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Impacts of 21st century sea-level rise on a Danish major city – an assessment based on fine-resolution digital topography and a new flooding algorithm

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Abstract. This study examines the potential impact of 21st century sea-level rise on Aarhus, the second largest city in Denmark, emphasizing the economic risk to the city's real estate. Furthermore, it assesses which possible adaptation measures that can be taken to prevent flooding in areas particularly at risk from flooding. We combine a new national Digital Elevation Model in very fine resolution (~2 meter), a new highly computationally efficient flooding algorithm that accurately models the influence of barriers, and geospatial data on real-estate values to assess the economic real-estate risk posed by future sea-level rise to Aarhus. Under the A2 and A1FI (IPCC) climate scenarios we show that relatively large residential areas in the northern part of the city as well as areas around the river running through the city are likely to become flooded in the event of extreme, but realistic weather events. In addition, most of the large Aarhus harbour would also risk flooding. As much of the area at risk represent high-value real estate, it seems clear that proactive measures other than simple abandonment should be taken in order to avoid heavy economic losses. Among the different possibilities for dealing with an increased sea level, the strategic placement of flood-gates at key potential water-inflow routes and the construction or elevation of existing dikes seems to be the most convenient, most socially acceptable, and maybe also the cheapest solution. Finally, we suggest that high-detail flooding models similar to those produced in this study will become an important tool for a climate-change-integrated planning of future city development as well as for the development of evacuation plans.

1. Introduction

Anthropogenic climate change is causing a global sea-level rise, which is expected to accelerate over the 21st century [1, 2]. The potential effects of future sea-level rise on coastal zones are one example of the impacts of 21st century climate change that are likely to become a major challenge for society [1, 3, 4]. The total value of the economic assets located within 500 m of the European coastline is currently estimated at € 500,000,000,000 to 1,000,000,000,000, and several million people live in these areas [5]. The most recent predictions foresee a mean sea-level rise of up to 1.35 meter by 2090-2099 [2]. A sea-level rise of such a magnitude is likely to have drastic consequences for coastal cities in terms of regular and maybe even permanent flooding of low-lying areas as well as an increased risk of

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catastrophic flooding and associated losses of human lives. In 2005, as the hurricane Katrina reached southeast Louisiana it drew a path of destruction across the area and caused the flooding of nearly 80% of the city of New Orleans and an overall mortality of the exposed human population of ~1%, with the mortality risk increasing with water depth [6]. As numerous major cities around the World are located by the coast, the expected future sea-level rises will increase the threat of catastrophic flooding due to extreme weather events like the hurricane Katrina. Exacerbating this risk, global warming is predicted to cause extreme weather events to increase in intensity over the 21st century [1].

In Denmark, the ten largest cities are all coastal [7], typically located in topographically homogenous landscapes only a few meters above sea level (a.s.l.). Weather events have historically not become as extreme as the hurricane Katrina, but storms and even category 1 hurricanes regularly sweep over the country [8, 9]. The waters around Denmark frequently rises in response to these strong winds especially when they come from the west or northwest and subsequently pushes huge amounts of water into the Inner Danish Sea and the Baltic Sea. For example, this scenario was borne out on a day in November 2006, causing the water level to rise to 1.68-1.72 m above the normal water level in the harbor of Aarhus, a large Danish coastal city [10, 11]. The event caused no remarkable damage [11], but if the starting point had been 1.35 meters above current sea level (a.c.s.l.) consequences could have been massive economic losses. Furthermore, extreme weather events such as the above are foreseen to increase in intensity and frequency over the 21st century [1]

Most storms are often predicted relatively early [10], allowing timely evacuation of humans in the case of an emergency. Thus, humans are not in immediate danger in most coastal cities, at least in the more developed parts of the World, but buildings may be. Coastal real estate constitutes a relatively high value compared to real estate further inland, and, at the same time, is particularly at risk from future sea-level rise.

Predictive ability in terms of flood risk is crucial for preventing future catastrophes when extreme weather events combine with an increasing normal water level. For this reason, the European Commission recently identified flood risk mapping as a major component in the EU action programme for flood protection [5]. Under a given average or extreme weather scenario the most obvious way to conduct flood risk mapping would be to designate all areas below the estimated scenario sea-level as likely to become flooded. However, natural topographic features such as hills and artificial infrastructure such as embankments and roads may constitute barriers that will prevent water from reaching all areas that would otherwise become flooded. Consequently, detailed information about potential barriers is central for accurately predicting flooding risk. Rather than simply basing predictions on elevation, improved predictive capacity will result from implementing flooding algorithms that directly models water flow as a function of terrain features. So far the feasibility of this approach has been limited by its huge requirements in terms of elevation data accuracy and computing time [12].

Here we take on this challenge and use data on real-estate pricing, a completely new national Digital Elevation Model (DEM) in very fine spatial resolution (~2 meter), and a new highly computationally efficient flooding algorithm that accurately models the influence of barriers to assess the economic real estate risk posed by future sea-level rise to Aarhus, the second largest city in Denmark. Using several sea-level scenarios for 2090-2099, we specifically assessed: (1) Which areas will become subject to flooding during extreme weather events? (2) What is the real estate composition of these areas, in terms of residential vs. non-residential areas, and (3) high vs. low relative economic value? In addition, we make a short assessment of possible adaptation measures that can be taken to reduce the future flood risk.

2. Data and methods

2.1. Study area

Aarhus (N 56°9′, E 10°12′) is found on the eastern coast of the peninsula of Jutland (figure 1). The city’s southern coastline and a small section of its northern coastline consist of relatively tall, steep

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bluffs, preventing flooding more than a few meters inland. However, the majority of the northern city is rather flat and low-lying, probably rendering this district especially vulnerable to flooding (figure 2). A 2.1-m tall dike prevents flooding of the area in the case of high waters [11]. At the city center, the Aarhus River valley holds some low-lying residential areas as well. The region of interest was delimited by the Aarhus city zone (figure 1; hereafter simply referred to as Aarhus).

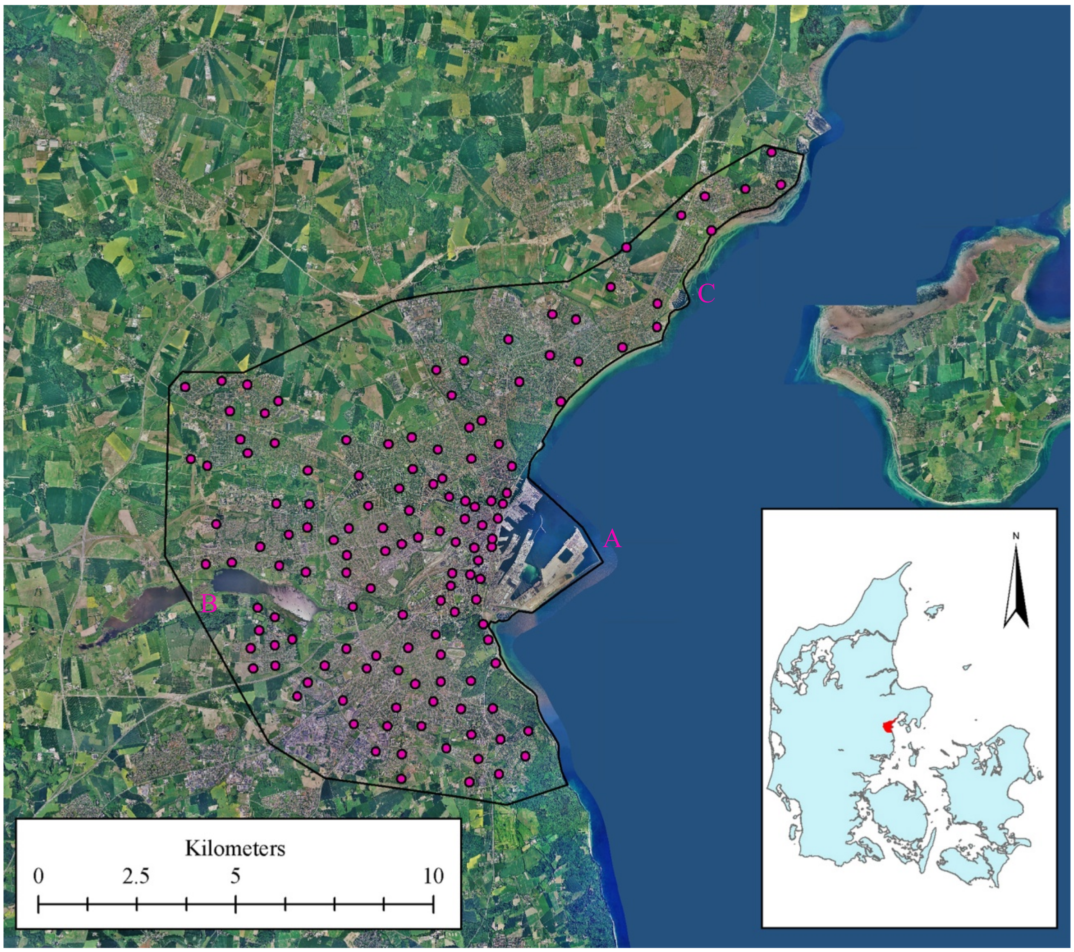

Figure 1. The city of Aarhus. The red dot on the insert map indicates the location of Aarhus. The analysis mask (black line) as well as the 135 buildings chosen for the study (violet dots) is indicated as well. The harbour of Aarhus is seen in the central part (A) of the image while the Brabrand Lake is located westernmost in the analysis mask (B) and the Egaa Marina 6-7 km north of the harbour (C).

2.2. Real estate pricing

To assess the geographic pattern of real-estate economic value in Aarhus we obtained data on real estate assessments from several Danish real-estate registers: Bygnings- og Boligregistret (BBR), Ejendomsstamregistret (ESR), Statens Vurderingsregister (SVUR), and Officielle Standardadresser og Koordinater (OSAK). The data were combined to a georeferenced point data set consisting of the official value estimate (DKK per residential m^2) for 2005 according to the Danish authorities for each building listed in the above registers. Only a subset of buildings was available, but geographically they were broadly distributed across Aarhus and, hence, probably representative of the general pricing pattern. Still, the data set contained numerous erroneous values due to the way the value per square meter was originally calculated, namely by dividing the value of a building by its residential area. In some cases this area is much less than the total resulting in unrealistically large value estimates for some buildings. These and other apparent errors were handled by selecting 135 buildings that were broadly distributed across Aarhus (figure 1). 10 buildings were picked within 7 of the city's postal districts (8200, 8210, 8220, 8230, 8240, 8250, 8310, and 8381) and in the large districts (8000, 8260, and 8270) 20-30 buildings were chosen. These were selected to present the district neighborhood by comparing a set of 3-8 neighboring buildings (depending on the number of available buildings in the neighbourhood). If these agreed with regard to value per square meter, one building was haphazardly chosen to represent the group. If they disagreed markedly, we used our thorough knowledge of real estate pricing in Aarhus to select the most representative value.

We used the log-transformed values for the 135 selected buildings to compute a continuous spatial surface of residential area square-meter values (DKK m^{-2}) using ordinary kriging. Kriging was implemented using the Geostatistical Analyst in ArcGis 9.3. Its default kriging settings were used, except that the following settings where changed to optimize the semi-variogram yielding the most statistically likely estimated surface: Second-order trend removal, neighbourhood of 25% global and 75% local data points, nugget = 0, lag size = 200, and number of lags = 12. We note that the estimated value surface is generally in line with our impression of real-estate prices in Aarhus, except that the central city zone is probably more expensive than our estimates.

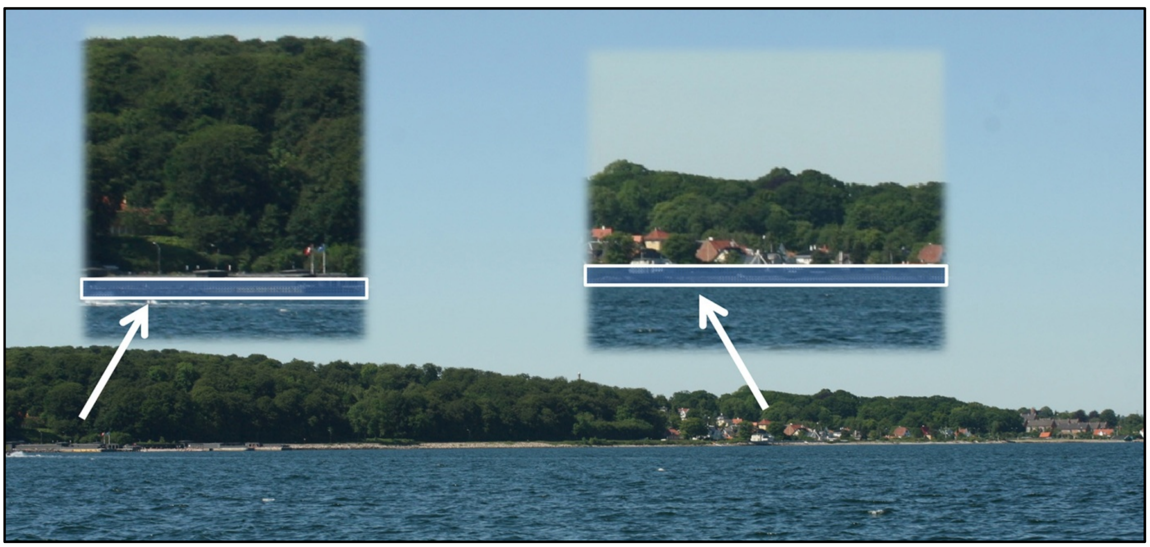

Figure 2. A sea-side view of the northern part of the city. The forest to the left is a small urban beech forest. Its right (northern) limit marks the beginning of the northern residential areas at risk from flooding in the case of extreme weather events in 2090-2099. The enlarged segments of the photo illustrate a likely sea level during such events (approximately 2.5-3.5 m sea-level rise).

2.3. Digital Elevation Models (DEM)

Detailed topographic data was extracted from a new national DEM derived from airborne laser altimetry (LiDAR: Light Detection and Ranging) technology [13]. We used two available DEMs: (1) One DEM featured only the raw terrain, with all artificial infrastructure removed, while (2) another DEM included all bridges in the landscape as impervious barriers. We used the latter to assess the potential role of flood-gates at the bridges in flooding prevention. LiDAR produces high density and precision 3D points by emitting a laser pulse for which both first and last return of the backscatter is stored specifying the (x,y)-coordinates, the elapsed travel time for the signal and the intensity of the backscatter. In this study each pulse had a footprint of approximately 50 cm on the ground and the sampling interval was 1.6 m on average [14].

The LiDAR approach has been documented to be an effective and reliable method for terrain data collection in large areas [15-18], and it has the advantage that it can be used both day and night as well as under low-intensity cloud conditions. This facilitates the efficient capture of data, for which reason it is fair to assume that the resulting DEM is considered a "snapshot" in time; i.e. the acquisition is performed within a few weeks for the whole country and not over periods of years, as otherwise has been the standard procedure for recording national topographic data.

The DEMs used here are constructed as raster grids with 2-meter pixel resolution and come with a 80-cm horizontal and 10-cm vertical accuracy in vegetation-less areas with simple microtopography [14]. Each DEM only embraces Aarhus, take up approximately 350 MB, and consists of 90,000,000 raster cells.

2.4. TerraSTREAM

TerraSTREAM [19] is a series of tools that can perform various computational tasks on very large DEMs. The algorithms used have provable efficient performance, even on very large elevation models (hundreds of gigabytes) that do not fit in the main memory of a computer. In such cases, the model must reside on large, but slow disks and the transfer of data between a disk and the computer's main memory often becomes the primary bottleneck, rather than the CPU computation time. Thus, the algorithms that form the core of TerraSTREAM ensure that the disk is used efficiently and enables us to process terrains in hours or a few days that would make most GIS software crash or stall for weeks and months. TerraSTREAM contains a number of tools for hydrological analysis of terrains including flow accumulation computation and watershed hierarchy extraction. In this study we used TerraSTREAM to compute which cells become flooded when the sea level rises.

TerraSTREAM contains an implementation of a flooding algorithm where a cell is only marked as flooded if there is a path from that cell to the flooding source (the ocean in most cases) that never passes through a point that is higher than the new water level. This algorithm ensures that points in the terrain protected by dikes are not flooded unless the water level increases to a level higher than the dikes. TerraSTREAM enables us to compute flood risk maps on nationwide high-resolution terrain models on standard desktop computers, although here we focused on the relatively small Aarhus area.

2.5. Future climate scenarios and extreme weather events

Reflecting the trend that the future climate change scenarios are judged to most likely become increasingly severe as global temperature rise [1, 20], we focused on the two Intergovernmental Panel on Climate Changes (IPCC) scenarios predicting the most severe temperature increases in the 21st century, A2 and A1FI [1]. However, the corresponding sea-level rise predictions are probably too conservative [2, 21, 22], and we therefore used updated sea-level rise scenarios for the IPCC A2 and A1FI climate scenarios [2]. These scenarios predict a mean sea-level rise of 1.15 m and 1.35 m by 2090-2099, respectively.

The November 2006 high-water level of 1.68-1.72 m a.s.l. was the most extreme level observed during the last 118 years [10, 11]. To our knowledge no local extreme weather water-level rise scenarios exist. Therefore, we use the above high water level (1.68 m) to exemplify an extreme high water level during a strong storm. Adding this to the two future sea-level rise scenarios yields a future high-water level of 2.83 and 3.03 m a.c.s.l. for the A2 and A1FI, respectively. We contend that these estimates are rather conservative as extreme weather events are predicted to increase in intensity and frequency over the 21st century [1].

Flooding simulations were performed for both DEMs and the two future extreme high-water estimates using the TerraSTREAM flooding algorithm. This resulted in four flooding maps that were used for pin-pointing residential areas at risk from future flooding. In addition, flooding simulation was also performed for both DEMs using only the predicted mean sea levels (i.e., 1.15 m and 1.35 m).

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An analysis mask was produced in ArcGIS 9.3 to delimit residential areas within the city zone of Aarhus, and the effects of flooding on real estate were primarily considered within this mask.

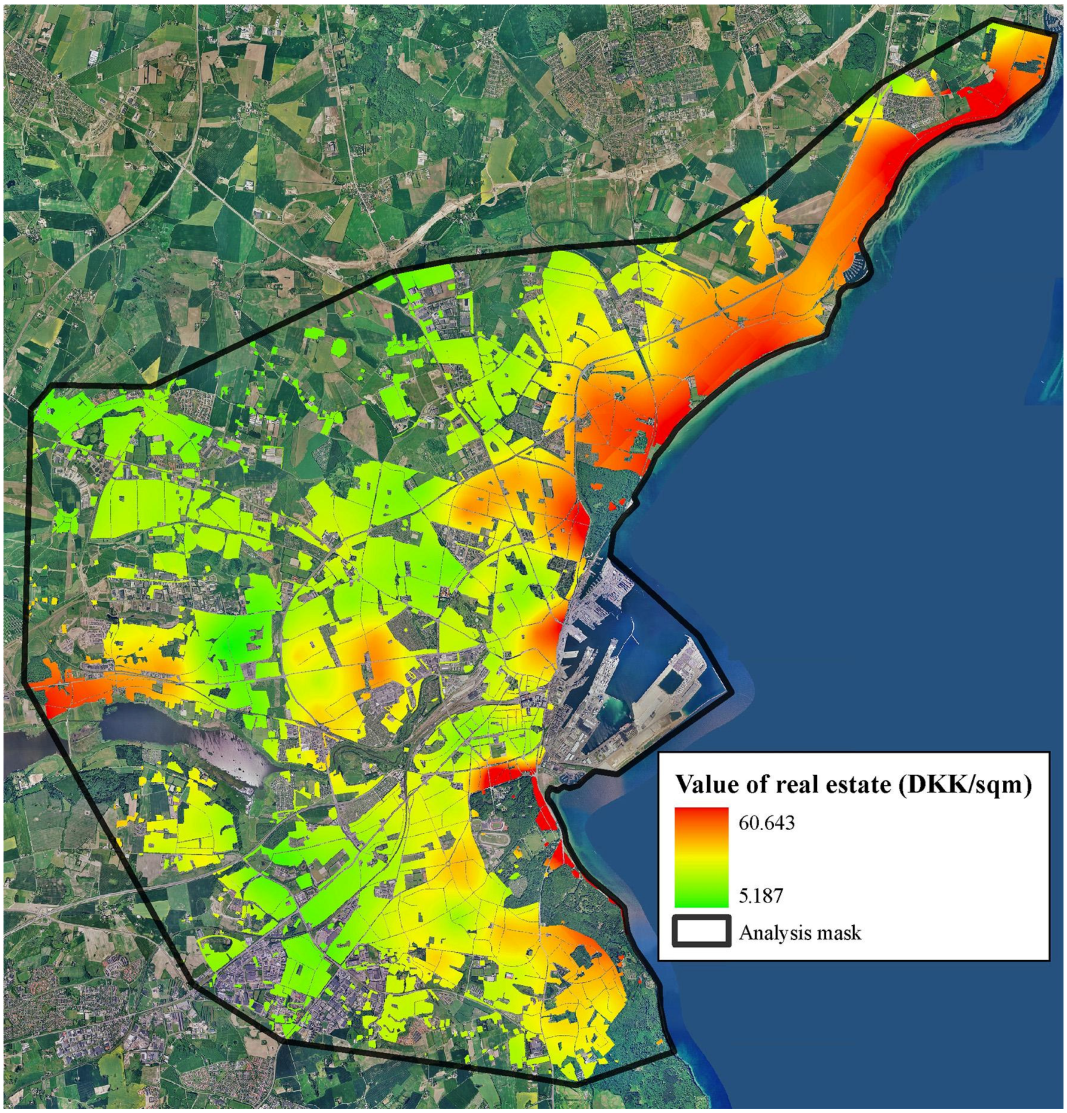

Figure 3. Real estate values represented in DKK per residential m^2. Only real-estate areas are shown.

3. Results

The most expensive residential areas in Aarhus tend to be found near the coastline, with the exception of the city center (figure 3). The flooding simulations based on the predicted mean sea levels showed that almost no contemporary land areas in Aarhus are at risk from permanent flooding in 2090-2099 (not shown). However, for all combinations of sea-level rise scenarios and DEMs a considerable part of the residential areas are estimated to become flooded in 2090-2099 under extreme high-water situations similar to the November 2006 storm (figure 4). The flooding simulations for the DEM that represented bridges as barriers (figure 4, A and C) revealed that flood-gates would prevent the flooding of the residential areas around the Aarhus River, while large residential areas in northern

Aarhus would still be likely to become flooded. The flooding simulations for the DEM without artificial infrastructures showed that relatively large residential areas in northern part of the city (figure 2) as well as areas around the Aarhus River are likely to become flooded (figure 4, B and D). In addition, most of the harbor and the areas fringing the Brabrand Lake would also risk flooding. Small but clear differences were seen between the extent of flooding under the A2 and the more extreme A1FI climate scenarios. About ⅔ of the residential areas likely to become flooded were located in areas of high-value real-estate, i.e., areas with real-estate values greater than the general mean value for Aarhus (figure 4).

4. Discussion

Our results exemplify the challenge posed upon the society by potential effects of future sea-level rise. We found that 21st century sea-level rise may well put large residential districts in Aarhus, the second-largest city in Denmark, at risk from flooding during likely extreme weather events. Much of the area at risk represents high-value real-estate neighbourhoods. Our results, however, also show that strategic placement of flooding barriers could dramatically reduce the flooding risk for some areas.

The flooding simulations performed on the DEM including bridges as impervious barriers provided an instructive illustration that strategically placed flooding barriers, in this case flood-gates, could form an important defence against future catastrophic flooding. We note that recently a proposal in fact has been made to construct a lock at the mouth of the Aarhus River, with exactly this purpose in mind [23]. We also note that the use of artificial infrastructure to prevent flooding is likely to have further complexities, notably requiring the installation of pumps to handle water inflow through underground connections in the sewer system as well as river water damming up behind the flood-gates.

As flood-gates are not currently installed at the mouth of the Aarhus River, we focus in the following on the flooding results from the flooding simulations for the DEM without artificial infrastructures (figure 4, B and D). Approximately ½ the areas identified in this study as being prone to flooding are residential zones and about ⅔ of these are relatively high value real-estate neighbourhoods. If these areas have to be abandoned following future sea-level rises relatively large values will be lost. However, it seems fair to anticipate that society, notably the municipality, or local citizen groups will attempt to prevent flooding of these areas by a number of measures (e.g. [24]). At least three preventive measures are possible: (1) constructing or enhancing existing dikes, (2) elevating [25] or (3) sealing houses [26]. The construction or retrofitting of dikes has an estimated cost of €0.9 million to €9 million per linear km [25]. In Aarhus, at least 5-7 km of dike protects the zones vulnerable to flooding. These are 2.1 meter tall [11] and will have to be elevated by at least one meter and preferably more under the scenarios used here. At some locations it is possible that entirely new dikes have to be constructed as well. The costs of such a solution will be shared among all >1000 households in the neighbourhood [27] or perhaps paid by the municipality. Elevation of the exposed houses is a relatively costly process: elevating a 90 m^2 house some 60 cm costs approximately €41500 [25]. The real houses in the northern part of Aarhus are at least double or triple that size and according to the DEM many of them will have to be elevated more than 60 cm. Preventing water to enter a 90 m^2 house by sealing only costs around €5000 [25], but the sealing inevitably will have to be renewed frequently. Adapting the two last solutions entails regular flooding of gardens and neighbouring roads, a scenario that is unlikely to be acceptable to citizens living in the area.

Apart from the residential areas, large parts of the areas flooded in the event of extreme future weather is on the harbour of Aarhus, with a smaller area at the marina in Egaa as well. Here, the water masses might induce great damage to buildings and on-ground cargo [28] as well as cause the leakage of harmful chemicals to the surroundings. Because of space limitations, dike construction is probably not possible on the harbour, in which case parts of this would have to be either elevated [11, 29] or sealed.

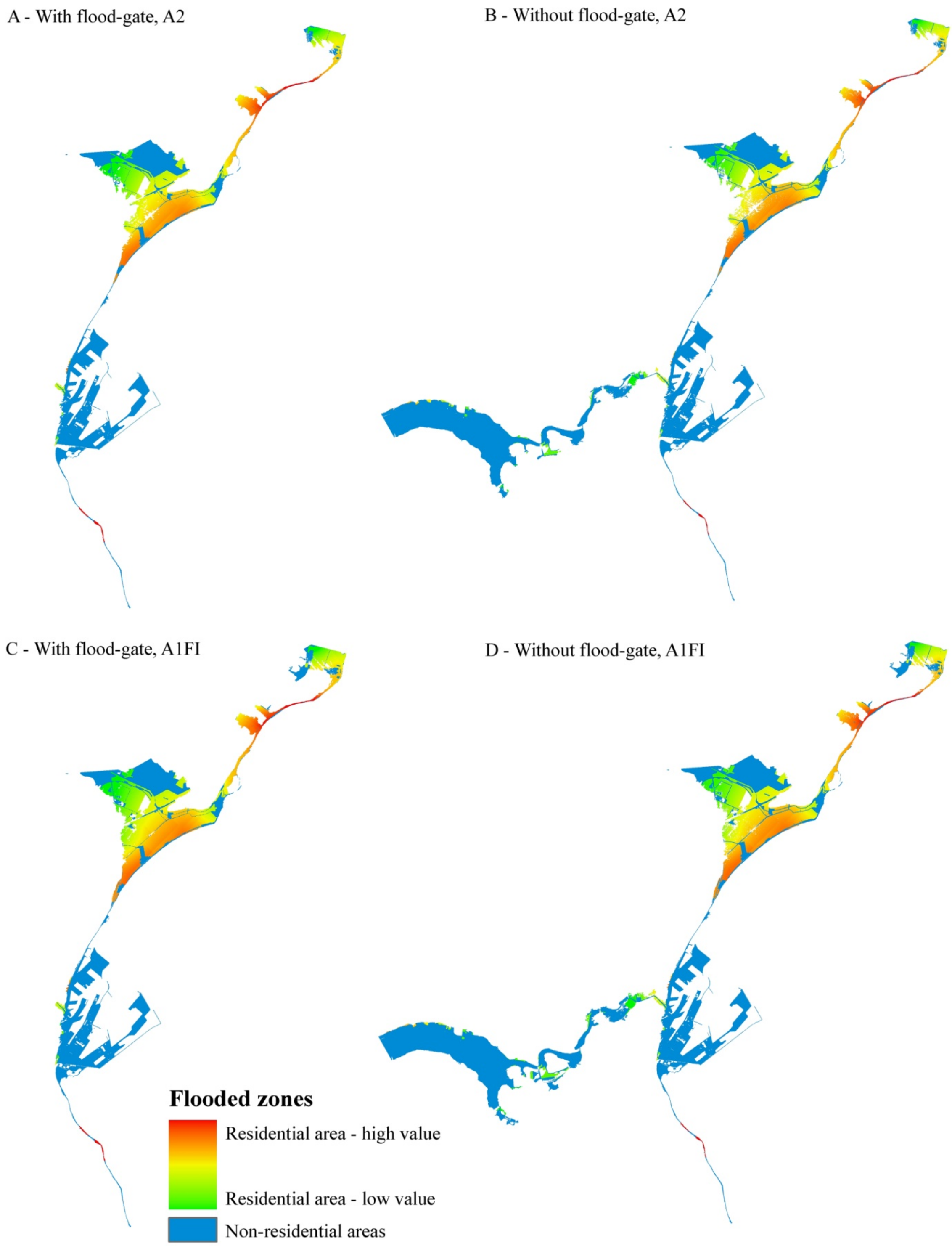

Figure 4. Simulated extreme-weather flooding of Aarhus (colonized areas) in 2090-2099 under the A2 (A, B) and A1F1 (C, D) climate change scenarios (see data and methods for detail). In A and C, strategically placed flood-gates were simulated by setting bridges in the DEM as water impervious barriers. The colour code indicates the real-estate value (see figure 3).

In addition to the predicted sea-level rises in the 21st century, current extreme weather phenomena are foreseen to become even more extreme as well as frequent [1]. From this study it is therefore clear that huge areas especially in the northern part of Aarhus and around the Aarhus River will become vulnerable to extreme weather flooding in the 21st century. As much of the area at risk represents high-value real estate, it seems clear that proactive measures other than simple abandonment should be taken. Among the different possibilities for dealing with an increased sea level, the construction or elevation of existing dikes seems to be the most convenient, most socially acceptable, and maybe also the cheapest solution. As fine resolution DEMs logically reveal small features in the landscape not necessarily found in coarser terrain models, flooding simulations using fine-resolution topography generates detailed predictive maps of exactly where flooding will take place if the water reaches a given level. Therefore, in line with previous studies [5, 30], we suggest that large editions of maps similar to those produced here will become an important tool for the planning of future city development in relation to expected climate changes, hereunder the strategic placement of flooding barriers to efficiently reduce flooding risks, as well as for the development of evacuation plans.

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