



Towards an assessment of coastal flood damage potential in Europe

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Abstract

This study makes a first step for the assessment of exposure to coastal flooding due to storm surge in Europe. The objective of this report is to assess the available data for a further detailed assessment of potential economic damage from coastal flooding. Many seamless European datasets are necessary for the implementation of a comprehensive assessment. We describe the conceptual modelling approach for calculating flood damage potential. Within this approach each component of the system represents a specific dataset. The first step of this project, as included in this report, is the identification and acquisition of the datasets for the implementation of the proposed assessment in future phases.

As example of the collected data a series of maps for selected European areas are provided. In the maps we assume a coastal flood resulting from a surge of 2 meter above mean sea level. The flooding area was mapped assuming no defences. This report is a non exhaustive assessment and only a limited number of cases have been selected. Seven critical areas across Europe are included i.e. Amsterdam, Hamburg, Copenhagen, London, Porto, Norwich and Riga. In further steps of this project all the European coastal areas will be assessed.

1. Introduction

This study makes a first step for the assessment of exposure to coastal flooding due to storm surge in Europe. The objective of this report is to assess the available data for a further detailed assessment of potential economic damage from coastal flooding.

As example of the collected data a series of maps for selected European areas are provided. In the maps we assume a coastal flood resulting from a surge of 2 meter above mean sea level. The flooding area was mapped assuming no defences. This report is a non exhaustive assessment and only a limited number of cases have been selected. Seven critical areas across Europe are included i.e. Amsterdam, Hamburg, Copenhagen, London, Porto, Norwich and Riga. In further steps of this project all the European coastal areas will be assessed.

Many seamless European datasets are necessary for the implementation of a comprehensive assessment. We describe the conceptual modelling approach for calculating flood damage potential. Within this approach each component of the system represents a specific dataset. The first step of this project, as included in this report, is the identification and acquisition of the datasets for the implementation of the proposed assessment in future phases.

We assess coastal floods arising from storm surges or extreme events such as exceptionally high tides or large waves. Indeed coastal floods are usually the result of the coincidence in time of high tides and/or large waves with storm surges. Floods as consequence of other sources, such as tsunami, are not considered in this study.

Definition and types of coastal floods

Coastal floods as result of storm surges occur along the coasts of seas. Strong winds and low atmospheric pressure cause set-up of water levels on the coast. When this situation coincides with astronomical high tide at the coast, this can lead to extreme high water levels and flooding of the coastal area. Flooding is usually most severe when a storm surge coincides with spring tides¹. The magnitude of storm surges is measured as the difference in elevation between the observed water level and the average tide (Smith and Ward, 1998).

Regional differences can be important for the setting-up of storm surges. A first type of storm surge occurs in enclosed seas such as the Baltic Sea or Adriatic Sea. In this case surges usually affect the entire sea simultaneously. This is because the sea area is small in comparison with the spatial dimension of the atmospheric disturbance. A second type of storm surge occurs in open coastlines. Here surges travel as “running waves” over very large areas of the sea. Surges of this type are usually confined to those caused by intense storms such as hurricanes or tropical cyclones, and in such cases the storm surge may be considered as a “dome” of water sometimes reaching 100 km wide. This type of storms does not affect our study area.

¹ Spring tide is a tide of greater-than-average range around the times of new moon and full moon. Neap tide is a tide of minimum range occurring at the first and the third quarters of the moon.

Storm surges are complex processes and many surges share the characteristics of both the open and enclosed sea types, as in the case of the North Sea and the European coasts of the North Atlantic Ocean (Smith and Ward, 1998). In these regions even severe storm surges can be quite localised in area.

2. Factors of coastal floods

Storm surges may occur in any coastline. However, there are several combinations of meteorological and geomorphologic conditions that make some areas more prone than others to extreme storm surges. Figure 1 shows the contributing factors for the formation of storm surges and coastal floods. Extratropical storms, also known in Europe as winter storms, are the triggering factor for storm surges and so for coastal flooding. Nevertheless winter storms do not always produce storm surges. Winter storms are necessary for the occurrence of coastal floods but they are not enough, other factors must take part in the process. Severe coastal floods occur when extreme meteorological conditions of atmospheric pressure, and wind i.e. speed, constant direction and fetch, are coincident in time with high water levels due to the tidal regime or large waves.

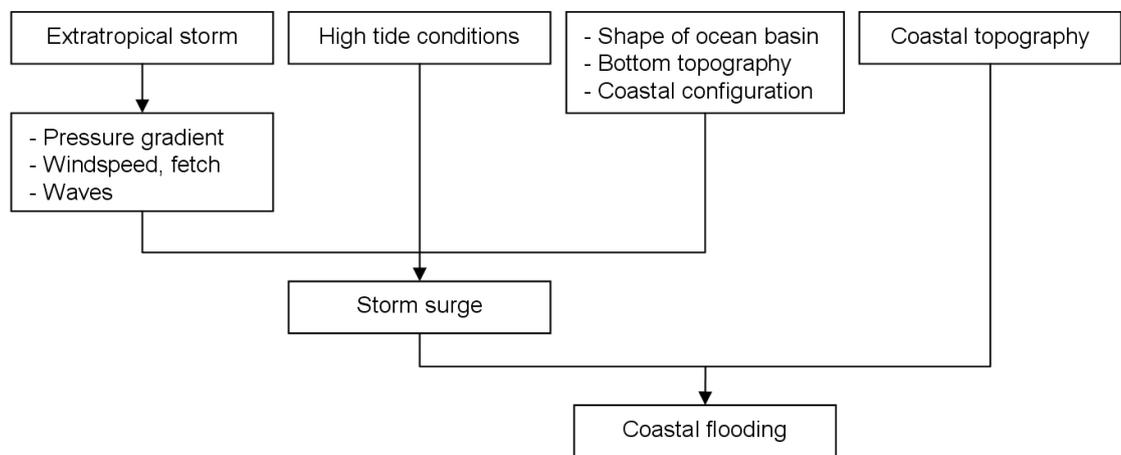


Figure 1: Meteorological and geographic factors of storm surges and coastal floods.

Winter storms are mid-latitude weather systems (between latitudes 35° and 70° north and south of the equator) that derive their energy from horizontal temperature contrasts between cold, polar air masses and warm, subtropical air masses. The temperature contrasts between these air masses are greatest during winter, and so do the frequency and intensity of European winter storms (Munich Re, 2008). Winter storms produce severe meteorological conditions that may contribute to the formation of storm surges (Fig 1). The pressure gradient and windspeed are two of the critical factors for the setting-up of storm surges. Wind speed can reach 140-200 km/h, although in extreme cases winter storms may also reach 250 km/h in exposed coastal locations. Winter storms can have wind fields up to 2,000 km wide (Munich Re, 2008). A map showing the frequency and pathway distribution of winter storms in Britain is shown in Box 1.

Windspeed produces the displacement of huge volumes of sea water against the coastline and generates large-scale turbulence and waves which contribute further to the maximum sea surface elevation. The depth of the low pressure system (pressure gradient) also contributes to a rise in sea level. It is understood as an inversed barometer effect. Lower is the atmospheric pressure registered, higher the elevation of the sea surface. A decrease of one millibar of atmospheric pressure should produce an

increase in sea level of one centimetre (Smith and Ward, 1998). If we consider that in normal conditions the pressure is 1013.20 mbar, the sea level difference in the case of extreme extratropical storms can be close to 0.5 meters if, for example, the pressure decrease to less than 968 mbar as has been observed in the 1953's storm surge affecting the Netherlands and England. Nevertheless this effect is rarely observed in full because of a series of factors such as the effect of shallower waters close to the coastline.

Water levels along most coastlines show semi-diurnal fluctuations due to tidal rhythm, with two high and two low tides each day. The maximum tidal amplitude is reaching at spring tides and it decreases to a minimum at neap tides. In many European coastlines of the North Sea the maximum tidal range can be in the order of 4 m to more than 8 m. In the Mediterranean coastlines the tidal range is rather smaller and its effect is mostly negligible. The effect of the storm surge is considerably amplified by the high water levels of the tide. Conceptually a storm surge may be considered as the difference in elevation between the observed water level and the predicted tide in normal conditions (Fig. 2). Nevertheless, it is usual that the interaction between the surge and the ordinary tide produce water levels that reveal some difference with this approach (Smith and Ward, 1998).

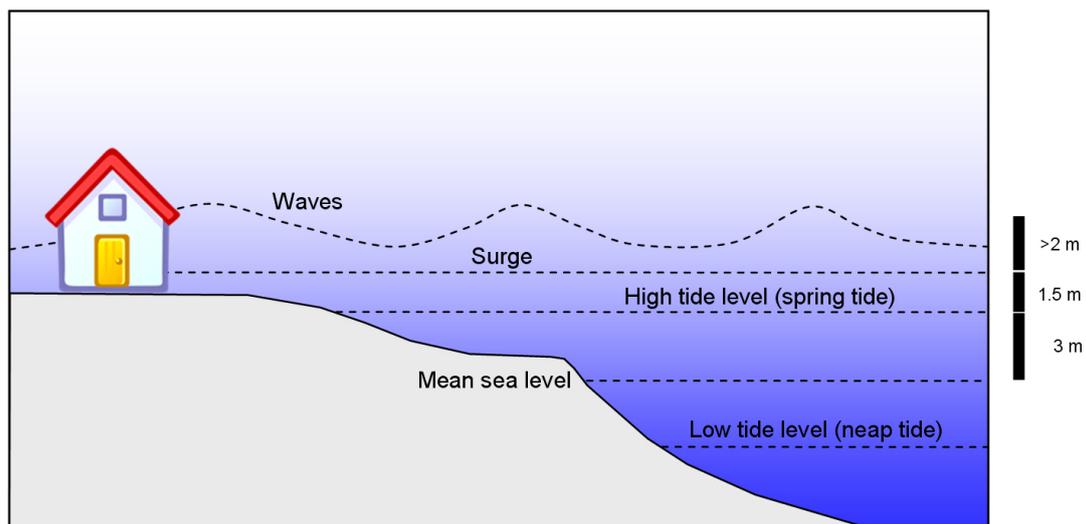


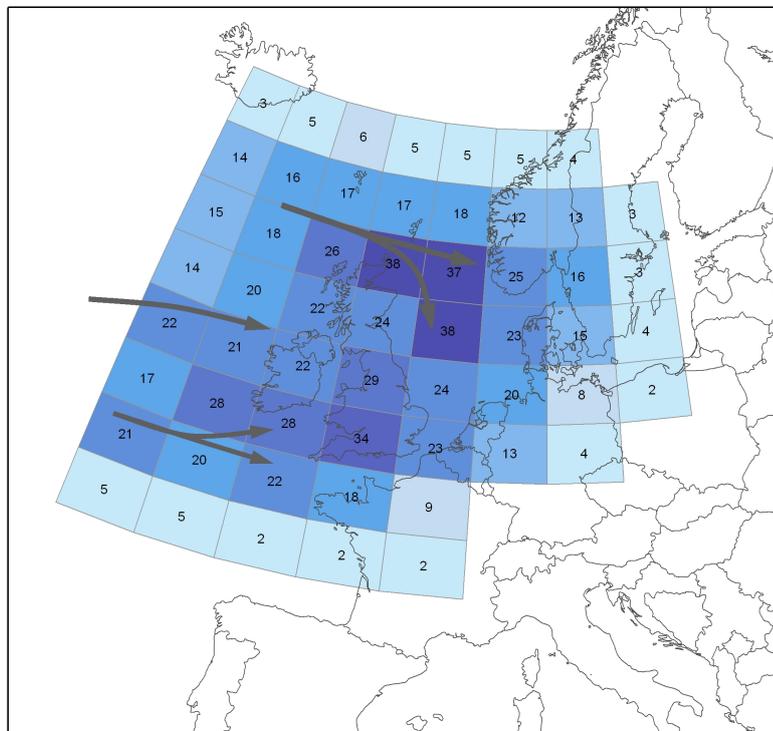
Figure 2: In this example the combination of a high tide of 3 m, a surge of 1.5 m and the effect of waves (>2 m) describes the water level of a storm surge and the associated costal flooding.

Among the geographical factors that may influence the magnitude of a storm surge the configuration of the coastline and seabed must be considered. Mainly in relatively enclosed areas the magnitude of storm surges is influenced by the shape of the ocean basin, its bottom topography and coastal configuration. Coastlines characterised by a wide and shallow continental shelf are more susceptible to severe surges than those where the shelf shows a steeped slope. Also the roughness of the bed is a factor that may increase or decrease the effect of the surge. In addition, basin shape may have an effect in tidal oscillations. The combination of basin shape and wind characteristics may contribute to the formation of standing waves oscillations which might intensify the effects of storm surges (Smith and Ward, 1998).

The configuration of the coastal land is a factor that must be considered for the assessment of the flooded areas as consequence of storm surges (Fig. 1). The topographic configuration of the coastal land may contribute to the propagation and accumulation of sea water pushed on land by storms surges. Flat coastal areas having an altitude of a few meters above, or even below, sea level are areas prone to coastal flooding. There are many European coastal areas of the southern North Sea exposed to coastal flooding. However, it is worth noting that major improvements in sea defences and the implementation of early-warning facilities in recent years have led to great storm surge catastrophes becoming less common (Munich Re, 2005).

Salt water and waves force are other two factors contributing to increase flood damage. They should be considered for assessing the potential damage of coastal floods.

Box 1. Zong and Tooley (2003) produced a map showing the distribution of winter storm frequency in the North Sea (see map below). Their study is limited to storms that were related with coastal flood events in Britain. The principal pathways (grey lines) shown in the map are in line with Munich Re (2008). Zong and Tooley (2003) examined synoptic weather charts from 1911 for identifying storm frequencies (numbers in the cells). The frequency of these storms passing through each grid (2.5° latitude by 5° longitude) was then counted. The storm tracks were recorded onto a grid map covering an area as defined in the map. It can be observed that the three main storm tracks are coincident with the cells having the higher frequencies. Coastal floods in the North Sea are associated with storms having different pathways. And each pathway has its unique characteristics and surge factors such as tidal surge and onshore waves on the associated coast [source of the figure: modified from Zong and Tooley (2003) and Munich Re (2008)].



3. Data and methods

Several seamless European datasets are needed for the implementation of a comprehensive assessment of economic damage potential from coastal flooding. Figure 3 shows the conceptual modelling approach for calculating flood damage potential. Each component of this system represents a specific dataset. The first step of this project, as included in this report, is the identification and acquisition of the datasets for the implementation of the proposed assessment in future phases.

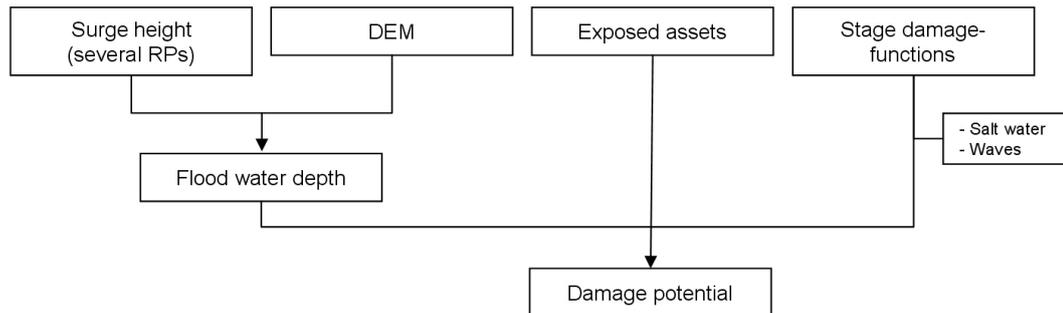


Figure 3: Conceptual model for direct economic damage assessment resulting from storm surges with different return periods.

The flood damage potential layer will be derived by using GIS, spatial analysis techniques and scripting tools. Water-depth and land use are the inputs for evaluating which assets would be affected by the given water depth and how much they are affected in terms of inundation depth.

The proposed approach studies coastal flood potential direct damage with an economic perspective, impacts such as human health or environmental damage will not be considered. Flood damage potential is the maximum possible damage in a flood prone area. Damage potential does not necessarily translate into impact. This approach assesses damage potential on the basis of calculated flood water depths for several return periods associated with storm surges. It is widely agreed that natural risks are the product of the hazard and its consequences. Flood damage potential is considered in this study on the basis of exposure and hazard. For more comprehensive figures, such as risk, information of flood defences must be assessed and this information is not available within a single data standard for the overall study area.

Within this framework hazard is defined as the occurrence of a coastal flood event with a given probability. The hazard factor is represented by flood water depths for a given return period (Fig. 3). Storm surges are the driver of the hazard component. Flood water depth will be calculated by using data from the DIVA database (Vafeidis *et al.*, 2005) on surge height for several return periods and the DEM from CCM2 at 100 m cell size (Vogt *et al.*, 2007) which was generated based on SRTM data (Farr *et al.*, 2007). Among other datasets the DIVA database provides information on surge height on each coastline segment. This information was derived from many inputs, such as data on tidal levels (thus including high-water-level), barometric pressures, wind speeds and sea bed slopes. Having a global coverage this database includes coastlines of the entire world. The data is available in a shapefile of the world

coastline represented by several segments. Surge heights are available for many return periods, i.e. 1: 1, 1: 10, 1: 100, 1: 1000 year (Vafeidis *et al.*, 2005).

Among the limitations of this study, one is the vertical resolution of the DEM. The SRTM is originally a surface model, thus the influence of land cover can introduce non-negligible noise in the height data (Vogt *et al.*, 2007). SRTM elevations represent the elevations of the reflective surface (e.g. vegetated areas, buildings) for the radar return and have not been reduced to the “bare” earth (Slater *et al.*, 2006). This is considered a critical issue for water depth calculation. The effect of structures may produce an underestimation of the flood water depth in urban areas. The same effect may influence water depth in vegetated areas, because canopy heights and proportion of coverage have an influence in the elevations of the SRTM (Hofton *et al.*, 2006). The method for water depth calculation is based only on elevation differences in the coastal zones. The method does not consider water propagation and dynamics. Rodriguez *et al.* (2006) published a detailed accuracy assessment for the SRTM data. They have shown a number of sources of error in the elevation data that may further increase inaccuracies in the flood water depths in our study.

Exposure is among the anthropogenic factors that contribute to coastal flood damage potential. Exposure is represented by the assets that are present on each location. This is typically expressed by statistics on population, socio-economic data on sectorial activities and infrastructure. In this project exposure will be assessed on the basis of land use information from CORINE cover datasets at 100 m grid size (EEA, 2000).

Vulnerability is defined as the susceptibility of the exposed structures at contact with water. This factor measures the extent to which the subject matter could be affected by the hazard. Flood-damage functions provide information about the susceptibility of the exposed elements to flooding. The available set of damage functions are absolute damage functions in current Euros (Huizinga, 2007). One of the advantages of the methodology is that the damage-determining factors are given both on the hazard side (water depth) as well as on the side of vulnerability (stage-damage functions for individual land-use classes) (Bücheler *et al.*, 2006). Flood damage functions show the susceptibility of assets to certain inundation characteristics, in this study specifically against inundation depth. A factor for assessing the increase in damage of salt water and waves will be additionally considered since the stage damage functions were originally implemented for riverine flooding.

4. Examples of coastal flooding as result of a 2-meter surge

The aim of this section is to show a collection of maps of areas exposed to coastal flooding. We simulated a surge height of 2 meters on each case (Figs. 4 to 11). The maps have an illustrative purpose and potential damage is not calculated here. It is noticeable that in the selected areas a 2-meter surge represents an event rather below the 100-year return period surge. In the Amsterdam region, for instance, the 100-year surge is estimated to be of more than 4 meters on the coastline. Of about 4 meters in Hamburg and more than 3.5 meters in the London region after the DIVA database (Vafeidis *et al.*, 2005).

The maps of the Figs. 5 to 11 have been produced by overlaying the water depth layer and the urban land-use classes from CORINE (in red). The water depth layer was obtained by simulating a surge height of 2 m above mean sea level on the DEM and then extrapolating the flood water over the inland. We assume that only the areas topographically connected to the coastline are actually affected by coastal flooding, whereas isolated areas, such as depressions situated lower than the coastline are unaffected. Thus the water depth is based on elevation data only. Other effects such as water propagation were not considered.

Figure 4 is an example showing the simulated flooded area and resulting water depths in the Amsterdam region. In Figure 5 the urban land use classes from CORINE are overlaid with the data of the previous figure. As mentioned above the vertical resolution and characteristics of the DEM may have an influence in the elevation data and thus in the calculated water depth. A consequence of this would be that water depth in the cells corresponding to urban coverage could be underestimated to some extent.

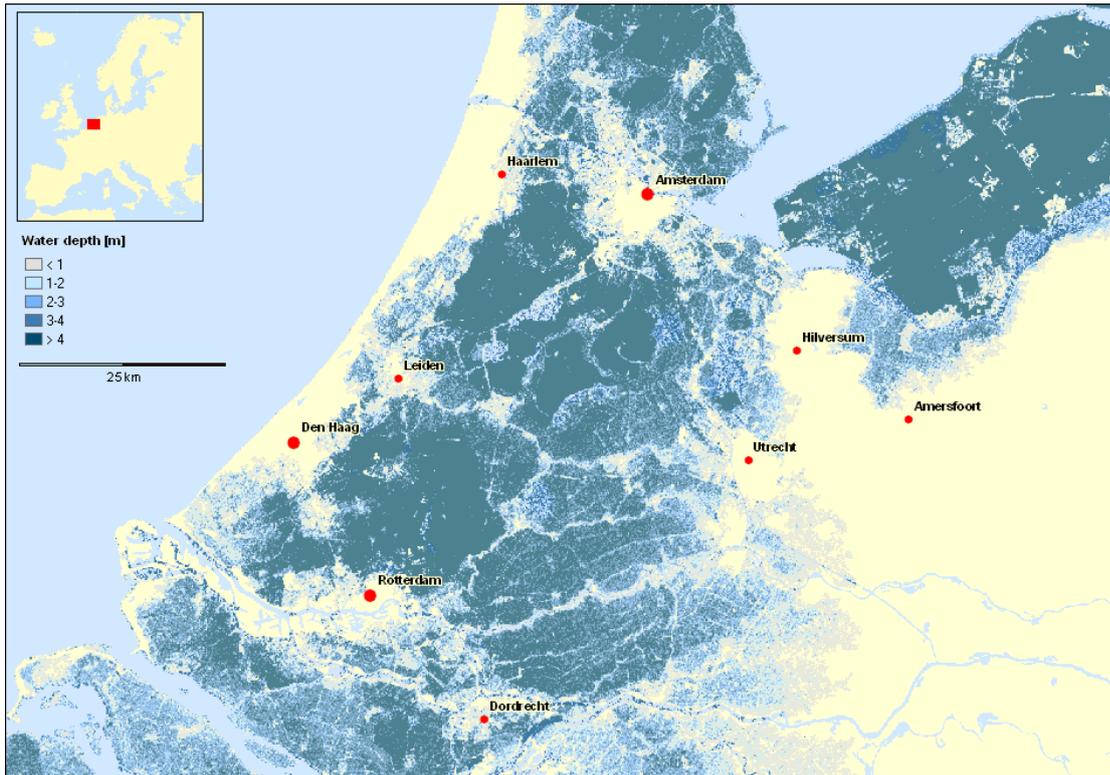


Figure 4: Simulated coastal flooding in the Amsterdam region after a storm surge of 2 meters assuming no defences.

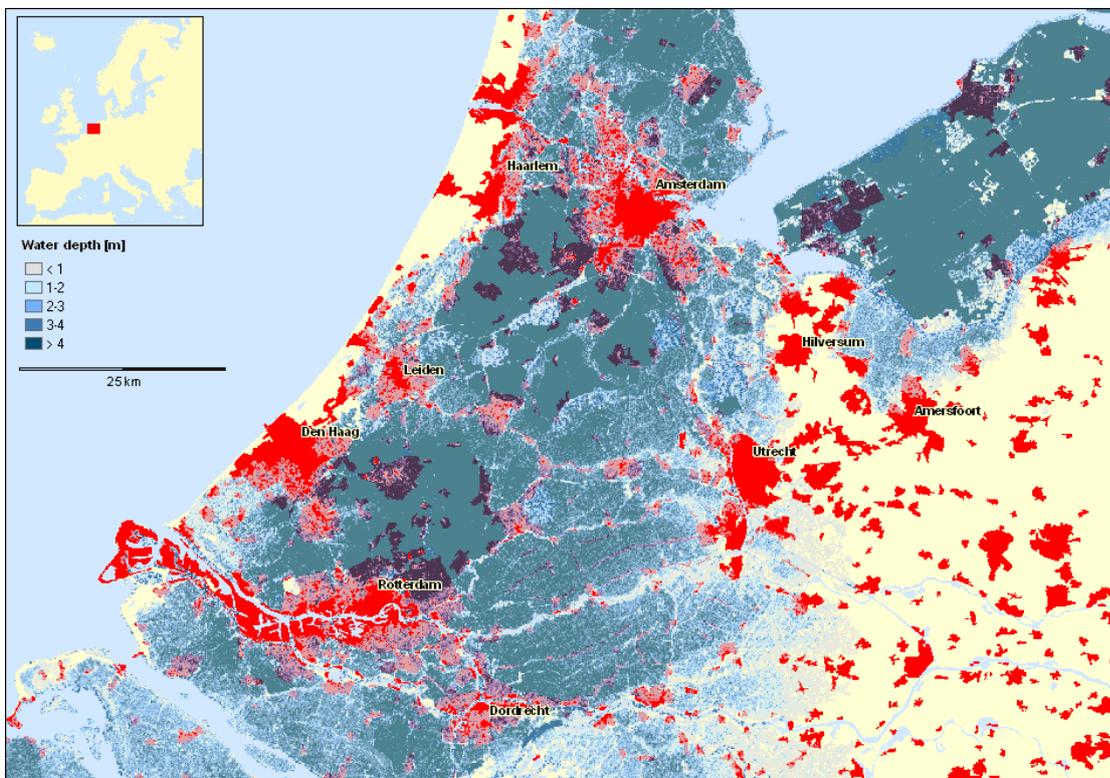


Figure 5: Simulated coastal flooding in the Amsterdam region after a storm surge of 2 meters assuming no defences (urban areas in red).

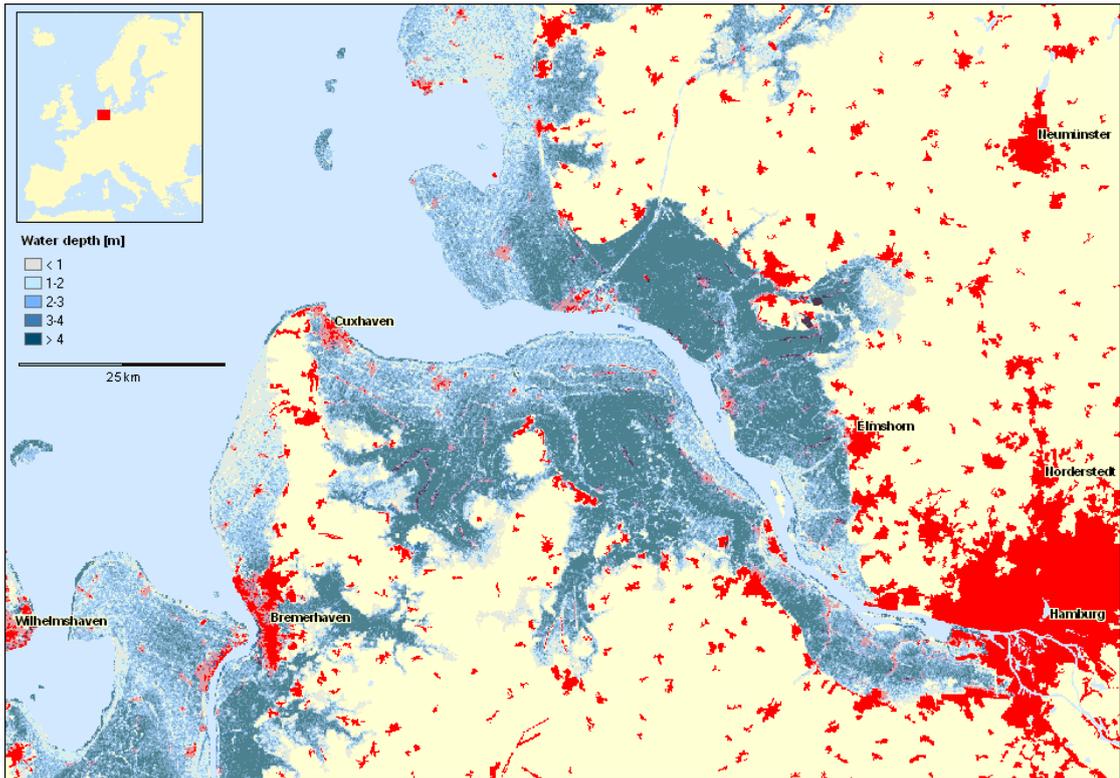


Figure 6: Simulated coastal flooding in the Hamburg region after a storm surge of 2 meters assuming no defences (urban areas in red).

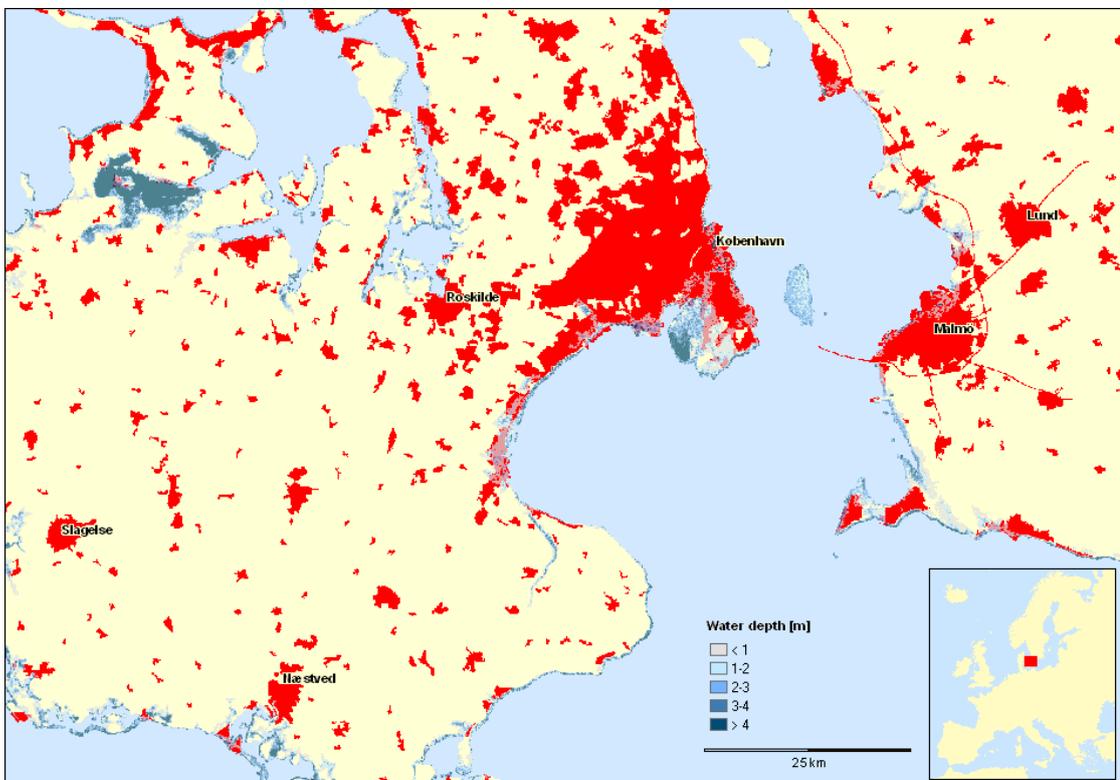


Figure 7: Simulated coastal flooding in Copenhagen after a storm surge of 2 meters assuming no defences (urban areas in red).

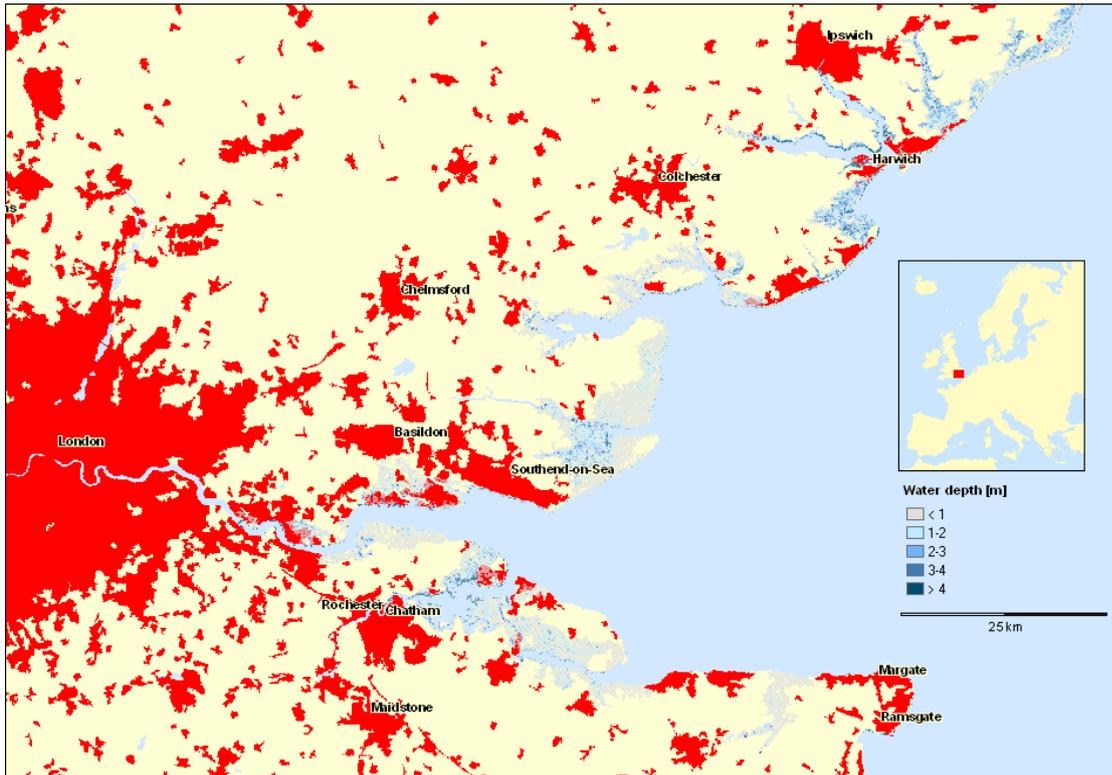


Figure 8: Simulated coastal flooding in the London region after a storm surge of 2 meters assuming no defences (urban areas in red).

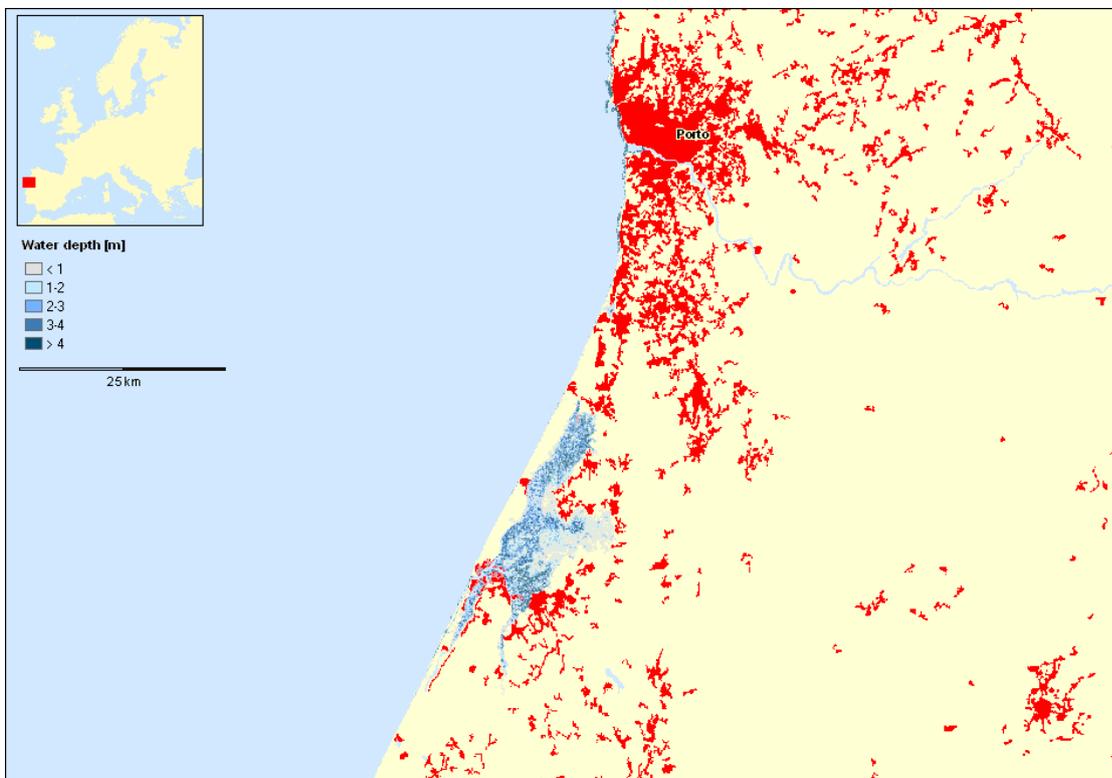


Figure 9: Simulated coastal flooding in the Porto region after a storm surge of 2 meters assuming no defences (urban areas in red).

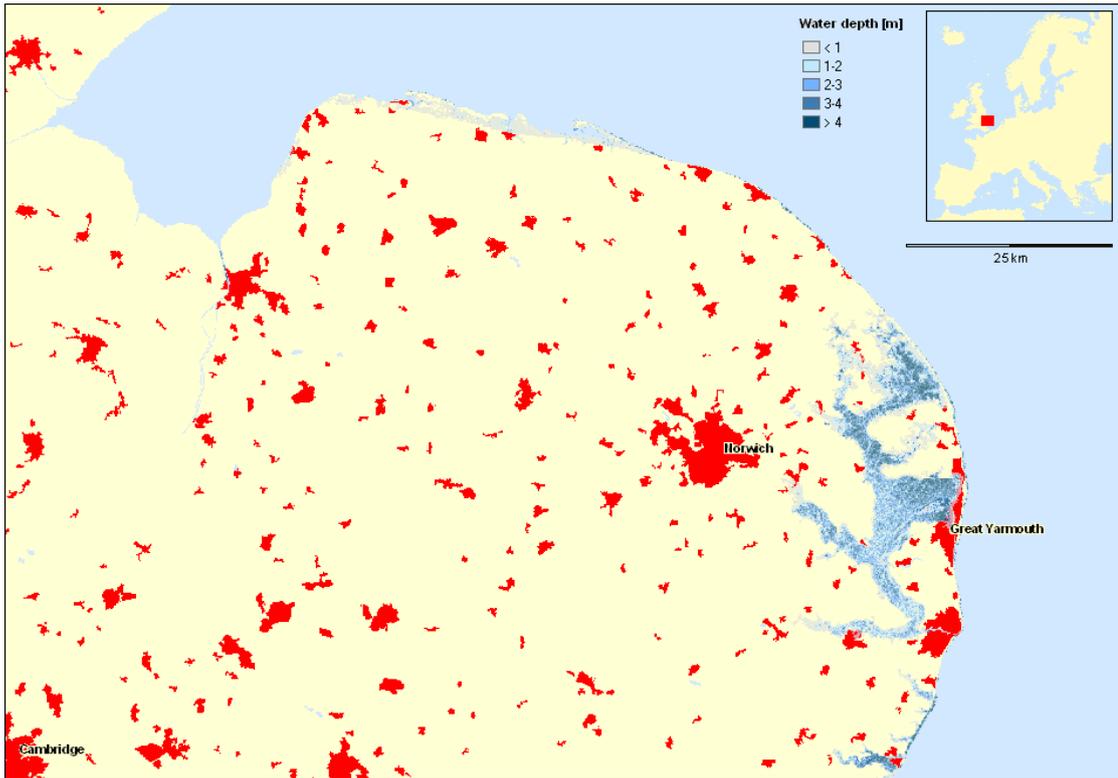


Figure 10: Simulated coastal flooding in the Norwich region after a storm surge of 2 meters assuming no defences (urban areas in red).

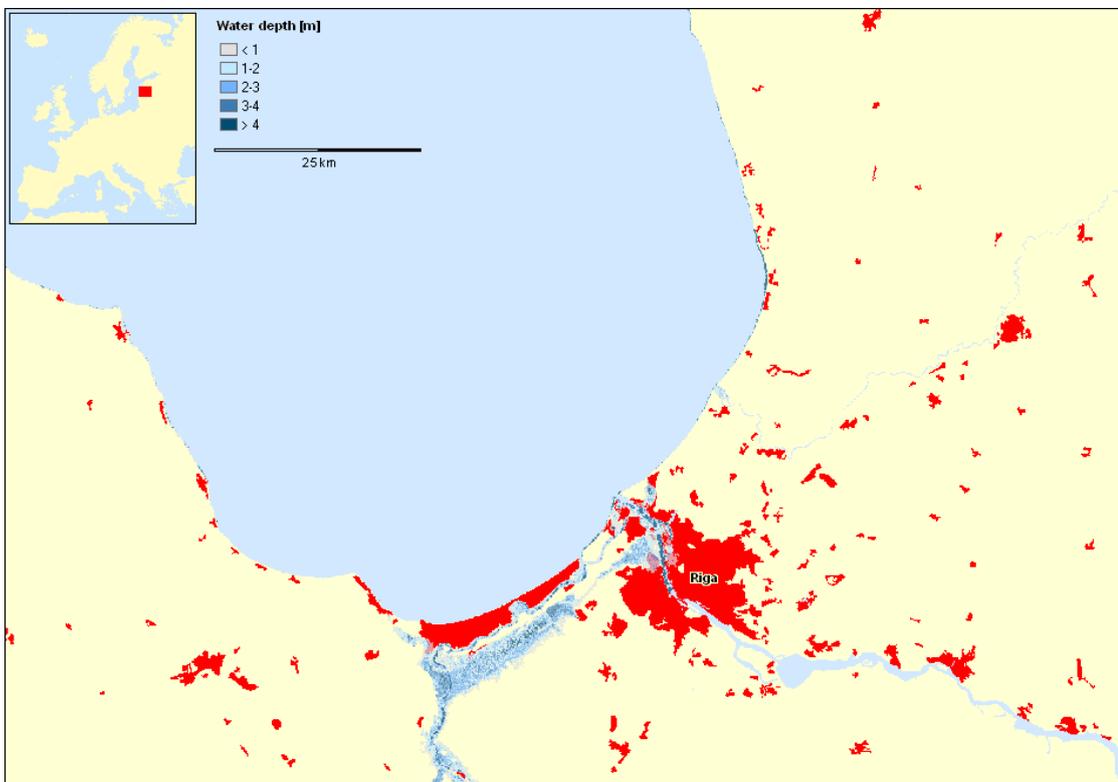


Figure 11: Simulated coastal flooding in Riga after a storm surge of 2 meters assuming no defences (urban areas in red).

5. Further work

This project structure follows six methodological steps (Fig. 12). This report contains the description of the first three steps. All the data needs have been identified and the datasets acquired. The next steps consist in the implementation of the methodology, production of results and mapping of the coastal flood damage potential in Europe. The entire European coast will be assessed and not only the main urban areas. This fact is a marked point of departure from previous studies that assessed, for instance, only a subset of coastal cities at global level (e.g. Nicholls *et al.*, 2008). Assessing damage potential by using flood damage functions and land use datasets is considered a relevant aspect that will further contribute to a more detailed assessment of the exposed assets to coastal flooding.

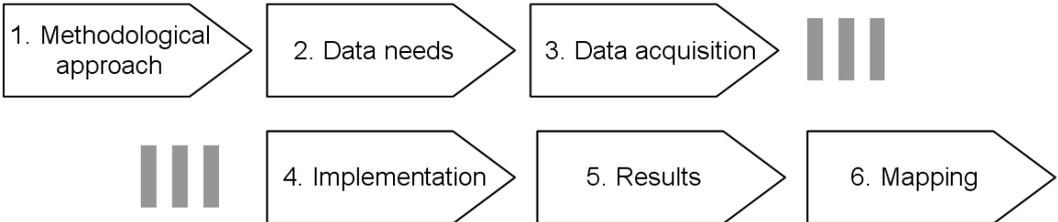


Figure 12: Methodological steps of the project

The mapping phase will follow a similar approach as described in Barredo et al. (2008). Indeed, their map and the map to be provided in this project for coastal flooding will be comparable in many respects such as scale, metric described and unit of measurement for the potential damage i.e. international Euros expressed in purchasing power parities (PPP).

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