CHAPTER 250

Sea Level Rise and Coast Evolution in Poland

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Abstract

Trends established for ten Polish tide gauge stations show the annual mean sea level (AMSL) growth rate from 0.8 to 2.9 mm per year in recent 35 years, and a linear trend computed for the years 1901–1990 yields some 1.2–1.6±0.2 mm/yr. Annual SL maxima (ASLM) trends are about one-half of the ASLM trends. Positive 6-hr SL increments Δh from storm events show a growing trend associated with 'storminess'.

In the 'retreat' option for Polish coast, the impact zones between contour lines 0–0.3 m, 0.3–1 m, and 1–2.5 m cover respectively 845, 883 and 476 km^2, thus 2204 km^2 in total, in addition to 30 km^2 of beaches and dunes likely to dissapear for ASLR2. Described by Zeidler (1992) are various 'full protection' techniques adopted.

The Baltic atmospheric circulation is found to change as to direction but not as to wind speed. Subsequent (Fig. 9) insignificant changes in the net sediment transport, in the order of 15% per century are noted. Hence the coast evolution due to climatic changes in wind circulation patterns seems less important than the anticipated sea level rise induced changes.

1 INTRODUCTION

The Baltic Sea forms Poland's borders along 500 km. It is a shallow, almost land-locked sea. Its salinity is low, barely 7-8 ppth in the Polish coastal zone.

The Polish coast consists of two basic types — sandy dunes (including barrier beaches) and cliffs. The former stretch along most of the coast while cliffs occupy slightly above 80 km. Coastal barriers between the sea and lakes are well developed in the central and eastern parts of the coast. The Hel Peninsula is a unique spit system separating the Gulf of Gdańsk from open sea. Because of its intensive erosion and multifarious importance, it has become a subject of concern to both Polish and international authorities.

The present climate of both Poland and its coast is believed to undergo perceptible change due to global warming. However, as for many other areas, the possible changes in precipitation, evaporation, transpiration, and their uncountable outcomes over the Baltic Sea and its drainage area, are all not amenable to

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ready prediction. Global circulation models (GCM) are not yet powerful enough to yield a reliable prediction of climate change in regions such as Poland's coastal zone. Yet one can focus attention on the most likely and conspicuous outcome of such change, the sea level rise.

At the same time, some research programmes under way in Poland and the Baltic area (cf. Miętus 1993, 1994) are centered around changes in regional atmospheric circulation, thus adding to identification of hazardous meteorological and hydrologic processes in the Polish Baltic coast zone and coupling of atmospheric circulation and sea level. The two aspects of climate change, i.e. sea level rise and wind patterns are dealt with in this paper, in linkage with coast evolution.

The warming of climate in southern Poland is seen in Figure 1 while changes perceptible in seawater are noted in Figure 2.

2 ACCELERATED SEA LEVEL RISE (ASLR)

2.1 *Annual Mean and Maximum Sea Level in Poland*

Recent examination of trends and statistical distributions in sea level datasets, revised and updated for the Polish coast, has partly confirmed some earlier conclusions drawn for mean sea level and exposed new findings for extremum sea levels. The trends have been established for ten Polish tide gauge stations, which show the mean sea level growth rate from 0.8 (Kołobrzeg) to 2.9 (Gdańsk) mm per year in last 35 years, with acceleration in recent years (Zeidler et al. 1994). A linear trend for the years 1901–1990 has not been rejected statistically at the 0.05 significance level, and has been found to be smaller than the above figures for 35 years (i.e. some 1.2–1.6 ± 0.2 mm per year).

2.2 *Storminess and Wave Climate*

Annual sea level maxima (ASLM) add to the present knowledge of the Polish Baltic hydrology. Inherent trends and periodicities have been examined (cf. Zeidler et al. 1994). The ASLM trends have been found to approach 0.53 mm/yr at Swinoujscie, 0.7 mm/yr at Kołobrzeg and 1.73 mm/yr in Gdańsk, thus about one-half of the mean-sea level trend. Hamming windowing displayed significant periodicities about 8, 5–6 and 3 years. Bartlett testing confirmed the data independence for Gdańsk but not for the other stations. Seasonal occurrence of the maxima is obvious — 74% of all ASLM occurred between November and February, these months encompassing all ASLM with 10-% exceedance and 91% of 25-% exceedance (remaining 9% in October and March).

Another interesting research objective attacked now consists in description of the correlation matrices for joint sea level and wave height events under storm conditions observed and hindcast along the Polish Baltic. This programme is hoped to be fruitful both scientifically and practically (design of coastal and maritime structures basing on more than just one storm parameter such as sea level).

For the identification of both 'regular' and extreme storm-induced sea level changes as well as definition of hazardous sea states it is worthwhile to examine short-term increments of SL and count them in some statistically representative classes in order to see if those numbers change in longer time scales, which would point to the presence of what could be labelled a 'storminess change'. This has been done under the programme indicated in the acknowledgements, and

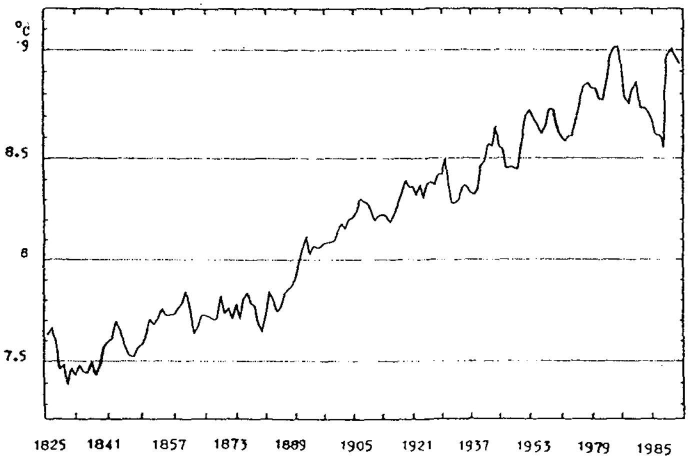

Figure 1. Air temperature in Cracow (20-year moving average)

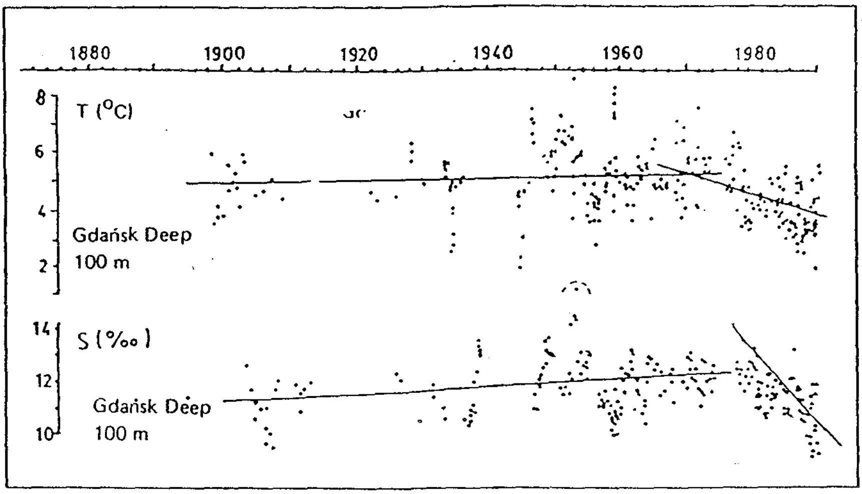

Figure 2. Water temperature and salinity variation in the Baltic Sea as exposed by Piechura in 1993.

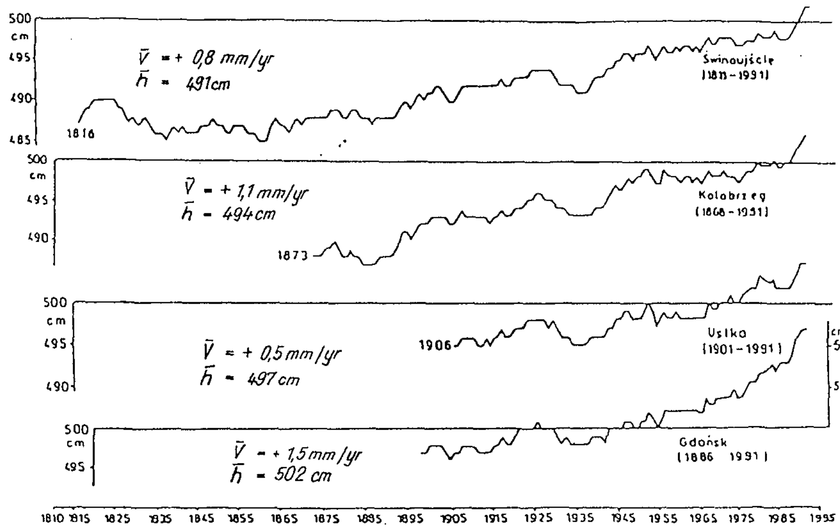

Figure 3. 11-yr moving-average mean SL at the most reliable Polish tide gauge stations (cf. Zeidler et al. 1994).

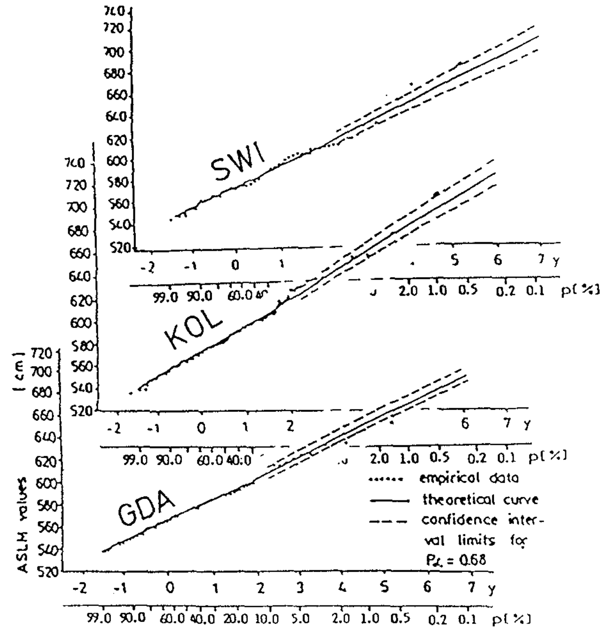

Figure 4. ASLM exceedance curves fitting the Gumbel distribution for three Polish tide gauge stations; (A) Świnoujście; (B) Kołobrzeg; (C) Gdańsk; cf. Zeidler et al. (1994).

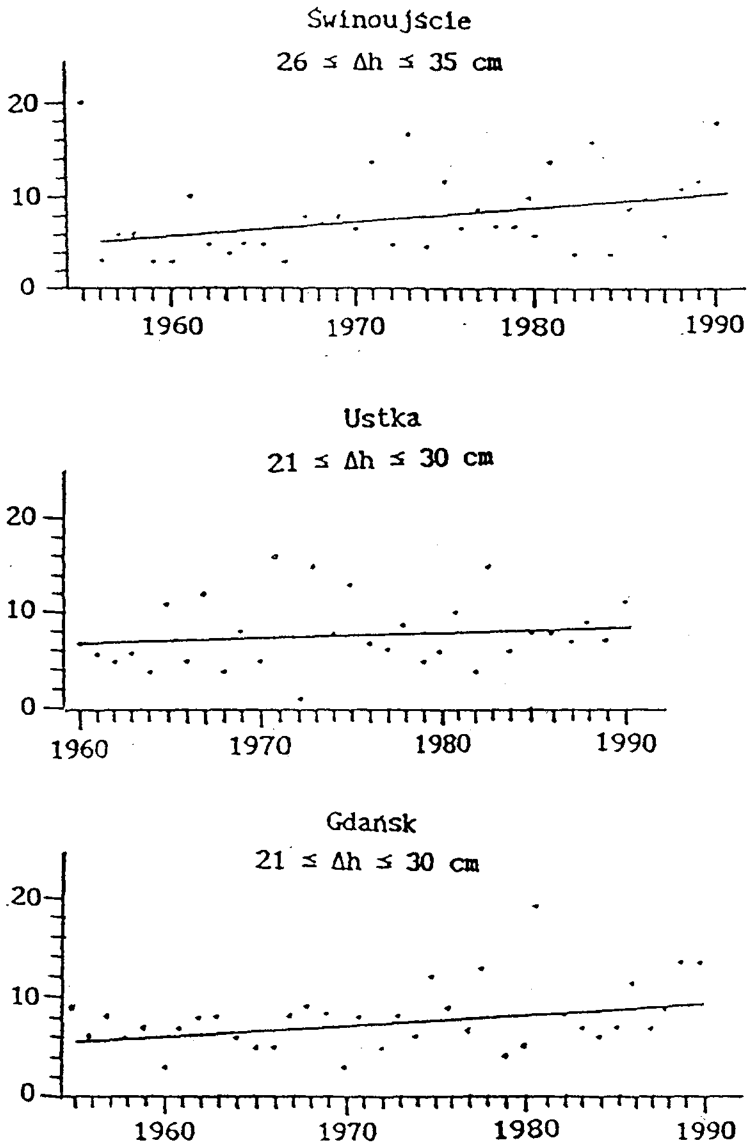

Figure 5. Trends in annual occurrence numbers for 6-hr sea level increments Δh for three Polish stations.

the basic findings are illustrated in Figure 5. For the three stations analyzed, the positive 6-hr SL increments were found from time series extending over some forty-odd years. As they had to be statistically meaningful, the increments Δh were arranged in three classes (slightly different for every station), and the central class data are presented in Figure 5. It is seen that the occurrence numbers of Δh show a growing trend.

The above conclusion agrees with similar findings for the occurrences of annual crossings of some sea levels regarded as 'warning' and 'emergency' levels (roughly 60 and 80 cm above MSL in Poland, respectively). Those occurrence numbers, too, have been observed to grow over decades. To further investigate this issue, statistical series have been found under our programme for both Δh and sea level alone. Similar behaviour and agreement of the two families with Pearson type III exceedance functions, above some thresholds of 70 cm for SL and 25 cm for Δh, is notable. This proves that sea levels above 70 cm (or 570 as a standard format of reference in Poland) can indeed be identified with a short-term rise in SL (recall that Δh classes in our analysis have been only positive). Then the statistical distributions of high sea levels are representative of hazardous situations associated mostly with growth of the sea level, not incidental fall.

3 POLAND'S VULNERABILITY TO ASLR

3.1 *General*

Of the three response strategies suggested by IPCC we selected only two, i.e. 'retreat' and 'full protection' ('adaptation' was largely neglected).

The Polish *'Study Area'* has been defined as the area within which the physical effects of the accelerated sea level rise (ASLR) over the next century could be felt. The inland boundary of the study area was chosen as the +2.5 m contour.

Out of the total length of the Polish coastline, the 'open sea' coast is almost exactly 500 km (of which 72 km on both sides of the Hel Peninsula), while the banks of the Szczecin Bay measure about 240 km, and those of the Vistula Bay about 100 km.

Because of their distinct features, distinguished have been four major *Areas*: the Odra Estuary (Area 1), western dunes and barrier beaches (Area 2), central-east dunes and barrier beaches with the Hel Peninsula (Area 3), and the Vistula Delta (Area 4). Area 1 includes the agglomeration of Szczecin (and Świnoujście), while Area 4 encompasses the three-city complex of Gdańsk, Gdynia and Sopot, together with Elbląg.

The division into three *impact zones* permitted a convenient distinction through the study area cross-section within which flooding probablitites could be assessed: (I) between 0.0 m and +0.3 m MSL contours: (II) between +0.3 m and +1.0 m MSL; (III) between +1.0 m and +2.5 m MSL.

The data collected from maps, reports, computations, studies and other sources (e.g. land-use, socio-economic etc) were entered pertaining to each of the impact zones separately in working tables. Flooded areas (i.e. areas 'lost') could then be readily deduced as zone I at ASLR1 (30 cm/100 yrs) and zones I+II at ASLR2 (1 cm/yr), while the area at risk was defined as II+III at ASLR1 and III at ASLR2.

For the purposes of assessment, the following habitats have been distinguished: coastal waters, beaches and dunes, forests, lagoons and barrier lakes, rivers and estuaries, and swamps/bogs. Coastal forests display the highest biodiversity among all coastal habitats.

3.2 *The Extent of Vulnerability for the 'No Measures' Option*

The extent of inundation and population hazards in our study area are visible in Tables 1 and 2.

The impact zones between contour lines 0–0.3 m, 0.3–1 m, and 1–2.5 m cover respectively 845, 883 and 476 km^2, thus 2204 km^2 in total, in addition to 30 km^2 of beaches and dunes likely to dissapear as a result of ASLR2 (and some 10 km^2 due to ASLR1).

The principal ASLR impact in the Odra estuary will consist in inundation extending at ASLR2 up to River Rurzyca (KM 695). Polder dykes have crests about 1.5–2 m above MWL. At higher stages most polder dykes will be overtopped. The inundated polders will include those of Miedzyodrze (between East and West Odra), around the Szczecin Bay, Swina and Dziwna. Equally endangered by flooding are urban areas of Szczecin (primarily Dąbie district), Świnoujście, Trzebież and other towns. Indirect effects encompass damage to sewarage and other infrastructure. Parts of the Ports of Szczecin, Świnoujście and Police are also vulnerable. The impact zones I and II within Area 1 measure in total 163.8 and 496.6 km^2, respectively.

All Polish coastal polders, arranged in eight complexes of 243 polders measuring 183,557 hectares will be at stake.

In Areas 2 and 3, narrow coastal barriers between the sea and low-lying lakes (much as lagoons or embayments in other area) could erode, making inland areas widely accessible to sea water. The higher levels attained by storm surges in ASLR scenarios will destroy foredunes and erode barrier islands and spits. The lowered barriers will then be susceptible to storm washover. The lakes will grow more saline.

Słowiński National Park and Łeba dune field, a memorable natural landscape, special enough to be included on UNESCO's list of the world's Biosphere Reserves, are endangered as well. The Hel Peninsula, a quite unique spit formation separating the Gulf of Gdańsk is most vulnerable, and will become a smaller island if no measures are applied.

Gdańsk, Szczecin, Świnoujście and Gdynia ports are all flooded and at risk, though to different degree. For instance, the industry of Gdańsk (ports included) occupies 430 and 330 hectares in impact zones I+II and III, respectively. In addition, Gdańsk is now a lively industrial, scientific and cultural centre of northern Poland. The endangered urban areas of Gdańsk cover 450 and 680 ha in the same zones. Full prevention measures should be taken to avoid any loss of this valuable and historical piece of our study area.

One should point out the importance of ports and several shipyards in Gdańsk, Gdynia and Szczecin, the industrial hinterland, such as oil refinery linked to oil terminal in Gdańsk in Area 4 and the Lower Odra power plant and the large chemical plant and port at Police in Area 1, the architecture, historical, and cultural values of old cities, primarily Gdańsk in Area 4, and numerous roads and railways, in addition to other infrastructure.

The Vistula Delta covers an area of 2,320 km^2 with major cities of Gdańsk, Elbląg and Malbork. Its polder area occupies 180,000 hectares (2% of the land area of Poland). Most of its depressions and low land will be damaged. The dikes already built will be too low for the new hydrological conditions, especially ASLR2. They have been designed to stay under water not longer than a couple

Table 1. Distribution of Land-Use Categories in Impact Zones I, II and III; area in hectares, length in kilometres.

Area	AH	AL	AO	F	W	U	I	R	NR	RD/LR/TL/RL/NT/B
Impact Zone I — 0.0–0.3 m.										
1	90	11,955	2,635	1415	30	40				30/25/41////
2		30	400						430	
3		130	40							
4	64,870	130	1,685		352	130	150			291/108/302/29/6/
Tot	64,960	12,245	4,760	1,415	382	170	150		430	321/133/343/29/6/
Total Impact Zone I Surface Area = 84,512 ha										
Impact Zones I + II — 0.0–1.0 m										
1	297	34,338	5,435	7,290	550	640	505	35		70/89/74/15/1/17
2		11,100	995	2,745	110	90			465	27/11/30/1/1/4
3		11,531	118	24	17	5	8	12		6/8/7/2///
4	86,910	1,930	2,265	1,260	2,590	705	430	95	275	428/179/415/61/65/26
Tot	87,207	58,899	8,813	11,319	3,267	1,440	943	142	740	531/287/525/79/66/47
Total Impact Zones I+II Surface Area = 172,770 ha										
Impact Zone III — 1.0–2.5 m										
1		7,935	145	1,690			300			36/9/35/6/2/4
2		5,380		2,315	370					36//7/5/3//1
3		3,210		330	155	85		730		28/10/7/11////
4	21,520	200		795	1,215	815	370			97/12/60/8/9//
Tot	21,520	16,725	145	5,130	1,740	900	670	730		197/38/107/ 28/11/5
Total Impact Zone III Surface Area = 47,560 ha										

NOTES: The land-use category 'Industry' (I) includes 'Ports' here (!)
(RD) road; (LR) local road; (TL) power transmission line; (RL) railway; (NT) narrow-track rail; (B) bridges (# !!).

Table 2. Population of the Study Area.

Area	Zone	Urban	Rural	Total
1	I (0–0.3 m)	1,630	3450	5,080
	II (0.3–1.0 m)	21,080	9,630	30,710
	III (1–2.5 m)	28,960	2,940	31,900
2	I	0	270	270
	II	1,210	4,580	5,790
	III	870	2,880	3,750
3	I	0	110	110
	II	740	9,310	10,050
	III	1,550	2,490	4,040
4	I	9,590	25,810	35,400
	II	40,980	17,650	58,630
	III	36,080	13,030	49,110
Total		142,690	92,150	234,840

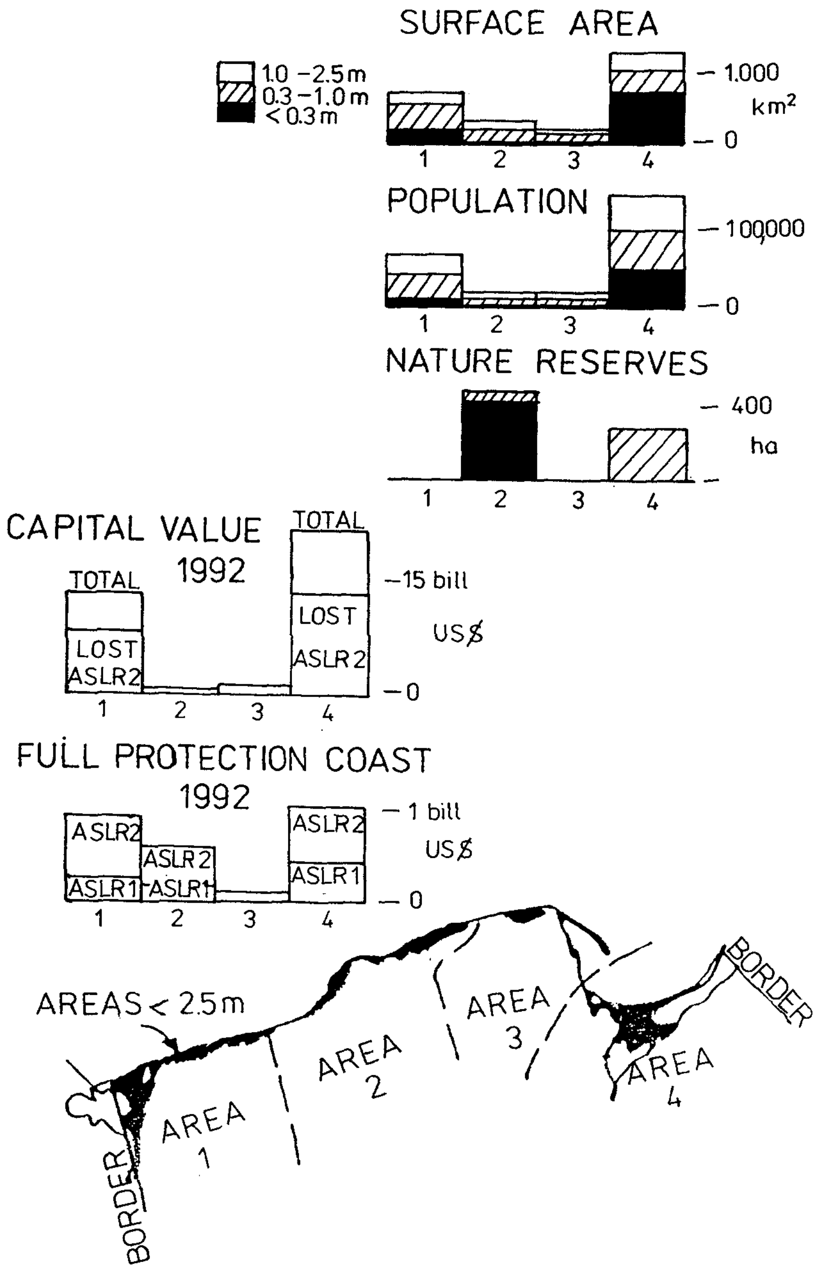

Figure 6. Poland's study areas, lost values in retreat and costs of both retreat and 'full protection

of days. In summary, the area losses under ASLR1 and ASLR2 are very heavy — 672 km^2 (80% of all Area 1–4) and 948 km^2 (55%) respectively. The length of roads flooded is 400 km and 564 km in the two cases, in addition to 35 and 126 km of railways, 300 and 415 km of primary power lines, and 26 bridges.

Enhanced shoreline erosion and shore retreat has been analysed by the use of field data, Bruun computations and numerical models. All results point to a figure exceeding 150 m of shoreline and dune retreat in the course of 100 years of ASLR2 scenario. The counterpart for ASLR1 can be estimated at 50 m per 100 years.

Hence the impact zones between contour lines 0–0.3 m, 0.3–1 m, and 1–2.5 m cover respectively 845, 883 and 476 km^2, thus 2204 km^2 in total, in addition to 30 km^2 of beaches and dunes likely to dissapear as a result of ASLR2 (and some 10 km^2 due to ASLR1).

5.3 *Outline of the Full Protection Option*

Described by Zeidler (1992) are various protection techniques adopted. From that variety of possible coastal defence measures we have chosen dykes, seawalls, offshore breakwaters, artificial beach nourishment and land elevation, in addition to local land abandonment. Many structures are new, and some existing structures are proposed for reconstruction and adaptation to new ASLR conditions.

Inter alia, full protection of the Odra estuary means preservation of the polders on peripheries of the estuary. (107 and 280 km of new dykes must be constructed in Area 4 under ASLR1 and ASLR2, respectively; the lengths of adapted dykes are 243 and 324 km). In Areas 2 & 3, new polders require new facilities such as pump stations, drainage and other infrastructure. In our concept of Hel Peninsula protection we rely mostly on artificial nourishment. In Area 4, it seems imperative to keep the present agricultural use of the Vistula Delta (much as the lower Odra Valley), especially in the polder areas.

Hence full protection of Zulawy polders at ASLR2 requires a bulk adaptation of the existing dykes and the construction of some new dykes and storm and flood prevention facilities. At ASLR2, one should construct 52 km of new dykes and adapt 647 km of those presently in use. Under ASLR1, the respective numbers are 13 and 600 km.

The adaptation should encompass river dykes on Zulawy, frontline dykes on the Vistula Bay, lower dykes around Lake Drużno, and river dykes along Rivers Szkarpawa and Nogat, and Kanal Jagiellonski, which make up the navigation route between Gdańsk and Elbląg. The Vistula dykes should be adapted on some 35 km from the mouth upstream. Other rivers will require new dykes, in addition to the adapted ones.

The storm barrier at the entrance of River Tuga should be virtually redesigned in view of ASLR2, and other river gates must be considered to keep storm surges away from the delta.

Additional protection should also be secured on polders around the Vistula Bay (at Krynica Morska, Przebrno, Kadyny, Tolkmicko and Pasłęka).

An outline of the damage and cost incurred over the four Study Areas of Poland's coast in the case of the two response strategies is given in Figure 6 for the sake of better illustration of the notions and quantities in the description above.

It is worthwhile to note that the cost of protection, although high in absolute terms and demading as to huge investments, is roughly tenfold lower than the value of the property lost, not to mention the fringe losses.

4 POLISH COAST EVOLUTION

4.1 *Historical Lessons*

The vulnerability assessment for Poland was basically aimed at quantification of the losses and protection measures due to flooding and inundation, as beach erosion contributed marginally to the overall damage. Lessons of such flooding were learned in the past, as illlustrated in Figure 7 for the Vistula Delta ('Żuławy'). The mouth and branches of the Vistula River were migrating in the past, with obvious bearing on the overalll shore evolution. Long-term evolution of 'open sea' was also recorded. Depicted in Figure 8 is an example of cliff retreat encountered in Poland over roughly 700 years. The factors controlling long-term changes are currently analyzed and modelling approaches are now endeavoured at IBW PAN.

Routine topographic and bathymetric data have been collected at the *IBW PAN* Coastal Research Facility situated on the Polish coast of the Baltic Sea some 80 km from Gdańsk. Along with parameters of wind, waves, currents and other hydrologic factors, topographic features have been measured since 1983 on a 2.7-km beach and nearshore zone extending some 800 m from shoreline. The beach profiles have been arranged every 100 m. The first systematic and mutually compatible records of beach and shore topography date back to 1964, and echosoundings plus tachimetry are continued every four weeks.

In addition to Lubiatowo, a few other sites have also becn made available to *IBW PAN* staff, such as Bulgarian Black Sea or Senegalese coast off St. Louis, not to mention the cartographic material for Poland's coastal units such as Hel Peninsula. Hence we have insight into a considerable bulk of a reliable field database stretching over a reasonably long span of time. This data set encompasses mostly sandy beaches, and partly cohesive beds. It has been used for various research purposes. At present we focus attention on its use to model the large-scale coastal behaviour (Pruszak & Zeidler 1993).

4.2 *Gross Forecast of Coast Evolution*

It has been mentioned that the present attempt of the forecast of coast evolution due to climate change is largely confined to two factors: sea level rise and atmospheric circulation. So far they are teated separately: ASLR in VA and wind change via the chain of effects schematized in Figure 9. Both factors will hopefully be combined in a joint algorithm taking into account a variety of interactions.

At present wc adhere to the recent findings that the atmospheric circulation over the Baltic Sea changes as to direction but not as to wind speed (Międus 1994). The prevailing wind direction tends to follow more and more closely the major axis of the sea. Hence it is assumed that the south-westerly winds blowing along the Polish coast for most time now become more westerly, at the cost of the southerly ones. In the analysis it is taken for granted that among the major eight directional sectors the southern ones are reduced at a rate of 2.5% per 50 years while their northern counterparts gain the same, and the same is repeated in the west-east direction, at the cost of the easterly winds.

The procedure illustrated in Figure 9 reflects the natural and common logics: from wind to sediment transport. From statistical yearly distributions of wind speed and direction for the intervening Baltic fetches one computes waves by a spectral method, uses a Battjes-Jansen procedure for irregular wave trans-

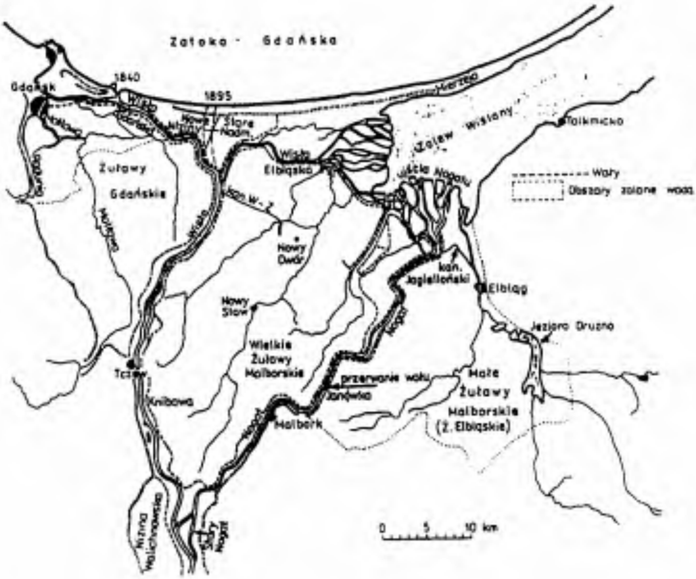

Figure 7. Extent of flooding in the Vistula Delta in 1988 and major events in recent history of the Vistula mouth.

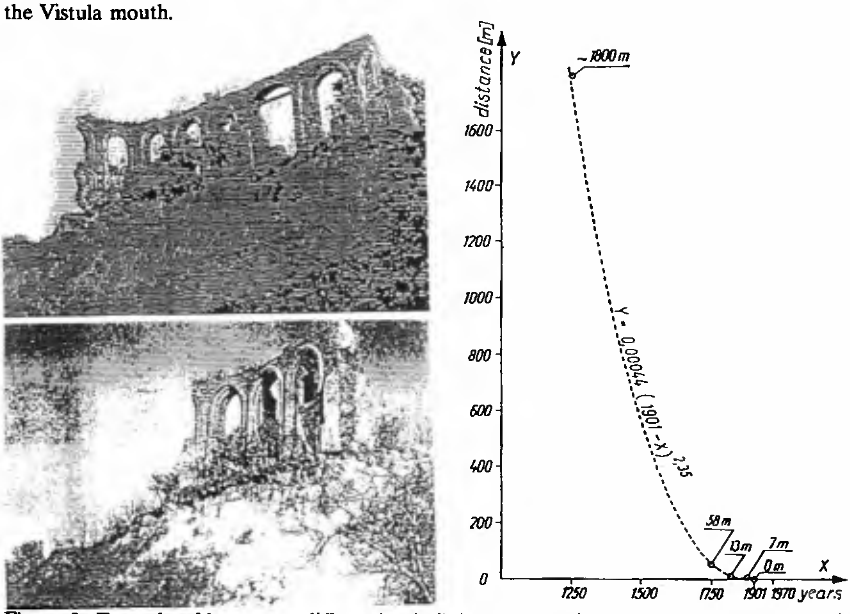

Figure 8. Example of long-term cliff erosion in Poland: ruins of church at Trzęsacz in 1972 (a) and June 1994 (c) and Estimated Erosion Rate (b).

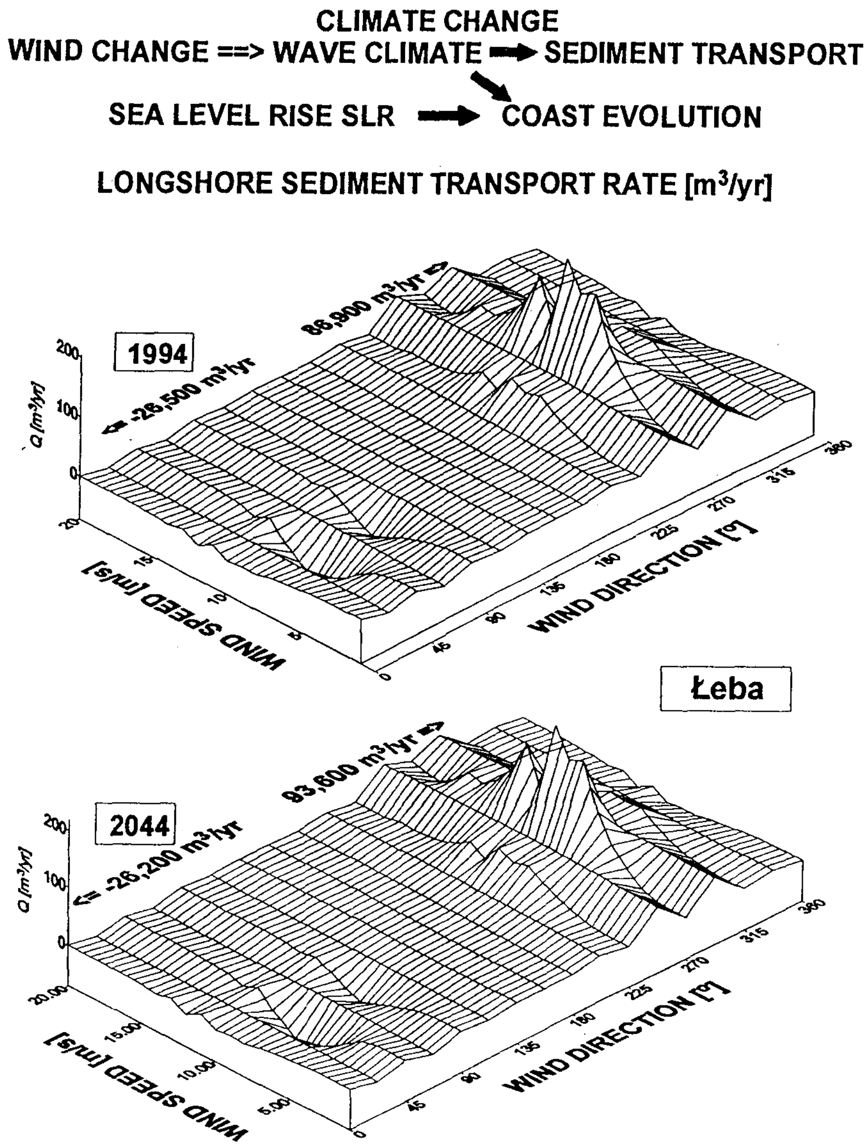

Figure 9. Two-dimensional (wind speed-direction) distributions of sediment transport rates across the entire shore profile at Leba (east-central Polish coast) in the years 1994 and 2044.

formation in the shoaling zone, employs the IBW PAN method for prediction of wave-induced currents, and computes the sediment transport rates basing on the modified Bijker method.

5 CLOSURE

The transition from sediment transport rate to shore evolution is being implemented by simple tools basing on one-line theory, apparently sufficient for this type of gross estimates. At present it is somehow striking to note fairly insignificant changes in the net sediment transport, in the order of 15% per century. It may then be concluded on a very tentative basis that the coast evolution due to climatic changes in wind circulation patterns are less important than the anticipated sea level rise induced changes.

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