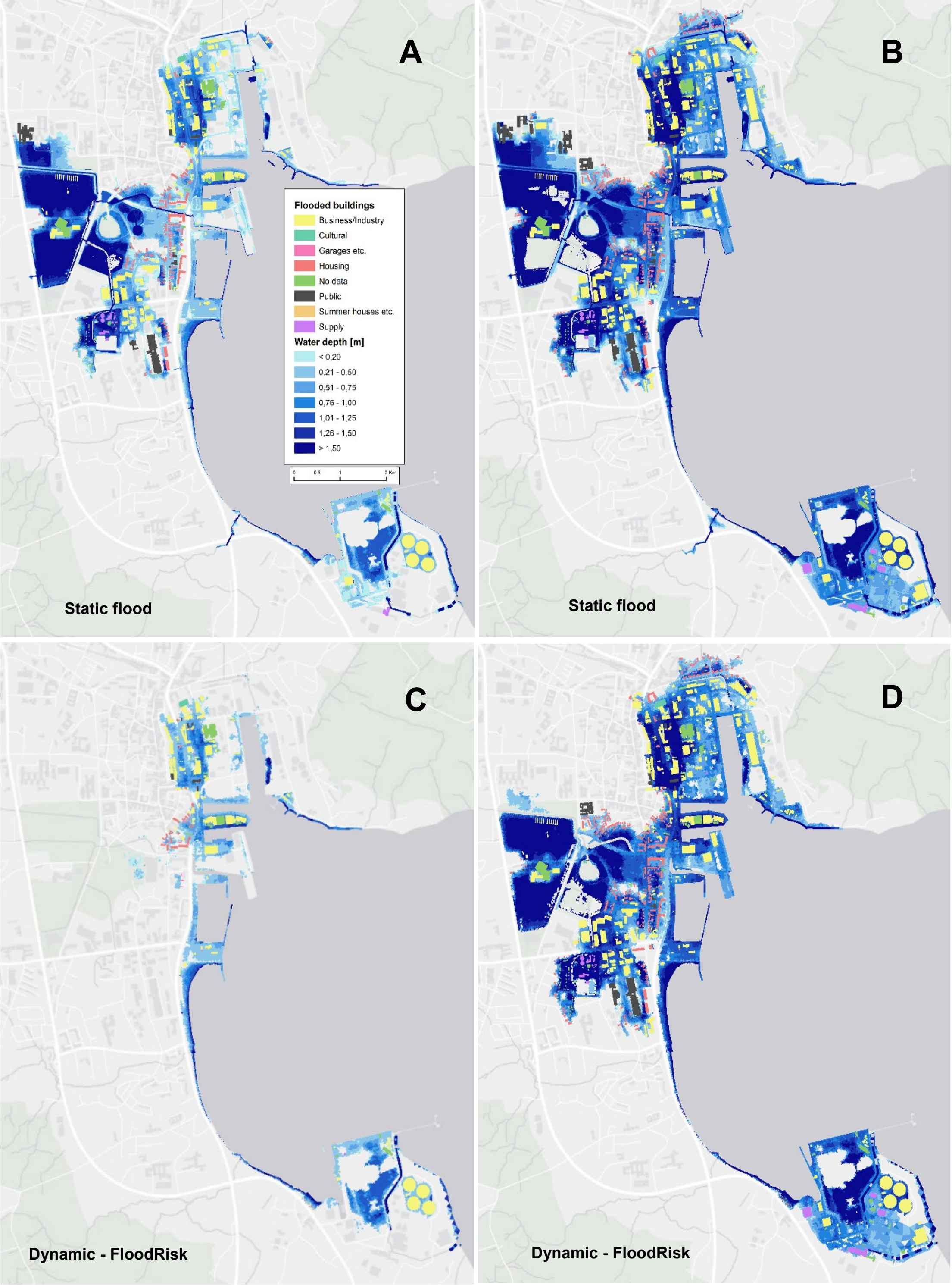


Figure 37: Flooded area and buildings in Aabenraa for A) Static flood, RP100_RCP8.5_2041-2070, B) Static flood, RP100_RCP8.5_2071-2100_90th, C) Dynamic flood, RP100_RCP8.5_2041-2070, D) Dynamic flood, RP100_RCP8.5_2071-2100_90th.

Studying the flooded buildings in each scenario, it becomes evident that they generally follow the same pattern as presented in figure 37 and figure 38(A, B, C and D). There is a gradual decrease in the number of flooded buildings from the highest to lowest scenario with static model having the largest number in each scenario (figure 39.1- figure 39.4). For the static model, the majority of flooded buildings are mainly business/industry, housing, garages, and no data, whereas for the dynamic model it is no data and business/industry. In the highest scenario the static and dynamic model have an almost identical distribution and total number of flooded buildings at around 1100 (figure 39.4). In the three remaining scenarios, the total number of flooded buildings are 192%-330% larger for the static flood compared to the dynamic (figure 39.1, figure 39.2, figure 39.3 and table 1) for the same scenario. This point to the fact that the larger flooded area by the static model, compared to the dynamic model, leads to an increase in the number flooded buildings. As seen in table 1, the less severe events show a larger difference between the models, both in terms of flooded area and flooded buildings. This is due to time factor of the dynamic flood limiting the water from reaching the in-land depressions.

Scenario	Flooded area	Total buildings
1) RP50_RCP4.5_2041-2070	309%	330%
2) RP100_RCP4.5_2041-2070	252%	289%
3) RP100_RCP8.5_2041-2070	183%	192%
4) RP100_RCP8.5_2071-2100_90th	11%	3%

Table 1: Difference between (%) the static flood model and the dynamic model in Aabenraa (static model is higher).

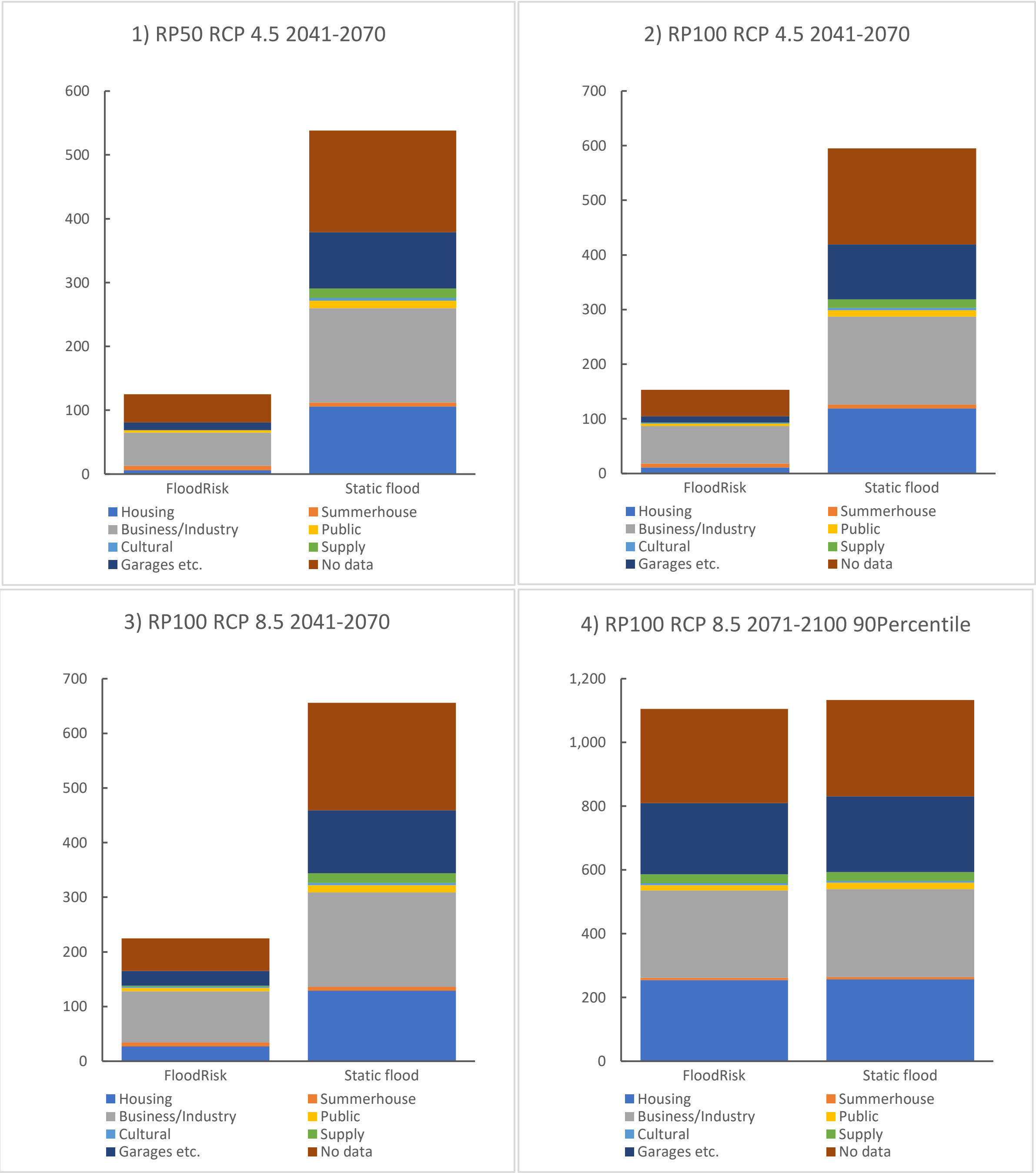


Figure 38: Number of flooded buildings in Aabenraa for the four flooding scenarios calculated using both a static and dynamic flood model. 1) RP50_RCP4.5_2041-2070, 2) RP100_RCP4.5_2041-2070, 3) RP100_RCP8.5_2041-2070, 4) RP100_RCP8.5_2071-2100_90th.

3.2 Odense

The dynamic modelling for Odense presented here is a FloodRisk model setup (DHI, 2020) based on the Mike Flood model which is also used in the risk area assessment by the Danish Coastal Authority (Kystdirektoratet, 2020). Figure 40 shows the total flooded area for each the four scenarios in Odense using the dynamic and the static model. For each model, there is a gradual increase in the flooded area from the lowest to highest scenario, but for scenarios 1 – 3, the increase is very limited. This indicates that one or more barriers are stopping the water in the first three scenarios, but that the barriers are eventually flooded. This is evident in figure 41A and figure 41B for the dynamic and static model, respectively. Furthermore, it is worth noting that the flooded area of the static model scenario 1 is almost identical to the dynamic model scenario 4 (figure 40, figure 41A, figure 41B).

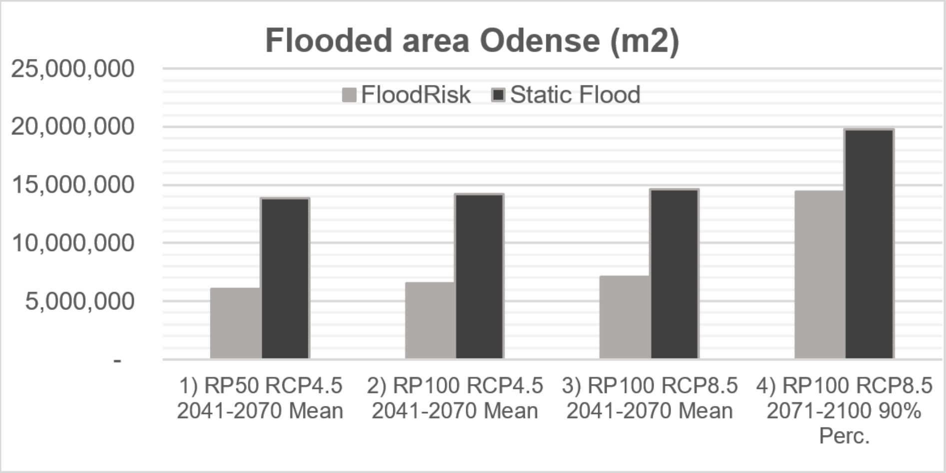


Figure 39: Flooded area [m2] in Odense of the four climate scenarios for both a dynamic (FloodRisk) and static flood model.

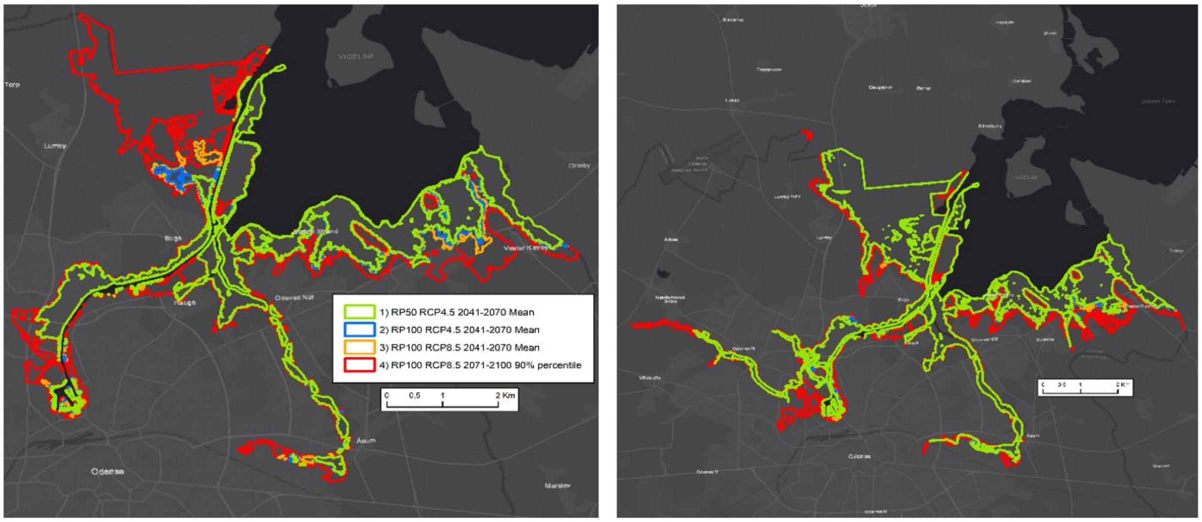


Figure 40: Flooded area of the four scenarios in Odense. Left) Dynamic model, right) Static model.

The number of flooded buildings for each flooding scenario is presented in figure 42.1-4. As expected, scenario 4 has the highest number of flooded buildings with 2862 and 2365 for the static and dynamic model, respectively (figure 42.4). Within each model type, scenario 1-3 has a similar amount of flooded buildings, thereby mimicking the flooded area in figure 40 and figure 41. In scenario 1, 2, and 3 (figure 42.1, figure 42.2 and figure 42.3) the number of buildings in the supply category is larger in the dynamic model compared to the static. This shows that the static model does not only flood a larger area but also misclassify areas as areas as non-flooded, which the dynamic model finds to be flooded. An example of this can be seen in figure 43.

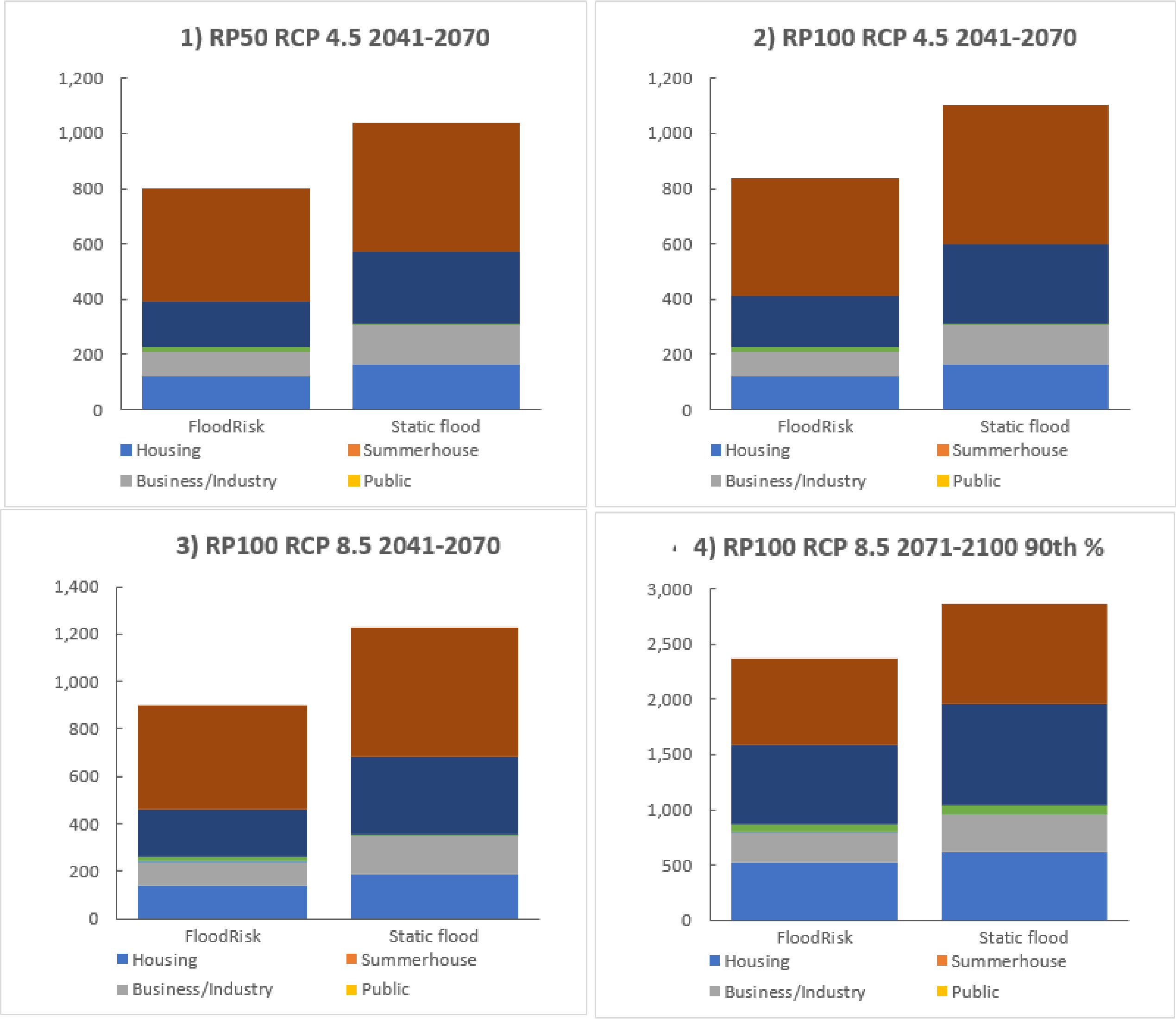


Figure 42: Number of flooded buildings in Odense for the four flooding scenarios calculated using both a static and dynamic flood model. 1) RP50_RCP4.5_2041-2070, 2) RP100_RCP4.5_2041-2070, 3) RP100_RCP8.5_2041-2070, 4) RP100_RCP8.5_2071-2100_90th.

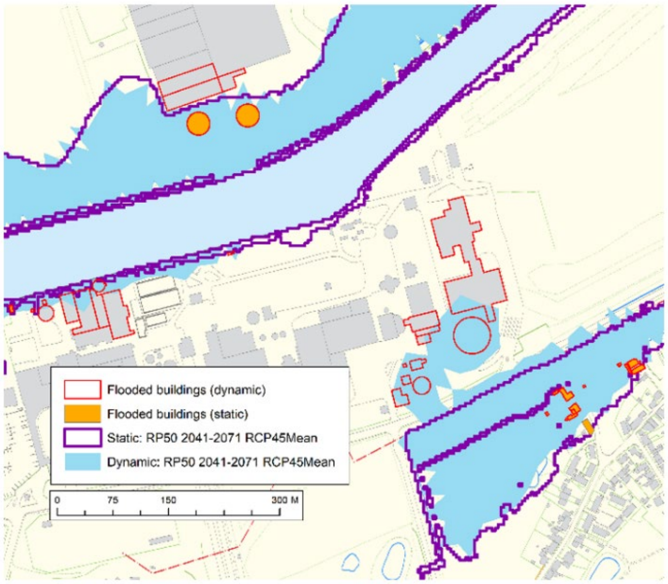


Figure 43: Example of misclassified flooding of the static model.

Table 2 shows the relative differences (%) between the static and dynamic models for Odense and as expected the static model estimates the highest levels for both the flooding and the number of flooded buildings in all scenarios. Of all flooding scenarios, scenario 4 has the lowest relative differences (37% flooding and 21% flooded buildings), which was also the case in Aabenraa (table 1). The gradual decrease seen in the flood area relative difference moving from scenario 1 (128%) to 4 (37%) is not mirrored in the number of flooded buildings which peaks in scenario 3 at 36% (table 1). This stresses the point that a higher estimation of the flooded area does not necessarily lead to a higher estimation of flooded buildings as it depends on the land use of the additional flooded area, which again underlines the importance of local scale and high-detail analyses when implementing adaptation or damage prevention measures. In general, the higher estimation of the flooded area and flooded buildings for the static model compared to the dynamic is much lower for Odense compared to Aabenraa. This demonstrates the difficulties of identifying a national scaling factor to adjust for the higher estimation of the static flood model results, but instead stresses the need for local dynamic flood model.

Scenario	Flooded area	Total buildings
1) RP50_RCP4.5_2041-2070	128%	28%
2) RP100_RCP4.5_2041-2070	118%	32%
3) RP100_RCP8.5_2041-2070	105%	36%
4) RP100_RCP8.5_2071-2100_90th	37%	21%

Table 2: Difference between (%) the static flood model and the dynamic model in Odense (static is higher).

6 Perspectives and further research

The core focus in this report is the differences in resulting damage cost estimates between two flood-modelling approaches and two ways to account for affected damages. The latter two are not directly comparable but each represent different ways to calculate resulting damages. For the national scale results, actual damage costs have been depicted, whereas the local scale results have been shown in terms of affected buildings and area only. This is because specific local scale damage costs are somewhat outside the scope of this report and requires special attention when disseminated, but also because other ongoing projects, such as COHERENT (COHERENT, 2020) will address these issues on damage cost in more detail.

7 Conclusions and uncertainties

In the study, the damage costs were calculated on the national scale based on two approaches: 1) Damage costs of flooded buildings based on insurance payouts from previous events and 2) the cost of buildings within flooded areas based on sales prices. Further, and on the local scale, two different approaches to flood estimates were employed: A static storm surge model and a dynamic storm surge model.

In the national scale analysis, Ringkøbing-Skjern, Lolland, and Tårnby are the municipalities with the largest number of flooded houses from the lowest flooding scenario (RP50_RCP4.5_2041-2070). For highest flooding scenario in this study (RP100_RCP8.5_2071-2100_90th), Copenhagen and Guldborgsund municipalities have the largest number of flooded buildings of +9.000 for both municipalities. Due to differences in sales prices, there is not a clear correlation between the number of flooded buildings and the total cost of floods across municipalities in Denmark. For example, Copenhagen and Gentofte municipalities have very high costs per flooded building. However, due to the aggregated level of sales prices on the municipal level, although still obtained separately for each building category, the effect of e.g. expensive holiday housing close to the coast is somewhat lost.

The damage costs are much more evenly distributed between municipalities (of similar flood level) when using the insurance based damage cost. This is because this method implies the same assumptions on the correlation between water level and insurance payout across municipalities. Since the damage function is based on a relative small sample of events with a very localized extent (many samples were from Jyllinge Nordmark for the 2013 Bodil storm surge), the geographical dependencies are not well reflected. With more samples as the basis for the damage function, this could be improved and maybe even differentiated geographically.

Some flooded buildings have no information about their building type, which means that they are excluded from the calculations of both methods. By investigation, these are however likely in categories of lower value such as outhouses etc. In other cases, some buildings have information about their type but no data on size, and therefore these were included in the calculations of damage function but not in the sales price method. This led to some differences in the number of flooded buildings for the two methodologies. In summary and related to the relative extent, these uncertainties do not affect the key conclusions shown here.

It is outside the scope of this report to analyze the influence of uncertainties in return period levels. However, and as a general remark, it is obvious that a very-high impact event with a magnitude that would significantly alter the return period statistics, would also affect the resulting damage cost calculations.

The locale scale analysis showed that the static model leads to floods that cover a significantly larger area compared to dynamic model in both Aabenraa and Odense. In both cases, there is a gradual decrease in the relative difference in the flooded area going from scenario 1 (lowest) to scenario 4 (highest), with Aabenraa showing the largest relative differences (309%). In Aabenraa, the relative difference in the number of flooded buildings mirror the relative differences in the flooded area. However, this was not the case for Odense, underlining that there is no correlation between the flooded area and the number of flooded buildings and stressing the need for localized dynamic flood modelling when working with local climate adaptation.

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