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# Short-term prognosis of development of barrier-type coasts (Southern Baltic Sea)

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ABSTRACT

The indiccatory forecasting of coastal zone changes is extremely important in view of proper management of this zone. Intense pressure on the development of coastal areas makes the importance of forecasting changes increased. The study presents prognostic variants (forecasts) for various development trends of the micro-tidal, wave dominated sea coast (Polish part of the Southern Baltic Sea) in the next 15 years. The main idea was to compare changes and to analyse them using various geoprocessing and statistical techniques based on the spatial analyses of different cartographical materials and extrapolation of historical trends. The basic premise for achieving this objective was to implement the problem-solving principle that makes the fewest possible assumptions. The performed works aimed at mapping the course of the shoreline at various time periods revealed significant changes in its location. All the presented forecasts ("shoreline extrapolation models" and "averaged shoreline changes model") are characterized by certain volatility and specific features. In authors' opinion the "averaged shoreline changes model" is the most suitable for bulk visualization of shoreline changes. It averages short-term variables that can affect transparency of the image. It also allows avoiding the accumulation of errors that can have an imprint on shoreline variations. The largest forecasted shoreline changes may exceed 100 m. However, this value is highly controversial. The forecast based on the course of the dune base shows more stable situation and the expected changes have a marginal extent. The biggest differences between the two prognostic lines generated basing on the rate from periods 2010–2016 and 2001–2016 can reach up to 40 m. The "averaged shoreline changes model" (which in authors' opinion is the most suitable for bulk visualization) indicates the shoreline changes will affect the beach-wide part of the coast (up to almost 70 m). The biggest dislocation of shoreline will occur in the area of the most intense erosion (vicinity of 144–145 km and 155.5 km) and can affect the dune base.

## 1. Introduction

Changes in the coastal zone are caused by various factors, among which the main place should be attributed to the diversity of geological conditions, both inland and offshore part of the coast and their derivative — geomorphology and topography. Other factors influencing the evolution of the coast that should be considered as significant are: climatic phenomena, hydrological and hydrodynamic conditions, vegetation, human activity. All are interrelated by overlapping effects of their impact and none of them should be considered without considering the others. These changes occur on a different time scales and affect the coasts around the world (Eurosion, 2004; Uścinowicz, 2006; Hapke et al., 2013; Weisse et al., 2014; Burvingt et al., 2017). These natural processes shaping the coasts are common in the case of epicontinental seas such as the Baltic Sea. Especially the coastal zone of the southern Baltic, from Germany in the west to Latvia and even some parts of Estonia and Russia (Gulf of Finland) in the east is exposed to intense erosional changes (Bitinas et al., 2005; Meyer et al., 2008; Spiridonov et al., 2011; Ryabchuk et al., 2012; Jarmalavicius et al., 2013; Tõnisson et al., 2013; Uścinowicz et al., 2014; Lapinskis, 2017). The central part of this zone — the Polish coast is subjected to transformations along its entire length. The Polish coast consists of three main types: cliffs, barrier-type coast and wetlands (Tomczak, 1995; Uścinowicz et al., 2004; Musielak et al., 2017). Negative changes affect each of the above mentioned types, and the most spectacular transformations can be observed within steep cliff coasts. These processes have been described many times (Subotowicz, 1995a; Uścinowicz et al., 2004, 2017; Kostrzewski et al., 2015). Wetlands which are associated with end sections of rivers have a limited range, and as a result, changes taking place there are of lesser importance. It is different with the

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barrier or spit sections that are dominant in the morphology of the southern Baltic coast, so their importance in the context of monitoring and predicting change is extremely important. Two basic barrier types that differ in morphology and processes governing their evolution occur on the Polish coast. The first type includes stationary (accreted) barriers with well-developed high dune systems, while the second comprises narrow and low landward-migrating barriers (Uścinowicz et al., 2004).

Intense pressure on the development of coastal areas, as well as increased awareness of geohazards, makes the importance of forecasting changes increased. For this purpose, various methods (Bruun, 1954, 1988; Sherman and Bauer, 1993; Jongejan et al., 2016; Kinsela et al., 2016; Davidson et al., 2017; Limber et al., 2017; Safak et al., 2017; Vitousek et al., 2017; Bruno et al., 2018) adapted to the encountered, natural conditions are used. Prognostic analyses on the Polish coast were conducted in small scale and are limited to the last few years (Deng et al., 2014, 2017a; Zhang et al., 2017). Earlier, such works were in principle, limited to cliff coasts and were based on a simple linear regression models (Subotowicz, 1995a,b).

Therefore, in the course of research tasks, aimed at visualization of coastal changes, a number of field and analytical works are carried out aiming at the most-accessible and appropriate presentation of natural spatial and temporal information. In the case of barrier and spit coasts, an extended remote sensing analysis can be applied; involving digital terrain models [DTM] and the implementation of GIS based techniques that allow following the coastline changes in relation to the oldest available cartographic materials. Such studies allow documenting the changes in a reliable way and extrapolate them into the future. In practice forecasting methods are often challenged, by the limits of natural complexity and as a result, the inability to meet the restrictive assumptions (Kinsela et al., 2016). Therefore, the aim of this work is to present prognostic variants for various developmental trends of the Polish Baltic coast in the next 15 years while the basic premise for achieving this objective is to implement the problem-solving principle that makes the fewest possible assumptions.

## 2. Study area

Study area is located on the Southern Baltic coast, along the Kaszuby Coast (northern Poland), and extends from east to west along a 22 km stretch of coastline between 17°49′43″ and 18°10′51″ E. Geographically, the area encompasses the lowland (Fig. 1) where the barrier is developed. Beach width reaches several tens of meters and its profile is variable depending on the time of season. The area is limited from the north by the sea, where the seabed gradually decreases (deepens) towards the north, north-east to a depth of about 15 m. Isobaths till this depth are more or less parallel to the shore. The average seabed inclination between the shore and 10 m isobath is between 1:70 and 1:100, whereas underwater coastal slope in other more stable section of Polish barrier coast is between 1:120 and 1:150 (Zawadzka, 2012). There are two, sometimes three sandbars close to the shore at depths up to 5 m. Their height is between 1 and 4 m. To the south and east the area under discussion is limited by the morainic upland while the western part is continuing as coastal lowland covered by dunes.

The geological setting of this area closely matches its morphological feature. The lowland consists of fluvioglacial sands covered by Holocene lacustrine and biogenic sediments — fine sand, mud, gyttja and peat. The barrier is rather narrow (from several tens of meters to 400 m). It consists of fine and medium sand overlain by dunes (aeolian cover). Dunes are not higher than 20 m. Locally, peat is presented on the beach under the thin cover of beach sand. In general, the thickness of the sandy sediments (both beach and marine) does not exceed 7 m. Further to the south, the morainic upland is built of glacial till of varied thickness, from several to over a dozen meters. There is fluvioglacial sand with a maximum thickness exceeding 20 m under the till.

This rather simple geological scheme is continuing offshore. Sand forming the barrier is underlined by Pleistocene fluvioglacial sand, sometimes mud and silt which thickness can reach 3 m.

The winds from western and south-western directions dominate on the Southern Baltic coast. In the coastal zone the highest mean wind speed (5-7 $\mathrm{ms}^{-1}$) is characteristic for autumn-winter season, whereas the lowest (2.5–3.5 $\mathrm{ms}^{-1}$) occurs from May to August (Zeidler et al., 1995).

Hydrography of the discussed area takes rather simple form. The waters of small rivers are directed from the morainic uplands to the sea. Lubiatówka and Piaśnica Rivers run northwards directly to the Baltic Sea. The coastal lowland is also intersected by a network of drainage ditches, in places developed for agricultural purposes.

In general, sea level along the southern coast of the Baltic Sea has been rising. The rate of sea level rise differs and is caused due to fluctuations in land subsidence and meteorological factors — wind forcing and air pressure (Uścinowicz, 2006). At a decadal time scale, Baltic Sea level variations are closely associated with the North Atlantic Oscillation (HELCOM, 2007, 2013). Mareographic records from Gdańsk (Fig. 2) showed that sea level rose at a rate of 4.6 mm per annum in the period 1886–1906 and 5.7 mm per annum in the period 1970–1990, whereas in the first half of the twentieth century and near the turn of the twentieth and twenty-first centuries, the rate of sea level rise significantly slowed down (Jurys and Uścinowicz, 2014). Amount and strength of storms on the Baltic Sea shows multi-decadal variations and are related to NAO. There are no evidences for long-term trend in storminess (HELCOM, 2007; Bärring and Fortuniak, 2009).

## 3. Materials and methods

The study was mainly based on the spatial analyses of different cartographic materials and extrapolation of historical trends (Table 1). The old topographic maps established approximately at the turn of the 19th and 20th century were used to analyse the rough coastal retreat. These old German maps (Messtischblatt) in scale 1:25 000 are characterized by the high level of details and accuracy in some cases up to 4–6 meters in comparison to the modern cartographic materials (Deng et al., 2017b). So, the maps are good source of information concerning the coastal topography at the beginning of the 20th century, and can be used to determine the general evolution of the study area. Another source of knowledge about position of shoreline at the beginning of 21st century is modern topographic map, which illustrates the situation actual for the year 2001. The shoreline on map is a linear feature of a width of approx. 0.5 mm and such a line was digitalized with a use of GIS based technics. So the position of the shoreline was adopted directly from the official cartographical materials. Such a procedure allows to achieving accuracy of a few meters or ultimately up to 10 m.

Second source of materials used in the studies were digital terrain models [DTM] based on laser airborne scanning with a resolution of 0.5 × 0.5 m. Two models were created for 2010 and 2016 during autumn seasons. The models have been made available thanks to courtesy of Maritime Office in Gdynia. All maps are related to the mean sea level. The coordinates X and Y on all figures are presented in the rectangular flat coordinate system (EPSG 2180). This system was also used for forecast calculations.

The main idea was to compare changes and to analyse them using various geoprocessing and statistical techniques. Such prepared cartographic collection was used for further analysis aimed at establishing of predictive models. In particular two methods of prediction of coastal changes are presented in the manuscript named: “shoreline extrapolation model” and “averaged shoreline changes model”.

The first step (1) in preparation of both predictive models was to determine the position of shoreline in the past: 1875, 2001 and 2010. Year 2016 is considered as the most actual information. Next, the perpendicular to the shoreline profiles were marked every 100 m and for two areas characterized by the highest value of erosion and accumulation rate (143,75 km–144,25 km and 152,90–153,40 km) also every 50 m. The points/places of occurrence of shoreline and the base