GEOLOGIJA. 2009. Vol. 51. No. 3–4(67–68). P. 146–152
DOI: 10.2478/v10056-009-0016-y

Hydrological assessment of the Baltic Sea impact on the Polish coastline

Roman Cieśliński

Cieśliński R. Hydrological assessment of the Baltic Sea impact on the Polish coastline. *Geologija*. Vilnius. 2009. Vol. 51. No. 3–4 (67–68). P. 146–152. ISSN 1392-110X

The purpose of this work was to assess the hydrological effects of the impact of the Baltic Sea on the Polish coastal zone. The research area includes the Polish Baltic coastal zone, the Vistula River Delta, and the Baltic Sea coastal drainage basin. Man-made and land-based factors take part in this area. The most important hydrological effect is the change in sea level. The seawater intrusions is another effect of the hydrological activity of the Baltic Sea.

Key words: Baltic Sea, seawater, intrusion, natural processes, coastline

Received 20 November 2008, accepted 27 January 2009

Roman Cieśliński. Department of Hydrology, Institute of Geography, University of Gdańsk, Dmowskiego 16a, 80-952 Gdańsk, Poland. E-mail: georc@univ.gda.pl

INTRODUCTION

The coastline is a place where physical and geographic processes and phenomena are much more dynamic than farther inland. Many of these processes and phenomena are not even observed in other parts of the world. This stems from the fact that, on the one hand, two large areas featuring entirely different physical characteristics – a marine body of water (the Baltic) and coastal areas with the neighboring lake districts – coexist side by side and, on the other hand, regional hydro-meteorological conditions that are the source of great hydrological variability in different types of coastal areas. As a result, all types of geomorphological formations are frequent in coastal areas. Such formations result from the destructive (abrasion) as well as constructive (deposition) action of the sea. The sea "produces" two types of coastlines: low (beaches) and high (cliffs). Changes in the location of the coastline are possible both in the long term and on a seasonal basis. Seasonal shifts in the coastline are often the product of sea storms. Finally, the general rise in sea levels, caused by the global warming, causes coastline changes as described by Miętus (2003), Pruszak and Zawadzka (2005, 2008).

The southern Baltic coastal zone is a place where the action of the sea not only influences the geomorphological conditions, but also produces hydrological effects. Hydrological processes along the Polish coastline are not caused by high and low tides as is the case with "open sea" coastlines (White et al., 1996; Otsmann, 1998; Beckers et al., 2002). The Polish coastline is affected by storm surges and exceptionally low inland freshwater levels during the summer season (Pitkänen, 2001; Dailidiene et al., 2006; Drwal, Cieśliński, 2007).

The purpose of this work was to assess the hydrological effects of the impact of the Baltic Sea on the Polish coastal zone. The designated research area included the Polish Baltic coastal zone, the Vistula River Delta, and the Baltic Sea coastal drainage basin (Fig. 1).

METHODS

This work is based on primary sources as well as a field research conducted from 2002 to 2008. The wieldwork included collection of water samples from the largest hydrographic objects within the coastal zone: rivers, canals, lakes, and wetlands. Samples were collected from 17 coastal lakes, 10 coastal rivers, and 6 canals. The samples were laboratory-tested to determine the concentrations of common cations and anions as well as to measure specific conductance. The fieldwork included also hydrographic photographs.

LANDFORMS IN THE SOUTHERN BALTIC COASTAL ZONE

Landforms in the southern Baltic coastal zone are generally the result of the Quaternary glaciation as well as the

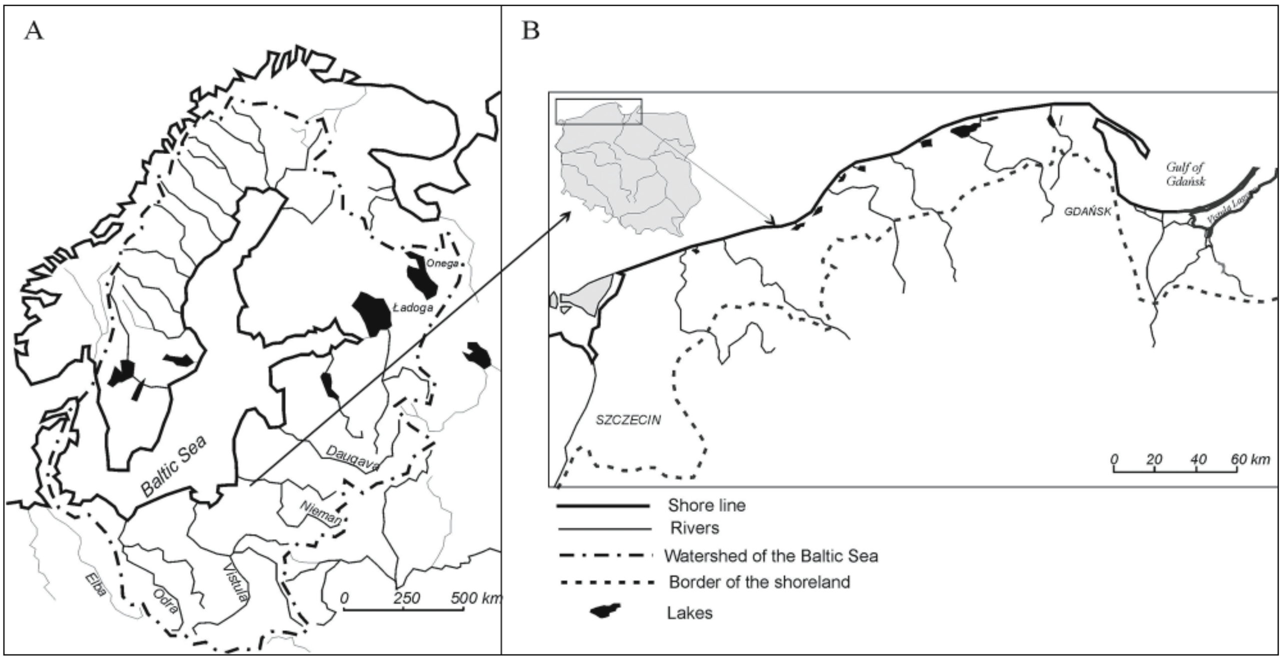

Fig. 1. The drainage basin of the Baltic Sea and adjacent coastal areas
1 pav. Baltijos jūros ir prisišliejusių pakrantės teritorijų drenažo baseinas

rising sea level following the recession of the Scandinavian glacier. The coastal landscape had already formed by the time the last ice age had transitioned into the Holocene. The sea level has risen about 105 meters since that time. Shifts in the location of the coastline have been associated with morphogenetic processes induced by the Holocene (mainly Atlantic) marine transgression. These processes can still be observed today.

The following factors played the key roles:

- the rise in sea level, modified by isostatic movements within the Earth's crust as well as by temporary storm surges
- wave action, releasing energy at the bottom of the littoral zone and currents acting within this zone
- transport of material along the coastline, leading to deposition or dumping of debris the eroded off coastline or bottom of the littoral zone
- aeolian transport of debris deposited on beaches
- dune-forming processes.

DESTRUCTIVE ACTION ALONG THE COASTLINE

The ever changing coastal landscape is the result of the destructive power of the sea. This is particularly apparent during sea storms. The intensity and duration of sea storms induce abrasive processes in the littoral zone. A typical example is the undercutting of cliffs. Sea storms cause most of damage in the littoral zone and can reach as far as a 100 meters inland, destroying buildings, beaches, forests, and roads in the process. Mud accumulation in river mouths can also be a result of sea storm activity. For example, the autumn storms of 2004 destroyed dunes, small port facilities and other man-made structures such as a pier in the city of Sopot.

TRENDS IN COASTLINE SHIFTS ALONG THE SOUTHERN BALTIC

The observed tendency – caused by the greenhouse effect – of the Baltic Sea level to rise most often results in a shift of the coastline. The Baltic Sea level rose between 10 and 20 cm during the 1875–1983 time period. Current forecasts predict that it will rise up to 80 cm by the end of the 21st century (Miętus, 2003; Pruszak, Zawadzka, 2008). This will put areas located below 2.5 meters a. s. l. at risk (Fig. 2). This would be the case with most coastal lakes and rivers. Poland stands to lose, depending on the estimate, between 2500 and 8000 sq. km of land.

From 1875 to 1983, the Polish coastline retreated on average by 10 meters. However, there are sections of the southern Baltic coastline where shifts have been far from average. There are places where a lot of land has already been lost to the sea. In the Ustka region, the coastline retreated 450 meters during the above-mentioned period. According to various forecasts, if the sea level rises 1 meter, this will increase the risk of flooding in low-lying alluvial plains tenfold. It is estimated that such a rise in sea level would triple the erosion rate of sandy beaches, coastal dunes, and sandbars (Pruszak, Zawadzka, 2005). The result will be seawater flooding of coastal plains and a gradual conversion of coastal lakes into marine bays. A secondary effect will be a southerly shift in saltwater intrusions into freshwater bodies.

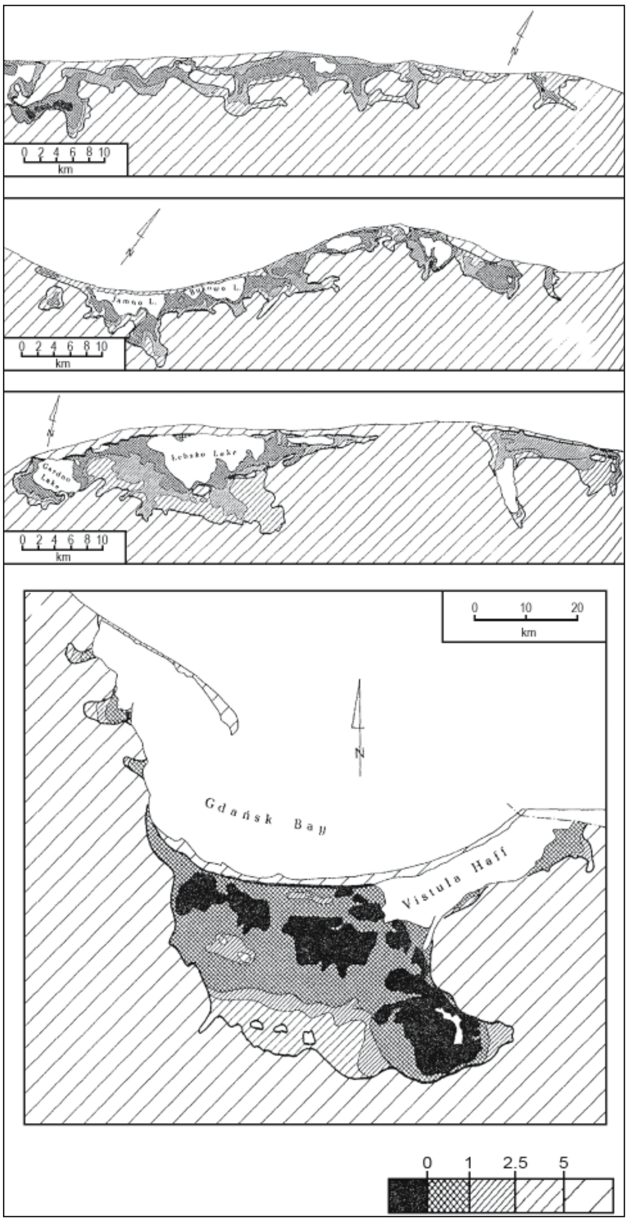

Fig. 2. Threats to lowlands along the central southern Baltic coast, resulting from a predicted rise in sea level (Rotnicki et al., 1995)

2 pav. Prognozuojamo jūros lygio kilimo grėsmė pietų Baltijos kranto pajūrio žemumoms (Rotnicki et al., 1995)

SEAWATER INTRUSIONS

The southern Baltic coastal zone is characterized by a recurrence of brackish water intrusions which cause changes in water levels and water quality in selected hydrographic objects. This phenomenon is most often observed in large coastal lakes. It results from the fact that lakes are bodies of standing water with a limited number of natural factors that could interfere with the influx of seawater. At the same time, these bodies of freshwater do have only one link to the sea, which limits the number of potential surface seawater influx routes to one. Of course, there does exist a group of coastal lakes where the effects of seawater intrusions are barely noticeable and may not even exist. This is most often associated with human activity where man-made hydraulic structures (weirs of all types) are built at the sea-end of the waterways linking the lakes to the sea. Examples of this are Lake Wicko and Lake Żarnowieckie. Periodic blockages of lake-sea connecting waterways can also limit the occurrence of saltwater intrusions. Such blockages are the result of sand deposition at the sea-end (Lake Kopań and Lake Jamno) or an extensive plant growth in river channels and canals, especially in the spring and summer seasons (Lake Modło). The effects of seawater intrusions can be most readily observed via chloride analysis. It is generally accepted that chloride concentrations in excess of 100 mg dm^{-3} are a proof of seawater intrusions in hydrographic objects within the Polish coastal zone. Therefore, it can be stated that some of the analysed lakes have permanently elevated chloride concentrations, some have elevated concentrations only during actual periods of saltwater intrusion, while some never show such concentrations of chloride (Fig. 3).

On the other hand, the terminal sections of coastal rivers are characterized by a substantial variability in terms of chloride concentration values. In many cases, the minimum values range from a dozen to several dozen milligrams, while the maximum values range from 600 to 1000 mg dm^{-3}. There exist two cases where chloride concentrations have reached almost 4000 mg dm^{-3}: the Martwa Wisła River and the Głowica River. On the other hand, chloride concentration values in rivers such as the Płucnica, the Piaśnica, the Chełst, and the Zagróska Struga have never exceeded 100 mg (Fig. 4). Canals directly connected to the sea are a different story. Water in such canals tends to have very high concentrations of chlorides regardless of the hydro-meteorological conditions present. Chloride concentrations in canals range from 800 to over 4000 mg dm^{-3}. The Baltic Sea does exert a substantial influence on water quality in coastal canals. In two cases (the Jamneński Canal and the Łupawa Canal) the minimum values reached 120 and 78 mg dm^{-3}, respectively, which indicated periods of temporary desalination. However, the fact is that these canals are normally highly saline, the average salinity values ranging from 455.5 to 1530.1 mg dm^{-3} (Fig. 5).

CHANGES IN WATER QUALITY

The southern Baltic coastal zone, as previously mentioned, is a place characterized by a substantial variability in terms of water relationships and the marine and land-based factors that affect this region. This results in a significant hydrochemical variability in the water of selected lakes and rivers. Such variability can be most easily observed in the water of coastal lakes which are affected by a large number of geographic factors. Some coastal lakes experience brackish water intrusions on a regular basis. Others are affected by the sea from time to time, while still others do not experience any appreciable marine influence. For these reasons, coastal lake water can vary a great deal in terms of its composition. Dif-

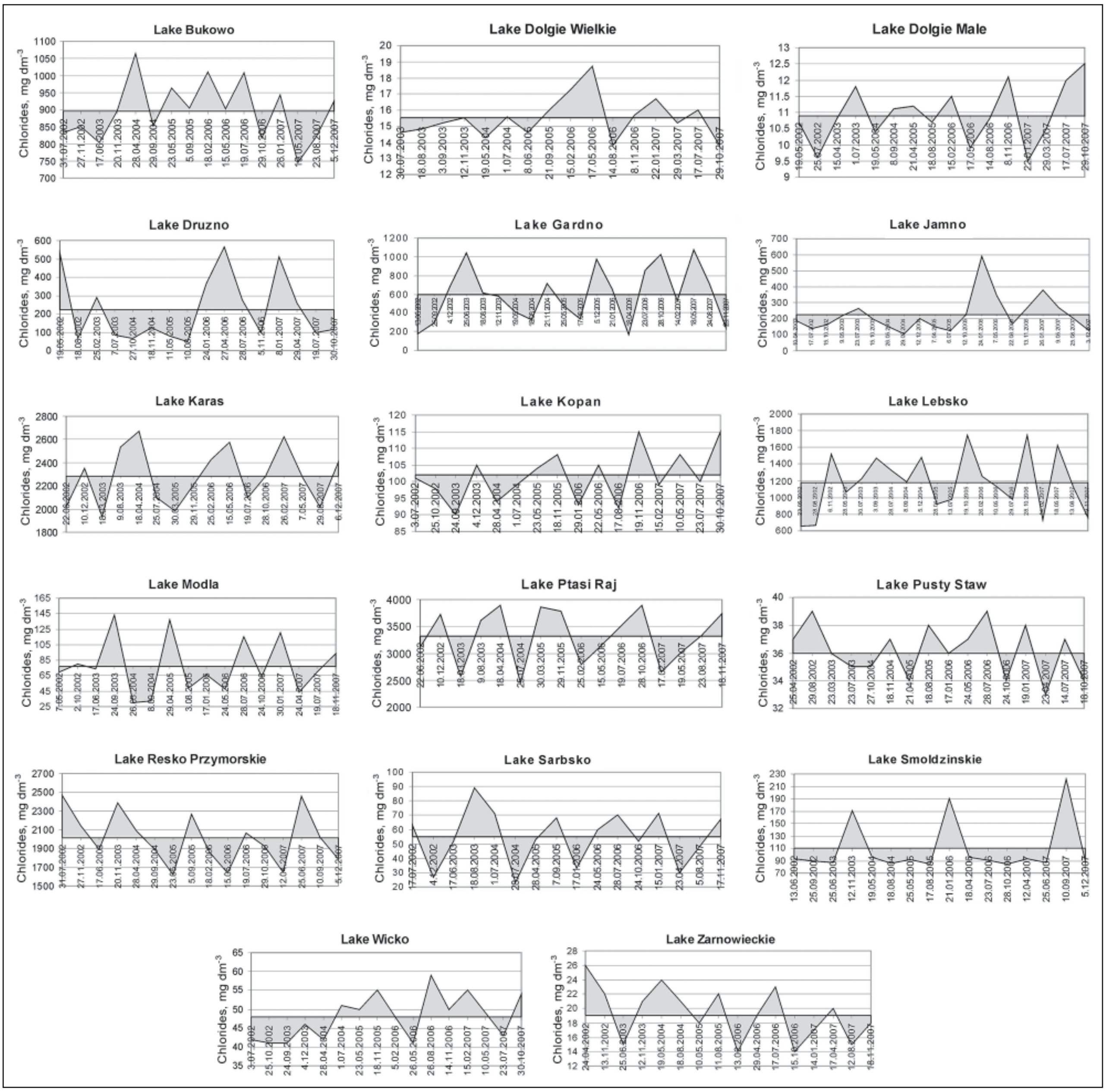

Fig. 3. Variability in chloride concentration in water of selected coastal lakes
3 pav. Chloridų koncentracijos kaita pasirinktuose pakrantės ežeruose

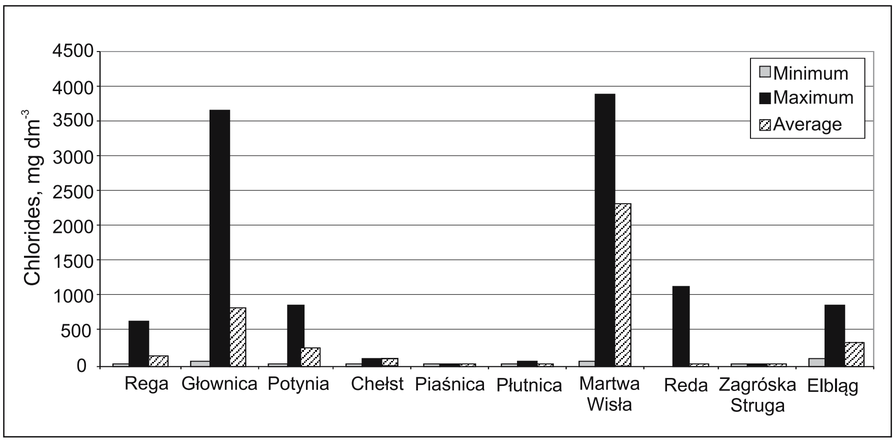

Fig. 4. Average, maximum, and minimum chloride concentrations in water of selected coastal rivers
4 pav. Vidutinis, maksimalus ir minimalus chloridų kiekis pasirinktose pakrantės upėse

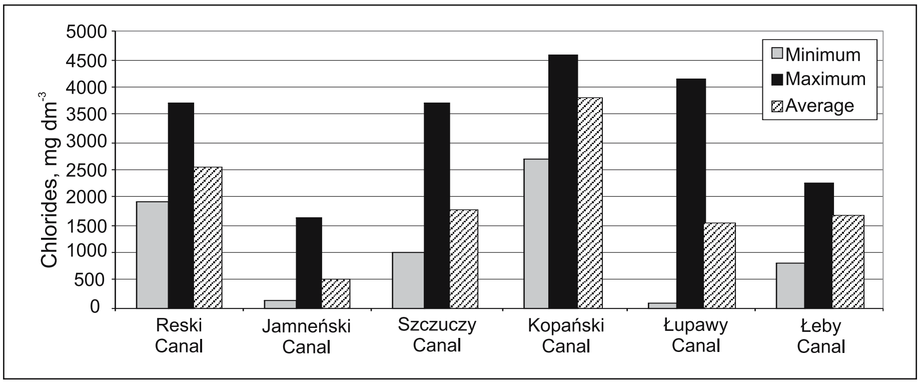

Fig. 5. Average, maximum, and minimum chloride concentrations in water of selected coastal canals
5 pav. Vidutinis, maksimalus ir minimalus chloridų kiekis pasirinktuose pakrantės kanaluose

ferences can be observed not only in the values of particular indicators, but also in their tendency to vary in time. Assuming that all the cations and anions add up to 100%, significant differences can be observed for different lakes. These differences can be attributed to the uneven influence of the Baltic Sea on coastal lake waters. The following lakes possess the anion content similar to that in seawater: Resko Przymorskie (Fig. 6), Bukowo, Gardno, Łebsko, Ptasi Raj, and Karaś:

$rCl^- > rSO_4^{2-} > rHCO_3^-$.

A similar distribution can be observed in lakes Jamno, Kopań, Smołdzińskie, and Druzno. Note the reverse HCO_3^- and SO_4^{2-} order (Folk, 1974):

$rCl^- > rHCO_3^- > rSO_4^{2-}$.

This indicates a greater influence of freshwater on the above lakes, although marine influence is still dominant. In the case of the remaining lakes, except for Lake Żarnowieckie, the anion order is typical of freshwater bodies (Fig. 7):

$rHCO_3^- > rCl^- > rSO_4^{2-}$.

The analysis of cation order in most cases confirms earlier conclusions. The following lakes exhibit a cation order that is normally found in marine waters: Resko Przymorskie, Bukowo, Gardno, Łebsko, Ptasi Raj, and Karaś (Lopez-Buendia et al., 1999):

$rNa^+ > rMg^{2+} > rCa^{2+}$.

A different cation order has been determined for the following lakes: Jamno, Kopań, Smołdzińskie, Druzno, and Dołgie Małe. This order suggests that the sea has an impact on lake waters, however, its impact is distorted by the influence of drainage basin waters. In this particular case, the cation order is the following:

$rNa^+ > rCa^{2+} > rMg^{2+}$.

The cation order for the remaining lakes, except for Lake Modła and Lake Żarnowieckie, is typical of freshwater bodies (Berner, Berner, 1996):

$rCa^{2+} > rNa^+ > rMg^{2+}$.

The last two lakes (Modła and Żarnowieckie) are characterized by the impact of their drainage basins, which may be distorted by underground water inflows. This results in the following cation order (Berner, Berner, 1987).

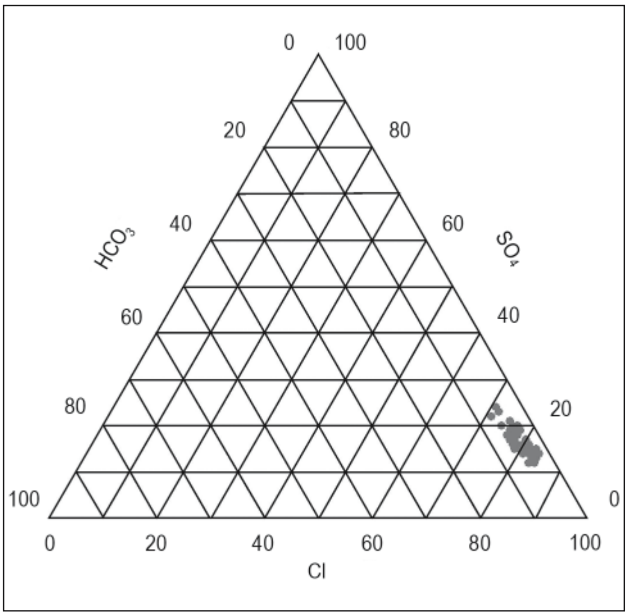

Fig. 6. Distribution of anion concentrations in Lake Resko Przymorskie
6 pav. Anijonų koncentracijos pasiskirstymas Resko Przymorskie ežere

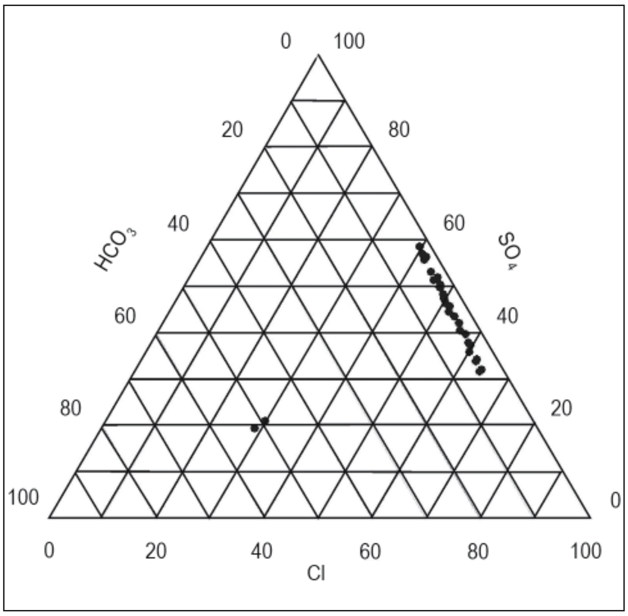

Fig. 7. Distribution of anion concentrations in Lake Pusty Staw water
7 pav. Anijonų koncentracijos pasiskirstymas Pusty Staw ežere

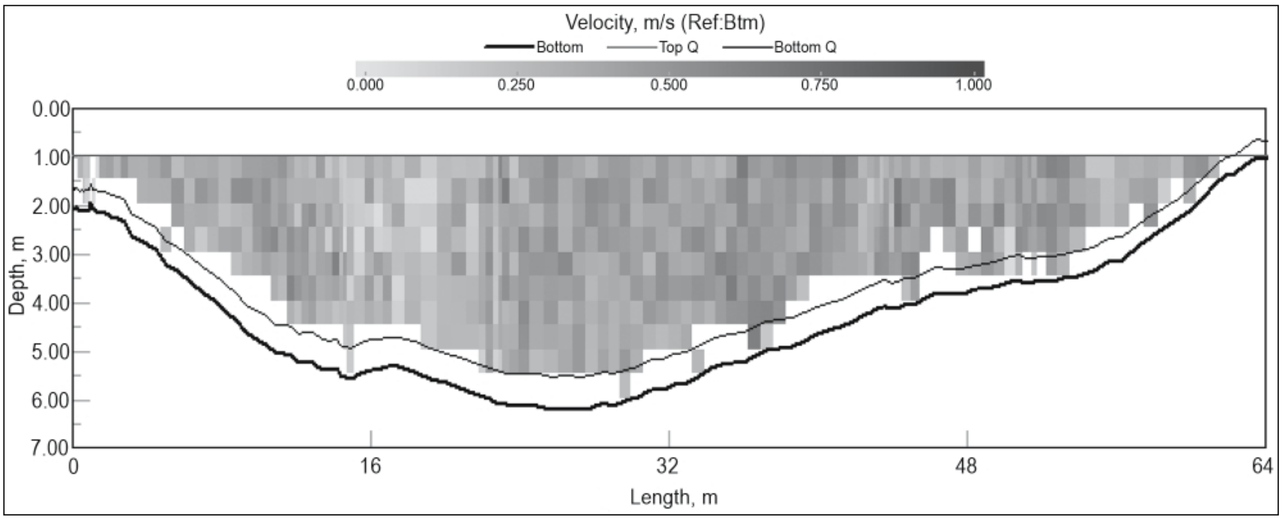

Fig. 8. Flow velocity distribution in the Łeba Canal on November 10, 2006
8 pav. Srovės greičio pasiskirstymas Lebos kanale 2006 m. lapkričio 10 d.

Differences in the concentration and direction of flow (reversals)

In order to confirm the substantial or less substantial influence of seawater on water in the selected lakes, flow rates at hydraulic structures located at the sea-end of lake-sea connecting waterways were recorded. The most variable of flow rates recorded over a longer period of time occurred in the Łeba Canal which connects Lake Łebsko to the sea. The sea-bound flow rates observed in this canal ranged from 15 to 30 $m^3 s^{-1}$. The average lake-bound flow rate (saltwater intrusions), on the other hand, was about 30 $m^3 s^{-1}$. The minimum flow rates were around 10 $m^3 s^{-1}$, while the maximum values were around 54 $m^3 s^{-1}$ (Fig. 8).

Flow rate measurements were also performed in other canals and rivers linking the remaining lakes to the sea. A significant variability was also noted in these waterways, especially in the Elbląg River. Research on the Elbląg River has shown that both lake-bound (10–12 $m^3 s^{-1}$) as well as sea-bound (25–40 $m^3 s^{-1}$) flows are present. Flow rates in the Piaśnica River (Lake Żarnowieckie) ranged from 1.1 to 2.9 $m^3 s^{-1}$ with a constant sea-bound flow direction. No lake-bound flows were ever observed in this river. Sea-bound flow rates in the Łupawa Canal (Lake Gardno), under normal circumstances, ranged from 10 to 20 $m^3 s^{-1}$, while the lake-bound flow attained the maximum value of 30 $m^3 s^{-1}$. Sea-bound flow rates in the Resko Canal ranged from 5 to 30 $m^3 s^{-1}$, while lake-bound flow rates ranged within 10 to 30 $m^3 s^{-1}$.

Flow rates are normally zero or close to zero (0.05 $m^3 s^{-1}$) in the Głownica River linking Lake Wicko with the sea. The same is true of the Potynia River (Lake Modła) where river discharge is almost imperceptible and only during brackish water intrusions attain the values of several $m^3 s^{-1}$.

The Jamneński Canal linking Lake Jamno with the sea had sea-bound flow rates ranging from 10 to 15 $m^3 s^{-1}$ and a lake-bound flow rate around 10 $m^3 s^{-1}$. Sea-bound flow rates in the Szczuczy Canal linking Lake Bukowo with the sea ranged from 0.3 to 9.0 $m^3 s^{-1}$ while lake-bound flow rates ranged within 6.0 to 10.0 $m^3 s^{-1}$. No lake-bound flow was ever observed in the Chełst River throughout the research period. This river constitutes an intermediate link between Lake Sarbsko and the Baltic Sea. Sea-bound flow rates in the Chełst River ranged from 1.5 to 3.5 $m^3 s^{-1}$. Finally, no lake-bound flows were ever recorded in the Kopański Canal, while sea-bound flow rates ranged from 2 to 4 $m^3 s^{-1}$.

CONCLUSIONS

The southern Baltic coastal zone is a place that experiences the constant destructive and constructive power of the sea. Man-made and land-based factors also take a toll on this area. The destructive action of the Baltic Sea is much more readily apparent than its constructive counterpart as its destructive processes are much more dynamic and spectacular in nature.

The geomorphological impact of the sea on coastal zones has always received a lot of attention, while the hydrological effects have been overlooked. This work has shown that such effects are quite numerous and have a decisive influence on the characteristics of the coastal zone and its landforms. The most important hydrological effect is the change in sea level, resulting from the warming climate, which leads to shifts in the coastline and the loss of land. The effect of a predicted 1 meter rise in sea level will be a tenfold rise in flood risk in low-lying delta regions and coastal alluvial plains. Another effect will be a tripling of the erosion rate of sandy beaches, coastal dunes, and sandbars. Shifts in the coastline are also a result of the destructive power of the sea (sea currents, waves, storms). The hydrological consequence of this will be a southerly shift in the coastline and the flooding of coastal plains by seawater. Coastal lakes will be gradually converted into marine bays, and seawater intrusions in freshwater bodies will shift farther south. The phenomenon of seawater intrusions is another effect of the hydrological activity of the Baltic Sea along its southern coast. This phenomenon is primarily a result of local hydro-meteorological conditions along with hydrographic factors. The brackish water intrusions change the quality of water in most of coastal lakes, mouth sections of rivers, and canals directly connected to the Baltic Sea or the Gulf of Gdańsk. Changes in water levels in the water bodies mentioned above are a physical effect of saltwater intrusions. Another physical effect is the reversal of water flow in many coastal waterways which are often the only link between coastal lakes and the sea.

References

1. Beckers J. M., Gregoire M., Nihoul J. C. J., Stanev E., Staneva J., Lancelot C. 2002. Modelling the Danube-influenced North-western Continental Shelf of the Black Sea. I: Hydrodynamical Processes Simulated by 3-D and Box Models. *Estuarine, Coastal and Shelf Science* 54(3): 453–472.
2. Berner E. K., Berner R. A. 1987. The Global Water Cycle: Geochemistry and Environment. New Jersey: Prentice Hall Inc. 397 p.
3. Berner E. K., Berner R. A. 1996. Global Environment Water, Air, and Geochemical cycles. New Jersey: Prentice Hall Inc. 376 p.
4. Dailidiene I., Davuliene L., Tilickis B., Stankevicius A., Myrberg K. 2006. Sea level variability at the Lithuanian coast of the Baltic Sea. *Boreal Environment Research* 11(2): 109–121.
5. Drwal J., Cieśliński R. 2007. Coastal lakes and marine intrusions on the southern Baltic coast. *Oceanological and Hydrobiological Studies* 36(2): 61–75.
6. Folk R. L. 1974. The natural history of crystalline calcium carbonate: effect of magnesium content and salinity. *Journal of Sedimentary Petrology* 44(1): 40–53.
7. Lopez-Buendia A. M., Bastida J., Querol X., Whateley M. K. G. 1999. Geochemical data as indicators of palaeosalinity in coastal organic-rich sediments. *Chemical Geology* 157: 235–254.
8. Miętus M. 2003. Long-term sea level variability along the Polish coast of the Baltic Sea. In: K. Haman, B. Jakubiak, J. Zabczyk (eds.). *Probabilistic Problems in Atmospheric and Water Sciences. Seria Fizyka Atmosfery*. Warsaw: Wyd. ICM. 170–181.
9. Otsmann M., Suursaar Ü., Kullas T., Astok V. 1998. Helmholtz response to the system of two semi-enclosed basins and four straits. *EMI Report Series* 9: 34–60.
10. Pitkänen H. 2001. Internal nutrient fluxes counteract decreases in external load: the case of the estuarial eastern Gulf of Finland, Baltic Sea. *Journal of the Human Environment* 30(4): 195–201.
11. Pruszak Z., Zawadzka E. 2005. Vulnerability of Poland's coast to sea-level rise. *Costal Engineering Journal* 47(2–3): 131–155.
12. Pruszak Z., Zawadzka E. 2008. Potential implications of sea-level rise for Poland. *Journal of Coastal Research* 24(2): 410–422.
13. Rotnicki K., Borówka R., Devine N. 1995. Accelerated sea level rise as a threat to the Polish coastal zone – quantification of risk. *Journal of Coastal Research* 22: 111–135.
14. White I., Melville M., Sammut J. 1996. Possible impacts of saline water intrusion floodgates in Vietnam's Lower Mekong Delta. *Seminar on Environment and Development in Vietnam*. Canberra: Australian National University. 419–425.

Roman Cieśliński

HIDROLOGINIS BALTIJOS JŪROS POVEIKIO LENKIJOS KRANTO ZONAI VERTINIMAS

Santrauka

Darbo tikslas – įvertinti geomorfologinių ir hidrologinių veiksnių poveikį jūros kranto zonai. Tyrimas apima Lenkijos teritoriją, Vyslos deltą ir drenažo baseiną, Pietų Baltijos kranto zoną.

Kranto zona kinta dėl natūralių gamtinių ir antropogeninių veiksnių. Vertinant jūros poveikį krantui daugiau dėmesio buvo skiriama geomorfologijai, hidrologija buvo vertinama mažiau. Nustatyta, kad jūros hidrologinis režimas yra labai reikšmingas ir dažnai netgi lemiamas kranto zonos savybėms ir reljefui. Kranto linijos padėtį ir sausumos mažėjimą labiausiai lemia jūros lygio kilimas. Jei jūros lygis pakiltų metrą, potvynių rizika Vyslos deltoje padidėtų dešimt kartų.

Kranto linijos pokyčiai priklauso ir nuo griaunančios jūros energijos (stiprios audros, srovės, bangavimas). Hidrologinė šio proceso pasekmė – pasislenka kranto linija, pajūrio lygumos užliejamos jūros vandeniu, jūros vanduo patenka į gėlavandenius telkinius. Į pakrantės ežerus, upių žiotis ir kanalus, tiesiogiai besijungiančius su Baltijos jūra arba Gdansko įlanka, patekęs druskingas vanduo paveikia šių telkinių vandens kokybę.

Роман Цеслинский

ГИДРОЛОГИЧЕСКАЯ ОЦЕНКА ВОЗДЕЙСТВИЯ БАЛТИЙСКОГО МОРЯ НА ПОБЕРЕЖЬЕ ПОЛЬШИ

Резюме

Цель работы – описать гидрологические и геоморфологичные эффекты воздействия Балтийского моря на пространство польского побережья. Объект исследования – польская часть побережья южной части Балтийского моря и дельта Вислы, входящая в состав бассейна Балтийского моря и Приморья. Береговая зона южной части Балтийского моря подвежена воздействию со стороны моря (как положительному, так и отрицательному),также со стороны суши и человеческого фактора. Здесь особенно проявляются результаты разрушающих процессов, которые, в отличие от положительной деятельности моря, протекают более динамично и явно. Ранее наиболее часто говорилось о геоморфологических изменениях воздействия моря на береговую зону, без учета гидрологических эффектов этого воздействия. В этой работк показано, что последние решительным образом влияют на характер и формы береговой зоны.