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Coastal Response to Climatic Changes: Discussion with Emphasis on Southern Baltic Sea

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Abstract: The influence of climate change on coastal areas is indisputable. Natural or anthropogenic elements of the coastal zone often reveal unforeseen changes, not comparable with earlier observations. However, human activity is influenced by climatic events that affect settlements and local economies. This paper presents the increasing threat of climate change to world coastal safety with an emphasis on field research from the coast of the southern Baltic Sea. The main climatic factors that influence the land and shallow seas of the coastal zone are: wind, waves, storm surges, ice jams and flooding. We are forgetting about the relationship between these factors and parts of the affected environment. A costly shore protection scheme in one area forces erosion in another. It is proposed not to analyse the environmental events on average; such scientific results do not provide the basis for calculating real land erosion. In this paper, it is argued that nature does not respect average values; we need to prepare for greater change due to the escalation of those factors affecting the coast.

Keywords: coastal changes, climate factors, South Baltic coast

Introduction

The coast is a border of variable width between land and water. From the human point of view, it is mainly land with neighbouring sea. In the modern understanding, it is a shallow sea that can be managed for economic purposes, such as artificial islands, wind farms or larger open-sea harbours. People divide the coastal zone according to their needs. Each part is threatened in a different way, bordered and protected physically by fences, national borders, or legally by different laws and management rules. The nature on the coast is uniform and has a linear course; it changes only where the land and marine processes exhibit variations due to affecting factors.

The coastal zone is one of the most dynamic environments where natural factors, such as storm surges, other water level fluctuations, the strength of the wind and plant existence are the result of climatic conditions. However, human activity is influenced by climatic events that affect settlements and local economies. Climatic change and its influence on the environment is a fact; the natural or anthropogenic elements of which often show surprising changes, not comparable with earlier observations.

The aims of this paper are to present the increasing threats from climate change and the impact of climatic events to the safety of coastal areas, based both on the literature and on own studies of the Polish coast of the southern Baltic Sea.

Specificity of the coast

For centuries, man has settled on the shores of seas and oceans, usually on river estuaries. Sea and rivers were transport routes and rich sources of food but the emergence of tourism has led to increased development of coastal infrastructure. Currently, coasts are densely populated areas, which is largely associated with job opportunities in many sectors of the economy centred on coastal tourist resorts. These centres are usually located in low coastal areas with estuaries, where it has always been easier to access the sea. These low, sandy coasts are not that resistant to damage and are thus, very susceptible to ongoing influences. They constitute the majority of the world's coasts, found in any climate and on every continent. Some examples might be the shore of western Europe stretching from Denmark to France

(Breton Peninsula) and further west and south, a narrow spit surrounding the United States (called the Outer Banks in North Carolina), stretching from New York to Florida and along the coast of the Gulf of Mexico, or the sandy coast of eastern Australia. These are examples of some of the longest sandbars, which are densely populated with intensively developing infrastructure.

Coastal sandbars formed as sand belts where spits separate the bay, lagoon, or lowland terrain from the sea. Mainly they are low-lying areas only 2–4 m above sea-level with one or several coastal dunes between the land and the beach. On these areas Western civilisation has developed ports, shipyards, factories, power plants, including nuclear plants (UK, Spain, Japan), military areas, airports (Indonesia, Singapore, Denmark), town entertainment (UK, Japan) and tourist facilities, including marinas (USA, Caribbean Islands, Southeast Asia, Europe, Australia). In countries with non-European cultures, on the sandy coast there are landfills (African countries), cemeteries (Muslim countries) or temples (India, Morocco). Nowadays, in order to maximise the zones for coastal development people artificially expand coastal areas by simply building wider beaches in tourist zones or by building whole islands or wider waterfronts (Japan, Singapore, United Arab Emirates, USA). Additionally, increasingly longer parts of the coast are developed with tourist infrastructure (Spain, Italy, Egypt or Mexico).

There is no indication that this trend of increasing development will be reversed (Nordstrom 2000). However, the coastal zone is a very dynamic environment and the relative height position of the land may be changing rapidly due to natural processes. Nowadays, we mainly observe the retreat of the land due to storm surges and sea level increase.

This phenomenon requires infrastructure for higher coastal protection. Since the Middle Ages have been built in Europe in order to protect settlements against storms. In the 18th century preventative measures that were more concrete were developed. Heavy armoured structures have been constructed to counteract the shifting shore and land erosion. In some places, whole towns or areas of land may be protected by a seawall (Galveston in Gulf of Mexico, the Netherlands), whereas other coasts are completely built-up by protection measures (Japan, the Netherlands or cities in United Arab Emirates). These measures disrupt the natural flow of sea sediment and cause unexpected erosion in neighbouring zones. There are several examples of marinas, piers and breakwaters resulting in siltation of ports and marinas on the one hand and increased erosion on the other. Wrongly located historical investments can today result in large expense on protection or artificial nourishment of coastal beaches and dunes.

The Polish Baltic coast has a length of 500 km and is built of soft and loose material like dune sands, organic deposits or till and clay in cliffs; over 80% of the total coastal length comprises dunes of differing widths and heights (Fig. 1).

Climatic threats to the coastal zone

Various factors interact in coastal areas, the actions of which are the result of environmental changes. Among these, sea level change and storm waves play the leading roles. These two factors are responsible for coastal land erosion and accumulation, as well as the emergence of beaches and their variability. Waves are formed due to the strength of the wind associated with changing pressure systems and their passing fronts. Wind is the factor responsible for the aeolian processes – mainly the transport and accumulation of sediment. The rate of wind impact is also related to climatic circulation, such that each year the aeolian processes are of varying intensity. Changing seasonal climatic conditions and local weather conditions cause the development of storms, which are accompanied by storm floods (Hünicke & Zorita 2008). Wind and water destroy the land and the surrounding infrastructure. Flooding in the estuarine sections of rivers, which are the most densely populated areas covered with infrastructure, may be the result of rainfall phenomena and not just associated with sea and tidal processes. During winter periods in temperate climates ice cover may form, which can cause the destruction of beaches and natural or artificial dykes protecting the land. The phenomenon of ice can also cause jams in the mouths of rivers, which results in flooding. Long-term elevated sea water level on the coast also has the effect of raising groundwater and flooding the low-lying coastal areas.

Sea level

We record two types of sea level rise (SLR): annual oscillations caused by weather conditions and the long-term slow growth recorded in connection with the rising level of the ocean. Seasonal sea level changes are associated with storm surges causing flooding and erosion. The North and the Baltic Seas, largely controlled by the mean sea level of the North Sea and atmospheric pressure patterns over the North Atlantic, strongly influence the volume of water in the Baltic Sea. During the prolonged domination of westerlies, the Baltic Sea receives inflows from the North Sea, resulting in a sea level increase. During periods of prolonged domination of easterly winds, the sea level is observed to decrease due to the outflow from the Baltic Sea into the North Sea (Sztobrnyn et al. 2005). In the Baltic region, short-term

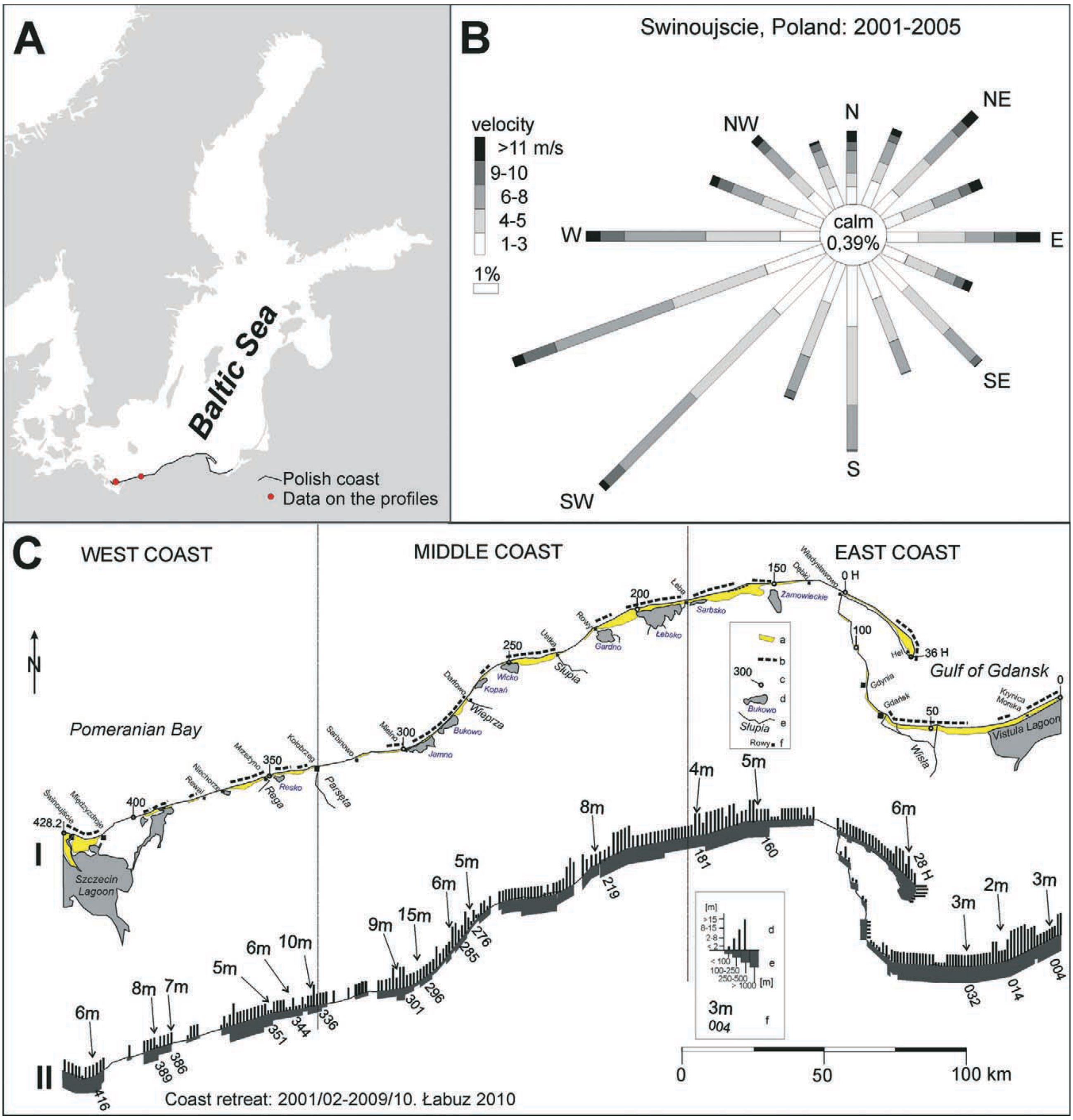

Fig. 1. Baltic Sea. A – location of research on South Baltic coast, B – wind regime on west south Baltic coast, C – The characteristic and localisation of dunes and retreat rate of the Polish coast (Łabuz 2005, changed)
I – dunes localisation: a) dune coast, b) foredunes with pioneer plants, c) kilometrage of the Polish coastline, d) lakes, e) rivers, f) main touristic resorts; II – the height of dune coast (d) and the width of coastal dune areas (e), coast kilometrage and erosion rate (f)

sea level variations are caused mainly by meteorological forcing (Heyen et al. 1996; Samuelsson & Stigebrandt 1996; Wróblewski 1998; Cyberski & Wróblewski 1999; Johansson et al. 2001; Suurssar et al. 2003; Jasińska & Massel 2007). Annual oscillations in the sea level are associated with oscillations of pressure systems and the formation of wave-generating winds (Pruszak & Zawadzka 2005; Hünicke & Zorita 2008). The amplitude of the registered sea level oscillations extends over 3.2 m (in Świnoujście town).

The second type of rise in sea level is the worldwide annual trend caused by the changing climate and isostatic movements of the land. In the 20th century, the rate of sea-level rise was 1.7±0.3 mm/year and a significant acceleration in this process was observed (Church & White 2006). Amsterdam's gauge recorded a rise of 1.5 mm/year. On the Baltic Sea coast, the relative sea level is receding in the north where the land is uplifting by up to 8 mm/y and the sea level is rising in the southern Baltic Sea where the continental crust is sinking at about 1 mm/y. On the Baltic

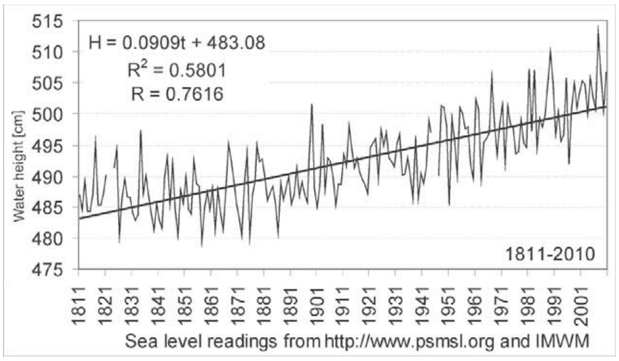

Fig. 2. Sea level changes and growth trend in Świnoujście (Kowalewska-Kalkowska & Marks 2011)

southern coast, because of the sinking continental crust and sea level rise, the apparent annual rise in water level is on average 0.6–1.5 mm/year (Pruszak & Zawadzka 2008). During the last 20 years, the rate of rise has reached 2.2–3.9 mm/year and this could result in a sea level 45–65 cm amsl by 2100 (Pruszak & Zawadzka 2008). As an example from the Baltic southern coast, the longest record of sea level fluctuations may be that from Świnoujście, which shows that the permanent sea level increase has been almost 20 cm during the last 200 years (Fig. 2).

During periods of elevated sea level, tides or storm waves can encroach on higher shore areas. Thus, the erosion impact zone is moved further inland, beaches and dune ridges are washed away and developed areas are endangered and flooded.

Storm surges

During storm surges, the water level is extremely high with growing waves on the coast, which produces flooding of low-lying areas. The most endangered regions are: western European coasts, the southern Baltic coast, the eastern and southern coast of the United States and the low coast in southeast Asia (e.g., Bangladesh).

The most widely known causes of storm surges are tropical cyclones (called hurricanes, typhoons) characterised by a large low-pressure centre and numerous thunderstorms that produce strong winds, heavy rain and high waves. These events are very evident on the eastern and southern coast of the USA. Some of them, like Andrew in 1992 or Katrina in 2005, were reported live. During these phenomena on the east coast of North America, waves on the coast can reach up to 9 m with an average height 5 m amsl. The Damage and losses caused by them can be counted in billions of dollars. Hurricane Isabel in 2003 washed away several islands from the Outer Banks (OBX) in North Carolina. One of the earliest hurricanes to be well reported was in 1900, which struck the developing coastal town of Galveston in Texas. The town lay just 2.7 m above sea level on a narrow sandbar in the Mexican Gulf. The hurricane raised the water level by 4.6 m. The town was flooded, houses were destroyed and 6000 to 12000 people were killed (Table 1) with estimated losses of 99 billion US dollars (Pielke et al. 2008). Following that storm, the sea defence barrier was raised up to 5 m and a seawall was built with numerous groynes.

Table 1. Costliest US hurricanes (prepared after Pielke et al. 2008)

Rank	Hurricane	Year	Costs (USD)	Killed
1	Miami	1926	$157 billion	373
2	Galveston	1900	$99.4 billion	8,000–12,000
3	Katrina	2005	$81.0 billion	1,836
4	Galveston	1915	$68.0 billion	53
5	Andrew	1992	$55.8 billion	c.a. 12

During storm surges in the temperate European zone, the generated waves are lower (2–3 m on average) but the sea-level rise may exceed 5 m. Even in modern times with flood security in Western Europe, flood events can cause the loss of civilian lives. In February 1962 in Hamburg, situated 100 km from the coast, seawater moving up the river Elbe overflowed into part of the city and killed 318 citizens (Ratter et al. 2010). On the southern Baltic coast, the sea level during a storm may rise by up to 1.5–2 m above the average level but water inflows on the land can reach 3.5 m amsl (Łabuz 2009b). This has been the highest recorded range during the last ten years (Table 2, since 2001). The number of strong storms on the Polish coast with water levels higher than 0.7 m amsl is similar each year but the number of extreme events is increasing, causing greater erosion and the loss of land or private property. These events in the Baltic States are caused by westerly winds and on the south Baltic coast by northeasterly and northwesterly winds.

Each subsequent storm surge noticed on the Baltic coast seems to have a bigger impact because the coastal relief is not recovering. The land withdrawal (dunes and soft cliffs) is 0.9 m/year and after one storm event, it may be even 5–8 m (Łabuz 2009b, Łabuz 2011). Only land protected by a beach higher than 3.5 m is more or less safe. The most threatened area is low land on sandy shores and thus, the dune environment of the Polish coast is seriously threatened with erosion (Rotnicki & Borówka 1990; Zeidler et al. 1995; Schwarzer et al. 2003; Pruszak & Zawadzka 2005).

On the southern Baltic coast, the largest storm surge occurred in 1872, when the sea level at the Schleswig-Holstein coast exceeded the mean level by 3.5 m. The highest sea level rise on the Polish coast was recorded in February 1874 at 2.17 m and 1.96 m amsl in Kołobrzeg and Świnoujście, respectively (Zeidler et al. 1995). Nowadays, during the whole au-

Table 2. The list of storm surges with water level 1 m above mean one (amsl) noted on west Polish coast (Świnoujście 2001–2012, data from Maritime Office), (Łabuz 2005, completed) in comparison with land erosion rate on examined field profile 1 m width (416 km of coast), (sand volumes: Łabuz 2011, completed)

Date		Storm surges		Wind		Dune erosion	
Year	Day / Month	Max. sea level [m a.s.l.]	Sea waving [Bft]	Direction	Velocity [ms^{-1}]	Foot retreat [m]	Sand volume per 1 m profile width [m^2]
2001	8–11 Nov	0.96	6	N	11–13	3.60	7.34
2001	15–17 Nov	0.97	6	NW	11–14		
2001	22–25 Nov	0.98	7	NW	13–15		
2002	1–3 Jan	1.04	7 (9)	NNE	13–15	No data	No data
2002	19–22 Feb	1.42	7	NE	14–16	4.50	2.72
2003	6–7 Dec	1.04	7	N	14–16	3.00	1.25
2003	21–25 Dec	1.01	8	NW–N	16–18	No data	No data
2004	22–25 Nov	1.29	10–12	NW	17–20	6.40	5.18
2006	31 Oct–4 Nov	1.47	8–9 (12)	N	16–20	1.90	4.00
2007	18–20 Jan	1.40	10	NW	15–19	3.00	8.65
2007	21–28 Jan	1.25	7	NW	14–16	2.00	4.00
2008	21–23 Mar	1.04	7	NE	12–15	1.00	1.10
2009	13–16 Oct	1.33	8–9	NNE	15–18	3.00	7.15
2010	15 Dec	1.32	6	NNE	14–16	3.50	6.89
2011	17 Dec	1.23	10–11	NW	17–20	3.50	4.6
2012	06 Jan	1.06	7–10	NNW	15–18	2.50	3.4
2012	14 Jan	1.30	7–9	NW	12–16		

tumn-winter period the sea level is higher than the average. This condition may persist for 1–2 months, causing flooding of land areas adjacent to the shore. Sztobryn et al. (2005) estimated that in 1976–2000 about 40% of all storm surge events on the south-west coast of the Baltic Sea were caused by a strong northerly air flow over the Baltic, resulting from high atmospheric pressure over Scandinavia and a depression moving southwards near the eastern boundary of the Baltic.

Most storm surges occur in autumn and winter. On the western coast, most storms (above force 6 on the Beaufort scale) are the result of N winds (55%), then NW (31%) and NE (14%). The strongest storms, with wind strength between force 10–12 on the Beaufort scale, are produced by NE winds (after Zeidler et al. 1995). About 55% of the storm surges resulted from gale-force winds developing at the rear of atmospheric depressions moving eastwards across southern Sweden, the southern basins of the Baltic Sea, or across the land close to the southern coast, as occurred with the November 2004 storm surge (Łabuz & Kowalewska-Kalkowska 2011). On Polish, southern Baltic coast all autumn-winter storms cause erosion and a southward retreat of the coast, with an average rate of 0.1 m/year over the last 100 years and 0.5 m/year from 1960 to 1983 (Zawadzka-Kahlau 1999). A similar situation occurs on the German, Lithuanian and Latvian coasts, where coastal erosion is of the order of 0.5–1.5 m/year on average.

Due to this increasing threat, large fractions of the Baltic Sea coastline is now protected; however, the techniques applied are not sufficient to prevent sand losses. The longer a section of the coast is protected, the less sediment there is available to rebuild the beaches. The best technique currently in use is artificial nourishment but this requires large amounts of money and repeated action. For example, artificial nourishment is required annually in Łeba, Ustka, every two to three years in Dziwnów, Mrzeżyno but rarely in other coastal towns and villages. In Kołobrzeg town the situation is very bad because after each storm surge the whole beach is flooded and abraded and water enters the lowland behind the narrow dune belt (Fig. 3). The last artificial nourishment in Kołobrzeg was realised in September 2005; this was partially washed away after one year and totally removed by November 2006. Subsequently, without any protection, 160% of the sediment from the beach was lost by February 2007 in relation to 2005 (Fig. 4). Until 2010, the beach could not be recovered due to a scarcity of sediment (Łabuz

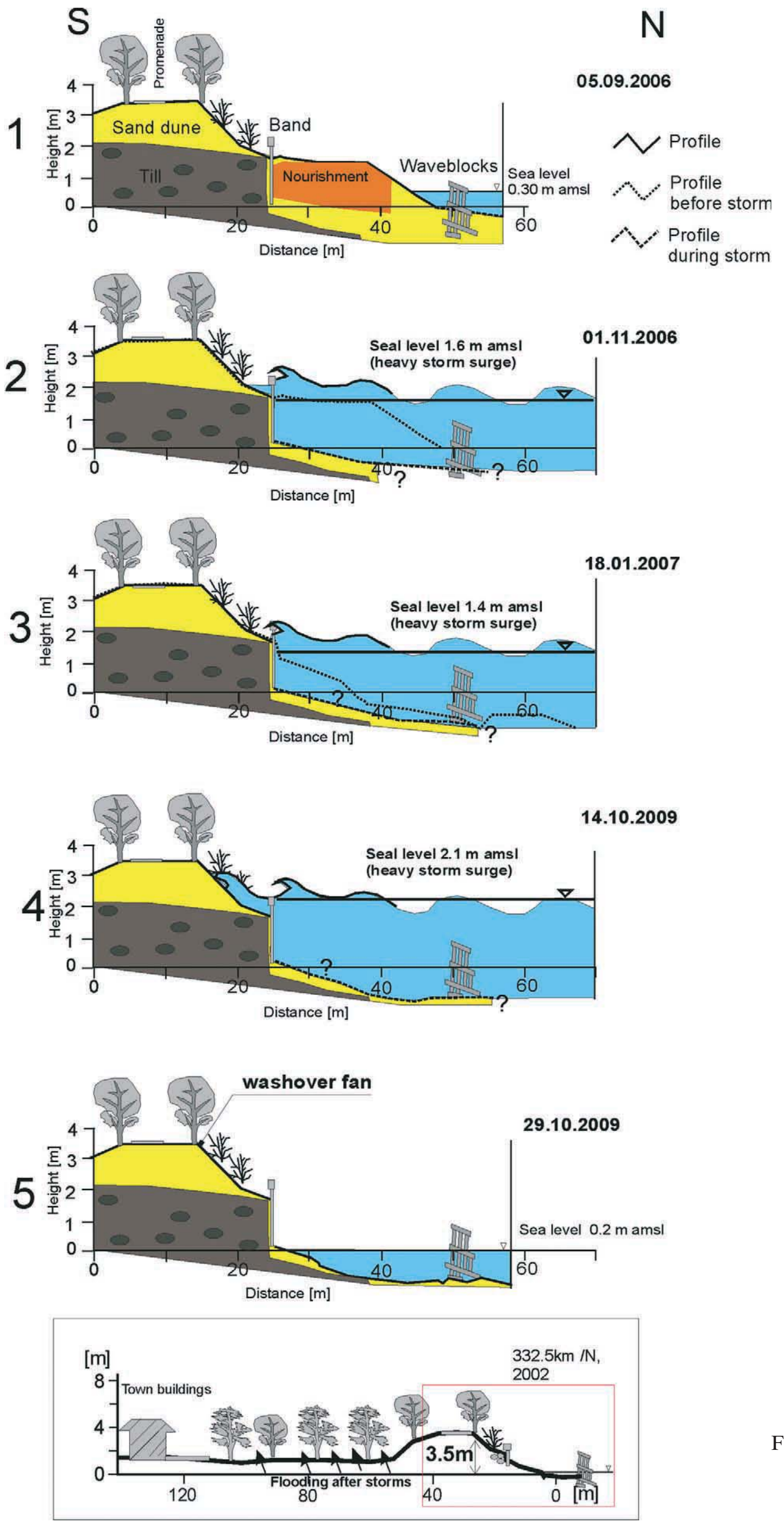

Fig. 3. The example of storm surges effect on protected coast in Kołobrzeg town endangered by erosion (Łabuz 2012)

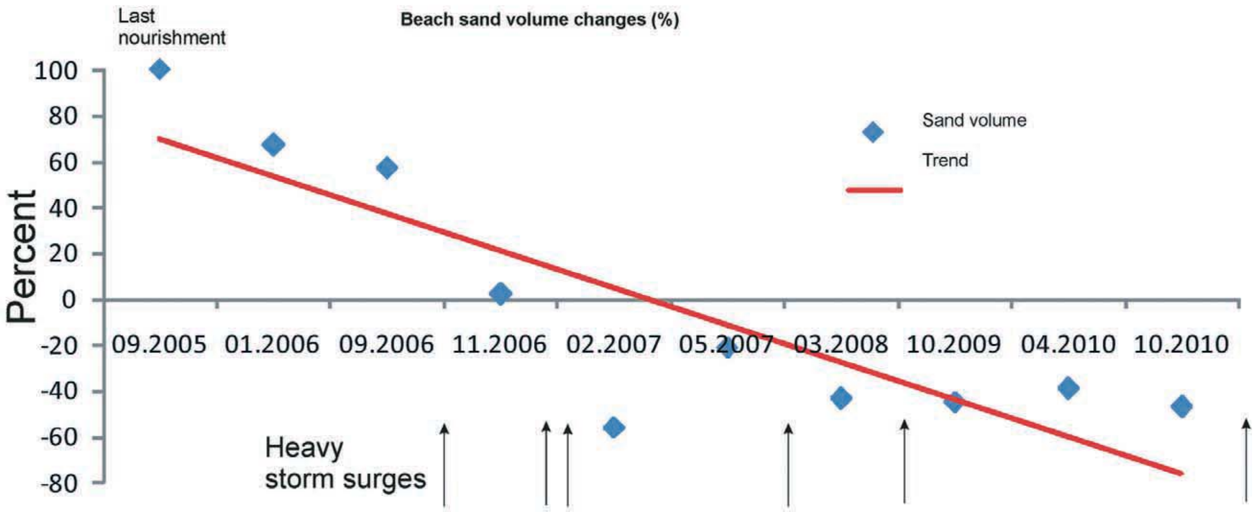

Fig. 4. The rate of nourished beach erosion, example form Kołobrzeg town (Łabuz 2012)

2012). Currently, to stop further erosion, an 88 million euro project funded by the EU is being implemented. Many research projects on coastal protection are currently established using new techniques of investigation and monitoring but we still lack an understanding of coastal changes on scales larger than the local scale.

Flooding

The incessant devastation of the coastal dune belt, a natural protection of the low-lying coastal background, may lead to the flooding of the infrastructure situated behind it. This is a real threat, especially when a permanent coastline retreat on many sections of the coast is a reality. The situation requires continuous measurement and reconstruction of beaches and coastal areas. However, heavy rainfall may cause flooding in the densely inhabited river mouth regions. On the south Baltic coast, lowlands up to 3 m in height are seriously endangered by this force and have suffered from it in the past (Łabuz 2009c). It is not only coastal areas that are threatened but also valleys up to hundreds of kilometres inland. Such flooding occurred in 1962 in Hamburg with water 3 m higher than average, or in 2005 when hurricane Katrina flooded New Orleans by up to 5 m. Several times flooding caused by storms on the South Baltic coast has been experienced (e.g., 1995 in Swinoujście, Kołobrzeg, 2006 in Gdańsk or in 2012 in Gdynia, when the water level was 2–2.5 m higher than average).

The most endangered areas are river deltas and estuaries (Mississippi, Ganges with Brahmaputra or Vistula in the southern Baltic region). Flooding may cause devastation of the river mouth or even the emergence of a new mouth (as occurred in the Polish town of Łeba or Dziwnów in 19th century). In certain circumstances after prolonged rainfall, when the sea level is higher than average, flooding may occur. Such rainfall may cause landslides of high coastal cliffs (as in 2007 on the Polish Baltic coast). In June 1996, after heavy rainfall and silting of the mouth of the small river outlet, low-lying areas near Kołobrzeg and Ustronie Morskie were flooded. In addition, snowmelt following large winter snowfall could lead to flooding of coastal areas. Such an event occurred in March 2010 east of Kołobrzeg, where collecting water in the swamps of Eko Park breached the narrow dune belt. Subsequently, seawater entered this protected area and destroyed many rare habitats. More serious was the heavy rainfall in July 2001 in Gdańsk; this caused flooding in the city and the death of four people. Furthermore, increasing precipitation levels will produce increased river flows and may be a threat for small coastal catchments. Additionally, due to warming, lower river inputs into the sea will reduce the supply of sediment for beaches or the rebuilding of spits. River mouths reinforced by breakwaters interfere with the alongshore sediment distribution, which can lead to the situation where one side of a river outlet the coast is prograding, whilst on the other side sediment scarce (as in Warnemünde, Ustka, Łeba or Władysławowo on the southern Baltic coast).

Ice jams

Ice jams in the mouths of rivers may cause flooding of the surrounding land. The ice pushed ashore by the waves may erode the beach and land relief, as well as destroy the infrastructure, damaging piers and coastal protection measures. The ice cover on a beach in the spring prevents the accumulation of sediment by wind and reconstruction after the storms of the autumn and winter period. This was observed on the Polish coast in February and March 2003, 2006, 2010 and 2011. It simultaneously destroys the coastal relief and stops rebuilding. Ice jams combined with storm surges may cause coastal dune retreat and are responsible for beach lowering and such beaches are more at risk from further flooding.

Furthermore, longer periods of time in the recent past without ice cover in the Baltic and the Gulf of Finland has apparently created more opportunities for strong storms to attack the coasts (Jevrejeva et al. 2004).

Winds

The most effective winds for sand accumulation on the dune ridge are those that are oblique to the beach (Arens 1994). It has been proven that the wind strength plays a key role in the volume of sand transport. The most effective are strong winds that blow above 10 m/s. On the coast, such winds are predominant during the heavy storm surges.

Wind gusts, often associated with stormy events, might cause losses in infrastructure, like households or power transmission. Wind is capable of producing powerful high waves that might destroy coastal areas. Waves depend on the velocity and direction of the wind and the duration of their occurrence. Prolonged high velocity winds blowing from the open sea generate storm waves that are accompanied by coastal water surges. Winds during a hurricane may exceed 200 km/h. During storm events in temperate climates, the wind frequently blows at speeds of 100 km/h. During storm surges on the southern Baltic coast, the wind can exceed 70–90 km/h. During field investigations on 23rd November 2004, a NW wind of about 22–23 m/s (ca. 80 km/h) was recorded (Łabuz 2007). Such a wind is also an essential factor for sand transportation along the beach or further inland. After 2 days of such an event, fresh sand accumulation on dune ridges could reach a layer 10–15 cm deep. The increasing velocity of the wind due to climatic changes may be a natural factor restoring eroded dunes but without sediment available on the beach, this cannot be possible.

We cannot forget that in natural conditions the sand transported by the wind accumulates behind the beach in places where obstacles (like vegetation) might promote dune development. However, in modern times, at the back of the beach, man builds pavements, roads or terraces and hotels; these facilities may often be covered by sand but are useless in terms of coastal protection.

Coastal response to storm surges – southern Baltic study

The Baltic Sea coast is a non-tidal area, where only the wind, waves and nearshore currents play the main role in coastal development. The sea level in the Baltic Sea varies substantially during the year because of the combination of effects of a number of meteorological and hydrological factors.

These events can cause flooding of areas up to 3.5 m amsl. Water overflows low dune ridges, artificial paths and depressions up to 4 m amsl, causing washover fan development (Łabuz 2009c). All relief forms below this level are abraded and dune ridges in the beach hinterland are subject to regression. The size of the coastline erosion and retreat depends on both the sea surge height and its duration. If the beach is higher than 3.5 m amsl (covered by incipient dunes), it may be able to withstand erosion and prevent damage to inland forms (Fig. 5). In such places, after a storm there can be observed marine accumulation on the beach and aeolian accumulation on the dune ridge (Łabuz 2009a). Thus, storm surges bringing sediment from eroded areas can cause land increase; however, this situation is mainly present on only 10% of the Polish Baltic coast (Łabuz 2005). In other zones where the beach is lower than the highest water, the affected dunes slowly retreat. This process was observed after the 2006/2007 stormy season when four strong surges with water levels over 1.3 m amsl caused dunes to retreat (4–7 m) in many investigated places.

In many sections, where the land is up to 3 m amsl, the buildings are protected by numerous biotechnical and hydrotechnical solutions. These are mainly concrete seawalls, tetrapod mounds and groynes. Nowadays nourishment is used in every endangered coastal town but when the level of nourished dune or artificial dyke is lower than 3 m, it may be eroded after one strong storm with water higher than 1 m. Biotechnical solutions, which include planting of selected species, retain the sand on the dunes. However, all these activities decrease the number of species in dune habitats (Piotrowska & Gos 1995).

The data from the field study concerning sand transportation across the beaches, during developing storm surges on the Polish Baltic coast, converted to another scale shows that transportation across the open surface of the upper beach is 1.133–5.017 kg/min/m, depending on wind gusts (17–22 m/s). Sand transportation responds to wind variability over time. The comparison of all collected data from the experiments shows that almost 50–80% of the sand was transported within a layer 3 cm above the beach and 90% of the sand was transported within a layer 20 cm above the beach (Łabuz 2007). During the storm event, the developing strong wind transports sediment onto the foredune ridge. This is some kind of feedback for the ridge during the biggest phase of storm (the height may grow by up to 0.2 m during one day). However, if the beach before the storm is low and narrow, this feedback does not occur.

Over the last 10 years, the Polish coast has been subjected to several storms with a sea level 1 metre

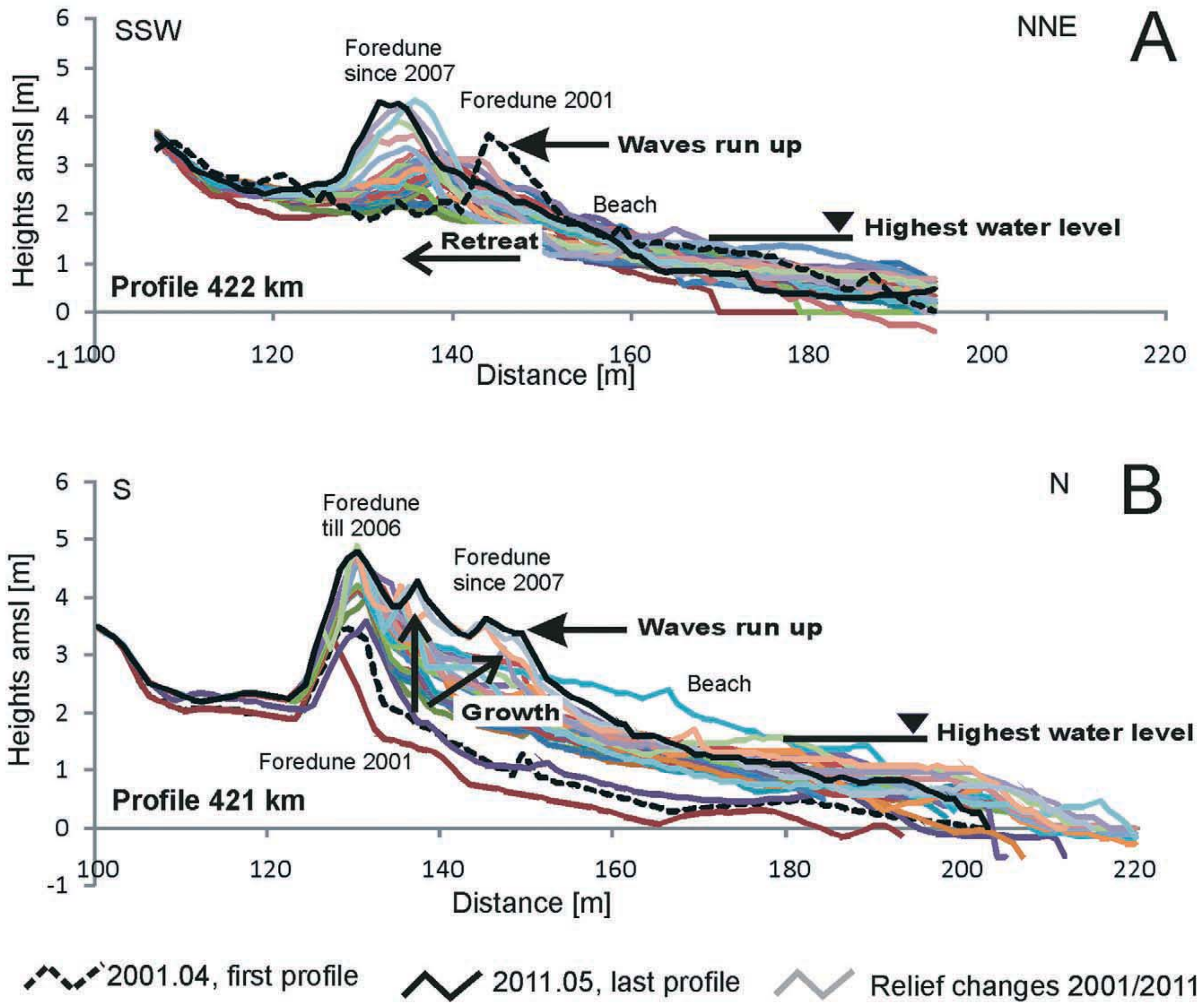

Fig. 5. Coast short and long term response in neighbourhood areas with erosion (A) and accumulation (B) tendencies (421, 422 km– Polish coastline kilometrage)

above the mean level (Table 2). After such storms, the dune retreat was 3–6 m (Fig. 6). The more such events occur in one season, the harder it is for nature to rebuild during the calmer periods. Therefore, this leads to reduction of the sand volume in the foredunes and consequently to their retreat (Fig. 7).

Conclusions

The studies conducted on coastal dynamics, considering how changes in land, plant habitats and anthropogenic factors affect the observed changes help to indicate the strong dependence of the observed natural phenomena on human actions. Locally, we grapple with the retreat of the land due to erosion over longer and longer sections of the shore but we forget about the relationship between the environmental aspects. The strongest storm surges that affect the southern Baltic coast occur from the northeast to northwest direction. The coast is mainly exposed for oblique wind directions producing aeolian processes that can rebuild eroded sections. In Poland, higher water overflow on the coastal land during storm surges ranges up to 3.5 m amsl. This is caused by sea level rise and permanent beach reduction, resulting in a slow retreat of the land; the coastal dunes and cliffs in particular. Beaches and dunes that have been reduced cannot be rebuilt between storm seasons due to:

- heavier erosion, more frequent storm surges (due climate changes and isostatic land movements),
- scarcity of the sand (flowing into the deep sea),
- reduction of sand sources (coastal protection measures and river bed regulations),
- human influence on sand drift (piers, harbours, breakwaters, beach tourism etc.).

Expensive actions taken to protect one section of coast can force erosion of another section. Processes of coastal accumulation and erosion work together and do not depend on the boundaries of cities, regions and countries. Local efforts to protect coasts

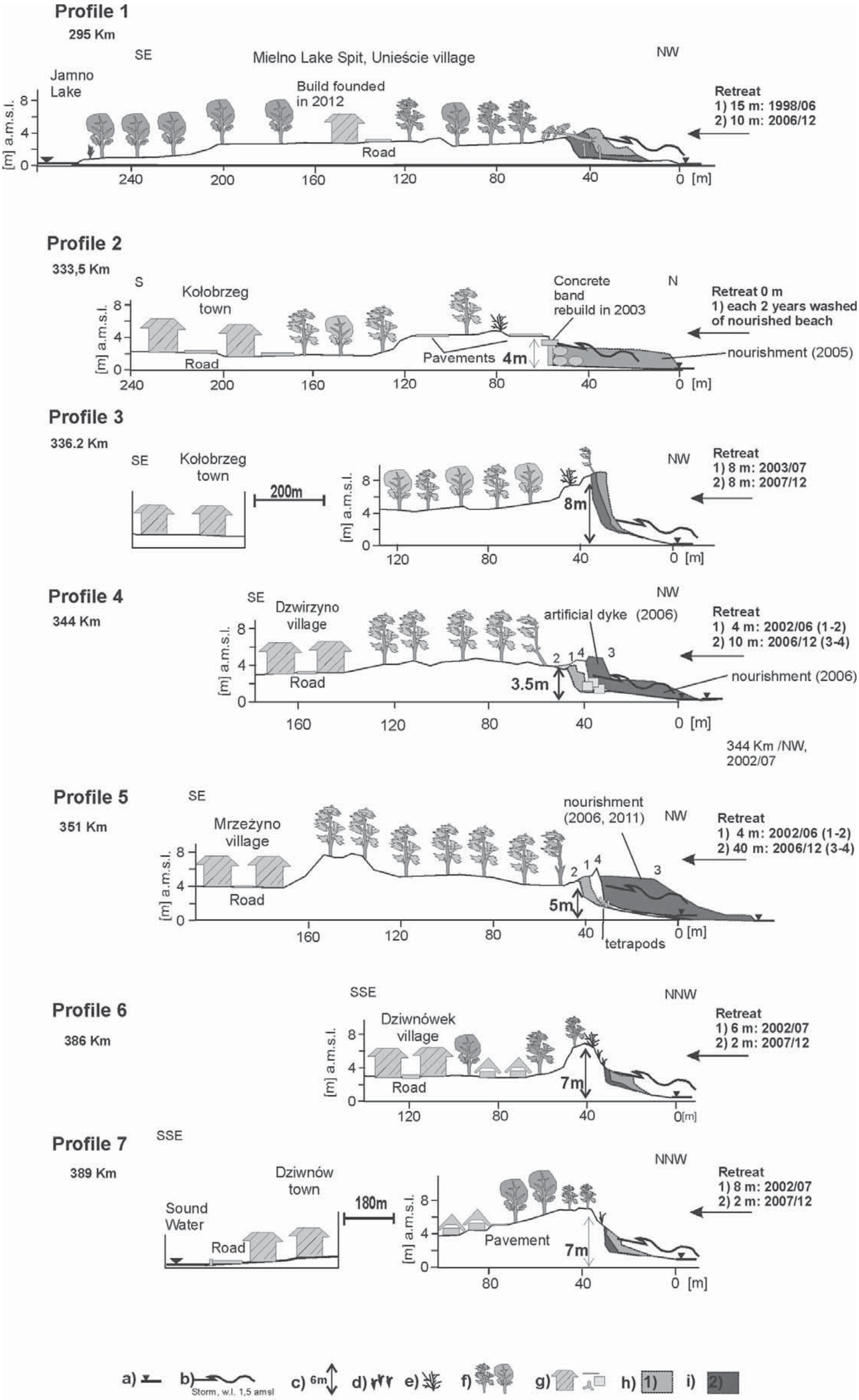

Fig. 6. The examples of the dune coast retreat between 2002/12, a) mean sea level, b) sea level during highest storms (1.5 m above mean), c) dune height, d) grasses, e) shrubs, f) tries, g) buildings, roads, protection structures, h) erosion in first period, i) erosion in second period (Łabuz 2009b, completed)

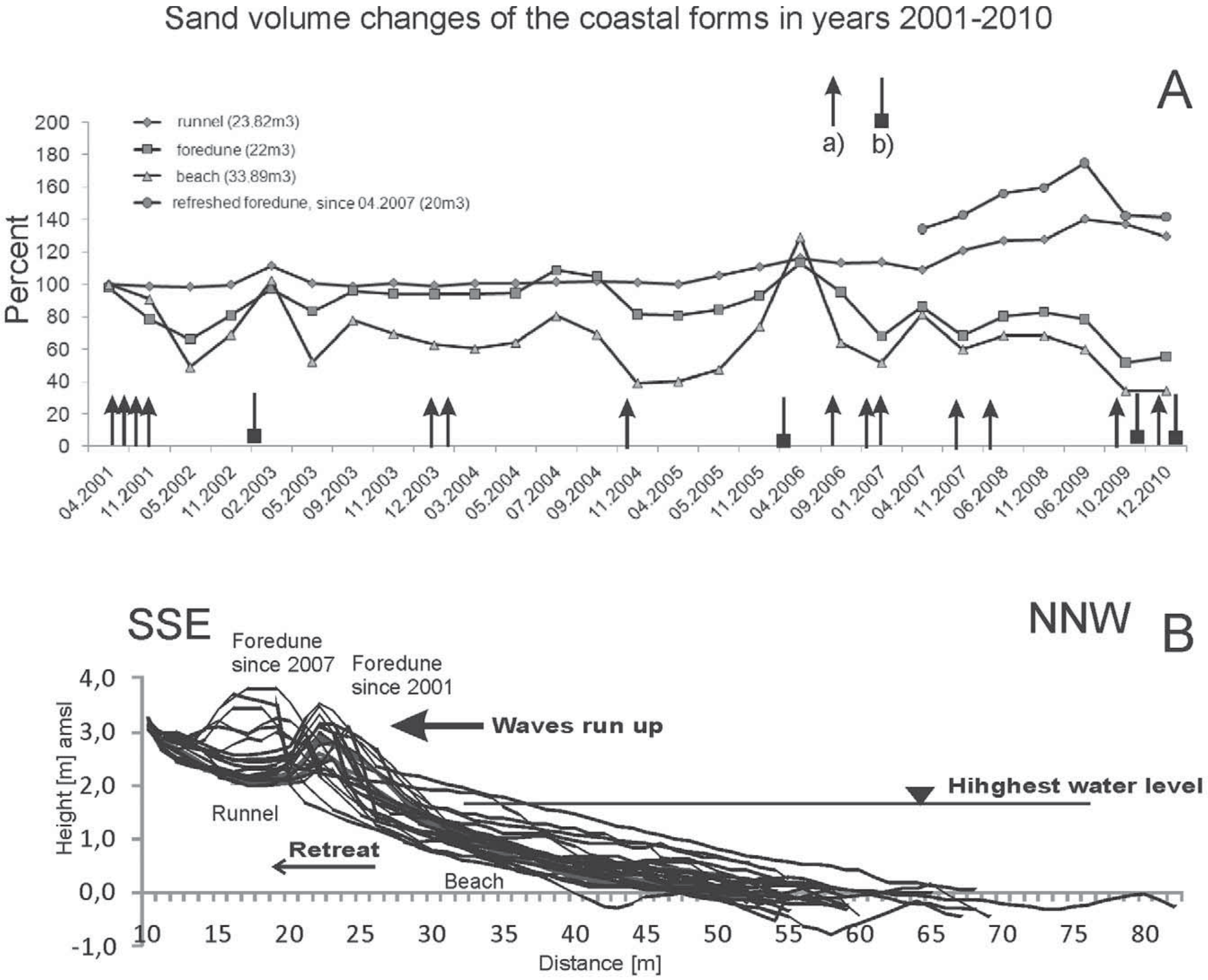

Fig. 7. Long-term sand volume changes of the coastal forms (A) and coastal profile dynamics (416 km) in time (B)

against retreat without the understanding of the linearity of this process cannot be successful in the long-term. Another subject is the need for further infrastructure development in coastal areas, which requires anti-erosion measures. Beaches are shrinking and thus, this is a reduction of a potential source of sediment for rebuilding coastal dunes. Dunes are natural protection for coastal land and investment. Due to natural area decrease, we are constantly losing natural habitats, biodiversity and natural landscape. In addition, extreme events increase the risk for flooding or drought. These threats lead to:

- loss of coastal resilience,
- loss of a greater number and larger area of natural habitats,
- loss of public infrastructure, private property and economic incomes,
- unpredictable land changes due to extreme storm events,
- increasing cost to society and management authorities for coastal protection.

It is proposed not to analyse the environmental events as an average; one occurrence of a severe storm causes greater changes than those recorded annually. We observed periods of both more frequent storms, causing greater erosion and years when the storms were less than average; however, there may also be ice periods, which can also erode beaches.

Averaged results do not provide the basis for calculating the rate of change and the scale of the threats. Therefore, the data are not true and the statistical analyses modelled using average conditions do not provide a presentation of the real threats. This is mainly why the appearance of such conditions comes as such a surprise. Methods of remote observation cannot provide us with information of local changes and the scale of their affect in developed areas due to a single event. We must realise that nature does not know the meaning of average values.

Increasingly numerous protective measures are implemented to counteract these adverse tendencies. Longer and longer sections of the coast are supported artificially and dunes are being supplemented with coastal protection structures. The constantly increasing threat from the sea has stimulated the conceptions of coastal protection strategies: ICZM or other programs, like EUROSION that provide various potential scenarios for future threats. Other regional or local initiatives, such as BALTEX, study the impact of climate change on the Baltic coast, or project FoMoBi (www.fomobi.pl), which concerns the threats to Polish coastal dunes, are good examples of scientific action leading the way for an understanding of rapid coastal changes.

The need for research on coastal area development is becoming more important than ever because of the increasing threats, such as from storm surges and human impact. The quantitative analysis of the morphological evolution of coastlines plays an essential part in the integrated management of coastal zones. The coastal zone is a linear environment that knows no national and decision-making boundaries.

References

Arens S.M., 1994. *Aeolian processes in the Dutch foredunes*. Landscape and Environmental Research Group, University of Amsterdam: 150 pp.

Blake E.S., Rappaport E.N. & Landsea Ch.W., 2007. *The deadliest, costliest, and most intense United States tropical cyclones from 1851 to 2006 (and other frequently requested hurricane facts).* NOAA Technical Memorandum NWS TPC-5, Miami.

Davidson-Arnott R.G.D. & Law M.N., 1990. Seasonal patterns and controls on sediment supply to coastal foredunes, Long Point, Lake Erie. In: K.F Nordstrom, N.P Psuty & B. Carter (eds.), *Coastal dunes*. Form and processes. John Wiley & Sons, Chichester: 177–200.

Church J.A. & White N J., 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* 33(L01602): 1–4.

Cyberski J. & Wróblewski A., 1999. Recent and forecast changes in sea level along the Polish coast during the period 1900–2100. *Quaternary Studies*, Special Issue: 77–83.

Heyen H., Zorita E., & von Storch H., 1996. Statistical downscaling of monthly mean North Atlantic air-pressure to sea-level anomalies in the Baltic Sea. *Tellus* 48A(2): 312–323.

Hünicke B., Zorita E., 2008. Trends in the amplitude of Baltic Sea level annual cycle. *Tellus* 60A (1): 154–164

Jasińska E. & Massel S.R., 2007. Water dynamics in estuaries along the Polish Baltic coast. *Oceanological Hydrobiological Studies* 36(2): 101–133.

Jevrejeva S., Drabkin V., Kostjukov J., Lebedev A.A., Leppäranta M., Mironov Ye.U., Schmelzer N., Sztobryn M., 2004. Baltic Sea ice seasons in the twentieth century. *Climate Research*, 25(3): 217–227.

Johansson M., Boman H., Kahma K.K. & Launiainen J., 2001. Trends in sea level variability in the Baltic Sea. *Boreal Environment Research* 6: 159–179.

Kowalewska-Kalkowska H. & Marks R., 2011. *200 years of sea level measurements at the Swinoujscie tide gauge – an unique opportunity to study sea level variability at a regional scale*. Scientific symposium 200 years of oldest continuous record of tide-gauge in Świnoujście, 18 November 2011, Świnoujście, Poland.

Łabuz T. A., 2005. Brzegi wydmowe polskiego wybrzeża Bałtyku (Dunes of Polish Baltic coast). *Czasopismo Geograficzne* 76(1–2): 19–47.

Łabuz T.A., 2007. Rate of sand transportation across the beach during heavy wind action – an example from Świna Gate Sand Bar. In: *Abstracts of International Conference on Management and Restoration of Coastal Dunes*. Santander, Spain: 79–80.

Łabuz T.A., 2009a. The increase of the coastal dune area of the Swina Sandbar, West Polish Coast. *Z Dt Ges Geowiss* 160(2): 123–135.

Łabuz T.A., 2009b. The West Pomerania coastal dunes – alert state of their development. *Z Dt Ges Geowiss* 160(2): 113–122.

Łabuz T. A., 2009c. Distal washover fans on Świna Gate Sandbar. *Oceanological and Hydrobiological Studies* XXXVIII, Suppl. 1: 79–95.

Łabuz T.A. 2011. Wpływ spiętrzeń sztormowych na przebudowę profilu wybrzeża wydmowego Mierzei Bramy Świny. *Czasopismo Geograficzne* 82(4): 351–371.

Łabuz T.A. & Kowalewska-Kalkowska H., 2011. Coastal erosion on the Świna Gate Sandbar (southern Baltic Sea) caused by a heavy storm surge in November 2004. *Climate Research*, Special Issue 48: 93–101.

Łabuz T.A., 2012, Potencjalny wpływ planowanych podwodnych progów wzdłużbrzegowych i ostróg na zmiany brzegu w Kołobrzegu. W: Florek W. (red.), *Geologia i Geomorfologia pobrzeża i południowego Bałtyku*, t. 9, PAP Słupsk: 19–32.

Nordstrom K.F., 2000. *Beaches and dunes of developing coasts*. Cambridge University.

Pielke R.A., Gratz J., Landsea Ch.W., Collins D., Saunders M.A. & Musulin R., 2008. Normalized Hurricane Damage in the United States: 1900–2005. *Natural Hazards Review* 9: 29.

Piotrowska H. & Gos K., 1995. Coastal dune vegetation in Poland. Diversity and development. In: van Dijk H.W.J. (ed.). *Management and preservation of coastal habitats*. Proceedings of multidisciplinary workshop in Jastrzębia Góra, Leiden: 71–82.

Pruszak Z. & Zawadzka E., 2005. Vulnerability of Poland‘s to sea-level rise. *Coastal Engineering Journal* 47(2,3): 131–155.

Pruszak Z. & Zawadzka E., 2008. Potential implications of sea-level rise for Poland. *Journal of Coastal Research* 24(2): 410–422.

Ratter B.M.W., Neverla I., Lüthje C., 2010. *Hamburg 1962 then and now – a memory career of a regional geohazard*. Abstracts Storm Surges Congress 2010, 13–17.09.2010, University of Hamburg, Hamburg, Germany: 71.

Rotnicki K.& Borówka R.K., 1990. Impact of a future sea level rise in the Polish Baltic coastal zone. In: J.G. Titus, R. Wedge, N. Psuty & J. Fanscher (eds.). *Changing climate and the coast*. Washington D.C. (UN Environment Programme): 247–264.

Samuelsson M. & Stigebrandt A., 1996. Main characteristics of the long-term sea level variability in the Baltic Sea. *Tellus* 48A: 672–683.

Suursaar Ü., Kullas T., Otsmann M. & Kõuts T., 2003. Extreme sea level events in the coastal waters of western Estonia. *Journal of Sea Research* 49: 295–303.

Schwarzer K., Diesing M., Larson M., Niedermeyer R.O., Schumacher W. & Furmańczyk K., 2003. Coastline evolution at different time scales – examples from the Pomeranian Bight, southern Baltic Sea. *Marine Geology* 194: 79–101.

Sztobryn M., Stigge H., Wielbińska D., Weidig B., Stanisławczyk I., Kańska A., Krzysztofik K., Kowalska B., Letkiewicz B. & Mykita M., 2005. *Storm surges in the southern Baltic (western and central parts).* Report 39, Bundesamt für Seeschifffahrt und Hydrographie, Hamburg.

Wróblewski A., 1998. The effect of the North Sea on oscillations of the mean monthly sea levels in the Baltic Sea. *Continental and Shelf Research* 18: 501–514.

Zawadzka-Kahlau E., 1999. *Tendencje rozwojowe polskich brzegów Bałtyku Południowego*. Gdańsk (IBW PAN): 147pp.

Zeidler R., Wróblewski A., Miętus M., Dziadziuszko Z. & Cyberski J., 1995. Wind, wave, sea level and storm surge regime at the Polish Baltic coast. *Journal of Coastal Research* 22 Special Issue: 33–54.

www.fomobi.pl.