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# Integrated climate change risk assessment: A practical application for urban flooding during extreme precipitation

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ABSTRACT

Risk assessments of flooding in urban areas during extreme precipitation for use in, for example, decision-making regarding climate adaptation, are surrounded by great uncertainties stemming from climate model projections, methods of downscaling and the assumptions of socioeconomic impact models. The multidisciplinary character of such risk assessments also requires that research groups and experts from different scientific disciplines combine knowledge and share model outputs. This paper describes an integrated framework and tool, the Danish Integrated Assessment System (DIAS), which has been designed to address the complex linkages between the different kinds of data required in assessing climate adaptation. It emphasizes that the availability of spatially explicit data can reduce the overall uncertainty of the risk assessment and assist in identifying key vulnerable assets. The usefulness of such a framework is demonstrated by means of a risk assessment of flooding from extreme precipitation for the city of Odense, Denmark. A sensitivity analysis shows how the presence of particularly important assets, such as cultural and historical heritage, may be addressed in assessing such risks. The output of the risk assessment for Odense indicates that highly detailed geographical data reduce the overall uncertainty and assist climate adaptation decision-makers in focusing on protecting those assets that are considered to be relevant in the given context. Also, using an integrated framework such as DIAS enables the relative importance of the different factors (i.e. degree of climate change, assets value, discount rate etc.) to be determined, thus influencing the overall output of the assessment.



**Practical Implications**

Cities are facing increasing risks from flooding caused by extreme precipitation events, making housing, traffic, health, ecosystems and cultural and historical heritage vulnerable. Accordingly, planning adaptation measures has become a high priority for local government authorities and property owners in cities. However, the cost-effective planning of adaptation strategies is very complicated. The integrated assessment of climate events, associated flooding, damage costs and adaptation measures requires multidisciplinary work and close interaction between professionals and decision-makers. Damage cost assessments and adaptation planning also require context-specific data and modelling, which, taken together, can be very demanding in seeking to develop a basis for solid local decision-making. This paper presents an integrated framework and tool, the Danish Integrated Assessment System (DIAS) for localized risk assessments, which can support context-specific assessments of how cities may adapt to climate change. We exemplify the usefulness of such a framework though a case study of cost assessments of damage caused by urban flooding during high-intensity precipitation for the city of Odense, Denmark. DIAS contains a very rich database on climate, land cover and socioeconomic activities for Denmark, which provides a basis for spatially detailed assessments of the climate risks for various assets and for society as a whole. It may serve as an inspiration for the development of similar open-access databases both regionally and globally.

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## 1. Introduction

Risk analysis for current and future extreme precipitation in urban areas is surrounded by great uncertainties originating from complex linkages of climate models, methods of downscaling, impact assessments and socioeconomic impact models (Schneider, 1983; Moss and Schneider, 2000; Heal and Kristrom, 2002; Wilby and Dessai, 2010; Weitzman, 2011). The uncertainties related to the different steps in an integrated risk assessment have different characteristics. Structural uncertainties reflect incomplete understandings of the processes and components of the earth system in climate and impact models, while other uncertainties are related to economic models, where valuation issues, risk attitudes and discounting approaches can play a major role (Mastrandrea et al., 2010; Halsnæs et al., 2015). As Hawkins and Sutton (2011) and Wilby et al. (2014) argue, some climate change impacts, like extreme precipitation in local areas, are surrounded by particularly large uncertainties. Precipitation projections are in general very uncertain and predominantly short term, as there is a lot of noise from natural fluctuations (Field et al., 2012). The downscaling of the frequencies and intensities of extreme precipitation events to relevant geographical scales – here specific urban areas – adds yet another large element of uncertainty (Schneider, 1983; Sunyer et al., 2015a). Against this background, it can be argued that risk assessments of flooding in cities during extreme precipitation face these uncertainties simply because it is very difficult to estimate the probability of low-frequency, high-intensity events for specific locations. When assessing the risks of extreme events, it is therefore important to recognize that, although probabilities are very uncertain, large-scale consequences might occur, and that the willingness to pay (WTP) for avoiding them will then be very dependent on the general risk-averse attitudes of decision-makers and of society as a whole (Weitzman, 2011; Halsnæs et al., 2015). Recognizing these limitations, an analysis based on extreme rainfall simulations using flood models, combined with damage cost assessments and economic valuations, can still provide important insights into the specific consequences of flooding from extreme rainfall both today and in the future. Additionally, studies can also be supported by available data on insurance claims from past events that provide evidence for the physical and economic consequences of similar extreme rainfall events.

This paper presents an integrated framework and tool, the Danish Integrated Assessment System (DIAS), for localized risk assessments, and highlights key uncertainties related to modelling tools, data and assumptions. The usefulness of such a framework is demonstrated by a case study of urban flooding during high-intensity rainfall for the city of Odense, Denmark. We selected Odense as a case study for this paper due to the availability of most of the relevant information and of the data needed to conduct an integrated risk assessment successfully. However, as the integrated risk assessment method presented here is highly generic, we consider the approach appropriate for use in urban areas elsewhere, both regionally and globally. DIAS has been developed as a tool for facilitating short- to medium-term climate change risk analysis covering a time frame of ten to fifty years and beyond, the aim being to support decision-making in respect of local climate change adaptation, for example, for urban areas (Skougaard Kaspersen et al., 2012). It includes a very rich database on climate, land cover and socioeconomic activities for Denmark, which provides a basis for spatially detailed assessments of the climate risks to various assets and to society as a whole. In terms of the planning perspectives of governments and stakeholders, DIAS facilitates a broad cross-cutting assessment of climate risks associated with infrastructure, buildings, public services, nature, health and historical and cultural heritage. Also, it is shown how the uncertainties of a risk assessment can be reduced by using a detailed context-specific approach, where it is possible to identify particularly vulnerable areas. This enables the risk assessment to focus on more detailed climate data and impacts for specific areas, rather than on risk assessments, where uncertainties related to different modelling components are concealed by aggregation. Detailed assessments are made possible by open access to spatial data on land use, drainage systems, buildings, ecosystems and socioeconomic factors, on which basis critical flood risk areas and damage thresholds can be identified.

## 2. Methods and materials

### 2.1. Risk assessment

For the purposes of this paper, climate change risks are defined as the probability of a specific climate event multiplied by the consequences of that particular event. The risk of an event is thus based on a combination of information, from downscaled climate model outputs and spatially explicit impact assessments. Subsequently, the consequences can be assessed in the form of costs by assessing the value of those assets that are affected by the extra risk caused by climate change using methods of economic valuation. A generic structure for climate impact and risk assessment is presented in Fig. 1. It shows how information about the climate system, impacts, damage and related costs can support risk assessments.

Several linked modelling steps are included in risk assessments. Depending on the specific focus of the individual assessment, each step will include their own uncertainties, data limitations and/or the structural weaknesses of models and methodological frameworks. In discussing the case study of urban flooding in the city of Odense, we will highlight key uncertainties and suggest approaches for reducing them. Rather than going into all the sub-components of the assessment in depth, we will select focal flood-prone areas to demonstrate how the risk of particularly valuable assets can be assessed based on detailed context-specific data.

In our risk assessment framework, consequences are measured in terms of society's WTP for avoiding a given hazard. The perspective of the damage cost assessment is thus that of social welfare,[1] where the total damage cost is an aggregate measure of the costs to all individuals of damage to given assets. Total damage costs are estimated using a bottom-up approach, with cost parameters being assigned to different assets, including buildings, health, infrastructure, historical and cultural heritage, and ecosystems. Total damage is calculated as the sum of all damage in all the sub-categories.

### 2.2. Analytical tool for integrated risk assessment

The risk assessment for the case study of urban flooding is conducted using DIAS, which has been developed in order to support risk assessments as part of decision-making regarding climate change adaptation (Skougaard Kaspersen et al., 2012) (Fig. 2). DIAS aims at facilitating modelling groups and experts sharing outputs and data, given the understanding that the multidisciplinary character of risk and adaptation studies demands such a structured approach to collaboration. The system is based on open-source information for research groups made available by universities and public institutions. It includes geographical data on current and future climate patterns, land use, groundwater resources, soil types, specific ecosystems, population, income, buildings, historical and cultural heritage, infrastructure, traffic, industry and social institutions (hospitals, schools etc.), which are all represented in

[1] Social welfare reflects society's own perspectives in relation to, for example, climate change impacts.

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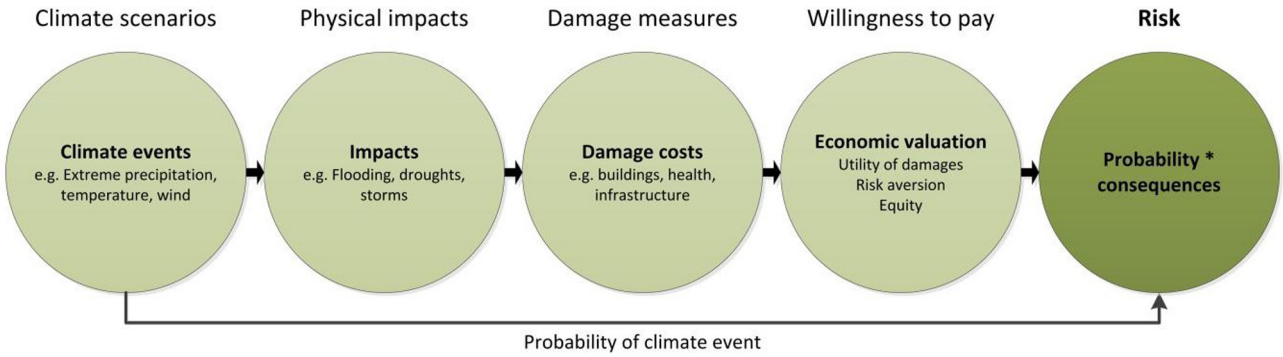


**Fig. 1.** Generic structure for climate change risk assessment.

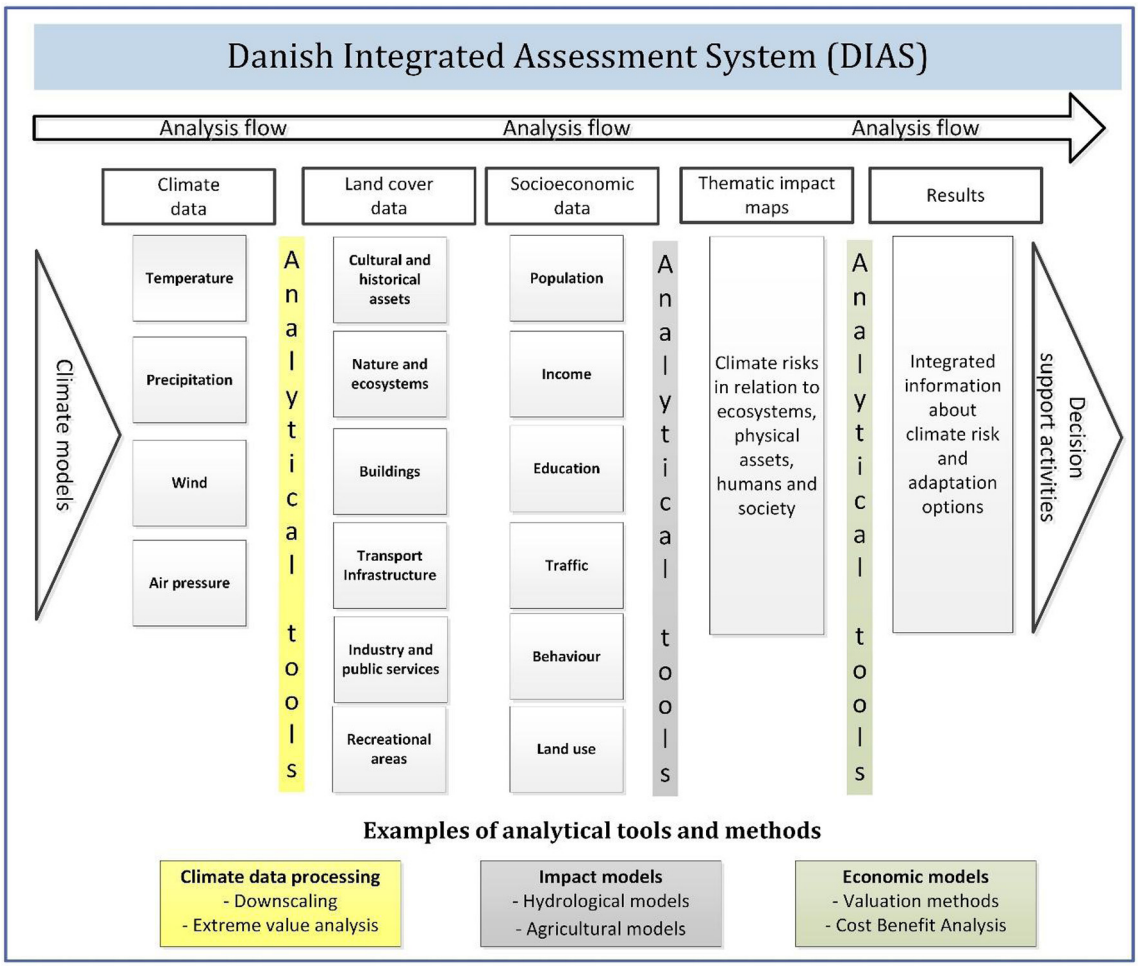


**Fig. 2.** Analytical structure and major elements of the Danish Integrated Assessment System or DIAS.

a Geographical Information System (GIS) for Denmark[2] (Fig. 2) (See Skougaard Kaspersen et al., 2012 for detailed information on the available data for Denmark that are relevant in the context of risk assessment and climate adaptation).

Examples of studies that can be supported by DIAS will, in addition to the information system, also need to be supported by various sector–specific, in-depth models and methods, such as climate models, downscaling methods, extreme value analysis, impact models (e.g. flood models) and different economic models and methods, including valuation techniques and cost-benefit analyses. These models, methods and analytical tools are available from universities and other centres of excellence studying climate change. The DIAS is a generic framework and tool describing key input data and modelling tools relevant for multiple hazards, including but not limited to floods, heat waves and windstorms, for a majority of urban areas globally. Data availability, quality and accuracy will differ between locations, and it will not be possible to include all types of information, as exemplified in the DIAS, but it is possible to use the framework in a flexible way based on more generic data, if there are context specific data limitations.

[2] The data are based on both modelling outputs and public databases, including Statistics Denmark.

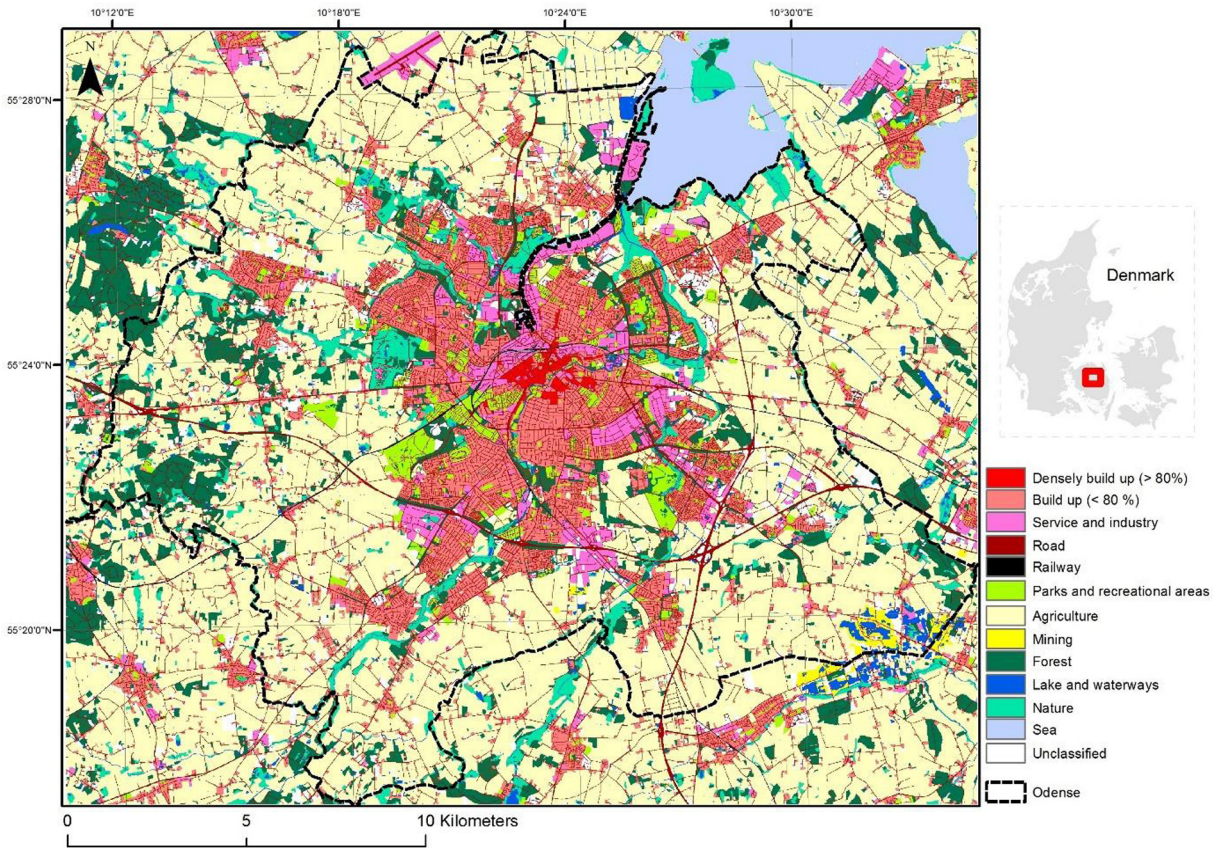


**Fig. 3.** Land cover and land use data for the Municipality of Odense (Levin et al., 2012).

DIAS is structured into five analytical elements (Fig. 2): (1) climate data; (2) land cover data; (3) socioeconomic data; (4) thematic impact maps, e.g. climate risks in relation to ecosystems, physical assets, humans and society; and (5) results, i.e. integrated information about climate risk and adaptation options.

The assessment system consists of different modelling tools, the first group of which link ***climate data*** to a specific geographical location. The tools here include empirical-statistical approaches for downscaling climate extremes from global coupled atmosphere-ocean circulation models (GCMs) and regional climate models (RCMs) (Willems, 2012; Sunyer et al., 2015b). The outputs of such analyses include design intensities for extreme precipitation under current and future climate scenarios (e.g. RCP4.5, RCP8.5) at horizontal resolutions (<25 km), which are suitable in the context of urban adaptation (Gregersen et al., 2013; Maule et al., 2014).

Following downscaling, the next step is to link the site-specific climate change information with ***land cover data*** and ***socioeconomic data***, which are key inputs in the assessment of climate change impacts. Land-cover data include information on land use and the location of roads, buildings, infrastructure, nature etc. (Fig. 3) (Levin et al., 2012). Socioeconomic data, on the other hand, contain in-depth information on the inherent properties and behaviour of humans and society within a given geographical area. An example of this is the value of urban recreational areas (Fig. 4) (Bjørner et al., 2014). These and similar types of information are valuable in taking account of the otherwise indirect and intangible impacts of climate extremes.

Climate impacts are assessed using analytical tools like hydrological models, agricultural models etc., one output of which are various ***thematic impact maps***. An example of such an impact map is a flood hazard map highlighting the extent and depth of flooding during specific rainfall events (Fig. 5). Flood hazard mapping is commonly conducted using flood models where both surface and sub-surface (drainage system) flows are represented, e.g. MIKE Flood (MIKE by DHI, 2014) or TUFLOW (TUFLOW, 2014). Information on the location of specific buildings and road infrastructure can be combined with flood-model outputs to provide rough quantifications of the risk of such assets during a variety of design high-intensity rainfall events (Fig. 5). Flood hazard mapping is very useful for decision-making activities in relation to climate change adaptation measures.

As previously argued, detailed knowledge of the location of areas with specific cultural values, such as historical buildings and monuments, is important in relation to decision-making, as these assets may be considered irreplaceable. As an example, Odense is an old settlement with some unique historical and cultural assets, including an old church and monastery, which date back to the thirteen century (Fig. 6). Furthermore, the home of the famous author Hans Christian Andersen is located in the city centre. Unique and irreplaceable cultural and historical locations are present in almost any city in the world, and it is important to consider such assets specifically when conducting impact assessments.

### *2.3. Flood risk assessment for the city of Odense*

#### *2.3.1. Study area*

Odense is the third largest city in Denmark, with a population of around 170,000. It is characterized by a combination of built-up areas and patches of service and industry in the city centre, surrounded by agricultural land, small areas of forest and different

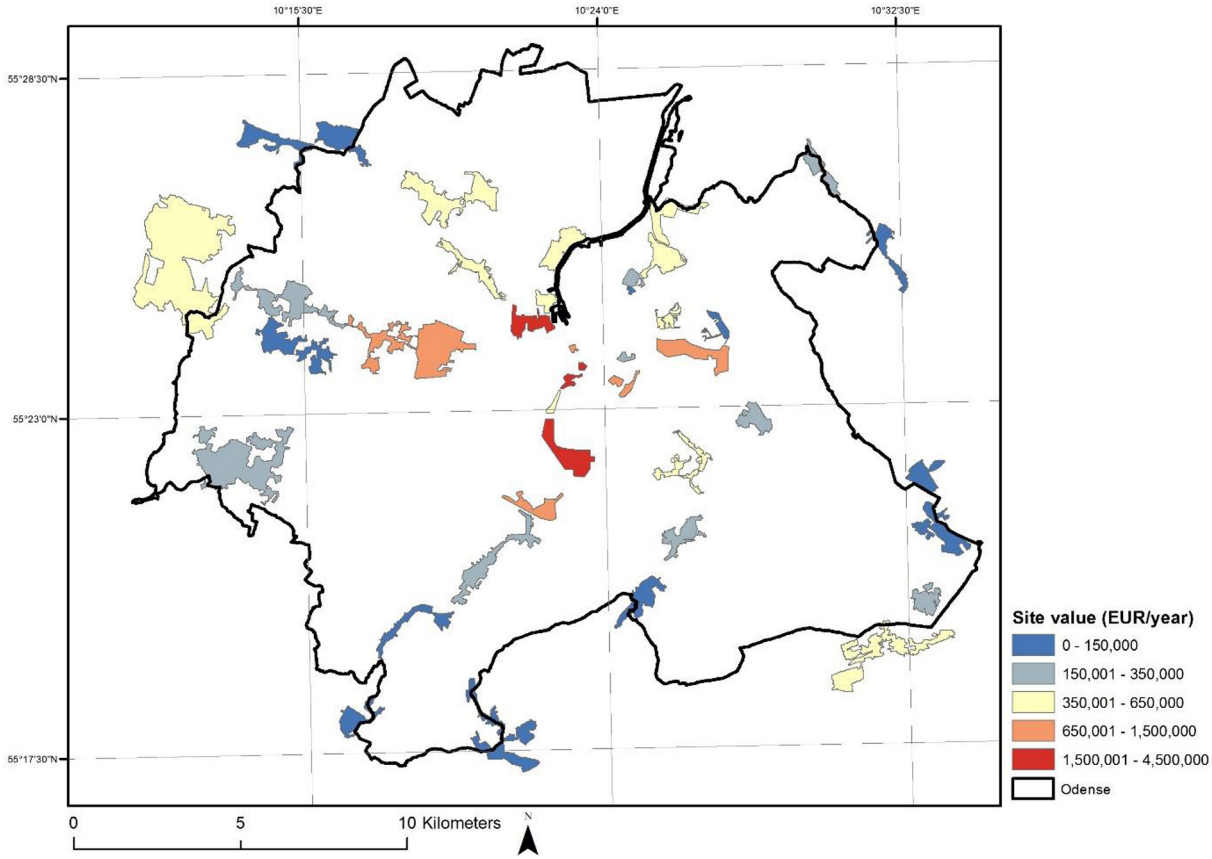


**Fig. 4.** Annual value of recreational, nature and forest areas in the municipality of Odense as an example of relevant socio-economic data (Bjørner et al., 2014).

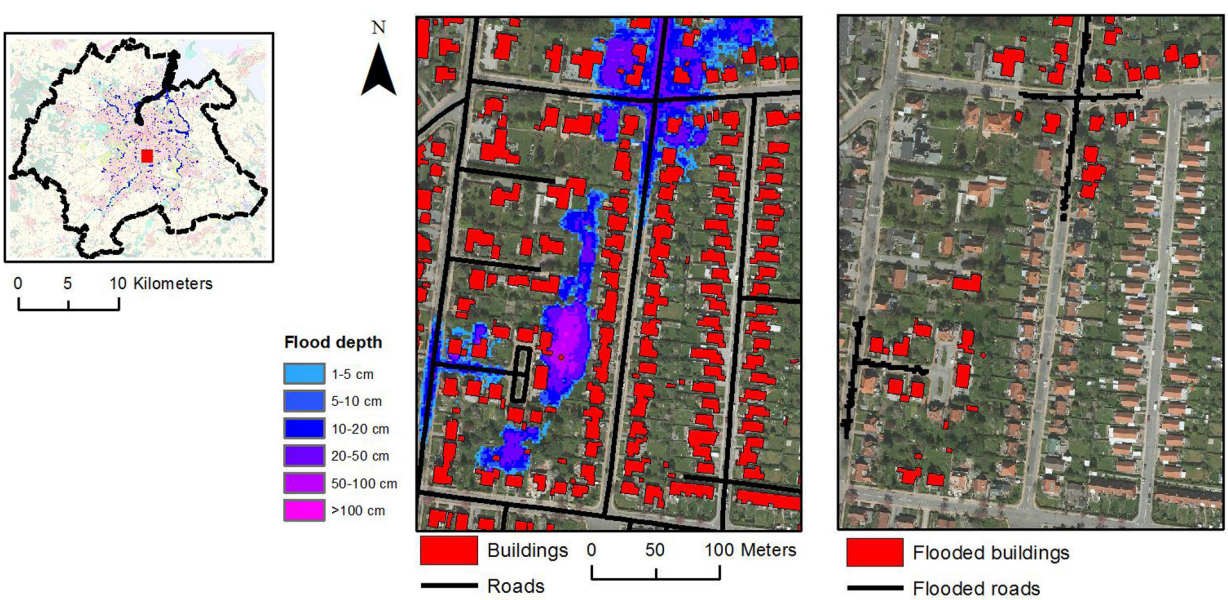


**Fig. 5.** Thematic impacts map showing flooded buildings and roads for neighbourhoods in Odense during high-intensity rainfall at a maximum intensity of 40 mm/h. The left-hand map shows the maximum extent and depth of flooding, while the right-hand map show houses and roads that have been flooded (Municipality of Odense, 2014).

types of natural environment (Fig. 3). A high share of impervious surfaces within the city centre, combined with the locations of the Odense fjord north of the city and the Odense river, which runs directly through the city centre, makes Odense highly exposed to flooding during high-intensity precipitation (pluvial/fluvial flooding), as well as from storm surges. Previous flooding events in Odense in 2006–2012 have shown that a wide range of assets are at risk during extreme precipitation, including transport infrastructure, buildings, human health, aquatic environments, recreational areas, and historical and cultural heritage.

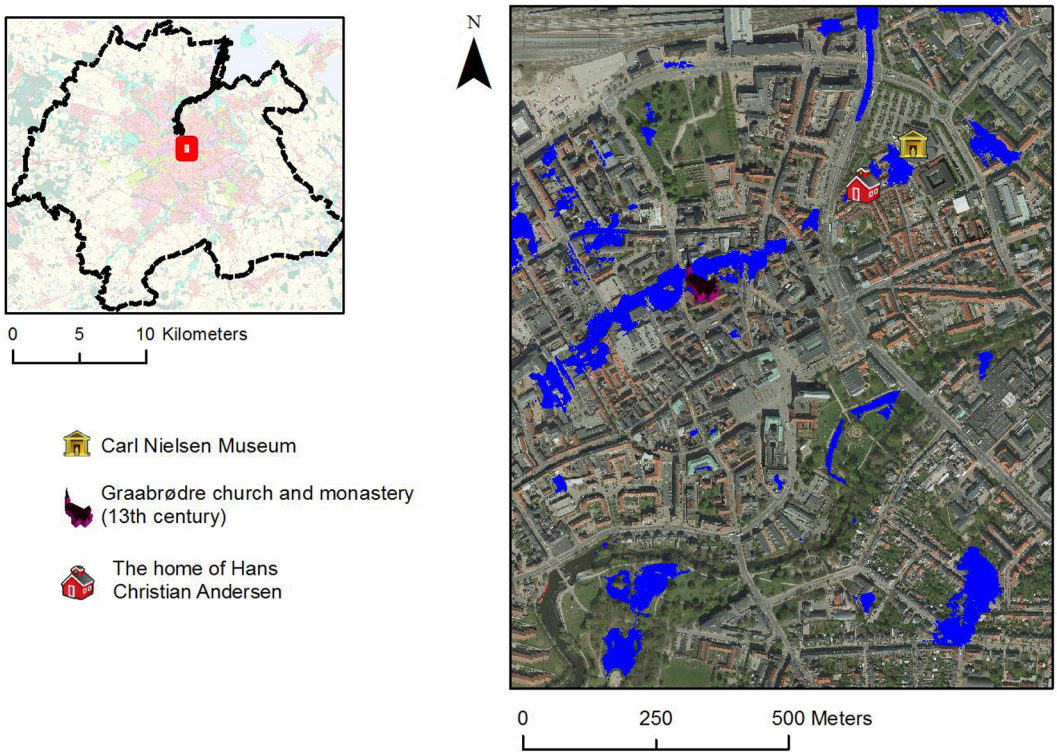


**Fig. 6.** Location of key historical and cultural assets in Odense city centre and flooded area during precipitation with a maximum intensity of 40 mm/h.

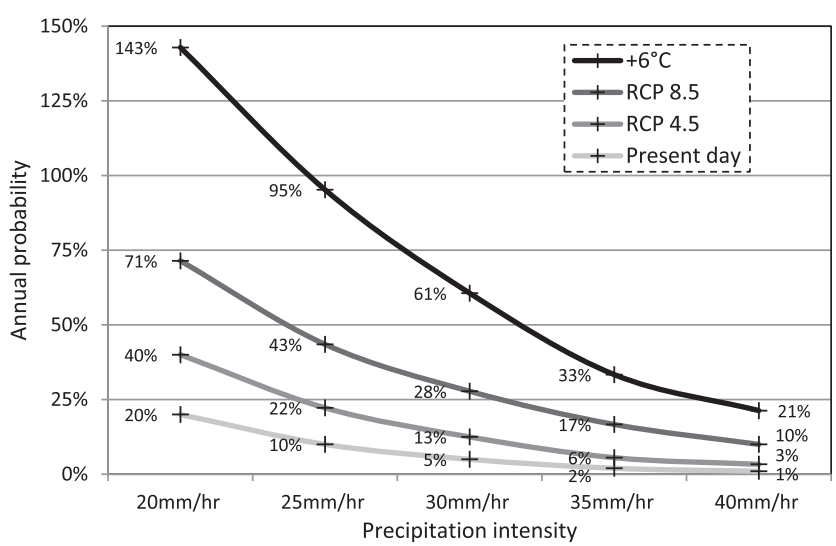


**Fig. 7.** Annual probability of high-intensity precipitation for different climate scenarios, present-day and climate scenario periods are 1976–2005 and 2071–2100 respectively (after Arnbjerg-Nielsen et al., 2015).

*2.3.2. Flood modelling*

The flooding risk assessment is conducted by linking information on the geographical location and properties of relevant assets (buildings, roads, historical/cultural assets, population etc.) with flood-hazard simulations conducted within a 1D/2D flood model framework (Municipality of Odense, 2014). Flood-hazard mapping during a number of design high-intensity rainfall events is performed using a combined drainage system and overland flow model, which enables surface and sub-surface flows during high-intensity precipitation (e.g. MIKE FLOOD) to be represented. Within this modelling framework, the occurrence of five different design rainfall events was simulated for the entire city of Odense (Municipality of Odense, 2014). The simulated events correspond to high-intensity precipitation occurring with a frequency of one in five years to one in a hundred years (under current climatic conditions), with maximum precipitation intensities ranging from

**Table 1**
Unit damage costs for different assets in Odense caused by flooding during extreme precipitation.

| Asset category | Inundation threshold (cm) | Unit costs of precipitation intensities (mm/h) of: | | | | | Unit |
|---|---|---|---|---|---|---|---|
| | | 20 | 25 | 30 | 35 | 40 | |
| **Buildings** | | | | | | | |
| Service and industry | 20 | 87,972 | 182,821 | 277,670 | 372,520 | 467,369 | €/building |
| Multistorage residential | 20 | 45,689 | 113,967 | 182,245 | 250,523 | 318,801 | €/building |
| Housing | 20 | 43,718 | 55,192 | 66,667 | 78,141 | 89,616 | €/building |
| Leisure housing | 20 | 1315 | 2324 | 3333 | 4342 | 5352 | €/building |
| **Basements** | 5 | 33 | 47 | 67 | 87 | 100 | €/m$^2$ |
| **Roads** | 5 | 167 | 233 | 333 | 433 | 500 | €/m$^2$ |
| **Railways** | 5 | 33 | 47 | 67 | 87 | 100 | €/m$^2$ |
| **Health** | 0.3 | 446 | 624 | 892 | 1159 | 1337 | €/person |
| **Water environment** | 20 | 33,333 | 46,667 | 66,667 | 86,667 | 100,000 | €/waterbody |
| **Historical/cultural assets** | | | | | | | |
| Ancient monuments | 20 | 66,667 | 93,333 | 133,333 | 173,333 | 200,000 | €/building |
| Churches | 20 | 666,667 | 933,333 | 1,333,333 | 1,733,333 | 2,000,000 | €/building |
| Conservation-worthy buildings | 20 | 66,667 | 93,333 | 133,333 | 173,333 | 200,000 | €/building |
| Medieval religious buildings | 20 | 66,667 | 93,333 | 133,333 | 173,333 | 200,000 | €/building |
| Statues and sculptures | 20 | 66,667 | 93,333 | 133,333 | 173,333 | 200,000 | €/building |
| Museums | 20 | 666,667 | 933,333 | 1,333,333 | 1,733,333 | 2,000,000 | €/building |

20 mm/h to 40 mm/h (Fig. 7). In order to quantify the impact of various climate-change scenarios on the overall flood risk, simulations were conducted under both present-day climatic conditions and for three different climate scenarios, i.e. RCP4.5, RCP8.5 and + 6 °C (Fig. 7) (Meinshausen et al., 2011; Christensen et al., 2015; Arnbjerg-Nielsen et al., 2015). The RCP4.5 scenario describes a future with increases in the near-surface air temperature of 1.8 °C (1.1–2.6 °C) towards 2100, while the RCP8.5 scenario represent a world in which the increased radiative forcing corresponds to an increase of 3.7 °C (2.6–4.8 °C) in 2100 (Intergovernmental Panel on Climate Change, 2014).

### 2.3.3. Impact of climate change on extreme precipitation

The probabilities of the different rainfall events are based on scenario runs and statistical downscaling conducted as part of a Danish project on regional climate change impacts, CRES, which included high end scenarios for extreme precipitation (Christensen et al., 2015; Arnbjerg-Nielsen et al., 2015; Halsnæs et al., 2015). Arnbjerg-Nielsen et al., 2015 presents climate factors for hourly extreme precipitation for Denmark for the RCP 4.5 (named "current planning" in Arnbjerg-Nielsen et al., 2015), RCP 8.5 and a global 6 °C scenario. All three scenarios were simulated using the general circulation model EC-Earth and downscaled to an 8 km spatial resolution (25 km for the global 6 °C scenario) with the DMI HIRHAM5 regional climate model. Detailed information on the climate models and downscaling approaches used to calculate the climate factors for the different scenarios are available from Arnbjerg-Nielsen et al., 2015; Sørup et al., 2016 (RCP4.5 and RCP 8.5) and Christensen et al., 2015 (global 6 °C scenario). The climate factors are calculated as the relative difference in precipitation intensities for high-intensity precipitation with return periods of 10 (RP10) and 100 (RP100) years between climate model simulations for the periods 1976–2005 and 2071–2100. RP10 and RP100 correspond to 25 mm/h and 40 mm/h respectively in Fig. 7. Based on this, we calculated climate factors for the remaining events (20 mm/h, 30 mm/h and 35 mm/h) using linear interpolation. We quantified the annual probabilities of extreme precipitation in the RCP 4.5, RCP 8.5 and + 6 °C scenario, as presented in Fig. 7, by calculating and comparing the intensities of future events with the intensities and return periods of present-day events. Since the frequency of extreme precipitation is expected to follow the degree of climate change, the annual probability of the individual events increases as the climate scenario becomes more severe (Fig. 7). In addition, it is seen that the probability increases more for the very extreme events compared to the lesser events. For example, the frequency of a 100-year event (RP100) increases by a factor of 10 in the RCP8.5 scenario (from 1% in the case of the present-day climate to 10%), while the frequency of a five-year event (RP5) is 'only' expected to increase by a factor of 3.5 (from 20% in the present-day climate to 71%) (Fig. 7). This reflects the fact that the probability density function for the precipitation events has a 'fatter tail' for the high-end climate scenarios.

### 2.3.4. Damage cost assessment

The consequences, in terms of society's loss of welfare from precipitation-induced flooding, are calculated by means of a two-step procedure. Initially, flood maps are combined with information on the location of relevant assets (Fig. 5 and Fig. 6 are examples) to quantify the number of assets that are at risk during extreme precipitation (Table 2). Risks are then calculated by adding monetary values in terms of damage costs and welfare losses for each asset (Table 1). The unit costs used to quantify the damage costs and welfare losses for the different assets are based on information from various data sources (see Box 1 for references to the different data sources), making a comparison of the relative importance of the risk to different assets uncertain. The damage functions used here are based on the general assumption that the unit damage cost increases with the intensity of the rainfall events (Table 1). From insurance data, we can see that the building insurance claims were as much as three to ten times higher for damage caused by very rare events as compared to more frequent events, and this relationship between unit damage cost and event severity has been transferred to the other damage categories (Danish Insurance Association (DIA, 2015). For each asset an inundation threshold is defined (the water level required to cause damage varies for different assets), and the unit cost is then kept constant for all flood depths beyond this threshold during the individual precipitation events, while it increases with the intensity of the events (Table 1).

Box 1 **Asset cost assessment**

*Buildings, basements, roads and railways:* Basements, roads and railways are damaged by flooding when the inundation depth reaches 5 cm, while 20 cm of surface water is needed to cause damage to buildings (Table 1) (Zhou et al., 2012; Municipality of Odense, 2014).
*Health:* Health damage costs are calculated based on the number of persons imposed to mixed rain- and sewage water, and is estimated using the number of basements flooded. It is assumed that on average 1.8 person gets in contact with polluted water per flooded basement. Damages are assumed to occur as soon as polluted water is present within a basement (0.3 cm) since only small quantities of polluted water are sufficient to cause infections (Zhou et al., 2012).
*Water environment:* Damages to the water environment is calculated by estimating the number of waterways (rivers and lakes) that receives mixed rain- and sewage water during flooding. Damages are assumed to occur when >20 cm of mixed rain- and sewage water is present within a river or lake (Zhou et al., 2012).
*Historical/cultural assets:* As for buildings 20 cm surface water is required to cause damages to historical and cultural assets. The unit costs of these assets are difficult to quantify as they are not directly replaceable. For this reason there is great uncertainty associated with the calculation of damage costs for this category (Municipality of Odense, 2014).

**Table 2**
Number of damaged assets in Odense caused by flooding during extreme precipitation with different intensities.

| Flooded assets | Inundation threshold (cm) | Precipitation intensity (mm/h) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 20 | 25 | 30 | 35 | 40 | |
| **Buildings** | | | | | | | |
| Service and industry | 20 | 59 | 94 | 174 | 231 | 278 | Buildings |
| Multi-storage residential | 20 | 38 | 56 | 95 | 103 | 123 | Buildings |
| Housing | 20 | 87 | 201 | 398 | 472 | 576 | Buildings |
| Leisure housing | 20 | 108 | 229 | 419 | 490 | 605 | Buildings |
| **Basements** | 5 | 178 | 311 | 573 | 569 | 726 | Basements |
| **Roads** | 5 | 120 | 212 | 374 | 434 | 533 | 1000 $m^2$ |
| **Railways** | 5 | 2 | 5 | 9 | 12 | 15 | 1000 $m^2$ |
| **Health** | 0.3 | 475 | 757 | 1356 | 1397 | 1659 | Persons |
| **Water environment** | 20 | 29 | 31 | 41 | 43 | 46 | Waterbodies |
| **Historical/cultural assets** | | | | | | | |
| Ancient monuments | 20 | – | – | 1 | 2 | 2 | Buildings |
| Churches | 20 | – | – | 1 | 1 | 1 | Buildings |
| Conservation worthy buildings | 20 | 10 | 22 | 58 | 60 | 74 | Buildings |
| Medieval religious buildings | 20 | – | – | – | – | – | Buildings |
| Statues and sculptures | 20 | 2 | 2 | 5 | 5 | 7 | Buildings |
| Museums | 20 | – | – | 4 | 4 | 5 | Buildings |

## 3. Results and discussion

From the analyses, we find, not surprisingly, that the number of flooded assets increases with the intensity of the extreme precipitation event (Table 2). We observe that there is a particularly large increase in the number of flooded assets when we move from maximum intensities of 20 mm/h to 30 mm/h. This is followed by moderate increases for more severe events (Fig. 8a).

The damage costs associated with flooding during extreme precipitation are likewise found to increase with the intensity of the precipitation events and the extent of flooding, ranging from ≈17 M€ for the smallest event to ≈320 M€ for the event with the highest maximum intensity (Fig. 8a). The development in total damage costs when moving from low- to high-intensity events is not linearly related to the maximum intensity of the individual events. Large increases in damage costs are observed when moving from precipitation events of 25 mm/h to 30 mm/h. It is therefore especially important for purposes of adaptation to consider the probabilities of these events in future climate scenarios (Fig. 7), as even small increases in the return periods will dramatically increase the overall risk. The level of expected damage costs, and thus the resources that are considered appropriate for climate adaptation, depend considerably on expectations of future climate scenarios.

The damage to service and industry, housing, multi-storey residential buildings and roads is responsible for the largest share of the total damage costs for all precipitation events (Fig. 8b). Conversely, damage to bodies of water, leisure housing, railways and health costs are only marginally represented in the cost summary (Fig. 8a + b).

As previously argued, risk analyses for flooding in local areas suffer from very uncertain assumptions about future changes in the intensity and frequency of extreme events. In the following, we will therefore introduce a sensitivity analysis in which we have focused on some very vulnerable and valuable assets, such as the historical and cultural sites in Odense that could be considered as setting some important critical boundary conditions for how much flooding can be accepted within the city. Here we are comparing two alternative sensitivity analyses, where the first approach assigns alternative economic assumptions to the valua-

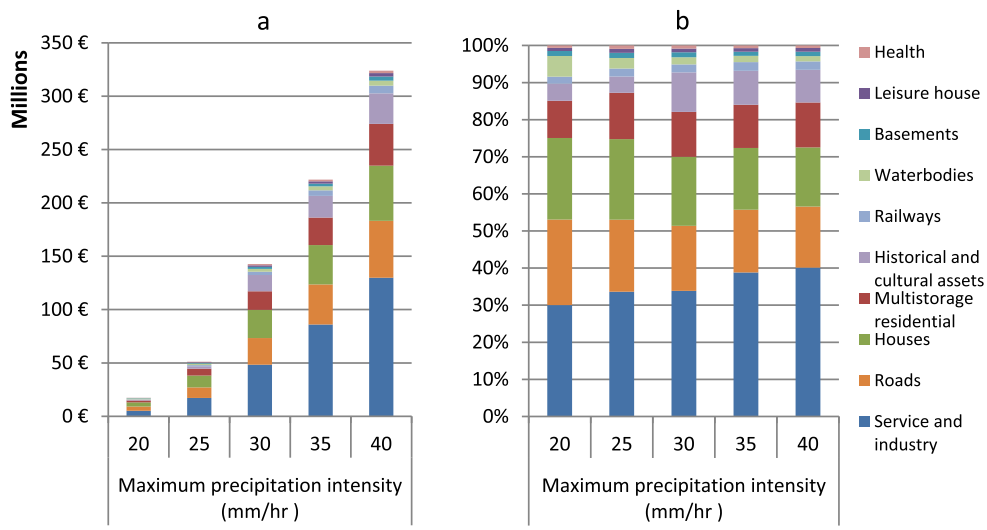


**Fig. 8.** Cost summaries for (a) total damage costs, and (b) share of total damage costs of flooding in the Municipality of Odense during high-intensity precipitation (costs are measured as the total loss of an event).

tion of the historical and cultural sites, while the second keeps the valuation constant, but applies different probabilities, depending on the climate scenario, to flooding events. We have chosen to focus on historical and cultural heritage, because there are specific challenges in integrating appropriate monetary values to such assets. Historical and cultural heritage is irreplaceable, and it is not suitable to use standard market evaluation methods to reflect these.

The **first** approach assigns a particularly high economic value to historical and cultural assets. For the sake of simplicity, here we multiply the unit cost for the irreplaceable assets with a constant, in this case set arbitrarily to three. This means that the unit costs for this category are three times higher when compared with the assumptions displayed in Table 1. The consequences of using a higher value for historical and cultural assets in the risk assessment are only marginal, since the damage to historical and cultural assets in any case represents a relatively small share of the total costs (Fig. 8, Fig. 9). Seen in the context of decision-making for climate change adaptation, adding higher values for economic damage for certain particular assets like historical heritage does not really have a great deal of influence on a purely economic case for larger investment programmes aimed at protecting cities from flooding.

The risks measured as the probability of precipitation events multiplied by the costs is shown for the alternative climate scenarios (Fig. 10). The costs are calculated as the total costs of an event transformed into Net Present Values (NPV) using a 3% discount rate.

The risks of flooding from high-intensity precipitation in Odense are maximised at 30 mm/h precipitation (Fig. 10). The risk stays almost constant at this level, as the intensity increases for the RCP8.5 and +6 °C climate scenarios. This could suggest that, assuming high-end climate change, adaptation measures should aim at a high level of protection from an economic point of view. In the case of lower climate scenarios like RCP4.5 or a continuation of the present-day climate, the risks are still maximised at 30 mm/h precipitation events, but fall to lower levels for the more severe events as compared to the RCP8.5 and +6 °C climate scenarios.

The **second** approach for addressing how the risks of the flooding of specific vulnerable assets might be assessed suggests using a climate scenario corresponding to greater changes in the frequency and/or intensity of extreme events. It is based on the argument that it is beneficial to invest in a higher safety level against flooding risks than has previously been the case in local planning. We can then, for example, compare the risk of a 30 mm/h precipitation event in the RCP4.5 case with that of the RCP8.5. Here the risk

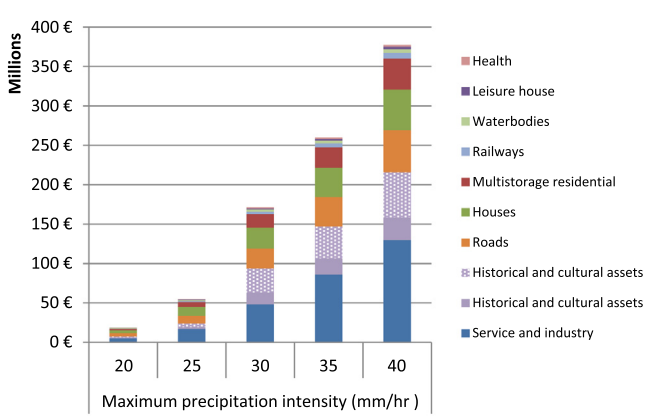


**Fig. 9.** Cost summary, total damage costs of flooding in the Municipality of Odense during high-intensity precipitation, including using a higher valuation of historical and cultural assets (dotted purple area = added damage costs when multiplying the regular value by a factor of three).

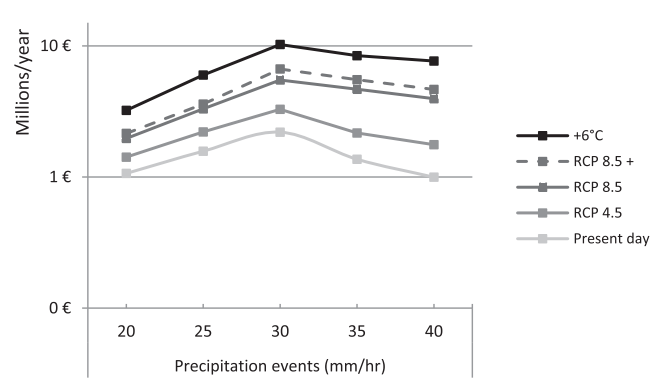


**Fig. 10.** Risks of flood damage over a 100-year period for different climate change scenarios using a 3% discount rate. RCP 8.5+ = RCP 8.5 where the value of historical/cultural assets is multiplied by three.

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increases from a NPV of 3.3 M€ per year to 5.5 M€ per year (Fig. 10). However, going for such a higher climate scenario in a climate adaptation context could be more costly than specifically protecting particularly valuable assets on an individual basis (if possible). In any case, the protection of particularly high-value or irreplaceable assets needs to be considered specifically when deciding on appropriate climate adaptation measures. In this context, the availability of detailed spatial data on the location of such assets is a key input into the decision-making process.

## 4. Conclusions

Risk assessments for urban flooding are influenced by different sources of uncertainty: in particular, small-scale projections of extreme precipitation, which are commonly used as input into urban flood models, are subject to a large degree of uncertainty. One way to address these uncertainties is to use a very detailed integrated data and modelling approach, such as the DIAS tool described here, which can help identify particularly vulnerable and valuable assets that climate change adaptation measures should protect. Linked climate and hydrological modelling shows that there is high risk of flooding from extreme precipitation in the Danish city of Odense, with damage approaching 330 million Euros for the most severe events. The actual risk will depend on a combination on the probability and intensity of extreme precipitation, the exposure and vulnerability of relevant assets and the valuation of these assets. Against this background, we conducted a sensitivity analysis focusing on historical and cultural values in Odense. The findings of this analysis highlight that very rare and historical or cultural assets, which should be included in risk assessments and adaptation plans, may need special attention in this context so as to influence the overall outcome of a standardized risk assessment. Assigning very high economic values to historical and cultural assets does not change the economic scope for adaptation plans strongly, but assigning higher probabilities to precipitation events in agreement with high-end climate scenarios (e.g. RCP 8.5) has a considerable influence on the risk estimates and thereby the scope for adaptation. In this way, it can be important to consider taking a precautionary approach in relation to specific assets in making decisions regarding climate adaptation. We are currently using the DIAS in several ongoing studies on climate change damages and decision-making, including studies on coastal flooding. In addition, we are exploring how the framework can be applied to represent cascades of uncertainties, addressing both climate scenario and model uncertainties and uncertainties related to key economic assumptions in cost-benefit analyses of climate adaptation.

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