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The impact of sea-level rise along the Polish Baltic coast

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Abstract. A DTM (Digital Terrain Model) map and the analytical powers of GIS (Geographical Information System) were used in deterministic and probabilistic methods for analysis of inundation of a coastal area. These methods were applied to evaluate the effects of a rise in sea-level on the coastal zone of the Puck Lagoon (Poland) over a period of 100 years. The analysis evaluated the following aspects: the threat to man-made objects such as buildings and roads; changes in the impact of the sea on the coastal environment manifested as the frequency of flooding of grasslands and marshland in the coastal depression, and the formation of a dune embankment. The analysis covered a ca. 5 km stretch of low-lying coastline, in which there are two rapidly growing villages and a nature reserve. The study showed that a sea-level rise of 40 cm would increase the frequency of flooding in the area and would probably cause the dune ridge vegetation to deteriorate.

Keywords: Climate change; Digital Terrain Model; Gdańsk; GIS; Puck Lagoon.

Abbreviations: DTM = Digital Terrain Model; GIS = Geographical Information System; IPCC = Intergovernmental Panel on Climate Change; psu = practical salinity unit; TIN = Triangulated Irregular Network.

Introduction

Sea-level along the Polish Baltic coast has been rising for the last 100 yr. The linear trend of the annual mean sea-level (AMSL) for Gdańsk is 0.16 ± 0.02 cm per year (Wróblewski 1994). This rising sea-level is related mainly to local glacial isostatic movements. The IPCC forecast of sea-level rise for the next 100 years is related to the emission of ‘greenhouse’ gases (CO_2 , CH_4, N_2O and CFCs) and, depending on which global warming scenario is used, (e.g. Warrick & Oerlemans 1990; Zeidler 1992) the forecast rise ranges from 25 to 60 cm. This global trend in sea-level rise should be added to the local one. Consequently, there is a high probability of a continuing and increasing rise in sea-level in the Puck Lagoon, part of the Gulf of Gdañsk. This study assumes that the mean sea-level rise in the Puck Lagoon will be 40 cm over the period 2000 - 2100. This rise in sea-level will have two main impacts; one is related to the intensification of coastal erosion processes, and to the greater danger of the inundation of the coastal zone during extreme storms (Zeidler 1992) while the other concerns the forecasting of changes to the coastal zone environment (van der Meulen et al. 1991; Day et al. 1998).

One of the main features of the Puck Lagoon is the diversity of coastal types. The lagoon’s brackish waters (ca. 7 psu salinity) make this a unique environment on the southern Baltic coast. One of the coastal types that is particularly sensitive to a sea-level rise consists of low sand dunes partially covered by vegetation, ca. 30 - 100 m wide, backed by marshland and meadow bogs. A typical example of this type of coast is the 2-km stretch between the villages of Rewa and Mechelinki (Fig. 1A, B). There is also strong pressure from land development as the area is close to the city of Gdynia. In addition, this part of the coastline is less sheltered from storm surges than other parts of the Lagoon. The flora and fauna of the area are very special because of the distribution of rare and endangered plant species, such as *Eryngium maritimum*, which is more frequent here than in any other part of the Polish Baltic coast (Stasiak 1988). To protect the environment, a nature reserve has been created in the area. Fig. 1C shows a map of the reserve indicating the main vegetation types with clear zonation according to distance from the sea.

The first zone is the 15 to 25 m wide beach, backed by a dune zone 30 to 60 m wide. The dune zone consists of a fore-dune ridge which ranges from 1 - 3 m in height. Most of the dunes in the area support plant growth, principally the *Elymo-Ammophiletum* community. Behind the dune zone are meadow bogs which gradually change into marshland up to 2 km wide. The meadow and marsh zones lie close to sea-level with a number of depressions, down to – 0.3 m. It was assumed in this study that environmental changes in this area may be brought about by a number of processes. One is the decreasing height and the destruction of the

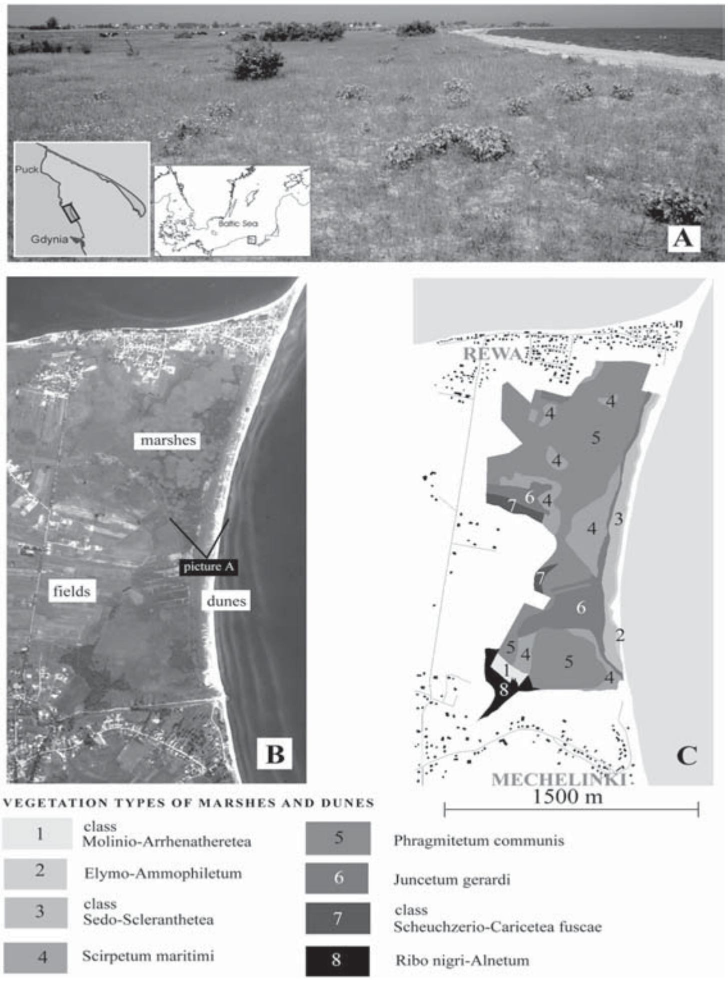

Fig. 1. A. Location and view of the study site; **B.** Aerial photograph of the study site; **C.** Map of the study site with roads, buildings and the nature reserve with plant communities.

fore-dune ridge due to storms and surges causing erosion and the movement of sand towards the land. Decreasing ridge height allows sea-water to wash over the ridge more often and to destroy the vegetation behind it. The restoration of the vegetation in this zone depends on the frequency of inundation. A second process is the change in frequency of sea flooding of different vegetation types. The effects of flooding could be more serious because of the presence of depressions in the area which prevent the free outflow and draining of water. There is another hydrogeological feature of the area which is not conducive to outflow: the water-bearing level in the vicinity of the Lagoon coast is split into different horizons by sludge-clay lenses and peat. These splitting strata lie at depths between 0.5 and 10 m. The water level of the lower horizon is of the pressure type and near the coastline stabilizes at 0.3 to 0.8 m above sea-level. The impermeable stratum maintains the pressure in the water-bearing stratum and thus the boundary between fresh and sea-water is moved seawards (Piekarek-Jankowska 1994).

The objectives of the present study are:

1. To design a method for creating a map based on a digital terrain model (DTM) by using GIS, a method that enables the dune barrier between the land and the sea to be mapped accurately.
2. To present both deterministic and probabilistic methods in GIS to examine a DTM-modelled flood area.
3. To use these methods to:
   - examine to what extent a sea-level rise would increase the frequency of flooding of populated areas in the region;
   - examine whether a sea-level rise would affect the nature reserve, which vegetation types would be flooded and how frequently;
   - evaluate the effect of a sea-level rise on the dune ridge between the sea and the nature reserve, particularly on the frequency of over-wash during storms.

The methods will be explained using a single sea-level rise scenario which, at present, seems most likely.

Methods and Techniques

Creating a DTM map

The main method used in the analyses is a cartographic modelling procedure using the DTM of the coastal zone (Eastman et al. 1995; Martin 1993). The DTM can be created either by using a raster data model in which each cell of the raster has an elevation value or by using a TIN vector data model. Although both models have advantages and disadvantages the crucial factor determining the quality of the map is the accuracy with which the line of the maximum height of the dune ridge is given. A typical low coast profile has a clearly visible point with its maximum height between the land and the sea. The correct and continuous presentation of this edge on a digital map makes it suitable for flooding analysis. Analysis attempts that used traditional hypsometric maps (1 : 25000 or larger) and with contour intervals of 1 - 5 m and with an accuracy standard stating that 90% of all locations were within a half contour interval, indicate that such maps are not sufficient for the analysis of local-area flooding. This is because there is too much error in mapping the line of the maximum height between the sea and the land. Hence, some tachometric surveys were used to create a coastal zone DTM map suitable for solving flooding problems.

The creation of the DTM raster map for the coastal area was achieved in stages: The first step was to determine the resolution, projection and edges of the map. The study area was then inscribed into a 3200 m ×1600 m rectangle with a raster cell size of 1 m, which it was decided would be most suitable and the map made using a plane local projection. The coastal line was created based on the classification of aerial colour photographs resampled to the proper projection. The aerial photographs were taken during calm weather and at a sea-level of 500 ± 5 cm. The elevation of the coastal line was assumed to be 0.01 cm. This line was rasterized to the raster map and then vectorized to the set of points. The result was the creation of a connected set of points. The process can be summarized by the cartographic model (the method of presenting the cartographic modelling process is described in App. 1):

```
/dtm0:raster              - blank raster map with value 0
/coast:vector:line        - line with attribute 0.01
/
/x:raster=       rasterization (y:vector) – transforms the vector
/                data model to raster data model
/y:vector:point = vectorization (x:raster) transforms the
/                raster data model to points described
                 by vector
/                data model
/
dtm0: raster = rasterization(coast)
point_coast:vector:point = vectorization (dtm0)
```

The position and elevation of the highest points along the dune ridge were measured using the electronic tachymeter following the line of the top of the ridge in such a way that all essential changes in elevation and position of this line were registered.

To convert the survey points of the top of the dune ridge to a continuous set of points with continuous changes of elevation the following cartographic model was used:

```
/lmax_dune:vector:line     - line created from survey points
                             (attribute =1)
/pmax_dune:vector:point    - survey points with measured elevation
                             in m
/dtm0:raster               - blank raster map of 3200 × 1600 area
                             with value 0
/
/y:raster = linear_interpolation(x:vector:point)- estimation of
value in the middle of each cell of raster using triangulation
/

dtm1:raster(3200 × 1600) = linear_interpolation(pmax_dune)
mask:raster = rasterization(lmax_dune)
dtm2:raster = dtm1 × mask
p_dune:vector:point = vectorization(dtm2)
```

This method allows continuity of the specific terrain lines to be maintained while using geostatistical estimation methods. The set of elevation points for the rest of the map area was created using the total station. The density of control points depended on the variation of elevation, the raster map of elevation was then created by interpolating all the collected point data. The DTM elevation map of the project area (Fig. 2A) was created by the universal kriging method (Isaaks & Srivastava 1989) using an anisotropic variogram model determined on the measured points. Fig. 2 B, C shows the experimental variograms that were used in modelling the variation before the map was masked over a sea area.

The final step was to determine the root mean square error (RMS) of the DTM obtained. Firstly, the number of control points needed for a specific confidence level of error estimation was calculated from Eq. (1) (Eastman et al. 1995).

$$n = \frac{z^2 \cdot RMS^2}{2e^2} \qquad (1)$$

where n = number of control points; e = confidence level; z = standard score for a specific confidence level; RMS = evaluation of RMS being calculated.

For the DTM of the project area, the following values were assumed: $e = \pm 0.1$ m; $z = 1.645$ (for a confidence level of 95%); $RMS = 0.5$ m, yielding $n = 34$.

Secondly, the position of the control points was determined using a random sampling scheme. For each point the elevation was measured to obtain the true value which was then compared to the values taken from the map.

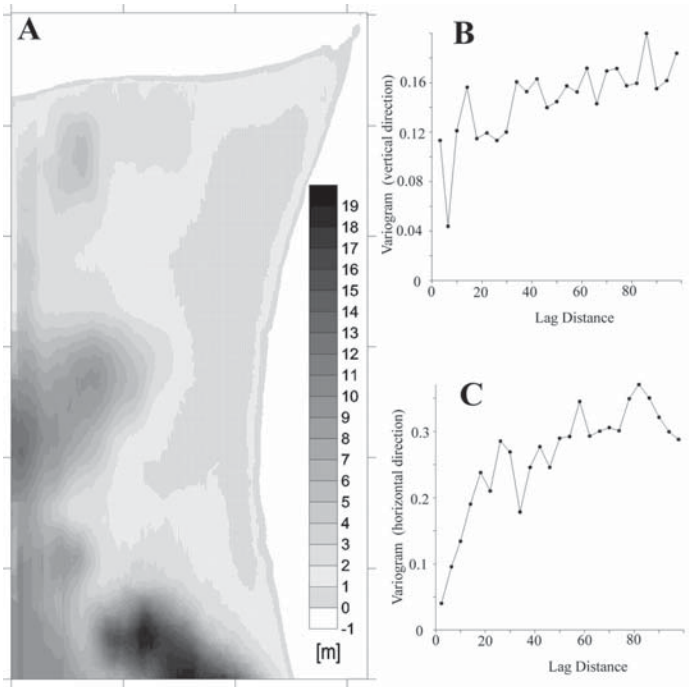

Fig. 2. A. Raster DTM of the study site; **B.** Experimental variogram in vertical direction; **C.** Experimental variogram in horizontal direction.

Thirdly, the RMS was calculated using Eq. (2):

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} (x_m - x_t)^2}{n}} \qquad (2)$$

where n = number of control points; x_m = value from map; x_t = true value.

The calculated RMS was 0.26 ± 0.1 m with a confidence level of 95%. The final DTM map may be used for deterministic as well as probabilistic analysis (Fig 2A).

Results and Discussion

Deterministic flooding analysis

The simplest way to determine the area which will be flooded using a DTM is to process the cartographic modelling as follows:

```
/dtm:raster                    - DTM map of the area
/x:value:real                  - increase of sea level
/
/y:raster:integer = reclass(x:raster) – classifies data into new  integer
/                                      categories
/y:raster:integer = group(x:raster:integer) – determines contiguous
/groupings of identically valued integer cells, cells belonging
/to the same contiguous grouping are given a unique integer identifier
/
dtmplus:raster = dtm - x
dtm1:raster:integer = reclass(dtmplus):pixels < = 0 - >1;pixels > 0 -> 0
dtm2:raster:integer = group(dtm1)
result:raster = reclass(dtm2):sea group - > 1;rest - > 0
```

The group function in this model has to be used to eliminate depressions from flooded areas, which are not connected with the sea. The resulting map shows the flooded area with an elevation less than zero and connection to the sea. Analysis of the sea-level changes in the Puck Lagoon (Nowacki 1993) shows that mean sea-level is 500 cm. There are 4 or 5 days each year (1.3% of the year) when the sea-level is above 550 cm. The maximum sea-level during the last 20 yr was 626 cm (1983) and during the last 100 yr 665 cm (1905). These values were used to estimate the present flood threat to the study area (Fig. 3). The analyses show that at a sea-level of 626 cm a large part of the nature reserve, and some village buildings, would be flooded. However, if the maximum sea-level recurs as in 1905, most of the nature reserve, many village buildings and the road would be flooded. To further the analysis a prognostic rise of 40 cm of the sea-level was used. Thus, the new modelled sea-level values are: 590, 666 and 705 cm. The deterministic analysis results of floods for those sea-levels (Fig. 3) show distinct differences in a scenario of the maximum sea-levels over the past 20 years (626 cm in 2000 and 666 cm in 2100). Although only one sea-level rise scenario has been discussed here, five different sea-level situations could be used to estimate how different sea-level rise scenarios will influence the flooding situation. A 40 cm rise in sea-level would considerably increase the area of the nature reserve flooded and the numbers of flooded buildings.

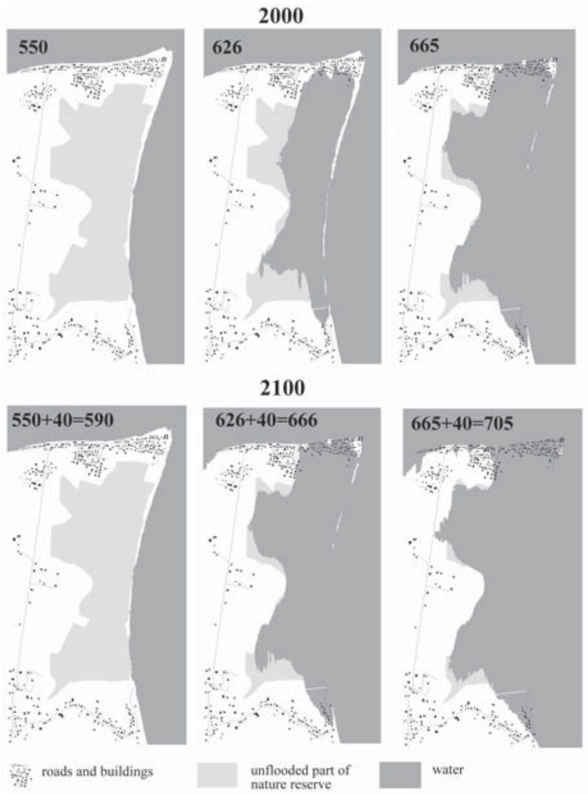

Fig. 3. A threat of flooding (deterministic analysis) for the different sea levels in 2000 and 2100.

Probabilistic flooding analysis

The deterministic method assumes that the DTM of the project area and the sea-level forecast are error-free. To calculate the flooding probability, the uncertainty of DTM and the forecast should be incorporated. It can be assumed that DTM errors and sea-level forecast errors have a normal distribution. To calculate the error of the map, algebraic operations are used in which two maps with different errors, and the formula for error propagation, are involved. (Eastman 1997). For the addition and subtraction operation of two digital maps the formula is:

$$S_{new}\sqrt{S^{2}_{old1}+S^{2}_{old2}} \quad (3)$$

where S = RMS error of map.
To obtain the probability of a flooding map, the following cartographic model was used:

```
/dtm:raster              - DTM map of the area with RMS = S_old1
/x:value:real            - increase of sea level with RMS = S_old2
/dune_ridge: raster      - binary mask of dune ridge (land = 1, rest = 0)
/ldune_ridge: raster     - binary mask of sea side of dune ridge (sea
                           side = 0)
/x:value:real            - essential value of probability
/
/y:raster = distance(x:raster) - calculate distance from each cell
                                 with value = 0
/                                to the nearest cell with value |0

level:raster = initial(dtm, x) with RMS = S_old2
newdtm:raster = dtm - level with RMS = S_new
probability:raster = pclass(newdtm, 0):        < 0
temp0:raster = probability x land
temp1:raster:integer = reclass(temp0): pixels < = x - > 0;
                   pixels > x - > 1
temp2:raster = dystans(temp1)
temp3:raster = reclass(temp2):pixels < = 50 - > 1; pixels > 50 - > 0
result:raster = temp3 x ldune_ridge
```

For the DTM map an RMS value determined earlier was used and for the forecast RMS was assumed to equal 0.1 m. The incorporation of the RMS of prognosis includes all the likely sea-level rise values in the analyses. Once a selected flooding probability level was established as significant, the probability map was reclassified into one of two classes (land or sea), the map was then processed as in the deterministic method for the elimination of depressed areas:

```
/probability:raster      - probability map of flooding
/x:value:real            - essential value of probability
/temp1:raster:integer = reclass(probability):pixels < = x - > 0;
 pixels >                  x - > 1
temp2:raster:integer = group(temp1)
result:raster = reclass(temp2):sea group - > 1; rest - > 0
```

The analysis was carried out for different flooding frequencies, for which sea-levels were chosen from tables of the occurrence of sea-levels (Nowacki 1993). The probability of a 50% inundation of the areas in question was regarded as significant. The results show (Fig. 4) that on a 10 yr-scale the area is not endangered by flooding. However, a 40 cm sea-level rise would significantly alter the situation; a large part of the reserve would be flooded at least twice a year and once every five years some buildings would be flooded.

For a more exact evaluation of the impact of sea-level rise on the reserve's vegetation, the percentage of the area of each vegetation community flooded was calculated for a given flooding frequency. The plant cover classes were taken from the map of the reserve (Mienko 1994). The results show that a major part of the reserve will be flooded every year if the sea-level rises (Table 1). The effects of flooding on the vegetation should be analysed separately; this is not the purpose of this paper.

Table 1. Percentage sea flooding of different vegetation types in the nature reserve at present and in 100 yr from now (a significant flooding probability of 50% and a forecasted sea level rise of 40 cm in the next 100 yr). 1. *Molinio-Arrhenatheretea* (meadows); 2. *Elymo-Ammophiletum* (dominated by marram grass); 3. *Sedo-Scleranthetea* (swards on sandy habitats); 4. *Scirpetum maritimi* (rush community); 5. *Phragmitetum communis* (reed community); 6. *Juncetum gerardi* (halophyte meadow); 7. *Scheuchzerio-Caricetea fuscae* (fen vegetation); 8. *Ribo nigri-Alnetum* (alder swamp forest). Flooding frequency abbreviations as in Fig. 5.

Types	%	2000							2100						
		G	F	E	D	C	B	A	G	F	E	D	C	B	A
1	1.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	2.1	10	8	6	5	4	1	0	87	77	59	51	42	8	6
3	6.7	1	1	0	0	0	0	0	99	98	93	90	85	1	0
4	15.6	0	0	0	0	0	0	0	73	70	66	65	63	0	0
5	53.8	0	0	0	0	0	0	0	77	64	59	57	53	0	0
6	14.7	0	0	0	0	0	0	0	80	78	76	75	74	0	0
7	2.5	0	0	0	0	0	0	0	7	4	0	0	0	0	0
8	3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0

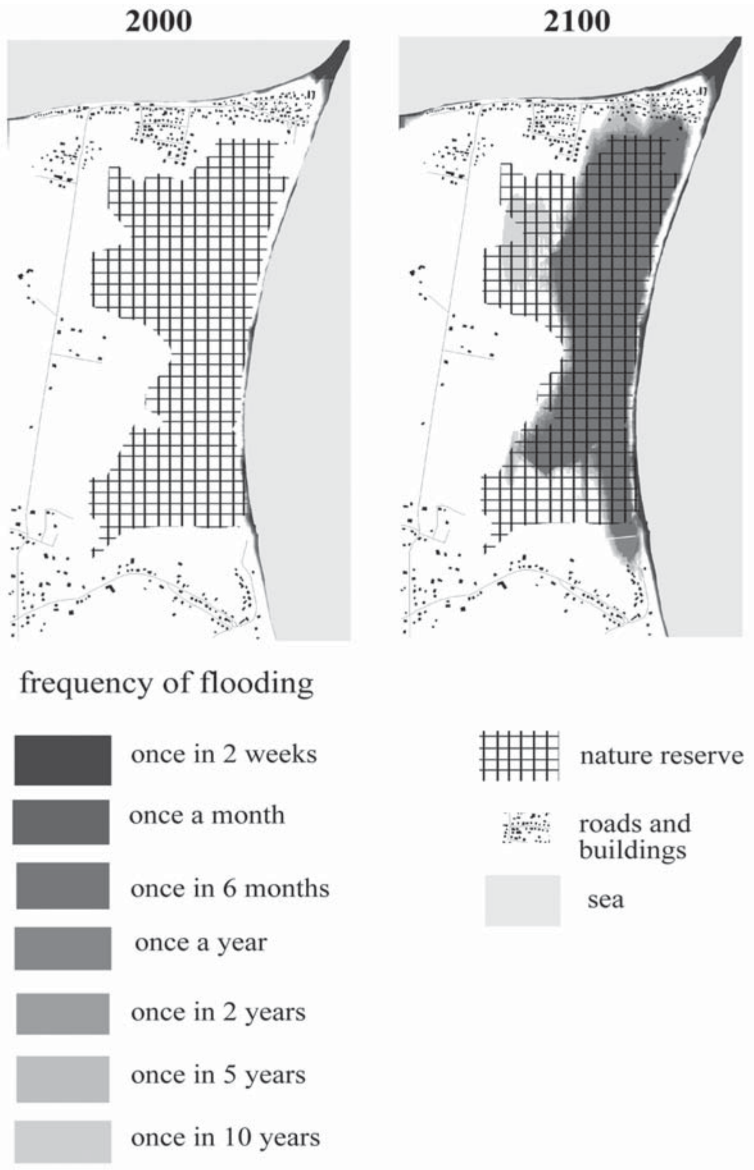

Fig. 4. Threat of flooding (probabilistic analysis for a probability of 50%) for different frequencies of flooding in 2000 and 2100

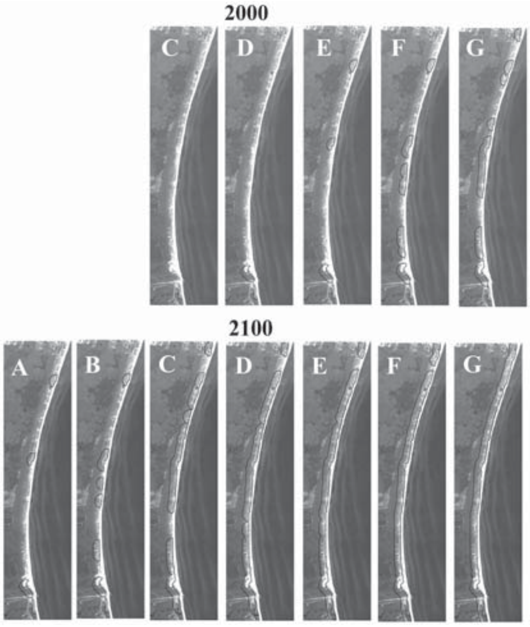

Fig. 5. Probabilistic analysis of the sea water over-wash through the dune ridge in 2000 and 2100. A = flooding once in 2 weeks; B = once a month; C = once in 6 months; D = once a year ; E = once in 2 years; F = once in 5 years; G = once in 10 yr.

Probabilistic analysis of sea-water over-wash across the dune ridge

The existing analysis did not take the wave motion of the sea into account. High sea-levels are very often combined with storms and extreme waves. These waves may wash over the dune ridge and have a crucial impact on the whole environment. In this section, the probability of dune ridge over-wash, at present and in 100 years time, will be discussed.

Sea-levels above 530 cm in the Puck Lagoon currently occur on ca. 27 days per year (7.3% of the year) (Nowacki 1993). High, shallow-water waves can develop in this area when winds are northeasterly, easterly or southeasterly. For sea-levels above 530 cm, winds blow from these directions for 40% of the year. This results in 10 days each year when sea-level is above 530 cm and with high, shallow-water waves. The parameters of wind waves in this area are 0.35 m (mean wave height) and 2.6 s (wave period) (Jarosz & Kowalewski 1993). Assuming that for the above-mentioned 10 days the wind waves may be described by 0.1 quantile of wind wave distribution exceeding height:

$$F = \left(\frac{H}{\overline{\overline{H}}}\right) \qquad (4)$$

and period,

$$F = \left(\frac{T}{\overline{\overline{T}}}\right) \qquad (5)$$

These formulae give values of a wave height of 0.6 m and a period of 3.9 s. This assumption may be justified by the fact that a high water level occurs most often under strong wind conditions. The up-rush of waves up a slope can be described by empirical formulae which are available in the form of nomograms (Massel 1992). According to these formulas, the ratio of the height of the up-rush of the wave to the height of this wave, h / H, is a function of cotangent τ and

$$\frac{H}{g \cdot T^2} \qquad (6)$$

where g = acceleration due to gravity; T = period of wave; τ = angle of slope inclination.

Using these formulae for $ctg\ \tau = 8$, $H = 0.6$ and $T =$ 3.9 s, the value h = 50 cm for an impervious slope is obtained. This value was reduced to h = 45 cm because of partial permeability. Thus, for 10 days per yr up-rushing waves reach a level of 530 + 45 = 575 cm. For the year 2100 this value should be increased by the sea-level rise forecast to 530 + 45 + 40 = 615 cm. It was assumed that both values have RMS = 5 cm. The analysis tracing the waves that wash over the dune ridge, i.e. the accumulative forms that are vertical to the coast on the photograph (Fig. 1B), showed that the traces reach a maximum of 50 m from the top of the dune. The following cartographic model was used to establish the sites of over-wash for the given sea-level:

```
/dtm:raster          - DTM map of the area with RMS = S_old1
/x:value:real        - increase of sea level with RMS = S_old2
/dune_ridge: raster        - binary mask of dune ridge (land = 1, rest = 0)
/ldune_ridge: raster       - binary mask of sea side of dune ridge
                             (sea side = 0)
/x:value:real        - essential value of probability
/
/y:raster = distance(x:raster)           - calculate distance from each cell
                              with value = 0
/                             to the nearest cell with value |0

level:raster = initial(dtm, x) with RMS = S_old2
newdtm:raster = dtm - level with RMS = S_new
probability:raster = pclass(newdtm, 0):        < 0
temp0:raster = probability x land
temp1:raster:integer  = reclass(temp0): pixels < = x - > 0;pixels > x - > 1
temp2:raster = dystans(temp1)
temp3:raster = reclass(temp2):pixels < = 50 - > 1; pixels > 50 - > 0
result:raster = temp3 x ldune_ridge
```

The analysis was carried out for flooding frequencies similar to the probabilistic one. The significance level was also 50%. For visualization, the ranges obtained were superimposed on an aerial photograph (Fig 5). The analysis shows that a 40-cm sea-level rise will significantly increase the frequency of the over-wash of the dune ridge. The present extensive over-wash occurs every 5 - 10 yr. It seems that the *Elymo-Ammophiletum* vegetation type and the protected *Eryngium maritimum* could be severely affected by such a change in sea-level.

Conclusion

From the standpoint of the prevailing forecast of a constant sea-level rise over the next 100 years, the problem of changes in the coastal zone environment due to a sea-level rise is very important. For efficient coastal management and the protection of coastal zone resources, the answers to questions about a potential sea-level rise and its effects on the environment are crucial to decision-making. The study shows that GIS and cartographic modelling enable an analysis allowing changes to the land due to sea-level rise to be evaluated. A knowledge of these changes is essential in modelling the expected impact of these changes on the whole coastal zone environment, which should be the next step. It should also be emphasized that the analysis of flooding and marine transgression requires reliable DTM maps.

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App. 1. Presentation of the cartographic modelling process.

The cartographic modelling in this paper is presented using the Descriptive Cartographic Modelling Language - DCML (Urbanski 1997). This language is not a formal system like that proposed by Tomlin (1990), and cannot be executed in any GIS system without a special arrangement. It was designed more as an alternative either to the graphic presentation of cartographic modelling (Berry 1993) or to the use of flow charts.

The cartographic model represented in this language has two parts. The first, the descriptive part, contains the description of input data structures followed by the data type and names of functions or operations to be used in the modelling. Each line starts with the sign /. The second part consists of a sequence of operations or functions used to process the data. Each line takes the form of an equation.

result_data:type=operation(input_data......):arguments of operation

The new result_data is created by an operation using input_data and some arguments. The operations may be defined in the descriptive part. This form of language allows different operations typical of particular GIS systems to be used and language structures like iteration to be programmed.