New estimates of potential impacts of sea level rise and coastal floods in Poland

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Abstract

Polish coastal zone is thought to be of the most exposed to sea level rise in Europe. With climate change expected to raise mean sea levels between 26 and 200 cm by the end of the century, and storms increasing in severity, accurate estimates of those phenomena are needed. Recent advances in quality and availability of spatial data in Poland made in possible to revisit previous estimates. Up-to-date detailed information on land use, population and buildings were used to calculate inundation risk at a broad range of scenarios. Inclusion, though imperfect, of flood defences from a high-resolution digital elevation model contributes to a further improvement of estimates. The results revealed that even by using a static “bathtub fill” approach the amount of land, population or assets at risk has been significantly revised down. In the perspective of the 21st century, s~~S~~ea level rise or storm surges are unlikely to reach intensity required to cause significant damage to the economy or endanger the population. The exposure of different kinds of assets and sectors of the economy varies to a large extent, though the structural breakdown of potential losses is remarkably stable between scenarios.

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1 Introduction

Contemporary sea level rise, triggered by the changing climate, is major threat to coastal areas. Global mean sea level has risen by 21 cm between 1880 and 2009 (Church and White

2011). Around 10% of world population lives in low-elevation coastal zones, including 7% of Europeans (McGranahan et al. 2007). Projections by IPCC (Church et al. 2013) indicate a possibility of a further increase by 26–98 cm by the end of the century, though a rise by 140–200 cm is suggested by other authors (e.g., Pfeffer et al. 2008, Rahmstorf 2007). The pace of water level rise in the Polish Baltic Sea coast is generally in line with global estimates. Tide gauge in Świnoujście, in the western part, has one of the longest instrumental records in the world (Permanent Service for Mean Sea Level 2015) and during 1811–2006 a trend of 0.4 mm per year was observed here, accelerating to 1.0 mm per year during 1947–2006 (Wiśniewski et al. 2011). The values increase moving eastward: Kołobrzeg (central part of the Polish coast) recorded an increase of 0.5 mm during 1901–2006 and 1.4 mm during 1947–2006, while Gdańsk (eastern coast) observed 1.6 mm during 1886–2006 and 2.5 mm during 1947–2006. The difference is largely due to uneven isostatic movement of the crust. Satellite altimetry reveals that the rise in water levels is virtually the same at various offshore locations in the southern Baltic Sea. It amounts to 3.3 mm per year between 1992 and 2012 (Stramska and Chudziak 2013), a pace very similar to the world ocean average.

At a shorter timescale, the coasts are endangered by storm surges. Several large coastal floods occurred in late 19th and early 20th century, with a few calmer decades thereafter. More recently, however, storms are on the rise: the number of surges exceeding the warning level of 570 cm (i.e., about 70 cm above mean) soared from about two per year in the 1950s to six per year in 2000s (Wiśniewski and Wolski 2009). Usually the event is too short to cause damages inland. However, during a storm surge in January 1983 water levels exceeded 1.3 m above average along the majority of the coast, affecting many locations, particularly in the eastern part. In the Żuławy region a total of 50 km^2 of land was flooded and almost 1,300 people were evacuated (Bednarczyk et al. 2006). Wiśniewski and Wolski (2009) estimated that a 100-year coastal flood could be as high as 1.95 m above average in Kołobrzeg, while a 1000-year flood might reach 2.5 m (the highest value actually recorded was 2.22 m, in 1872). Long-lasting storm surges, even though relatively insignificant at the coast, can cause a flood dozens of kilometres inland, on the low-lying banks of Odra or Vistula rivers. Water influx from the sea due to northerly winds at times increases water levels above the maximum observed at the coast (Wiśniewski and Kowalewska-Kalkowska 2007). The highest recorded water level in Szczecin, located almost 70 km inland, was 1.54 m above average during a storm surge in 1913 (Richter et al. 2012). The most recent storm surge resulting in a large inflow of seawater into the river network occurred in 2009, causing losses of several million PLN in locations all over the coast, mainly in the eastern part (KZGW 2011). Across the whole region, flood defences protect the lowest areas, particularly around river mouths and coastal lakes, while the rest of the coast is screened from storm surges by dunes and cliffs.

It is generally considered (Church et al. 2013, Hunter 2010, Xu and Huang 2013, Wróblewski 1994) that with the increase of mean sea levels also the extreme levels will soar. Rare events could therefore appear more frequently, while areas not considered as endangered today would become at risk in the future. It is therefore necessary to assess the number of persons and value of assets which could be at stake. In Poland, comprehensive research on coastal flood risk considering sea level rise (SLR) was originally spawned by IPCC's first assessment report released in 1990. Rotnicki and Borówka (1991) used 1:25,000 topographic maps to calculate the area threatened by rising waters along with a quantification of elements affected, such as land use, infrastructure, settlements and their population. According to an expanded version of that study (Rotnicki et al. 1995), a 2.5 m SLR could impact 2700 km^2 of land, including 93 km^2 of settlements, 374 km of railways, 906 km of roads and 297,000 people. Pluijm et al. (1992) used their data to obtain monetary value of land and structures at risk. The results indicated that a one-metre rise of mean sea levels would result in a loss of assets worth 24% of 1990 gross domestic product (GDP). Several studies based on the aforementioned publications also have been published (Zeidler 1997, Pruszak and Zawadzka 2005, 2008). Additionally, Poland was included in studies on global and European flood risk, with country-specific data most recently provided by Bosello et al. (2012). All of these studies used only low-resolution data and were kept on a high degree of generalization. Also, only a limited set of statistics is provided by all those studies and for only a few scenarios of water level rise; global studies mostly do not show country-specific data (e.g. Hinkel et al. 2014) or quote Zeidler's (1997) study (e.g. Nicholls and Mimura 1998, Nicholls and Klein 2005).

More recently, due to the obligations imposed by the European Union's "flood directive" (EU 2007), the national government ordered preparation of flood risk maps for selected regions of Poland. They were published in 2013 by the National Water Management Authority (KZGW 2015). Their main advantage is the use of up-to-date, detailed and high-resolution data, including lidar-derived digital elevation models (DEMs), aerial photography, land surveys and administrative registers. However, the main focus have been put on river floods, while only parts of the coast were investigated. Moreover, no sea level rise impacts were assessed, while the analysis of storm surges was limited only to one or two scenarios, depending on location. Finally, the results of flood risk calculations are provided only as a graphical representation on maps and the only aggregate statistics provided are the estimates of exposed population by settlement. The total value of assets at risk remains undisclosed.

In the light of the above, there is clearly a need for a high-resolution assessment of possible social and economic impacts of storm surges and sea level rise in Poland. In this paper we aim to provide more precise estimates of population and assets at risk at a broad range of scenarios, using the up-to-date and detailed cartographic materials, which have become available only recently. Most importantly, the digital elevation model used here includes the majority of flood defences in the area, which were missing in other studies.

2 Materials and methods

2.1 Polish Baltic Sea coast

The Baltic Sea is a non-tidal, semi-enclosed and shallow body of brackish water. Exchange of water through the Danish Straits is the primary regulator of water levels in the basin, causing dangerous surges primarily at its southern and eastern coasts (Ekman 2009, Wolski et al. 2014). Poland is one of 14 countries with access to the Baltic and has a 500-kilometre long, diversified coastline. At various locations along the coast there are sections of cliffs made of Pleistocene deposits, totalling around 90 km, or 18% of entire coastline. Areas where they exist are not endangered directly by floods (they can be up to 70 m high on Wolin Island), though their retreat due to erosion is a source of threat related to storm surges and sea level rise (Schwarzer et al. 2003, Kolander et al. 2013). Apart from an alluvial section in the Puck Lagoon (less than 3% of total), the remainder is a spit- and barrier-type coast, with dunes ranging in height from less than 2 up to 49 m. Behind the dunes, coastal plains of glacial or fluvioglacial origin filled mostly with peat are usually observed. Their surface is only 1–3 m above sea level. Depressions occur occasionally in the surroundings of shallow and relatively large coastal lakes such as Łebsko, Jamno or Gardno (Tomczak 1995). The biggest area laying below sea level are is the Vistula river delta, known as Żuławy Wiślane. At some locations the elevation is 1.8 m below mean sea level, hence the area needs to be protected by a complex system of dykes, channels, sluices and pumping stations.

Two large, shallow lagoons also exist in the Polish coastal zone, bookending the coast at the borders with neighbouring states. Szczecin Lagoon is the outlet of Odra river and is separated from open sea by Usedom and Wolin Islands, therefore it is connected to the Baltic only by three narrow straits, including one in Germany. Vistula Lagoon is a long and narrow body of water limited by the Vistula Spit and has only one strait to connect it with the sea (it is located outside Poland).

The coastal zone itself is not particularly vital to the national economy. Barely 0.6% of total employment is in the maritime sectors (shipping, shipbuilding, fishery etc.), while only a limited amount of goods and passengers move through Polish ports. It is not densely inhabited: the total population of municipalities with direct access to the sea was 1,070,000 in 2013, with three fourths concentrated the Tricity agglomeration (Gdańsk, Sopot, Gdynia). That is 2.8% of Polish residents and excluding the Tricity the population density in this area is a mere 90 persons per km^2, below the national average of 123. Additional 516,000 persons live in municipalities containing ‘internal maritime waters’ (as Szczecin and Vistula lagoons are collectively named by the government along with some other waters which enable access to ports), mainly in the harbour city of Szczecin (CSO 2015).

However, the coast is by far the most popular vacation destination in Poland. 35% of all overnight stays in accommodation establishments during July-August 2013 occurred in 55 municipalities considered by Eurostat as coastal regions (CSO 2015). That corresponds to an average 71 tourists per 100 residents during the summer. The economies of many coastal resorts are completely dependent on this short holiday season (Łonyszyn and Terefenko 2014). Any damages to infrastructure and buildings could therefore dampen the economic prospects of those localities.

The study area, as referred to hereafter, includes all municipalities in which there is some land laying no more than 5 m above mean sea level. There are 86 such municipalities, including 22 that further divide into a town and rural area. That gives a total of 108 basic administrative units with a combined population of 2.4m (2011 census). Fig. 1 outlines the study area within the Polish coastal zone.

~~2.2 Data sources~~

~~Two main sources of data were used in this study: the topographic objects database, containing information on land use as well as buildings, and a digital elevation model (DEM). Both were derived from national cartographic resources, which include recent output of large-~~

~~scale mapping projects. Statistical data on demographic and economic indicators have also be collected.~~

~~2.2.1 Digital elevation models~~

~~Quality of flood hazard analyses depends mainly on detailed information on the terrain in question. Here, a digital elevation model created through airborne laser scanning technology (lidar) was used. DEMs obtained using this method are commonly applied to coastal flood risk analyses due to their accuracy (Webster 2010). In recent years the national government launched a large measurement campaign specifically to provide data for flood hazard mapping. It was conceived in the coastal areas between 2010 and 2013, but mainly in 2011. The density of scanning was usually 4 points per m^2, except for urban agglomerations, where the density was 12 points per m^2. The final dataset in raster format has a spatial resolution of 1 m, which is fine enough to include flood defences and most of other small topographic features that can have a profound impact on flood hazard analyses. Nominal vertical accuracy of the dataset is 20 cm Average vertical error of the dataset is nominally less than 20 cm in areas scanning density of 4 pts/m^2 and less than 10 cm i areas with scanned with 12pts/m^2 (CODGiK 2014).~~

~~A very small area located in the western part of the coastal zone is not covered by the detailed lidar DEM. The gap was filled with a different DEM, which was created on the basis of aerial photographs. It has a spatial resolution of 40 m and a vertical accuracy of about 1.5 m. These are much worse values than for the lidar DEM, but it had to be used only for less than 0.1% of the area potentially at risk, so it has a negligible impact on the results.~~

~~2.2.2 Topographic objects database~~

~~In order to calculate the value of vulnerable assets, detailed information on land use and buildings are necessary. The primary source of information used here is the topographic objects database (pol. *baza danych obiektów topograficznych*), the digital successor of analogue topographic maps, created and maintained by Poland's surveyor-general. It consists of almost 300 types of objects with a vectorised representation of their geometry and additional qualitative and quantitative descriptors. Accuracy of the database in terms of~~

~~location and minimum size of objects ought to be similar to a 1:10,000 map, which. This is enough to represent the natural and socioeconomic environment down to a single parcel, road and building. The current structure of the database was implemented in 2011 (Law 2011/279/1642) and its content was updated during 2012–2013. The database used here is, nominally at least, accurate as of January–July 2013, depending on location. Quantitative information on the objects, such as their area, is expected not to deviate from real values more than ±20%.~~

~~Data on buildings include their area, functional characteristic and, in most cases, the number of storeys. In case the latter is missing, the building was assumed to have only one storey. Roads are represented in the database as a linear object, but for each section their width is given, so that they could be transformed into a surface. Only paved roads were included in the calculation. Railway and tram lines were transformed into polygons according to the track's gauge. Roads and tracks located on bridges or similar above-ground structures were excluded.~~

~~2.3~~2.2 Calculation of flood hazard

Flood hazard analysis forms a basis for flood risk calculations. It consists of the inundation extent and other hydrological parameters of the flooding, such as water depth. To calculate the floodzone, a “bathtub fill” approach was applied for this study (Bates and De Roo 2000, Poulter and Halpin 2008). It means that it is assumed that the sea at a certain scenario will cover all land laying below the assumed water level. For a sea level rise scenario that is an accurate description, because an increased mean water level would cover land permanently. However, for storm surges it is a straightforward simplification, as the temporal change in water levels is also an important factor determining the inundation extent. Unfortunately, the data required to include time in such a calculation were not available to the authors. In effect, the storm surge scenarios constitute a description of the worst-case event (Apel et al. 2009, Breilh et al. 2013).

After intersecting the planar water surface with the DEM some areas not connected directly with the sea are also highlighted. Because the resolution of the DEM is fine enough to include flood defences, isolated locations laying below the water level at a certain scenario were considered protected by surrounding high terrain. These areas were discarded to create the final flood zone using a four-side rule, which means that no water flow was allowed in diagonal directions (Poulter and Halpin 2008). Naturally, dikes and other structures could fail and flood the hinterland, but that aspect was not considered in this article. Also, the situation when water floods the land behind structures through culverts was not analysed. Protection from f~~F~~lood defences such as dikes, banks and other earthworks, as well as sluices and weirs ~~are~~ is included in the calculation.

Sea level rise and storm surges were analysed in intervals of 5 cm, providing scenarios of 5, 10, 15 etc. cm up to 5 m above mean sea level. In this way vulnerability at different elevations could be assessed in detail. The 5 m value was chosen as the rounded value of possible SLR from literature (2 m) together with a 1000-year coastal flood (about 2.5 m). Mean sea level along the Polish coast varies slightly, with 1947–2006 average in Gdańsk being 7 cm higher than in Świnoujście (Wiśniewski and Wolski 2009). As a minor simplification, the 500 cm ‘baseline’ level of all Polish tide gauges was used here, which corresponds to about +0.10 m in the European Vertical Reference System EVRS-2007 (Urbański 2012).

Results from the flood hazards calculations are juxtaposed here with future sea level rise scenarios included in the latest IPCC report (Church et al. 2013) and storm surges of certain probabilities of occurrence. The latter were obtained by applying Gumbel distribution to annual maximum water levels recorded at five tide gauges during 1947–2007 provided by Wiśniewski and Wolski (2009). Details on the methodology of probability calculations for Polish stations can be found in Paprotny (2014).

~~2.4~~2.3 Calculation of flood risk

Having obtained the inundation extent, the amount of losses caused by water was analysed. Following Hallegatte’s (2012) framework on investigating impact of SLR on economic growth, the analysis includes the following elements:

- Permanent losses of natural capital: market value of land; we also calculate the area of protected habitats,
- Permanent loss of physical capital: gross replacement cost of immovable and movable fixed assets,
- Permanent loss of social capital: number of affected population,

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- Temporary floods and their impacts: losses from coastal floods are considered alongside sea level rise.

Increased coast protection expenditures are not considered here, as we expect to analyse of adaptation costs and strategies in a follow-up study. Also, impact on economic growth rates is not investigated.

~~The investigation performed here covers three types of tangible assets which have a monetary value: land, immovable and movable fixed assets.~~ Each type of natural and physical capital (land, immovable and movable fixed assets) has different susceptibility to sea level rise or coastal floods, as presented in Table 1~~Table 1~~. In case of rising average water levels, land and immovable fixed assets (i.e. buildings and structures) are covered permanently by water and therefore lost completely. Movable fixed assets, which include machine tools, household goods, vehicles or livestock, can be evacuated from the endangered area given the gradual nature of SLR. Therefore, no losses in this category are assumed. In case of coastal floods, no losses are assumed for land, as water covers it only temporarily. Some productivity of land may be lost and consequently its market value could decrease, however this aspect was not analysed here. Damage to crops is not analysed, too, as they are not considered fixed assets, similarly to stocks of produced goods. Losses of fixed assets are calculated using damage functions, which relate losses to water depths (Apel et al. 2009).

Value of aforementioned assets was calculated here using 2011 data, the latest year for which complete statistics required here are available. The primary source were online databases of the Central Statistical Office of Poland (CSO 2015). Values of different types of land use are an estimate of their 2011 market price. Average sale price calculations made by CSO were used for arable land, meadows and pastures. Value of forests was taken from estimates of the State Forests, the manager of the vast majority of Polish woods (Ministry of Treasury 2012). Their calculations include both the value of land parcels and the trees covering them. Value of areas covered by buildings, transport infrastructure or non-built-up areas ready for construction was estimated using the relation between the sale price of those types of land use and the sale price of arable land in Germany in 2011 (Statistisches Bundesamt 2015). For other types of land use, numbers were assigned based on governmental regulations on estimation of real estate value (Law 2004/207/2109). As a result, woodlands or bushes are assumed to be worth equal to poor-quality arable land. Orchards were assigned the same value as arable land, while wastelands and other unutilized land were considered as equal to poor-quality meadows. Loss of inland surface water was not taken into consideration. Summary of land values is presented in Table 2. Agricultural build-up areas do not form a separate category in the topographic database; it was assumed that build-up areas adjacent to arable land and permanent crops fall into this category.

Information on buildings was compiled from several sources in order to calculate their value relative to their area (Table). Value of housing is the average construction cost of new houses as calculated by CSO. Stock of movable assets is difficult to estimate and no national statistics in this matter are available. However, the ratio between household durable goods' value and GDP is reported to differ only slightly between countries and throughout modern history. It was therefore assumed that the total value in this category in Poland constitutes 35% of GDP, which is the average ratio in four countries (Canada, Germany, United Kingdom and United States) for which data are provided by Piketty and Zucman (2014). GDP and housing area statistics from CSO were used in order to obtain the amount of movable assets per m^2 in 2011.

Commercial buildings were divided into three branches (industry, services, agriculture) and for each type its value was calculated using the following formula:

$$V = \frac{F \times L_s}{L \times A_s} \qquad (1)$$

where V is the value of a building per area in PLN, F is the value of fixed assets in Poland, L_s is the corresponding land use area in the study area, L is the corresponding land use area in Poland and A_s is the total building area in the study area. Fixed assets estimates were obtained from Eurostat (2015). Land use data for Poland is from CSO (2015), while for the study area the corresponding types of land use from the topographic database where used. Finally, building area was extracted from the topographic database, taking into account the multiple storeys several buildings contain.

Damage functions, which relate water depth to the relative loss of assets, were applied from Emschergenossenschaft/Hydrotec (2004), who created them using HOWAS database of flood losses (Merz et al. 2004). They were selected for this study, because there are no corresponding function created from Polish empirical data. Additionally, they are similar to damage curves created as a combination of various European methodologies by Huizinga (2007) and suggested for use in countries without national damage functions. The only exception is the damage function for transportation, which is a constant value rather than a damage function. As can be noticed in Table , the equations differ for immovable and movable housing assets, while for commercial activity they are combined. Finally, the value of transport infrastructure was taken from a Polish governmental flood risk calculations methodology (Law 2013/104). Total value of losses for a building can be described as:

$$R = A \times V \times Y(D) \qquad (2)$$

where R is the total loss for a building in PLN, A is the building area (including all storeys), V is the total value of the building per area and $Y(D)$ is the appropriate damage function for depth D (averaged within the building's contour).

Additionally, the number of people affected by sea level rise and coastal floods was estimated. Population data from the 2011 census (CSO 2015) provide information down to settlement level. By combining these data with housing area from the topographic objects database it was possible to further disaggregate the data and obtain the average number of persons per housing area in settlements and towns. All persons living in a residential building even partially covered by water were assumed as being affected by the event. Similarly, the amount of tourism traffic potentially lost was estimated by disaggregating the number of tourists and nights spent in establishments (at basic administrative unit-level) using the size of appropriate categories of buildings. For the purpose of this study, ‘tourists’ refer only to persons staying overnight in collective accommodation, excluding persons in camping sites.

2.4 Data sources

Two main sources of data were used in this study: the topographic objects database, containing information on land use as well as buildings, and a digital elevation model (DEM). Both were derived from national cartographic resources, which include recent output of large-scale mapping projects. Statistical data on demographic and economic indicators have also be collected.

2.4.1 Digital elevation models

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A very small area located in the western part of the coastal zone is not covered by the detailed lidar DEM. The gap was filled with a different DEM, which was created on the basis of aerial photographs. It has a spatial resolution of 40 m and a vertical accuracy of about 1.5 m. These are much worse values than for the lidar DEM, but it had to be used only for less than 0.1% of the area potentially at risk, so it has a negligible impact on the results.

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3 Results

In this section the consequences of coastal floods and sea level rise are presented as derived from the data through the methodology outlined above. Therefore, the data on coastal floods indicate the worst case scenario of waters reaching a given level in the entire study area. It should be noted that whenever statistics of inundated area are mentioned in the next sections, they do not include land covered by water under normal conditions. Also, all monetary values are in Polish Złoty (PLN) in 2011 prices (4.12 PLN = €1). Finally, detailed results can be found in the Supplement.

3.1 General results

Water inundates the study area at different pace depending on the analysed scenario. The flooded area encompasses 342 km^2 at 0.5 m water level, 1662 km^2 at 1.5 m up to a maximum of 3323 km^2 at 5 m (Fig. 2). The area at risk grows most dynamically between 0.3 and 1.6 m water level with an average of almost 13 km^2 for every cm of water level rise. The highest value of 371 km^2 is recorded between 1.2 and 1.3 m scenarios (Fig. 3). Besides that, two other peaks at intervals of 0.8–0.9 and 0.9–1.0 m are observed, covering 132 and 212 km^2, respectively. In the 1.5 m scenario the flooded area already reaches half the size of the 5 m hazard zone, which indicates a significant slowdown in the growth dynamic of the flood zone at higher water levels. Up until the very last scenario it increases by 3–5 km^2 per cm on average.

The number of affected buildings and population does not follow the aforementioned tendencies, especially in scenarios of low water level rise. Urban areas as well as other dense inhabited areas are either protected or generally not located at high flood risk zones. This results in an insignificant number of endangered buildings and people up to the level of 0.8–1.0 m. Crossing this barrier, in the range from 1.0 to 2.5 m water level, the number of both population and buildings in the hazard zones soars (Fig. 3). For buildings, the rate of increase of water levels peaks in the 1.2–1.3 m interval and significantly slows thereafter. Increase in the number of persons affected reaches maximum the 1.7–1.8 m interval and eases only above the 3 m water mark. In effect, in the range of a probable SLR or a coastal flood affecting areas deep inland (about 1.5 m) the density of construction is less than half of the regional average, and the population density a less than a fifth. There are around 20,000 buildings and 42,000 persons within the upper range of IPCC sea level rise projections; the number for a coastal flood corresponding to a 1000-year event in Szczecin (located deep inland) are approximately 46,000 and 101,000, respectively.

As can be seen in Fig. 4 and 5, the flood hazard in the Polish coastal zone does not concentrate near the shoreline, but primarily affects the alluvial plains located in Vistula and Odra rivers' mouths connected with two large lagoons. These estuarine regions encompass approximately 70–80% of the total flooded area at all scenarios. The Vistula Delta alone in some simulations covers almost half of Poland's area potentially at risk reaching 34% at 0.3 m water level through 41% at 1 m, 47% at 2.5 m and 46% at 5 m. Odra river mouth and the lowlands surrounding the Szczecin Lagoon gradually decrease its share in areas at inundation risk, starting from 40% at 0.3 m water level, down to 31% at 2.5 m and 30% at 5 m. The valleys of Odra and Vistula rivers located further upstream are barely affected directly, though a higher drainage base level can increase the risk of river floods. Finally, the area spread between those two regions along 300 km of coastline contributes around 20% to the hazard zone. Even then the flood zones cluster around numerous coastal lakes; other locations are generally well protected by dunes and cliffs. However, it should be remembered that those natural flood defences are endangered by erosion, in contrast to more stable lagoon and coastal lake surroundings. Some areas can also become surrounded by water without being directly flooded; the Hel Spit could be severed from mainland at a water level of 2.4 m, for instance.

Population residing in rural municipalities or rural parts of mixed units are disproportionately exposed to rising water levels. They contain 87% of land area in the region, but only 18% of its population. Interestingly, except for the least extreme scenarios (below 50 cm) the proportion of inundated rural to urban areas (7–8:1) is roughly the same as the value for the whole region. But 51% of population within the 1-m hazard zone live in rural areas, a value slowly declining down to 26% at 5 m water level. Urban municipalities have a bigger total number of population endangered than rural municipalities above 1.7 m water mark (for buildings, 2.5 m). Yet they are the safest place in all scenarios, followed by mixed areas. Population in main urban centres comes at risk in larger numbers only above 2 m water level. Gdańsk, located in the Vistula estuary, comprises more than a fifth of population at risk in scenarios above 2.5 m. Two other urban municipalities in the Tricity are to a vast extent less vulnerable, with almost no population in the flood zone below that value. Świnoujście comes second, with exposure soaring above 1.5 m water mark, putting the city's contribution to affected population at 10% of regional total.

3.2 Results by categories of assets

The structure of land at risk is similar in almost all scenarios and reflects the general composition of land use both in the region and country. Fig 6 presents the breakdown by five major groups. Barren land, the smallest group representing mainly beaches and dunes, covers more than 5% of the total flooded area only up to the water level of 20 cm. It decreases down to 0.7% at 5 m, above its 0.3% contribution to the region, since almost two-thirds of barren land is within that zone. Grasslands, which are mostly swampy meadows and pastures, constitute more than 85% of the total area at water levels below 20 cm. Its share significantly drop down afterwards and fluctuates, but remains the biggest land use group at risk until 1.25 m, when croplands come forward. Share of grasslands gradually decreases to 36% at 5 m water level, still above the 22% average for the region. Croplands are relatively less at risk up to 1.25 m, when its share reaches 43% and remains virtually unchanged for other scenarios, slightly above its regional contribution to land use of 39%. Permanent crops, which comprise a small part of croplands, are less vulnerable than arable land. More than 10% of the latter is already flooded by 1.25 m, while in case of orchards this threshold is not reached until the level of 3.9 m. Natural vegetation represented by woodlands and bushes contribute to about 11–16% of land at risk, except for areas below the 40 cm water mark. That is less than half of their share in the region (32%). At the same time, a quarter of all area covered by bushes could be flooded at 1 m water level, but only 3% of forests. It should be noted that newly-planted forests and tree nurseries are among the least vulnerable categories of all studied assets, as little area for new forests is available in the coastal zone.

The last group of land use, artificial surfaces (i.e., areas covered by buildings, infrastructure, landfills and similar human-made structures), is very diversified. Its share slowly increases from around 1% to 6% by 5 m water level, roughly the same percentage as its prevalence in the whole region. Areas used for storage and warehousing are most vulnerable, with 11% already at risk at 1.5 m water level and 36% at 2.5 m. Land underlying machinery and utilities is also disproportionately exposed. This can be explained by the existence of numerous facilities related with seafaring, such as ports, shipyards and naval bases. For the same reason industrial areas are more vulnerable than services. Agricultural build-up areas are slightly more at risk than single-family residential zones located further away from croplands. Multi-family residential areas are among the least exposed, with only 1.2% potentially at risk at 1.5 m water level (single-family – 5.8%). Finally, landfill sites are the least exposed, which is particularly desirable, since flooding of those facilities could lead to contamination of water. Only 6% of their area is within the 5-m hazard zone and 2% below 1 m.

The topographic objects database used for this analysis distinguishes 22 categories of buildings. In scenarios with lowest water levels only a few buildings are indicated as being at risk, mainly from the services sector, such as warehouses. Below 70 cm water level farmhouses are the main type of buildings in the hazard zone, followed by single-family houses. The latter dominate in number for all other scenarios, with a contribution oscillating just below 50%. Additionally they are the biggest group at risk by floor area for every scenario above the uncertainty range (20 cm). Multi-family house grow in number quickly above 1.2 m, but it is not until 2.55 m that their floor area exceeds that of farmhouses. This illustrates how areas outside urban centres, where single-family houses and farmhouses dominate, are vastly more at risk than densely-populated urban areas. The latter were mainly built in less flood-prone areas and are better protected by dikes. The proportion of population living in exposed single-family residences is almost 90% at 1 m water level and decreases at more extreme scenarios, before converging with houses containing two and more flats at 4.1 m water mark. The least vulnerable category of buildings in the 5-m hazard zone are those used for collective residence, such as social care centres, prisons or military barracks.

Non-residential buildings in industry and services are even more diverse in vulnerability. Fig. 7 compares the exposure of selected groups of buildings. Health care is among the least endangered, with barely 2% located within the 2-m hazard zone. This percentage, however, increases vastly thereafter and buildings used for health services end up as one of the most vulnerable groups. Tourist accommodation other than hotels is also safe at low water levels, but ultimately becomes the most exposed in all scenarios above 1.45 m. In case of hotels the percentage is lower, 48% compared to 68% for other accommodation establishments, though it still comes at second place in the 5-m hazard zone. Museums and libraries come third, with the percentage potentially at risk increasing sharply between the 1.5 and 2.0 m water marks (from 5% to 20%). Other assets disproportionately vulnerable include warehouses and other storage facilities as well as industrial buildings, which can be traced to the maritime sector of the economy. On the other end of the scale, schools and trade/services buildings are among the least exposed in both number and floor area.

Transport infrastructure is generally more exposed than buildings. Paved roads are the most vulnerable up to 2.3 m water level; above that value tracks come first, while airstrips are of least concern in all scenarios. As could have been expected, the magnitude of risk decreases with the increase of importance of a road. Motorways may only be flooded at water levels rising above 2.6 m; less than 3% of their total surface area in the region can be affected by water as high as 5 m. Expressways are more likely to be inundated (5% at 2.5 m), but are still the safest behind motorways, followed by national and regional roads (both 12% of the region's total at 2.5 m scenario). The value for roads maintained by counties is 15%, by municipalities 16%, by local communities and private owners 19% and by companies 39%. This ranking is mostly the same for all scenarios; the municipal and private roads are the biggest part of the network and their owners would have to deal with most of the infrastructure restoration costs. Meanwhile, 18% of railways are vulnerable at 2.5 m water level, albeit the figure is somewhat exaggerated due to the numerous sidings located in ports. More important arteries are less exposed – only 6% of the region's electrified mainlines are in the 2.5 m hazard zone. Tram lines exist only in three cities in the coastal zone and up until 2 m water level are the least vulnerable transport infrastructure apart from motorways. Finally, airstrips are not at substantially at risk. No commercial airport is within the 5 m hazard zone and only some military installations (operational or defunct) could be inundated.

3.3 Economic breakdown of losses

As shown in the previous section, the total economic losses due to sea level rise increase rapidly with the water level, and even more so for coastal floods. At the lower end of IPCC's SLR projections (40 cm), potential losses are estimated to amount to 1.4 bln PLN, while on the higher end (130 cm) they soar to 20.2 bln PLN (Fig. 8a). Notwithstanding, the structure of assets at risk changes little with rising water levels. Fig. 8c presents the breakdown by economic activity for SLR. Assets used for agriculture and forestry dominate at water levels below 90 cm, as low-lying grasslands, arable land and forests near estuaries and coastal lakes are flooded first. At higher elevations housing dominates as the prime asset at risk, with the proportion reaching 40% at 90 cm and gradually rising to a maximum of 53%. Industrial assets fluctuate around 10%, while the percentage associated with the services sector soars to slightly above 20% at 1.8 m, and remains at that level for other scenarios. In agriculture land is the main source of losses; for other economic activity it is predominantly buildings, with those used for storage worth most up to 1.3 m water level, for manufacturing and utilities between 1.3 and 2.4 m and tourist accommodation above that value. In total, land and buildings are almost equal in value up to 85 cm, when the losses associated with the latter increase sharply. Buildings constitute more than 60% of losses at water levels above 1.45 m and more than 70% above 2.4 m, before peaking at 74%. The percentage of potential losses connected with infrastructure slowly increases with the water level, but generally stays around 10%.

In case of coastal floods, the total amount of damages changes differently. Losses potentially caused by sea level rise soar between 1.25 and 2.1 m and slow down substantially afterwards, while those resulting from coastal floods accelerate with the increase of water levels. This is because the risk from storm surges is calculated using damage curves; the thicker is the water layer covering the buildings, the higher is the value of losses. These are estimated at 1.4 bln PLN for a 1 m surge and 16.6 bln PLN for a 2.5 m surge, provided that it occurs in the entire coastal zone (Fig. 8b). The breakdown of those losses by economic sectors is even more stable at various water levels than in case of SLR (Fig. 8d). Apart from water levels below the uncertainty range, where merely a few buildings or roads could be affected, housing dominates at around 40% of all losses. Industry comprises around 20% of total, while the services sector hovers up a growing fraction from less than 10% (below 1 m) to 23% (5 m). Assets in the agricultural sector are worth little and therefore responsible for only a small percentage of losses (only 4% at 1 m, 2% at 3 m). Infrastructure contributes significantly at low water levels (more than half of losses below 0.5 m), but less so for other scenarios; the percentage value drops below 30% at 1.25 m and below 20% at 1.9 m, ultimately reaching 7% at 5 m.

The overall impact of coastal floods and sea level rise on the national economy would be fairly limited. Fixed assets are the primary factor of production and a 1 m water level would affect merely 0.08% of immovable commercial fixed assets in the country, a value rising above 1% only at 2.4 m and coming close to 2% at 5 m. Even unexceptional storm surges could potentially incapacitate more than 0.1% of assets only by reaching more than 1.9 m along the entire coast. But the impact on the local economy would be nevertheless substantial, since the region contains less than 6% of commercial assets in the country. 34% of these are within the 5 m hazard zone for sea level rise and 14% for coastal floods. The total value of all investigated assets at risk due to SLR equals the combined GDP of nine NUTS3 regions involved at 5 m; it already exceeds 10% at 1.25 m. For coastal floods, losses exceed 10% of GDP of those regions above 2.5 m (around the size of a 1000-year event).

Tourism, the mainstay of the coastal regions' economy, is unlikely to be much affected directly by sea level rise. Virtually no tourist traffic (measured both by the number of nights spend or number of visitors) is endangered below 90 cm, near the upper range of SLR projections up to 2100. The numbers grow rapidly above 1.3 m, so that a 2 m surge could potentially disrupt the work of establishments used by 11% of tourists visiting the region. Places near the shoreline are the most attractive to tourists, so in total 62% of nights spent during 2011 in the region was in buildings laying below the 5 m water mark (15% of national total).

3.4 Losses to cultural and natural heritage

Our calculations of economic damage excluded two types of buildings whose real value is intangible. Buildings used for religious practices (mainly catholic churches) are the least vulnerable within the 5 m hazard zone of all 22 categories of buildings – slightly less than 20% are potentially at risk. They are also amongst the least endangered for other scenarios. This can be explained by the fact that most of the existing churches have been constructed before any flood defences appeared in the area. In effect, they are located on slightly higher ground. They are also more present in the sparsely-populated areas further from the coast than other kinds of buildings, especially industrial, commercial or tourist accommodation.

Almost 4,400 buildings in the region (1% of total) are included in the national heritage sites' list. Below 2.4 m water level the fraction under threat is narrowly smaller than buildings in overall, but for higher levels the opposite is true. In the 5-m hazard zone 31% of national heritage sites are endangered, compared to 26% for all buildings. It can be explained that buildings used for services, especially governmental, are more likely to be heritage sites. As noted previously, those buildings are disproportionally represented along the hazard zones. Museums and libraries are slightly less likely to be in hazard below the 1.7 m water mark, but 47% them are in the 5-m zone; only tourist accommodation has a larger fraction in danger.

More hazard is related to natural heritage. National parks, landscape parks, natural reserves and Natura 2000 areas (usually overlapping with the former and each other) cover a substantial part of the region. At the same time, 45% of their land area is below the 5 m water mark. 40% of that is contained within the 1 m hazard zone; the corresponding value for all land is 27% and for population a mere 5%. It is caused by the specifics of protected land, which consists predominantly of low-lying wetlands, grasslands and forests. In total 52% of land in the 1 m zone is under some form of protection (chiefly by Natura 2000 programme), including 77% of grasslands and 90% of forests. Below the 0.9 m water mark national parks have the highest exposure to SLR and coastal floods (mainly in Słowiński National Park); above that value natural reserves are the most vulnerable. Landscape parks are of least concern, due to their limited presence in the close proximity of the coastline.

4 Discussion

4.1 Uncertainties

As with all studies on SLR and coastal floods, also the result presented in the previous section have their limitations; there are also several sources of uncertainty. First of all, the data used are not perfect: the most crucial is the accuracy of the representation of the terrain and flood defence structures. Even though the DEM used here has a high resolution and good accuracy, it still has some imperfections which can cause inaccurate delimitations of flooded zones. A

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large low-lying area, which in reality is protected by higher terrain or flood defence structures can be marked as potentially flooded because a minor error in the data creates a “gate” for floodwater. Some of the structures (mainly sluices) seem to have been edited out of the DEM during post-processing. They are crucial for protection of certain areas, especially in the Vistula river delta. The effects of the DEM’s nominal accuracy (20 cm in most of the area) are presented in Fig. 9. The uncertainty is large around the 1 m water level, but still the difference with some other studies using the static approach to analyse SLR is considerable (also seen in Table 4 in the next section).

Secondly, the data used to derive the vulnerability of assets also carry some uncertainty. The geometrical representation of buildings has somewhat lower accuracy than the DEM, therefore they are occasionally incorrectly marked as flooded. It has some impact on the results for very small water levels. As noted before, the quantitative information in the topographic objects database has accuracy up to ±20%, hence the area of the buildings, which is a crucial statistic in the calculations, can potentially contain such error. Moreover, many statistics on value of assets had to be estimated due to lack of necessary information from national sources, also by filling the gaps using data from other countries,. Population data are also only estimates made by disaggregating settlement-level information instead of actual house-level information. However, this is already much finer-grained information than in other studies, except for official government flood maps (which are discussed in the next section).

Dynamics of the coast could substantially change the level of risk. Erosion of dunes and cliffs can cause destruction of those barriers protecting the inland from seawater, while sedimentation can reduce the vulnerability in some sectors. There is substantial variation along the Polish coast of those processes, and the impact on local morphology is still being investigated (Deng et al. 2014, Furmańczyk et al. 2014). In our context, of importance is how will the height of barriers separating the inland from the seawater change in the future. This would require a separate proper investigation – a method adequate to the resolution and scope of the study is currently lacking. In our comparison with other studies, only the one using DIVA model (Bosello et al. 2012) incorporated the dynamics of the coast. However, due to the use of a coarse global DEM that misses most coastal barriers the impact of erosion on the results is probably minuscule.

Additionally, rising groundwater levels due to sea level rise could result in inundation of low-lying areas otherwise fully protected from seawater. This aspect has not yet been properly investigated (Rotzoll and Fletcher 2013), especially in relation to the Polish coast.

Furthermore, sea level rise may be uneven along the coast. As noted in the introduction, recent trends at Polish tide gauges vary depending on location. One reason is glacial isostatic adjustment, which causes yearly uplift of the Polish coastal zone by about 0.5–0.6 mm, except for the far western part, where is around 0.4 mm per year, according to a dataset prepared by Peltier et al. (2015). Increase of water levels is also uneven regardless of the movement of the coast, as satellite altimetry reveals, though this effect is small along the Polish coast. Satellite-measured SLR trend between 1992 and 2015 was between 4.2 and 4.3 mm per year in the Baltic along the Polish coast; only in the far western part it was slightly higher, up to 4.5 mm per year (NOAA 2015). These two effect translate to a difference of only a few centimetres in a perspective of a century. Bigger spatial differences in SLR can be caused by ground subsidence, which is a very local factor; no large-scale data are available on this matter.

As for the storm surge analysis, some additional issues appear. The damage curves used in the calculation are subject to large uncertainty. Actual damage depends largely on buildings' construction characteristics and type of preparations made before the flood (Apel et al. 2009). Additionally, the equations used here were developed in Germany, since there is no methodology based on Polish empirical data. For the sake of illustration, in Fig. 10 we compare the results of coastal flood damage estimation using Polish government methodology (Law 103/2013) and generic damage functions for European countries from Huizinga (2007). However, these methods are less comprehensive than the one used and therefore not fully comparable.

Another concern is the assumption that storm surge levels along the coast are uniform. In reality they vary in each event. However, a catalogue of extreme coastal events by Wiśniewski and Wolski (2009) shows that for big surges (more than 1 m above average) the difference in water level between the western, central and eastern coasts is small: often less than 10 cm, rarely more than 20 cm. More exaggeration is the case with Vistula and Odra rivers mouths as well as the coastal lagoons. However, big surges would sometimes increase water levels far inland as much as in the coast; in 1913 a surge of 1.54 m was recorded in Szczecin (70 km inland), which was more than along the majority of the coast.

Finally, the ‘bathtub fill’ method exaggerates the risk posed by storm surges. For one thing, during a surge water levels are spatially uneven. The static Also any overtopping of flood defences would mostly cause inundation of a much smaller area than indicated here, since the water level remains elevated only for a short period of time. Breilh et al. (2013) estimates that the static method performs well for areas located no more than 3 km from the coast or estuary. In our case, around a third of the flood zone is within that limit for most scenarios (35% for 0.5 m, 31% for 1.5 m, 33% for 2.5 m). However, the proportion of exposed buildings in the 3-km zone increases from 8% for 0.5 m to 39% for 1.5 m and 53% for 2.5 m. Additionally, comparison with official flood maps, which were made using dynamic modelling, does not show large differences, as discussed in the next section.

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4.2 Comparison with previous studies

~~The results described in the previous section differ substantially from other~~ Our results can be contrasted with two studies that analysed impacts of sea level rise specifically on the Polish coast. Table 4 provides such a comparison, together with the estimated uncertainty of the results of this study (i.e. ±20 cm accuracy of the DEM and ±20% accuracy of assets value and population). Even taking the maximum values from our results the difference is substantial in terms of population and assets at risk. The primary reason is methodological: flood zones in Rotnicki and Borówka (1991) were delimitated without taking into account numerous barriers between the sea and low-lying areas, which was not possible at the resolution of their source material. Rotnicki et al. (1995) provide results for only one hazard zone of 2.5 m apart from identifying assets lying below sea level. According to the authors, the 2.5 m contour represents the water level of a 100-year storm surge (1.5 m) superimposed on top of a 1 m sea level rise. As presented in Table 4, the flooded area calculated by Rotnicki et al. is about 18% larger than our results indicate. The difference increases when analysing the number of population at risk.~~;~~ Rotnicki et al. put it at almost 300,000 persons, while in this study it is nearly 50% lower (though that study refers to demographic situation in the late 1980s, the Polish population numbers barely changed since then) . Such a big difference can be explained by the fact densely populated areas are mostly well protected by flood defences, which were not taken into account in that study.

A complementary study called VA '92 (Ziedler 1997) provides data for three flood zones, namely 0.3, 1 and 2.5 m and for two time periods: 1995 and 2025. As could be seen in Table 4, the inundated area is six times larger at 0.3 m in VA '92 compared to this study, but the difference decreases with higher water levels, converging at 2.5 m. Number of population at risk is substantially lower than in VA '92, while the value of assets is even more so. At the time of that study Polish was forecasted to increase in the future, hence the big difference for the 2025 scenario (currently the population is expected to decrease). Particularly striking ~~coruscating~~ is the difference in relative economic losses, estimated at 0.6% of GDP, while VA '92 study gives an extremely high value of 35% for 1995, forecasted to decrease to 15% by 2025. Our calculations also indicate less damage to transport infrastructure, though the low resolution of source material used in VA'92 somewhat distorts the statistics in this matter.

A more recent study by Bosello et al. (2012) using DIVA global coastal damage model gave a four times higher estimate of flooded area than this paper for a comparable scenario (95 cm sea level rise), yet reckon it would be worth relatively little. They put the value of inundated land at 0.03% GDP in contrast to our estimate of 0.15%, though their figure refers to the projected economic situation in 2085 instead of the current situation. That study also expects that rising waters will cause the GDP to drop by 0.046%, which is in line with our estimate of a 0.041% loss in commercial fixed assets.

~~As has been shown above, the use of more detailed topographic data significantly alters the statistics on the impacts of sea level rise and coastal flood. However, several limitations to this study still exists:~~

- ~~Even though the DEM used here has a high resolution, it still has some imperfections which can cause inaccurate delimitations of flooded zones. A large low-lying area, which in reality is protected by higher terrain or flood defence structures can be marked as potentially flooded because of a minor error in the data. Some structures such as sluices seem to have been edited out of the DEM during post-processing, though they are crucial for protection of certain areas.~~
- ~~The geometrical representation of buildings has somewhat lower accuracy than the DEM, therefore they are occasionally incorrectly marked as flooded. It has some impact on the results for very small water levels.~~

- ~~The 'bathtub fill' method exaggerates the risk posed by storm surges, an event which would have different water levels at various points at the coast or lagoons. Also any overtopping of flood defences would mostly cause inundation of a much smaller area than indicated here, since the water level remains elevated only for a short period of time.~~
- ~~The damage curves are subject to large uncertainty, connected mainly to buildings' construction characteristics and type of preparations made before the flood. Additionally, the equations used here were developed in Germany, since there is no methodology based on Polish empirical data. They substantially vary between countries (Huizinga 2007).~~
- ~~Many statistics on value of assets had to be estimated, also using data from other countries, due to lack of necessary information from national sources. Population data are also only disaggregated estimates instead of actual house-level information.~~
- ~~Dynamics of the coast could substantially change the level of risk. Erosion of dunes and cliffs can cause destruction of those barriers protecting the inland from seawater.~~
- ~~Rising groundwater levels due to sea level rise could result in inundation of low-lying areas otherwise fully protected from seawater.~~
- ~~Glacial isostatic adjustment and ground subsidence can also locally have an impact flood risk in the long-term.~~

In order to further assess the impacts of quality of data on our results we have juxtaposed them with official flood hazard maps (KZGW 2015). Those studies were prepared for selected parts of the coast, utilizing hydrodynamic modelling and locally-collected data. They mostly cover a single 500-year flood scenario, which translates into water levels of 1.7–3.0 m depending on location. Most of those maps present very similar flood zones, with the main exception being the Żuławy Wiślane area, which is protected by a more elaborate flood defence system of pumps, sluices and weirs. Our flood zones are much bigger because they do not fully apprehend those details, though it also shows that when the external line of defences is breached even at water levels of a few dozens of centimetres, there is nothing to stop the water from flooding a vast area. That is the reason for a few significant spikes in the statistic of affected assets and population at 0.9, 1.25 and 1.75 m water level. Table 5 presents estimates of population at risk in the main coastal cities in Poland. Water levels in KZGW maps are variable due to the use of hydrodynamic models, their 100-and 500-year flood scenarios are only approximately compared with our scenarios. The analysis reveals that the use of a static method exaggerates the number of person exposed to floods, but still gives the correct magnitude of the event. Additionally, part of the difference could be the effect of different sources of demographic data used in both studies. KZGW used detailed data from the population register instead of disaggregated estimates that are used here.

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4.3 Future developments

Apart from the issues of delimitating flood zones and future changes of the physical environment, the demographic and economic developments could also noticeably modify the magnitude of risk. A storm surge can occur at any time, but sea level rise is a phenomena which is unlikely to become substantial until well into the second half of the century. As a result, the number of persons living in areas at risk will be different when the sea actually rises to hazardous levels. This is due to demographic developments, especially migrations. The population currently endangered by water level of 1 m is 49% urban; for 2.5 m, the value is 65%.~~,~~ If we apply population growth rates from CSO's (2015) projections provided at county level with urban/rural breakdowns, by 2050 those values will drop to 39% and 57%, respectively. This is due to urban sprawl, i.e. the relocation of population from cities to the surrounding rural municipalities. At the same time very low birth rate will cause a general population decline in the region. The total number of endangered population will be 17% lower by 2050 given a 0.5 m water level, but at 1 m it be the same as in 2011. At 1.5 m it will be 5% smaller, gradually moving towards a drop of 10% at 5 m water level. It is difficult to conclude whether the population is likely to relocate towards more flood-prone areas. However, it should be noticed that 3% of buildings in the 1 m risk zone were under construction when the topographic database was last updated, slightly more than the percentage for ~~all~~ the entire study area.

Finally, since the economy will continue to grow in the future, the incomes and value of assets will also increase. Assets may become cheaper or costlier relative to income, easing or severing the economic impacts of coastal floods and sea level rise. This change can be very swift; price of arable land, for instance, increased fivefold between 2000 and 2013, while price of pastures and meadows quadrupled during the same period. Newly-built houses were twice as expensive in 2013 as they were a decade earlier. ~~However~~By contrast, the stock of commercial fixed assets increased only by 54% in real prices between 2000 and 2013, which is actually smaller than GDP growth during the same period (CSO 2015).

5 Conclusions

In this paper we have undertaken a broad analysis of the sensitivity of the Polish coastal zone to sea level rise and coastal floods. Its aim was to increase the precision and level of detail of country-wide risk estimates, covering both population and economics, compared to currently available studies. This was made possible by recent developments in the national stock of spatial data. Two main conclusions could be drawn from the analysis of results.

First of all, the use of detailed spatial data and the inclusion, however imperfect, of flood defences caused the aggregate statistics of ~~p~~damages to be significantly revised down compared to other studies. This applies most to economic value of assets at risk, less so for population figures and the least for land area. Sea level rise is unlikely to reach an intensity that would lead to serious direct effects on the coastal population and economy. Spikes in flood damage at 0.9 and 1.25 m are a notion that the water levels should be preferably prevented (by means of 'climate policy') from reaching such heights. That would help avoid spending money for adaptation of flood defences. On the other hand, since coastal floods are expected to become more severe in the future, some improvements would still be necessary. A 1.5 m surge could affect in the worst case scenario 59,000 persons and 4.6 bln PLN of assets, but if we add even a modest 40 cm SLR the values almost double to 101,000 persons and 8.7 bln PLN. This is particularly important for some major coastal cities, especially Gdańsk, which has the highest number of potentially affected population and buildings by 2 m or larger surges.

Secondly, the exposure of different kinds of assets varies to a large extent, while the structural breakdown of potential losses is remarkably stable between scenarios. Urban zones are less vulnerable than rural areas due to better protection, thus agriculture will be disproportionately affected within the probable range of sea level rise, mainly due to loss of low-lying arable land and pastures. Housing dominates in the total value of losses by a wide margin in scenarios above 90 cm, though at the same time it is proportionally less vulnerable than commercial assets or infrastructure. Industrial land and buildings are more at risk than the services sector, especially warehouses and similar structures, due to the maritime economy's predominance in the region. Exposure of infrastructure is closely related with its importance, with crucial arteries left largely unscathed even at most extreme scenarios.

But again, one should bear in mind that several simplifications have been used in this study and more research is required, especially on coastal flood scenarios, damage curves, future climate, population and economic projections; and, most importantly of all, on coastal dynamics. Additionally, sea level rise and coastal floods may not lead to significant financial losses or cause displacement many persons, but can still cause long-lasting effects. Tourist accommodation or commerce may not be much in direct danger, but the beaches and natural reserves which draw the visitors are the first in line to come under water.

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Table 1. Vulnerability assumptions for sea level rise and storm floods.

Asset	Losses caused by…	
	sea level rise	coastal flood
Land	100%	nil
Immovable fixed assets	100%	relative to water depth and type of asset
Movable fixed assets	nil	relative to water depth and type of asset

Table 2. Estimated commercial value of land in 2011 per hectare (1 PLN = €0.24).

Land use	Value [PLN per ha]
Built-up: services	4,294,000
Built-up: housing (dense urban)	2,802,000
Built-up: housing (scattered urban)	1,896,000
Transport areas, non-built-up areas	559,000
Built-up: agricultural	453,000
Built-up: industrial	444,000
Forests	37,976
Arable land, orchards	20,004
Woodlands and bushes	16,401
Meadows and pastures	14,259
Wastelands and other lands	12,337

Table 3. Value of fixed assets per area in 2011 and damage functions. Note: for housing, Y_1 is damage to immovable assets and Y_2 is damage to movable assets.

Type of building or structure	Value of fixed assets Immovable [PLN per m^2]	Movable [PLN per m^2]	Damage function Y – damage [%], D - water depth [m]
Housing	3858	604	$Y_1 = D + 18.77 \times \sqrt{D}$ $Y_2 = 4.83 \times D + 20.69 \times \sqrt{D}$ $\cancel{Y_1 = D + 18.77 \times \sqrt{D}}$ $\cancel{Y_2 = 4.83 \times D + 20.69 \times \sqrt{D}}$
Industry	2057	1712	$Y = 27 \times \sqrt{D}$ $\cancel{Y = 27 \times \sqrt{D}}$
Services	2678	923	Market services: $Y = 27 \times \sqrt{D}$ Non-market services: $Y = 30 \times \sqrt{D}$ ~~Market services:~~ $\cancel{Y = 27 \times \sqrt{D}}$ ~~Non-market services:~~ $\cancel{Y = 30 \times \sqrt{D}}$
Agriculture	393	166	$Y = 27 \times \sqrt{D}$ $\cancel{Y = 27 \times \sqrt{D}}$
Transport infrastructure	436	-	$Y = \frac{100}{3}$ $\cancel{Y = \frac{100}{3}}$

Table 4. Impacts of sea level rise in Poland: comparison of results from this analysis with VA '92 study as reported by Zeidler (1997) and a study by Rotnicki et al. (1995).

Category	Water level (metre)	This study		Zeidler (1997)		Rotnicki et al. (1995)
Reference period		2011		1995	2025	ca. 1990
Flooded area (km^2)	0.30	155.2	(16.4–341.8)	845.1	845.1	-
	1.00	885.0	(541.3–1,093.4)	1,727.7	1,727.7	-
	2.50	2,278.4	(2,178.4–2,376.5)	2,203.3	2,203.3	2,696.7
Persons affected	0.30	1,777	(0–3,362)	40,860	64,600	-
	1.00	19,966	(4,245–33,432)	146,040	230,600	-
	2.50	167,503	(112,497–230,672)	234,840	371,600	297,135
Value of assets at risk (bln PLN at 2011 prices)	0.30	1.1	(0.1–2.2)	47.8	78.1	-
	1.00	9.6	(2.5–15.9)	223.2	366.7	-
	2.50	80.9	(55.3–107.6)	366.7	574.0	-
Value of assets at risk (% GDP)	0.30	0.1%	(0.0–0.1%)	7.5%	3.1%	-
	1.00	0.6%	(0.2–1.0%)	35.0%	14.6%	-
	2.50	5.2%	(3.6–6.9%)	57.5%	22.9%	-
Railway lines (without sidings) affected (km)	0.30	2.4	(1.4–3.1)	35	35	-
	1.00	25.5	(7.7–28.6)	180	180	-
	2.50	160	(138–185)	219	219	347

Table 5. Impacts of coastal floods in selected major coastal cities. Water level in the table is an approximation of KZGW's 100- or 500-year flood scenarios.

City	Population in 2011 ('000s)	Water level (metre)	Population at risk ('000s)	
			This study	KZGW maps
Szczecin	410.1	1.85	2.5	1.8
		1.60	1.6	1.3
Police	34.0	1.75	0.2	0.1
Świnoujście	41.5	2.60	15.4	14.1
		2.30	11.2	9.6
Kołobrzeg	47.1	2.00	0.7	0.3
Ustka	16.4	2.60	1.2	0.8
Gdynia	249.1	2.35	0.2	<0.1
Sopot	38.7	2.50	1.3	0.2
Gdańsk	460.3	2.50	38.4	34.7
		2.10	22.3	20.0
Elbląg	124.7	1.40	2.0	0.7

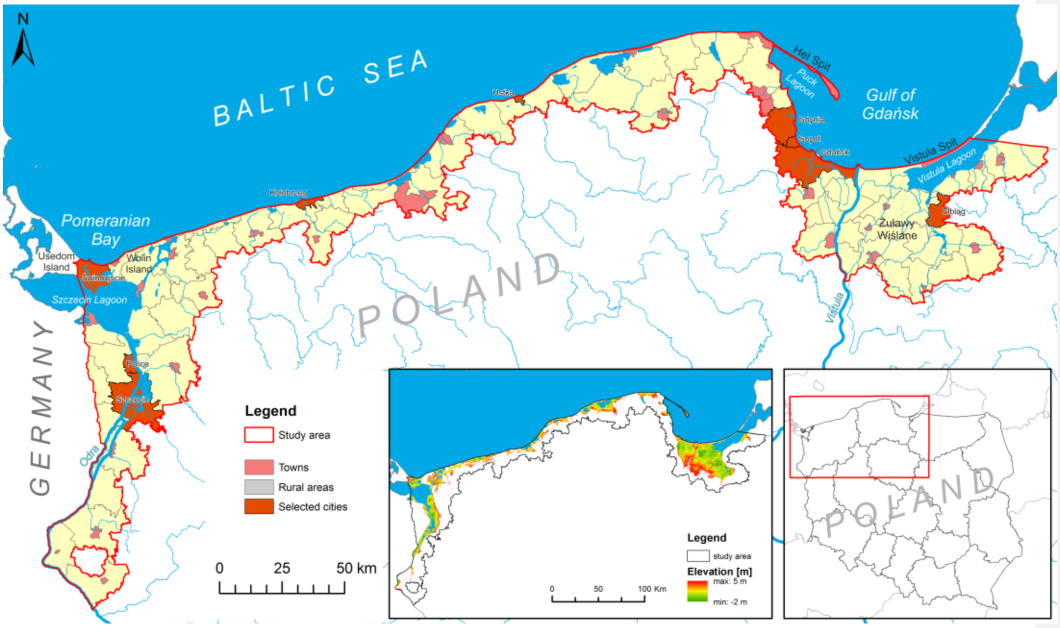

Figure 1. The study area (all municipalities with some land laying below 5 m a.s.l.) and the Polish coastal zone. The inner map presents elevation values.

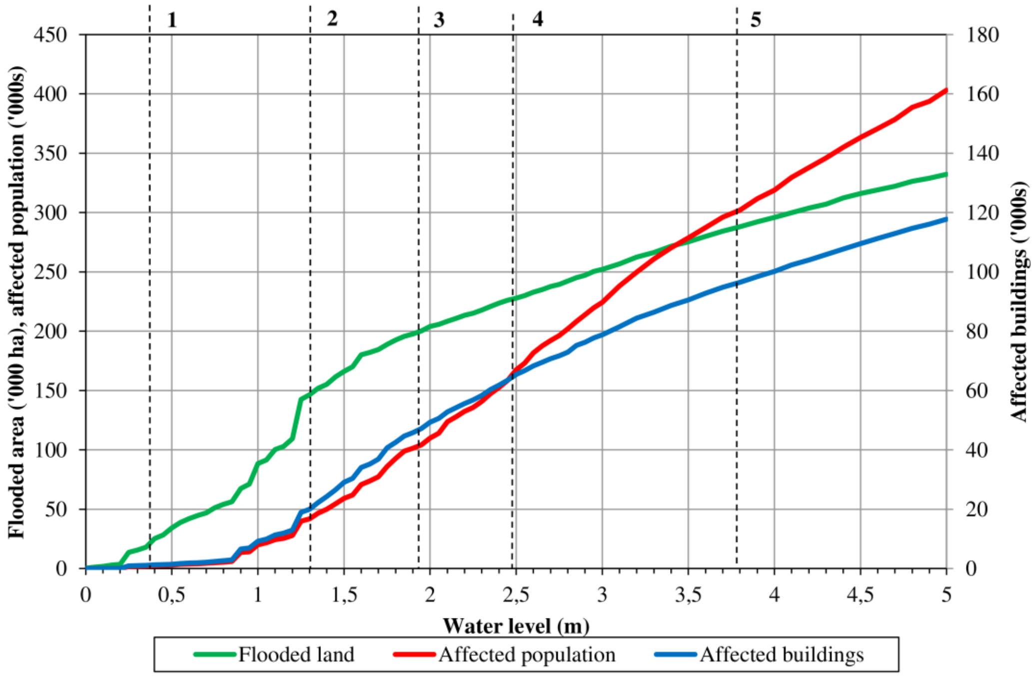

Figure 2. Cumulative numbers of land, population and buildings potentially at risk by water level. Numbers denote SLR and coastal flood scenarios: lower (1) and upper (2) range of SLR projection up to 2100 by IPCC, 1000-year flood in Szczecin (3) and Kołobrzeg (4) and a 1000-year flood in Kołobrzeg added to the upper range of SLR projection (5).

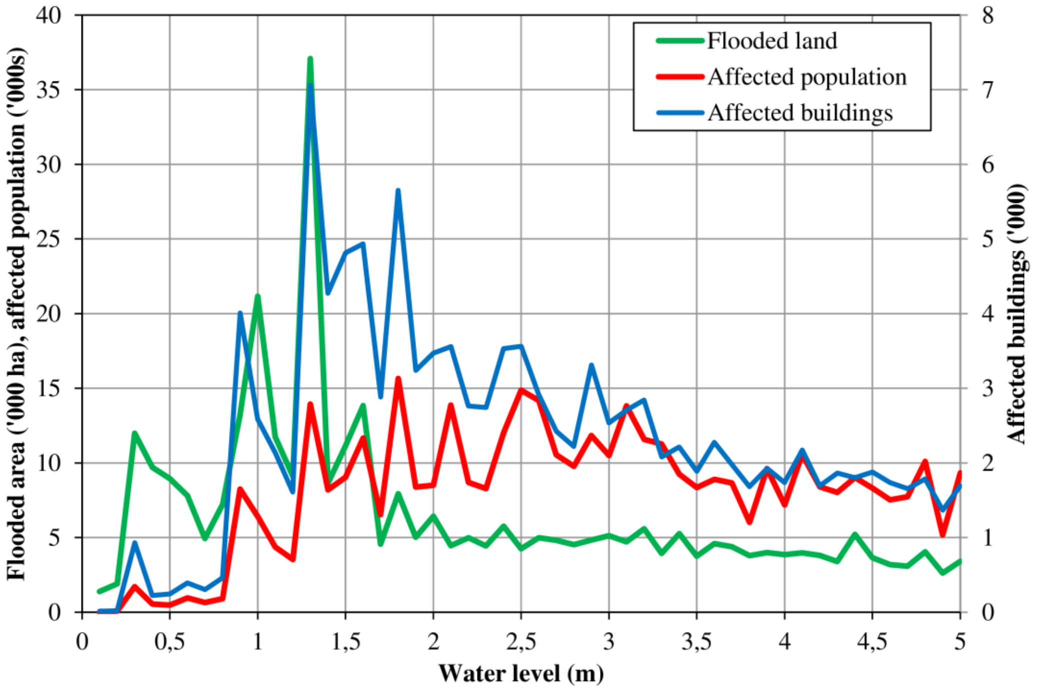

Figure 3. Increments of land, population and buildings potentially at risk by 10-cm intervals ending with the water level given.

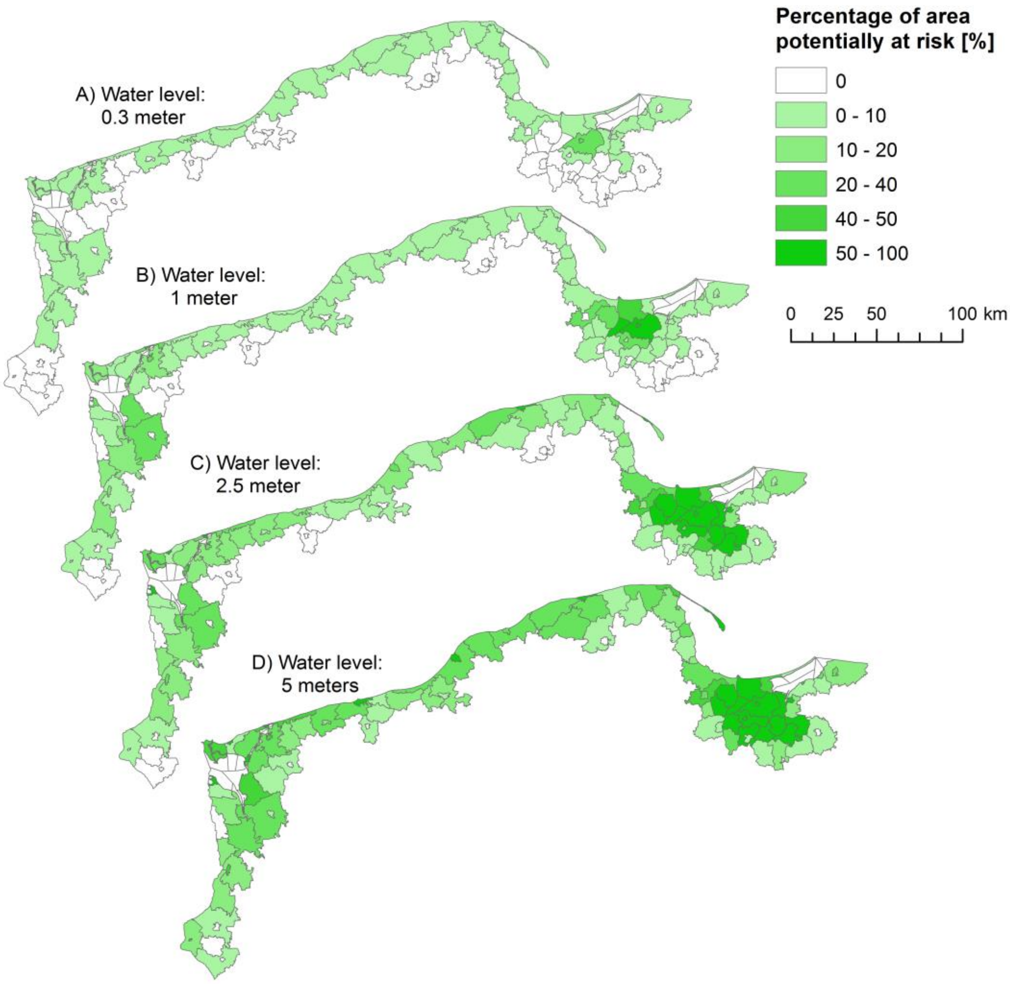

Figure 4. Percentage of area potentially at risk by water level and town/municipality.

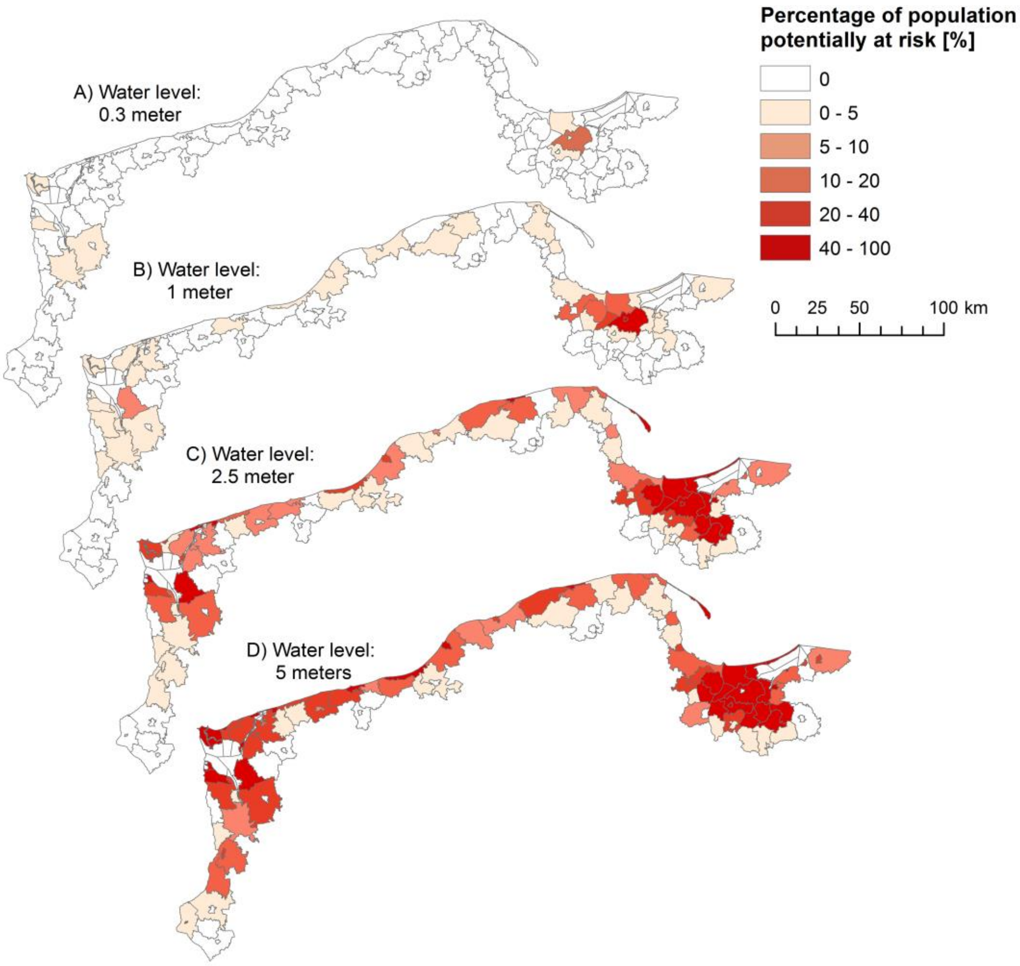

Figure 5. Percentage of population potentially at risk by water level and town/municipality.

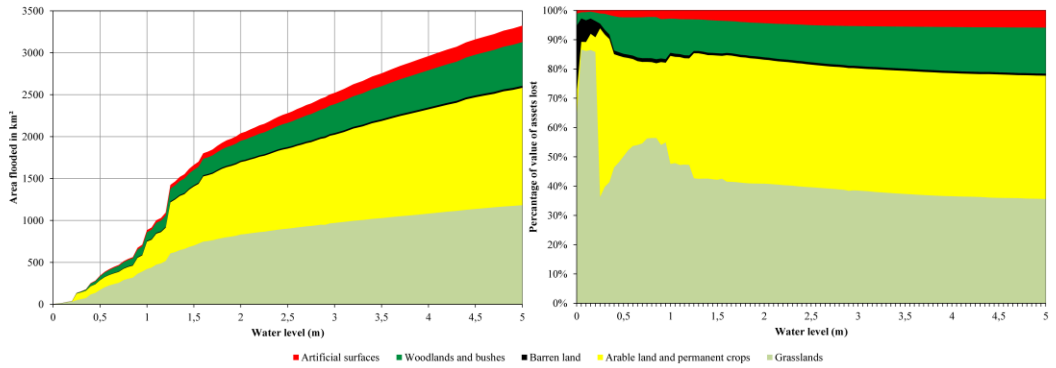

Fig. 6. Flooded area by major groups of land use classes: total area (left) and ~~,~~percentage breakdown (right).

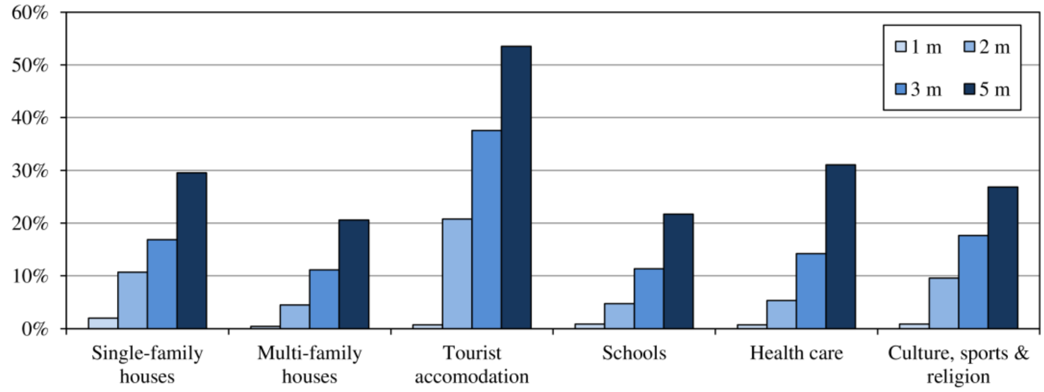

Fig. 7. Buildings at risk as a percentage of all buildings in the category in the study area.

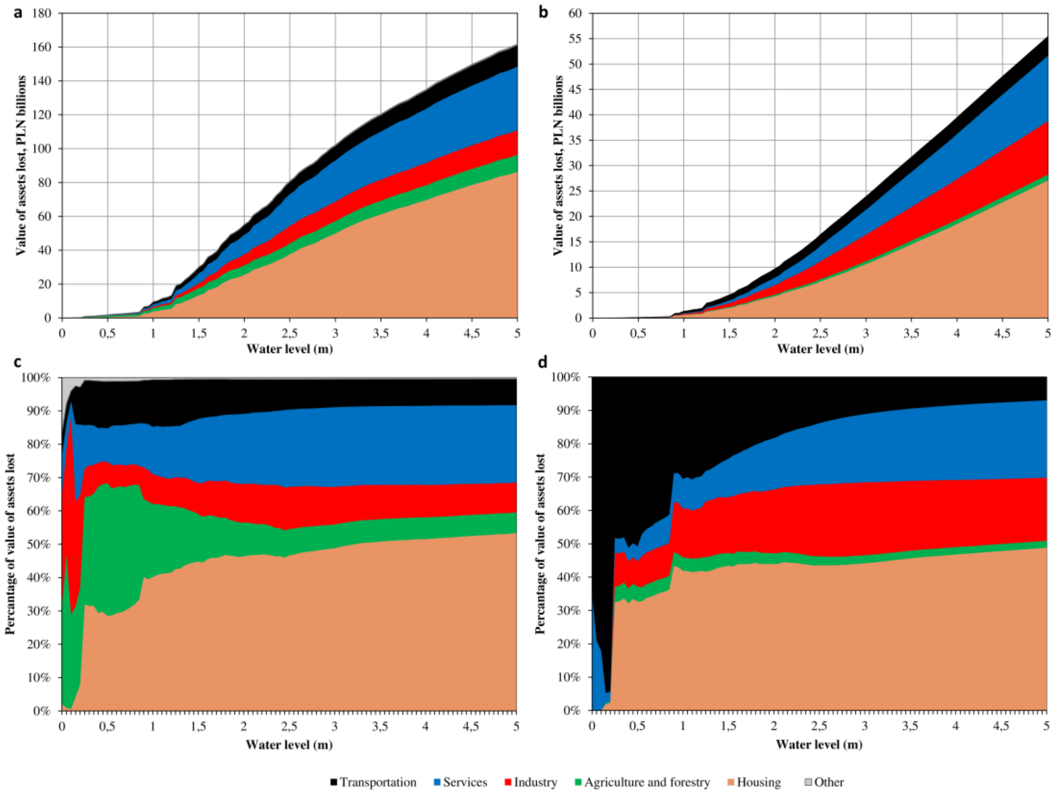

Fig. 8. Potential losses due to sea level rise: cumulative total values (a) and structural breakdown by activity (c). Potential losses due to coastal floods: cumulative total values (b) and structural breakdown by activity (d).

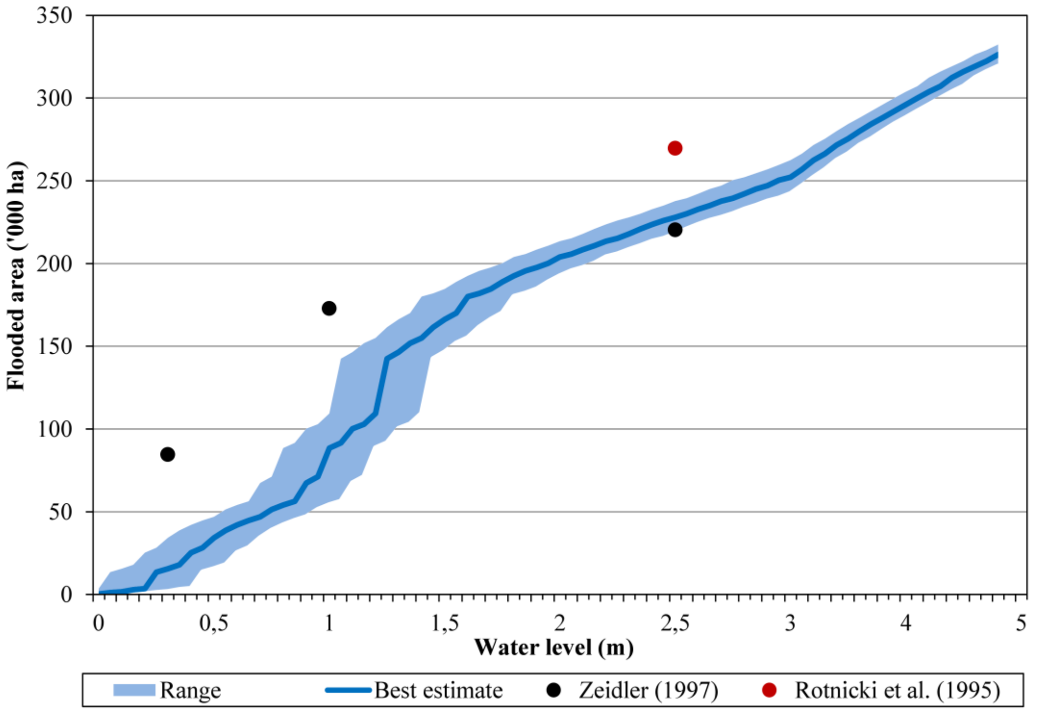

Fig. 9. Uncertainty in delimitation of the area affected by sea level rise, with comparison to two previous studies.

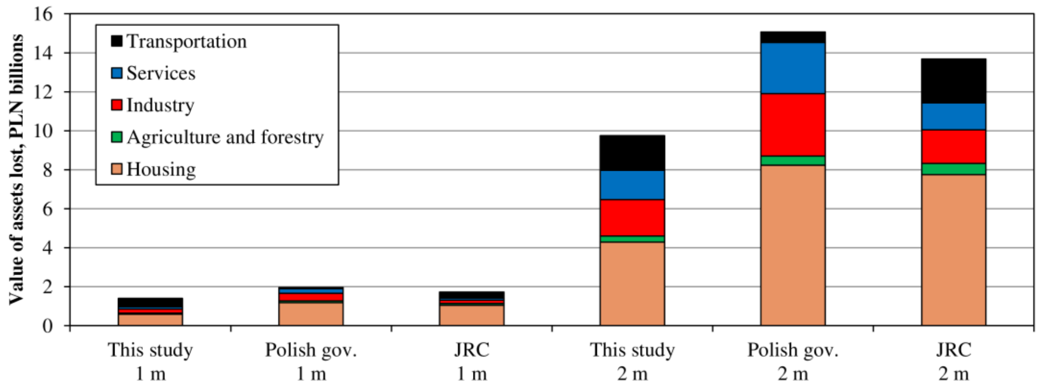

Fig. 10. Comparison of potential damage estimates from a 1-m and 2-m storm surge using two alternate methodologies from the Polish government (Law 103/2013) and Joint Research Center (Huizinga 2007).