Oceanological and Hydrobiological Studies
International Journal of Oceanography and Hydrobiology
Vol. XXXVII, No.3

Institute of Oceanography (3-20) University of Gdańsk
ISSN 1730-413X 2008 eISSN 1897-3191

DOI 10.2478/v10009-008-0011-3
Original research paper

Received: *July 21, 2007*
Accepted: *September 23, 2008*

Assessing flood risk and detecting changes of salt water inflow in a coastal micro-tidal brackish marsh using GIS

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Key words: brackish marsh, GIS, sea level rise, Baltic, Beka Nature Reserve

Abstract

In order to assess changes in salt water inflow and potential flood risks due to sea level rise in a micro-tidal Beka brackish marsh on the Polish Baltic Coast GIS was used. Such wetlands are important elements of coastal zone natural environments. Creating a geodatabase within a GIS system makes it possible to carry out broad analyses of complex systems, such as coastal wetlands. The results indicate that a 40 cm sea-level rise would considerably increase the frequency of flooding in the investigated area, in part because of the small range of the annual sea level oscillations there. A map of the index of changes in saltwater inflow, created with the help of cost-weighted distance (functions), shows that changes which have occurred along the shore, consisting of filling in the drainage channel outlets, have likely had a significant impact on the vegetation of the area.

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INTRODUCTION

Coastal wetlands are important components of the natural environment of the coastal zone. They form complex systems whose functions are determined by the interactions of biological and hydromorphological processes taking place across varying spatio-temporal scales. Both long and short term coastal zone dynamics ensure that coastal wetlands frequently undergo significant changes, or exist in a state of fragile balance. These areas are often important wildlife habitats, which – in addition to the role they play locally – perform an important function during seasonal migrations of birds. They are also of crucial importance for the quality of coastal waters, as well as for protecting coastal lands against erosion (Cooper et al. 2001). Some researchers also stress the role of coastal wetlands as part of human cultural and historical heritage (Azzari 2003). The surface area, however, of such environments, particularly in Europe, has decreased alarmingly during recent centuries because, until relatively recently, wetlands have been commonly perceived as wasteland areas (Carter 1988). Subsequently, much of the surface area of remaining coastal wetlands has been included in various protection and preservation projects.

The functioning of coastal wetlands result from a complex interweaving of distinct biological and hydromorphological factors interacting on various scales, and as a result scientific investigations of these areas are difficult. Instruments are needed that make it possible to integrate information from many distinct sources and also to carry out spatial analysis of that information. Geographic Information Systems (GIS) offer tools that satisfy those requirements. GIS technology has often been applied to produce new thematic maps of coastal wetlands, using both current and old maps, satellite data, and also current or archive aerial photographs (Cracknell 1999). GIS has been used to classify wetland surface areas and to produce vegetation maps. It has also been applied when analyzing results of change of use of wetlands, e.g., what happens when people stop grazing their cattle on wetland pastures. For the last several years the technology has been applied to analyze and predict sea-level-rise-induced changes (Thumerer et al. 2000). Three fundamental problems caused by sea level changes include growing frequency of coastal flooding (Fadden 2004), an increase in coastal erosion (Castillo et al. 2000), and changes in salt water inflow. The consequences of these three processes are equally important. Scientific investigations into how hydrogeomorphologically distinct coastal wetlands respond to sea level rises are very important research tasks. It is hence of fundamental importance to create GIS-based universal methods that will enable the analyses of these processes (Olivier 2003).

The primary objective of this project was to use GIS to study any increase in flooding risk due to sea level rise, and changes that have been taking place in

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the Beka coastal wetland system at various temporal scales. The wetland is a small salt marsh on the Polish Baltic Coast, in the Bay of Gdansk (Fig. 1 A, B). It can be described as a micro-tidal brackish marsh, which is separated from the sea by a low dune ridge (0.8 to 1.6 m high). Its annual sea level range is only 0.8 m and the salinity of the adjacent sea water is about 7 PSU. There are three ways in which sea water can penetrate the marsh (Fig. 1 C). The first is via channels that cross the dune ridge, which are man-made channels that were created in the past to drain the marsh after the spring thaw. Some of these channels are currently cut off from the sea by the dunes but, during high sea levels, sea water is able to enter some of them. The second way is dune ridge overwash occurring during storm surges. The marsh might have been flooded in this way several times in the twentieth century. In 1914, many areas on the coast of the Bay of Gdansk were flooded due to sea level rise to about 1.2 m. Possible changes in the frequency of flooding due to forecasted sea level rises of 0.25 – 0.60 m (for the next 100 years) are still important unknowns (Urbanski 2001). A third way for sea water to penetrate into the marsh is as seepage through the dune ridge.

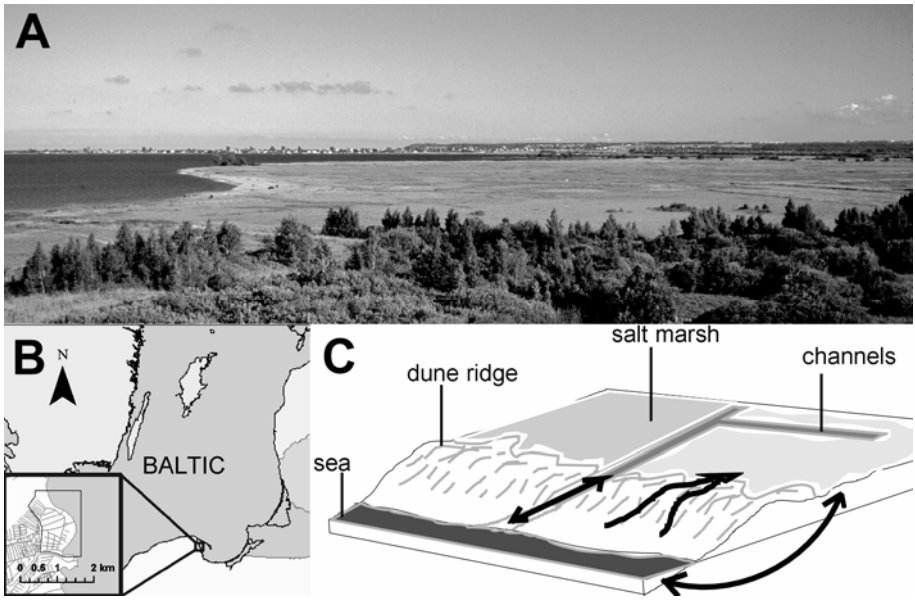


Fig. 1. A – View of the study site; B – Location of the study site; C – Salt marsh diagram (arrows show the three ways in which sea water can penetrate the marsh).

The marsh is a Natura2000 protected area of several halophytes and rare birds, and is also an important bird migration rest spot. Particularly important and widespread in this ecosystem is black grass (*Juncus gerardi*), which is used by dunlins (*Calidris alpina*) to nest. During the last twenty years, important changes in plant species composition have been observed here. The most significant process is the replacement of black grass by reeds, which has resulted in numbers of dunlins gradually decreasing. This process has been mainly connected with the giving up of cattle grazing (Lenartowicz et al. 1996). The processes taking place on the sea coast itself, or the evaluation of sea water inflow and its influence upon the environment, have not been investigated to date. Data exploration was the preliminary step in this project, in order to define operational research questions. Transforming all of the maps and photos of the area to the same projection, by means of overlaying them, has made it possible to visualize the general changes that have occurred over time (Fig. 2). Substantial changes in the position of the coastline are visible, its position changing by up to 200 m, and regions of marked erosion and accumulation have been detected. During the last 20 years accumulation in the southern part of the area has cut off several channels from the sea, and some brackish lagoons have formed. This might have changed sea water inflow to the marsh. Traces of flooding in the shape of a stream network with streams starting near the dune ridge can be seen in the 1947 aerial photo. After exploration of the data the following operational questions were formulated. Will the frequency of wetland floodings increase significantly with sea level rise? Do floodings leave traces in the wetland environment and, if so, for how long do they remain visible? Is there a relationship between the replacement of black grass by reeds, on the one hand, and a decrease of sea water inflow to the marsh resulting from changes in the wetland coastal area, on the other?

MATERIALS AND METHODS

Wetland geodatabase

At the outset a wetland geodatabase was designed that was intended to provide a single environment to store, integrate, and analyze all the data. Geodatabase technology (Kalman et al. 2004) not only facilitates data organization, but can also ensure data integrity and analyses within the GIS system. To conceptualize a database, one has to identify the data creation goals as well as data standards and the necessary ancillary data. The initial goals were to make an inventory of all the available data and to convert them to the same coordinate system, to enable the digitizing of the data in order to create new data layers, and to perform analyses. The kinds of layers needed for a given

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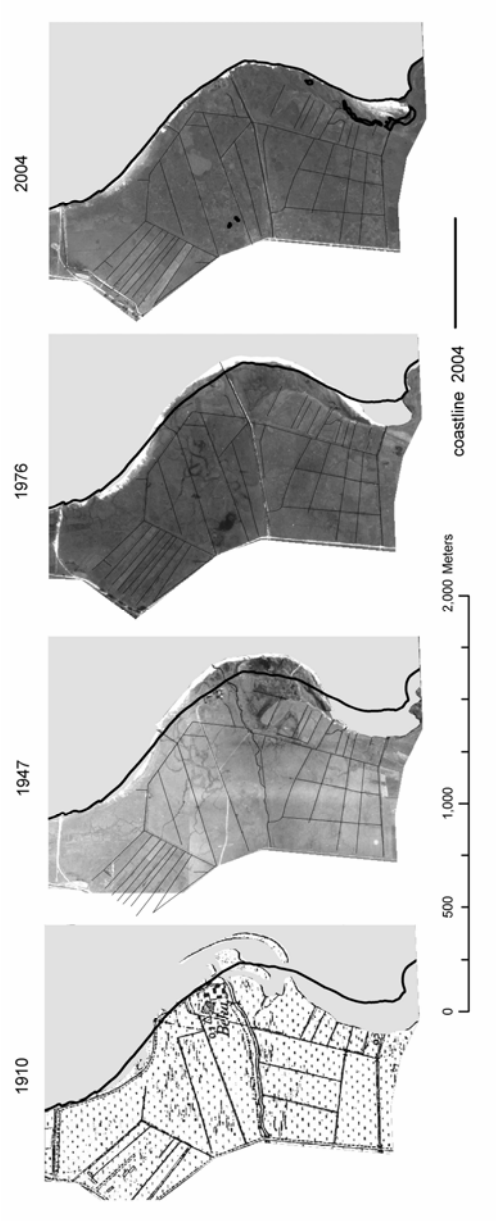


Fig. 2. Changes of the Beka marsh coastline during the last 100 years resulted, in the southern part of the area, in a loss of contact between channel outlets and the sea.

database were determined by the research questions. In order to analyze the overflow frequency it was necessary to create a map of the dune ridge elevation. To analyze overflow traces an archive of aerial photographs was used. The study of the relationship between changes in salt water inflow and vegetation distribution required maps of the coastline and channel placements (over the last 100 years), as well as maps of the vegetation coverage and of salinity distribution across the surface of the marsh. These were initially produced by transforming and organizing information provided by aerial photographs and analogue (paper) maps. Photographs of the Beka marsh area that were used were taken in the years 1947 and 1976 – 1997, at scales from 1:10000 to 1:25000. A topographic map from 1910 was used, as was a 1:5000 paper map showing the vegetation coverage of the area in 1995 (Lenartowicz 1995).

The second task was to create a structure in which to store the measurement data. The data included elevation measurements carried out in 2004 within the dune ridge zone, measurements of the position of the coastline, and measurements of the marsh surface salinity carried out in April and May 2004. Geodetic measurements were carried out with total station, salinity was surveyed using a salinometer (±0.1 PSU) combined with site positions being defined using GPS. As ancillary data, layers of a digitized topographic map (scale of details 1:10000) updated for the year 2000 were used. All these data were included in the set of source data (Fig. 3). The UTM-33N projection of the WGS84-datum was chosen as a common system of coordinates. All scanned photographs and maps were rectified to this projection. It was found that the artificial channels of the marsh were the most long-lived and well recognized features of the area and, as such, were used for georeferencing. The measurement data and digitized maps were all converted to UTM-33N projection, using tools offered by the GIS systems. In the newly created database raster and vector data models were used. The aerial photographs were stored as raster data. Subsequently the photographs, the rectified topographic map (from 1910) and the vegetation map were all digitized in GIS, and the following new vector maps were produced: of the coastline (polygons), of vegetation coverage (polygons), of the channels (lines) and of the small lakes (polygons). Point data referring to salinity measurements were converted with the use of the Kriging interpolation method into raster maps of marsh surface salinity. The elevations of the dune ridge, the beach and the area behind the dune were illustrated in the form of a raster map (with a specified root mean square (RMS) error). The Kriging interpolation method was also used in this case, with a high density of points along the breaklines, which were formed by the coastline and the line of the maximum height of the dune (Urbanski 2001).

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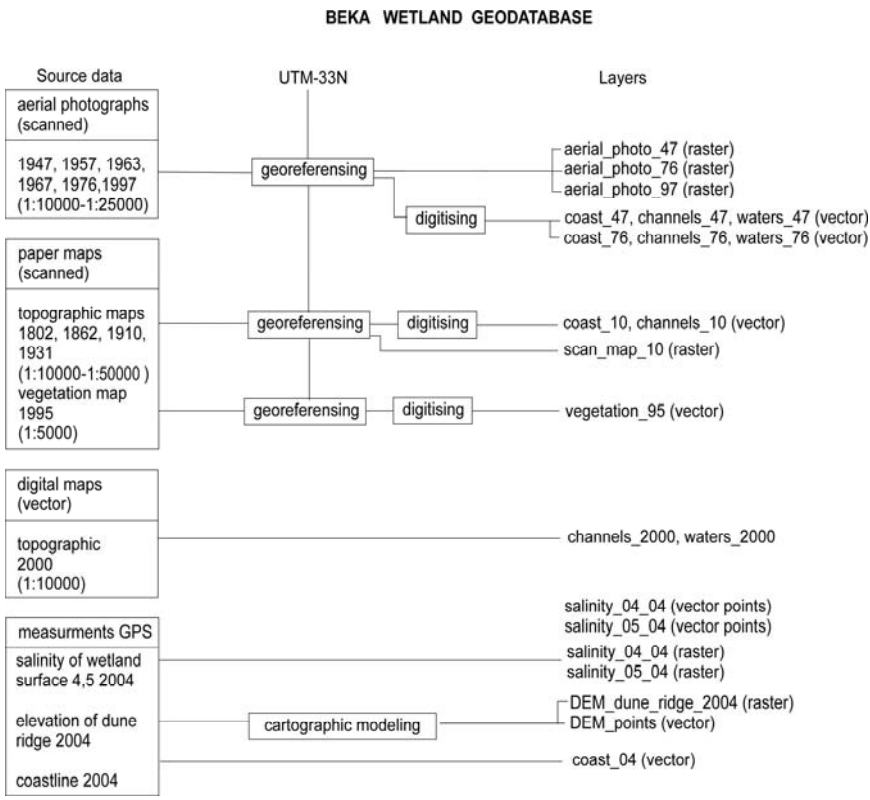


Fig. 3. Beka wetland geodatabase: source data and layers.

GIS modeling of dune ridge overflow

The modeling of dune ridge overflow was carried with the help of the cartographic modeling procedure using the DEM of the coast and uncertainty of sea level (Urbanski 2001). The DEM can be created using a raster data model or a TIN vector data model. The most important factor determining the quality of the map is the accuracy with which the line of the maximum height of the dune ridge is modeled. A typical low coast profile has a well marked point with its maximum height between the land and the sea. Correct and continuous presentation of this line on a digital map makes it suitable for flooding analysis. To satisfy all of the conditions a map was produced with the help of two breaklines. One of them defines and controls the sea coast (with the assigned value = 0) and the other defines the line created by points with the maximum height of the dune ridge. Both lines were created by means of point

measurements made using an electronic tachymeter carried out in such a way that all essential changes in the elevation and position of these lines were registered. In addition to the measurements creating the breaklines, the whole research area was covered by an irregular network of elevation points whose average measurement density was 1 measurement every 200 m^2. The DEM elevation map of the project area was created by the universal Kriging method (Isaaks, Srivastava 1989) using an anisotropic variogram model determined on the measured points. The final step was to determine the RMS error of the map, which was defined, for a representative set of control points, as the average difference between the real and modeled heights. The calculated error defines the uncertainty of the DEM model. The maximum sea level for a given period of time can be also determined allowing for the uncertainty defined as an RMS error. The uncertainty results from a probability distribution of the maximum annual sea levels.

The essence of analyzing terrain floodings caused by sea level rises lies in calculating the height of the terrain above the new sea level by means of subtracting from the DEM map the value of the level rise (Martin 1993). The operation is identical to subtracting from the DEM map some other map whose value is constant. If the newly created map is masked by means of the dunes ridge line, a new map will be produced showing all places where overflow can take place. An analysis like that, however, is deterministic and pays no attention to either the uncertainty resulting from the DEM map error, or to the uncertainty of prognosing the maximum sea level for a given period of time. In order to determine a map of places where, with a given probability, an overflow over a dune ridge could occur, the uncertainty of DEM and the forecast uncertainty should be incorporated. It is assumed that DEM errors and sea-level forecast errors have a normal distribution. For the subtraction operation of two digital maps the formula for the error of the resultant map is (Eastman 1997):

$$S_{new_map} = \sqrt{S^2_{old_map1} + S^2_{old_map2}} \qquad (1)$$

where $S = RMS$ is the error of map.

In this way, the map of the terrain height over the new level incorporates a given error resulting from the uncertainty embedded in all the maps that were used in the process of its creation. This enables creation of a map of overflows for a specified prognosis with some given probability (after defining, for some given probability, possible deviations from real values from the standard normal distribution).

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Using noneuclidean proximity mapping in change analyses

Global climate changes, rising sea levels and anthropogenic factors alter the flooding regime and salinity levels in coastal wetland areas. Changes of salinity levels can affect wetland soil parameters, and, as a result, changes of soil-dependent plant species (Baldwin and Mendelssohn 1998, Smith et al. 2001). Hence analysis of changes in salt water inflow to coastal marsh areas are essential in the investigation of coastal zones. A system of drainage channels is the fundamental and most effective way salt water flows into coastal marsh areas. Salt transport unconnected with channel systems, related, for instance, to marsh flooding or subterranean water, is a much less effective process, and is closely connected with the hypsometry of the marsh surface. Making use of GIS technology it is possible to calculate (by means of the distance function) for any point across the surface of a marsh, how far it is from a salt water source (i.e., the sea). Euclidean distance, however, is not related to the ease of water inflow to a given place, for flow effectiveness may differ depending on surface characteristics (presence or absence of channels, inclination of the marsh surface, etc.). A better approximation of the process results from making use of non-euclidean distance calculated with the help of the cost weighted distance function. Cost weighted distance functions apply distance in cost units, not in geographical units. For each cell the least accumulated cost of reaching the source cells is calculated. The calculation is performed using a cost raster map, which for each cell of surface contains the cost of passing it (Mitchell 1999). If it is assumed that salt inflow occurs as a result of the periodic filling up of the channels by salt water, then the effectiveness of salt water transport will depend on the time it takes salt water to get from the sea to a given point on the surface of the marsh, which is defined by the quotient of the distance and of the flow speed. If the map of water flow speed across the marsh (with higher speeds inside the channels and lower speeds on the surface of the marsh) is used as the cost raster map, then the resulting map will correspond to a map of salt water flow time allowing for different speeds with which salt is transported across the marsh. It is effectively impossible to determine the real process of transporting salt across the surface of the marsh, and the created cost raster map is only an approximation of the process, making use of the assumption that there exists a significant difference in effectiveness between the flow of salt water inside the channels and the flow across the surface of the marsh. Yet the differences illuminated by such maps produced for changing morphometric conditions, especially if they allow for changes in the placement of the channels, should result in a good index pointing to the importance of changes in salt water inflow to any point on the marsh surface. Such an index is calculated by standardizing

the differences of maps of noneuclidean distance from the sea, which describe the ease of salt water inflow to some given point of the marsh.

RESULTS AND DISCUSION

Changes in frequency of wetland floodings

To define the increase of flooding risk due to sea level rise a soft GIS method (as described above) was used. A sea level rise of 0.2 – 0.6 m is forecast over the period of the next one hundred years. During the last century the local sea level rise, primarily due to isostatic movements, was about 0.2 m. For this project a 0.4 m sea level rise to the year 2100 was assumed, with RMS = 0.1 m (defining the uncertainty of the prognosis). Initially a raster DTM map with a cell size of 1 m was created using survey measurements. A special technique was used to estimate the maximum height of the dune ridge forming a barrier separating the marsh from the sea. An RMS error of 0.23 m was calculated for the map, and the assumption was made that the DTM cell error values have normal distribution. Then, evaluating all the available sea level data (starting from 1886) and making use of the Pearson type III distribution (Dziadziuszko and Wroblewski 1990), the sea levels for specified frequencies that may occur now and in one hundred years' time were calculated. The results are summarized in Table 1. The table shows that a sea level rise of 1.22 m, which was the sea level during the 1914 flood, may currently occur once every 200 years. By the year 2100 the same event may happen once every 5 years. For the modeling process it was assumed that the total error describing uncertainty will equal

$$RMS = \sqrt{0.23^2 + 0.1^2} = 0.25 \qquad (2)$$

It follows, given a normal distribution, that the difference between the sea level and the land must be +0.41 cm for the assumption to be made (at the RMS error = 0.25 [1.62 × standard deviation]) with 95% probability that the level of water is higher than that of the land. Applying that value to the raster map of the dune ridge, the above (input data the map) was reclassified using the threshold values defined in Table 1. For the cells with values, where:

$$level - DEM > 0.41 \qquad (3)$$

it was assumed to be 1 (all other cells were defined as 0). In this way five maps were produced for each period (2000 and 2100). Addition of the maps,

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Table 1

Estimation of probability of sea level rises (in meters) over the average sea level of the Beka marsh coast now and in a hundred years from now.

	once in 2 years	once in 10 years	once in 20 years	once in 50 years	once in 200 years
2000	**0.67**	**0.90**	**1.00**	**1.14**	**1.22**
2100	**1.07**	**1.30**	**1.40**	**1.54**	**1.62**

separately for each period, resulted in new maps containing values ranging from 0 (no overflow) up to 5 (overflow on every single map, equivalent to once every two years).

The results of the analysis are shown in Figure 4. For the years 2000-2004 modelled water overflow across the dune ridge occured, at most, once every ten years for 15% of the analyzed segment, and once every twenty years for 40% of the analyzed segment. The results show more frequent water overflows than those observed over the last 100 years, and indicate some erosive lowering of the dune ridge in recent years. For approximately 27% of the dune ridge there is no danger of overflow at all. A forecast of the overflow situation for the year 2100 shows considerable variability. During the coming fifty years some overflow is predicted to occur at every single place along the dune ridge, and the frequency of overflows will significantly increase. Over 50% of the

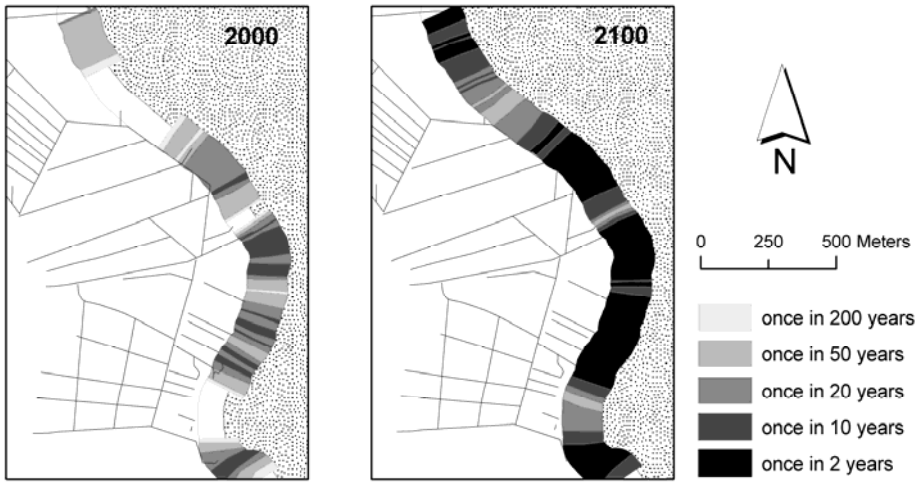


Fig. 4. Modeled frequency of the dune ridge overwash in the years 2000 and 2100.

analyzed segment of the dune ridge will be affected by overflows at least once every two years, which may change the shape of the dune ridge. One possible outcome is that the continuous dune ridge may disappear giving way to seasonal lagoons. Furthermore, inflow of salt water to the whole marsh area will increase substantially.

Traces of floodings in the wetland environment

Image enhancement techniques were used to find traces of past floodings. Traces (Fig. 5A) were found in the 1947 air photo in the form of a network of streams, all starting next to the dune ridge, showing how the water spread through the land after overwashing the ridge. The analyses of consecutive aerial photos show that these traces of flooding were visible over at least the next 20 years, although they cannot be seen in current aerial photographs. However, when the vector model of the old stream network was overlaid on a current vegetation map (Fig. 5B), it is possible to see that even now vegetation patterns match the old stream networks.

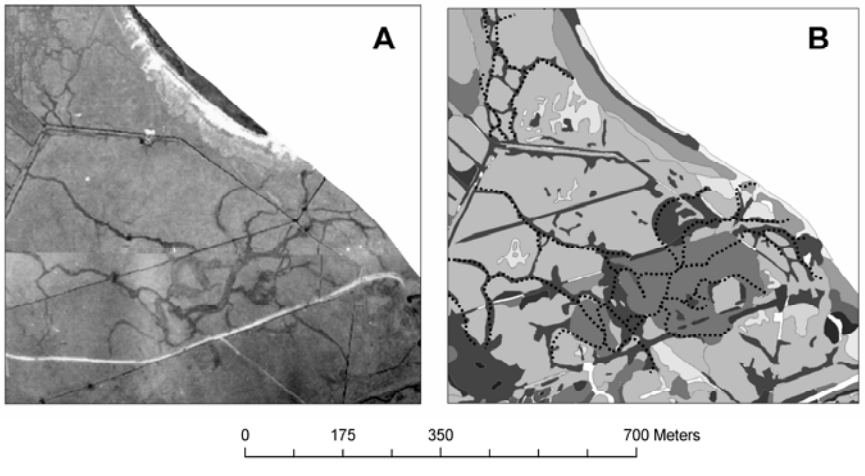


Fig. 5. A – Traces of flooding on the 1947 aerial photo; B – Overlay of flooding channel pattern on a vegetation map.

Detecting changes of sea water inflow into the marsh

The problem of decreasing biodiversity in the Beka salt marsh, and especially that of reeds succeeding black grass, has been proposed as resulting from the stopping of cattle grazing there (Lenartowicz et al. 1996). Data

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analysis suggests that radical changes in sea water access to the marsh might have taken place, which potentially could cause deterioration of the vegetative conditions for halophytes. Thus an examination of a potential relationship between the changes in the coastal zone (consisting in the cutting off of the drainage channels) and the replacement of black grass by reeds was undertaken. In order to study this possibility a hypothesis was put proposed that there is a relationship between the succession of reeds and the changes in sea water access. The index describing the changes of the access of sea water was based on proximity mapping using non-euclidean distance defined with the use of the cost weighted distance function. The friction or cost map used in the project was a slightly simplified model of the ease of water movement over the marsh area. It was assumed that through wide drainage channels water flows ten times faster than through narrow channels, and 100 times faster than across the surface area of the marsh. When an index map is created as normalized difference of two maps, only the proportions of the assumed values can influence the result. Besides, it was determined that any changes of these proportions have limited influence upon the result. The most significant difference is brought about when one changes the placement of the most effective water access routes. To produce the maps, functions found in the Spatial Analyst extension of the integrated collection of GIS software products known as ArcGIS were used. A method of creating a map where specific vegetation areas are assigned the mean of the index of changes in salt water access is presented in Figure 6. In the first place, two maps were created of cost weighted distance. To produce each of them a source map with the sea area is marked is needed, and also a cost map defining the ease of water flow across the area. After deletion of the two cost weighted distance maps and normalization of the map (so that it has only the values from 0 to 1 or from -1 to 1), the resulting map shows the index of changes in salt water inflow. This index is qualitative. In the analyzed example, the map was normalized so that all index values of 1 correspond to the maximum lengthening of the inflow route, while the 0 value corresponds to either lack of any change or to the shortening of the inflow route. A map of vegetation coverage is most often a polygon map. It is rasterized and grouped by means of the grouping function so that every polygon is assigned a unique identifier forming a separate zone. Then, using the function „calculate statistics" for zones, one can define, for each zone, the mean of the index of the area to which a given zone belongs.

Figure 7A shows all of the polygons with *Juncus gerardi* classified with respect to the mean index of changes in salt water access. Clear spatial diversification can be seen in the distribution of index values. The highest values occur in the southern part of the area and are related to the cutting off of the drainage channel outlets in that particular region of the coast. Figure 7B

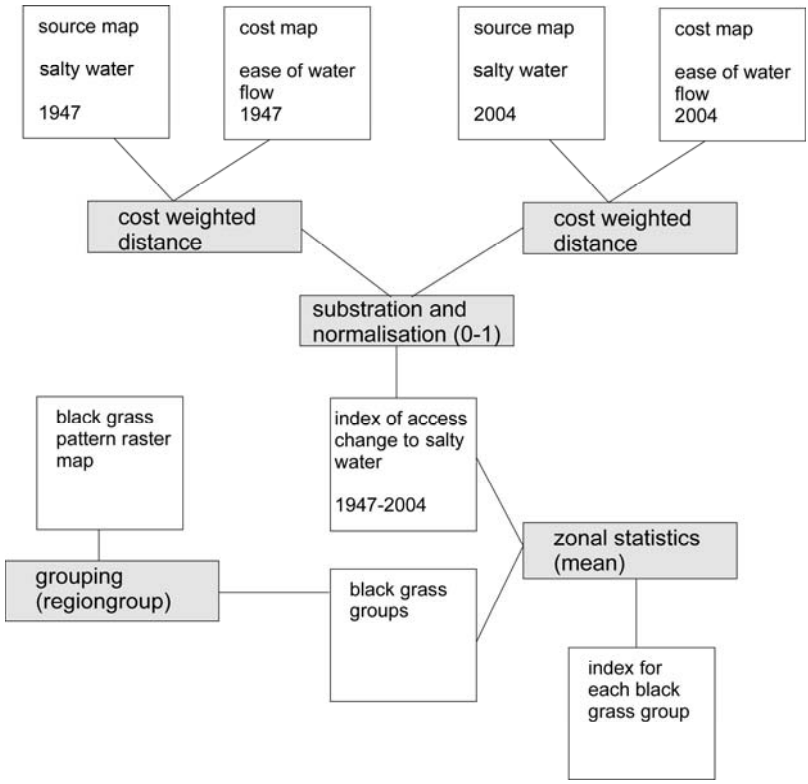


Fig. 6. Flow diagram of creation of map to show the index of changes in salt water access.

shows the polygons with *Juncus gerardi* where reed succession takes place and the area index is over 0.15, showing that in the areas with higher index values there is a marked tendency for reed patches to occur. The method adopted makes it possible to carry out quantitative analysis of the data consisting of statistical analysis of the index values in both subsets. Such analysis, however, has not been undertaken because of significant differences in coverage between the polygons with and without reed presence. The map shows that there may be a relationship between changes in salt water inflow and reed occurrence, although it is undoubtedly not the only factor contributing to the replacement of black grass by reeds. Results following changes of cattle grazing customs, and from uneven distribution of salt water over the area, which result from local elevation differences, are also likely to impact the growth of *Juncus gerardi* and play an important role in plant competition (Smith et al. 2001).

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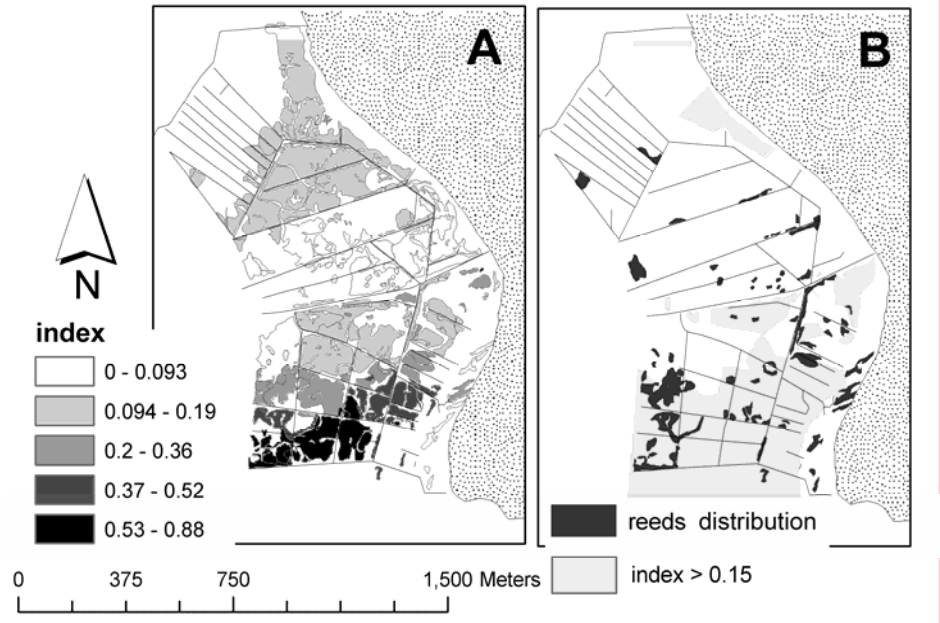


Fig. 7. A – Index of noneuclidean distance changes to sea water, calculated for all black grass polygons; B – Polygons of black grass with reeds patches and the area where the index is higher than 0.15.

The mechanism of salt water inflow into micro-tidal brackish marshes has not previously been investigated thoroughly. Figure 8 shows the average salinity distribution over the surface of the Beka marsh in spring 2004 (the results having been collected on two occasions in April and May 2004). The surface salinity of the soil directly behind the dune ridge was found to range between 1.5 and 2 PSU. With the lack of drainage channels, that could be the main source of salty water for the marsh. During high sea levels the drainage channels potentially enable sea water to overflow channel banks, spread over the surface of the marsh, and fill up depressions. When the sea retreats to its normal level the sea water inside the channels moves back to the sea while water on the surface of the marsh stays there, increasing local salinity. It is clear that salinity increases in the central part of the area, adjacent to the main and, at present, only important drainage channel. In the past when there was a second, equally wide channel, in the southern part of the marsh, a similar process might also have been taking place in the south western section of the area, where the indeces of changes in salt water access all show their maximum values.

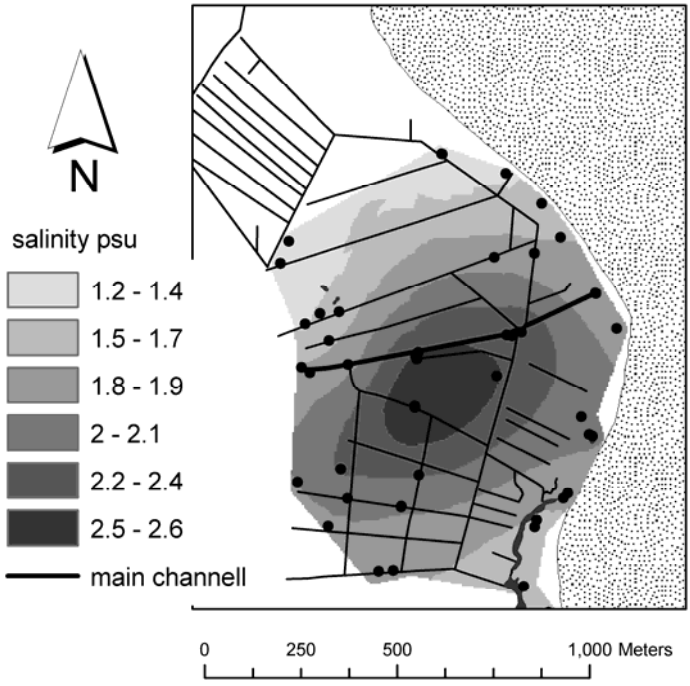


Fig. 8. Average distribution of salinity on the surface of the marsh in spring 2004 (based on measurements collected in April and May 2004).

CONCLUSION

In the Beka wetlands a sea-level rise of 0.4 m might cause enormous changes in flooding frequency. The normal annual range of sea-level variability of these wetlands is small, and the geomorphology of the coast, primarily the presence and height of the dune ridge, provides shelter from storms. This kind of coast seems to be extremely sensitive to even small sea-level rises, where overwashing of the dune ridge may cause flooding. Traces of flood channel patterns, in the form of a network of streams starting at the dune ridge and flowing from the coast towards the land, can last at least several decades. For even longer periods of time, they may be recognized in local patterns of vegetation. Morphodynamic changes that occur within the coastal zone have a strong influence upon coastal wetlands. For micro-tidal salty marshes, salt water inflow is a basic process that determines their state. The most important dynamic factors that generate the process are wind tides, whose episodic nature is a significant characteristic. Artificial drainage channels, often over 100 years

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old, are the main route of salt water inflow to these wetlands. Disturbing that structure, as a result of either human activity or natural processes taking place in the coastal zone, might lead to major changes in salt water inflow, which may, in turn, result in vegetation changes. GIS technology facilitates the creation of maps that illustrate the processes involved in the dynamic balance and disturbances of coastal wetlands.

ACKNOWLEDGEMENTS

This study was funded by the University of Gdansk grant BW-1330-5-0338-5.

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