7

Bodies of Water Along the Coast of a Tideless Sea in Areas with Young Pleistocene Accumulation from Scandinavian Glaciers (Baltic Sea)

Roman Cieśliński and Jan Drwal
University of Gdańsk, Institute of Geography,
Department of Hydrology, Gdańsk
Poland

1. Introduction

Oceanographers usually investigate coastal areas in terms of how they affect various processes taking place in the sea including wave action, high tide, low tide as well as flora and fauna. On the other hand, coastal areas may also be investigated in terms of the sea affects the strip of land along the coast. This strip is often called the coastal zone (Rotnicki, 1995). Water circulation in the interior and the action of the sea both affect water systems in the coastal zone depending on geographic conditions, which may help produce temporary flooding, seawater intrusions, increased water salinity and the formation of marshes.

Key geographic determinants include climate type, geological structure, relief and the resulting potamic discharge regime. Hydrography itself may also be considered a determinant. Key marine determinants include high tide, extent of high tide, short-term changes and sudden changes in sea level.

Half-closed seas are a special case, which occurs in the humid climate of the northern hemisphere, where Scandinavian shelf ice used to cover the area during the Pleistocene. The Baltic Sea is a half-closed sea. The southern shore of the Baltic is made of Pleistocene and Holocene clastic sediments with varying degrees of cohesion (Tomczak, 1995). The Polish section of the Baltic coast includes sandbars (79%) with dunes between 2 and 35 m high, cliffs (18%) up to 30 m high as well as alluvial coastlines (less than 3%). These characteristics make it difficult for discharge to take place along 75% of the Polish coastline (Drwal, 1995). This results in large marshy sandbars and grassy alluvial plains with a variety of bodies of water.

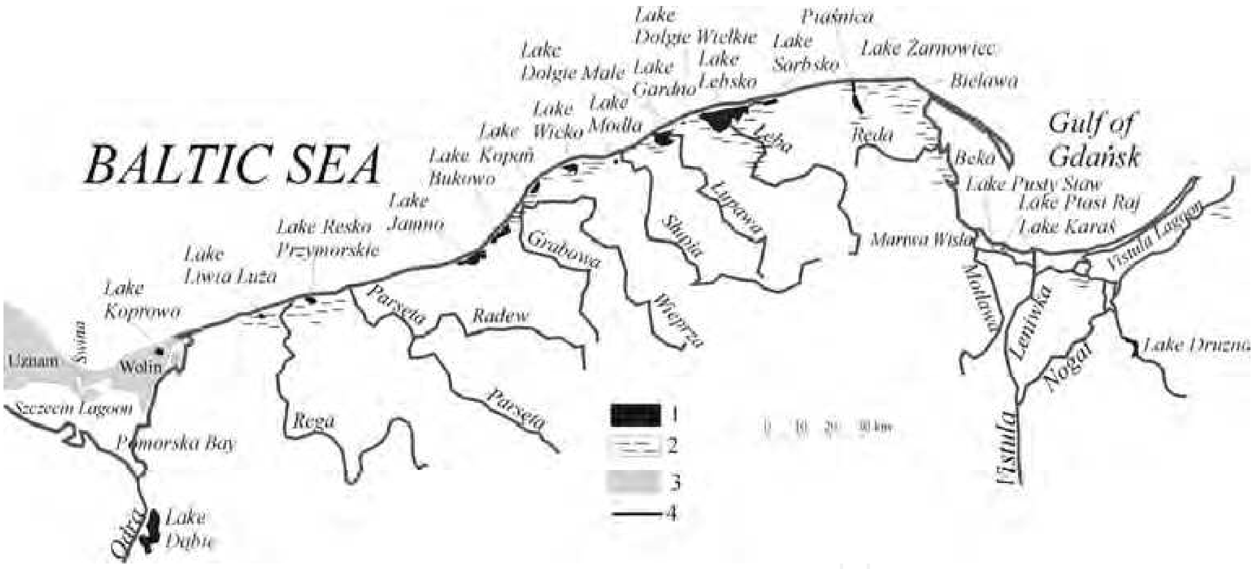
The virtually inland Baltic Sea is connected to the North Sea via the Straits of Denmark. This results in very small tides (15 cm) in the western part of the Baltic and even smaller tides (2 – 5 cm) in the southern part of the Baltic (Sztobryn et al., 2005). Their hydrological effects, therefore, should be negligible. In spite of this, some aspects typical of open seas may be observed along the southern Baltic coast (Drwal, 1995; Cieślinski, Drwal, 2005, Drwal, Cieśliński, 2007). The rationale for this may be found in climate conditions. Zaidler et al. (1995) argue that wind conditions resulting from pseudo-monsoon circulation characteristic of middle latitudes of the northern hemisphere cause a permanent exchange of air masses leading to significant daily and annual variability in wind direction and speed. This results in occasional storm surges along the western and southern Baltic coastline, reaching 300 cm above the sea's average level (Dziadziuszko, 1994).

The coastal zone of the southern Baltic Sea features young accumulation from Pleistocene glaciers and possesses a large variety of hydrographic entities, which may be affected by marine effects, as earlier research has shown. Sandbars with marshy deflation basins stretch along the Baltic Sea – separating the sea from lowlands featuring large wetland systems – many of which include polders, lakes, lagoons, deltas and estuaries. In some cases, these bodies of water form hydrographic systems (Cieśliński, 2004).

Changes in water chemistry are one indicator of marine impact on coastal bodies of water. Chloride concentration is often used to assess the influx of seawater into coastal bodies of water along the southern Baltic coast. Changes in all of the above conditions yield the current state of the hydrographic network along the southern Baltic.

2. Research subject

The research covered single hydrographic entities such as lagoons, lakes, mouth sections of rivers and wetlands as well as entire hydrographic systems along the Polish section of the southern Baltic coast (Fig. 1). The research sites were selected in a way that would capture any potential differences in environmental processes.



1 – lakes, 2 – wetlands, 3 – islands, 4 - rivers

Fig. 1. Location of objects investigation.

Fieldwork and library research were done in the period 2001-10. Fieldwork included hydrographic mapping and the collection of water samples for chemical analysis.

Chloride was selected as the best hydrochemical indicator, as it migrates well in the natural environment and does not react with other chemical entities (Hem, 1989). The chloride ion is also used in comparative papers for the southern Baltic coast (Cieśliński, Drwal, 2005).

The reference salinity level for brackish water varies from paper to paper. Appelo and Willems (1987) define it as 100 mg Cl^- dm^{-3}, while Davies and DeWiest (1966) define it as 200 mg Cl^- dm^{-3}. The reference level according to the Venetian Classification System is 500 mg Cl^- dm^{-3}. The reference level assumed in this paper for the southern Baltic coast in Poland is 200 mg Cl^- dm^{-3}.

3. Seawater intrusions in bodies of freshwater

Occasional storm surges occur along the southern Baltic coast. Low water levels occur periodically in the southern Baltic coastal zone. Both types of events cause seawater intrusions into bodies of freshwater along the Baltic coast. The Polish and international research literature contains a large quantity of descriptive information on seawater intrusions along the southern Baltic. Halbfass (1901, 1904) and Kunisch (1913) investigated two coastal lakes along the southern Baltic (Gardno and Łebsko) and found that the concentration of chloride decreased in canals linking the lakes to the sea with increasing distance to the sea. They explained this in terms of the influx of water from the Baltic Sea but found that it is quickly pushed out by freshwater. Kunisch (1913) also found that temporarily high concentrations of chloride in Lake Gardno may have been caused by sand blocking the lake's sole outlet – the Łupawa Canal. Kunisch also stated that the elevated concentration of chloride did not last long because it was reduced by the influx of large quantities of freshwater from the lake's drainage basin.

Szopowski (1962) wrote about water exchange taking place between Lake Łebsko and the Baltic Sea in 1956-58. He was the first to link the lake's influx of seawater with hydrometeorological factors. Szopowski based his analysis of changes in water levels in Lake Łebsko on measurements made at the Rąbka gauging site. He also used seawater data from a water gauge located in the Port of Łeba. His paper did not include a calculation of the quantity of seawater flowing into Lake Łebsko.

Mikulski, Bojanowicz and Ciszewski (1969) investigated the exchange of water between Lake Druzno and Vistula Bay and proposed a new method of calculating the influx of seawater into Lake Druzno based on differences in average water levels in the coastal lake and the neighboring Baltic Sea. The three researchers calculated channel cross sections as well as the slope and discharge for the river linking the lake with the bay. The length of river supplying water to the lake was calculated based on the ratio of discharge and influx time. If the calculations indicated that the theoretical river length was larger than the actual length of the Elbląg River, then it was inferred that brackish water from Vistula Bay was entering Lake Druzno.

Łomniewski and coworkers (1972) evaluated temporal and spatial changes in water salinity in the Vistula Delta. Majewski (1972) evaluated water exchange between the Baltic Sea and lakes Łebsko and Jamno. Majewski performed his research as part of a project on coastal lakes as transitional estuaries and assessed the number of seawater intrusions into Lake Łebsko (1972) during the period 1958-65.

Cieśliński and Drwal (2005) analyzed quasi-estuary processes along the Polish Baltic coastline and their impact on human activity. Drwal and Cieśliński (2007) analyzed seawater intrusions and their effects on selected coastal lakes with special attention being paid to the reasons for differences between the selected lakes.

Coastal areas are places where human life, safety and economic conditions often depend on phenomena and processes characterized by great intensity and dynamics. Seawater intrusions are some of the most common events taking place during extreme weather conditions. The effects of seawater intrusions have been observed in coastal lakes (Saeijs, Stortelder, 1982; Tiruneh, Motz, 2003), lagoons (Ishitobi et al., 1999; Tanaka et al., 2005), wetlands (Glover, 1959; Flynn, McKee, 1995) and mouth sections of rivers (Foster, 1980; Giambastiani et al., 2007). Seawater intrusions cause an increase in water salinity (van der Thuin, 1990) and abruptly increased water levels (Haslett, 2008). Seawater intrusions are easily detectable in lakes (Bear et al., 1999; Pulido-Leboeuf, 2004). The subject of seawater intrusions into coastal lakes has been covered by a number of researchers worldwide. The following citations are just a sample of the literature on this subject and were deemed most relevant to the theme of this paper.

Bowden (1967) identified the mechanism of water exchange in selected estuaries. Folk (1974) analyzed changes in the concentration of calcium and magnesium resulting from the influx of seawater. Davidson et al. (1991) characterized estuaries in Great Britain. Ishitobi et al. (1999) described physical effects resulting from seawater intrusions into the coastal lake Shinja. Godo et al. (2001) described the effects of wind on the mixing of water from two coastal lakes in Japan. Murray (2002) wrote about the natural environment and its effect on an estuary-type lake. Spagnoli et al. (2002) described the hydrological and sedimentation characteristics of the Laguna di Varano along the northern Gargano coast in Italy. Whittecar et al. (2005) wrote about seawater intrusions into a hollow along the Chesapeake Bay in the United States. Mosquera et al. (2005) determined the effect of the wind on seawater intrusions into Venice Bay.

Hsing-Juh et al. (2006) described the structure and function of a tropical lagoon experiencing minor seawater intrusions. Macdonald et al. (2006) wrote about surface runoff and its effects on the chemistry of sediments in estuary-type lakes. Sanderson and Baginska (2007) determined the influx of seawater into coastal lakes in New South Wales, Australia, caused by fluctuations in ocean water levels. A number of researchers have ascribed estuary-type characteristics to various lakes (Beletsky et al., 1999; Piasecki, Sanders, 1999).

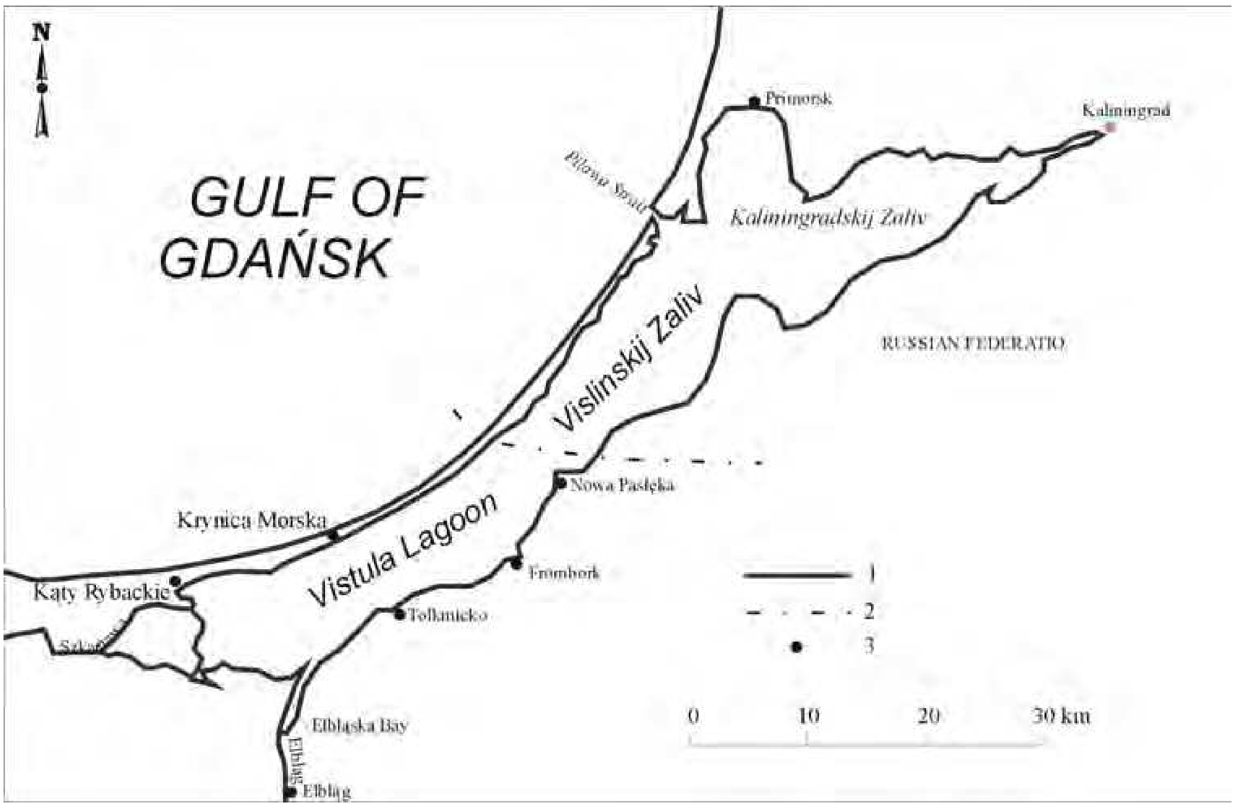
Seawater intrusions along the southern Baltic coast vary in extent and hydrochemical effects. The nature of the effect depends on the body of water and whether the given body of water is isolated or is part of a larger system of bodies of water.

4. Types of hydrographic entities experiencing seawater intrusions

The following types of bodies of water have been found to experience seawater intrusions: lagoons, standing water, mouths of rivers, canals linking lakes with the sea, wetlands, hydrographic systems. The research literature offers insight into the course of seawater intrusions and their effects.

4.1 Lagoons

Vistula Bay is connected to the Baltic Sea via the Strait of Pilawa (Fig. 2). The capacity of the bay is estimated at 2.3 km^3. The water salinity level in the nearby Bay of Gdansk is three times higher than that in Vistula Bay. The maximum depth of Vistula Bay is only 5.1 m, which favors the mixing of water from top to bottom. Water salinity in the bay can be classified in terms of salinity zones (Fig. 3). The lowest chloride concentrations are found in the western part of the bay (site no. 8). The western part of the bay is affected by the inflow of Nogat River. The highest chloride concentrations are found in the northeastern part of the bay (site nos. 1, 2, 3, 4). The salinity zones shift based on the rate of water exchange with the Baltic Sea and the magnitude of river water inflow.



1 – rivers, 2 – border of Russian Federation and Poland, 3 – more important town

Fig. 2. Vistula Lagoon.

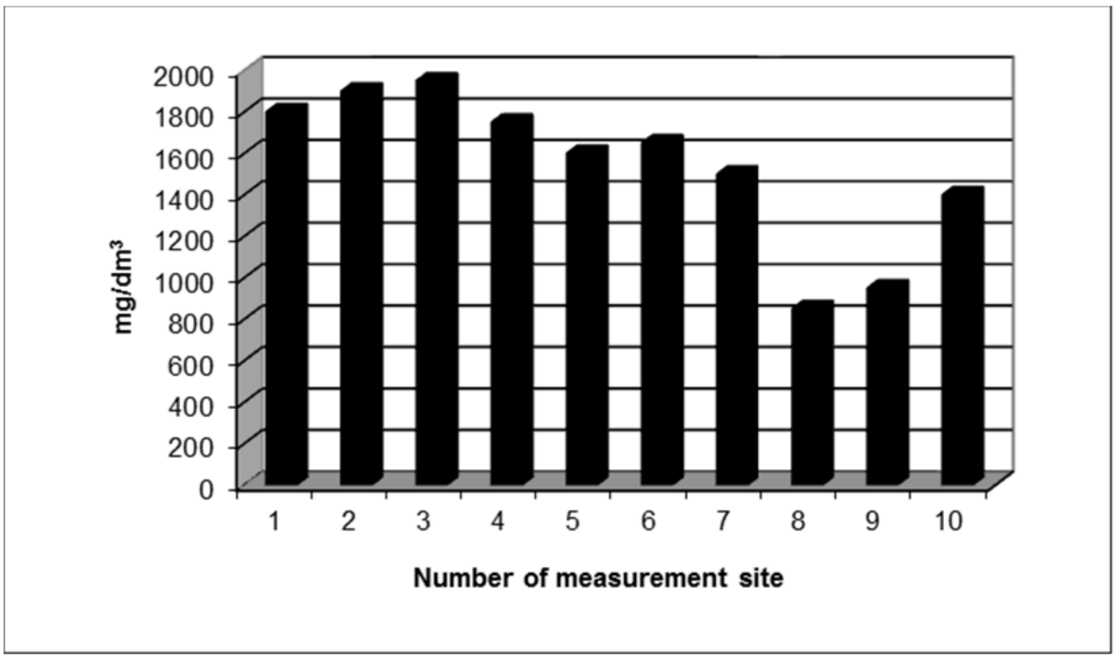


Fig. 3. Mean concentrations of chloride in the surface waters of Vistula Bay in 1996.

The mean concentration of chloride in the period 1996-98 ranged from 1,373 to 1,991 mg/dm^3. Extremely low and extremely high concentrations were noted in 1998 (121 mg/dm^3) and 1997 (3,025 mg/dm^3) (Elbląg WIOS[1] data). Low concentrations of chloride were detected during the spring surface runoff season in the drainage basin. High concentrations of chloride were detected at low bay water levels during the summer and during the autumn (mainly October) when Baltic sea storms are more common (Fig. 4), which results in more seawater intrusions. This is shown by measurements performed in 1996-98, which indicate elevated chloride concentrations at measurement site A (1,005 – 1,495 mg/dm^3). The concentration of chloride varied substantially at measurement site B ranging from 132 to1,783 mg/dm^3.

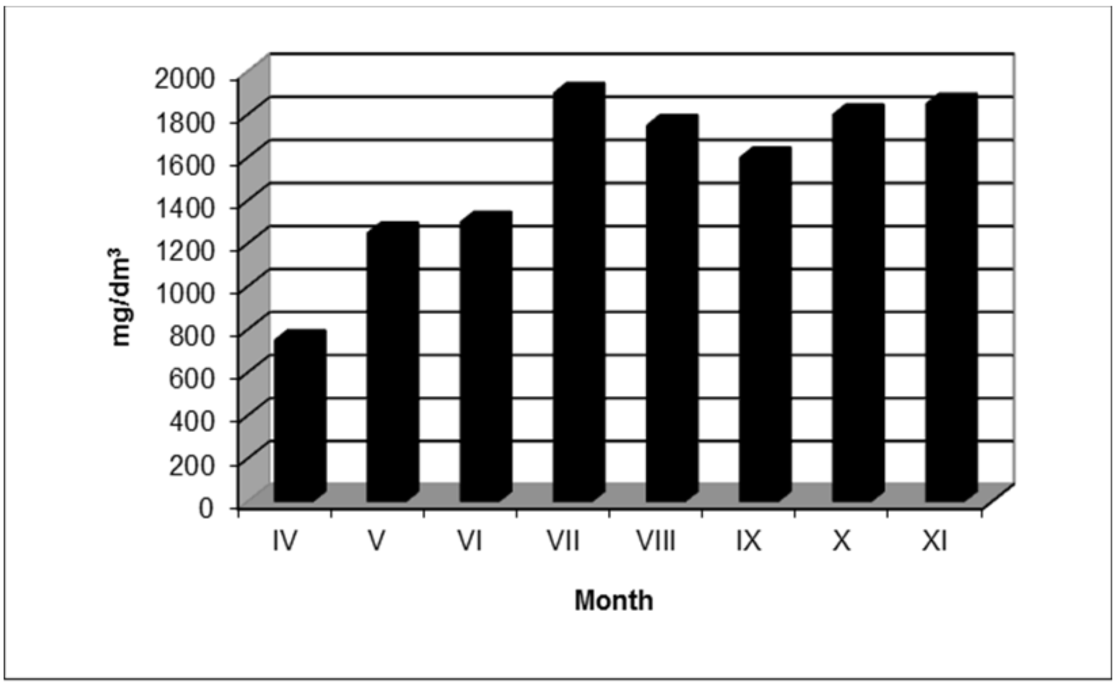


Fig. 4. Mean monthly concentrations of chloride (1996) in the surface waters of Vistula Bay.

4.2 Bodies of standing water

The coastal area along the southern Baltic Sea includes a number of bodies of standing water such as large lakes as well as small lakes formed in old hollows resulting from an uneven distribution of sediment in river deltas and due to being cut off from larger bodies of water thanks to sediment accumulation. Large lakes with mean chloride concentrations exceeding 200[2] mg Cl^- dm^{-3} include lakes Koprowo, Resko Przymorskie, Jamno, Bukowo, Gardno, Łebsko (Fig. 5). Corresponding small lakes include lakes Ptasi Raj and Karaś, (Fig. 5). Research in the period 2002-07 has shown that the concentration of chloride does not fall below 200 mg Cl^- dm^{-3} in lakes Koprowo, Resko Przymorskie, Bukowo and Łebsko (Tab. 1). It may, therefore, be inferred that these lakes constantly experience seawater intrusions. The weakest intrusions affect Lake Koprowo (320 - 780 mg Cl^- dm^{-3}).

---

[1] Provincial Inspectorate of the Environmental Protection

[2] 200 mg Cl- dm-3 is a boundary value signifying the impact of marine water

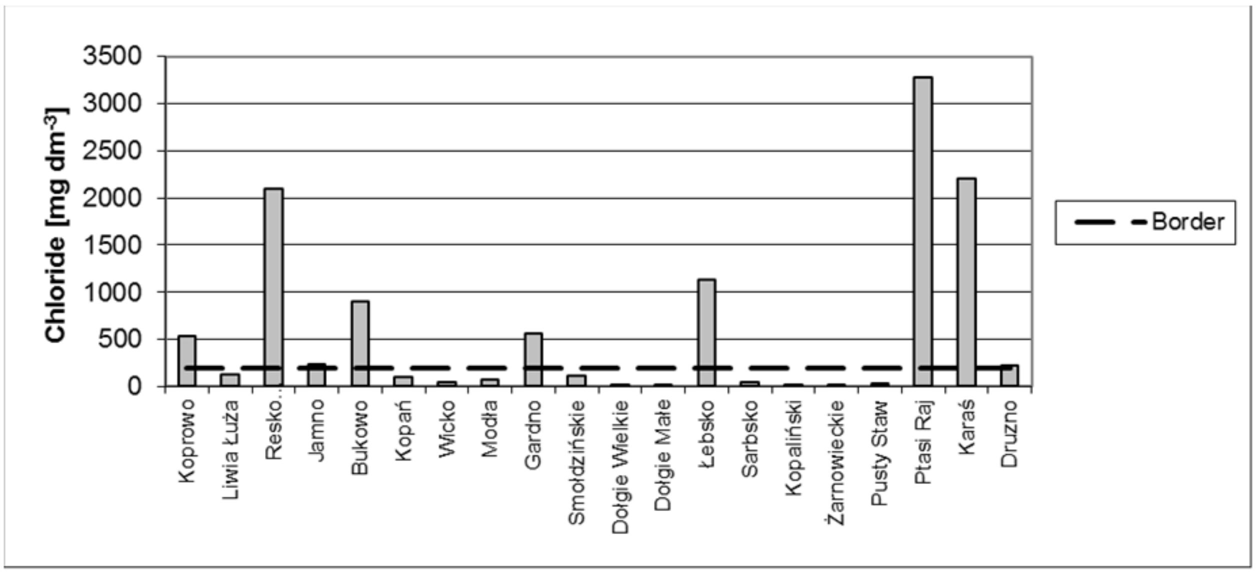


Fig. 5. Mean concentration of chloride in bodies of standing water in 2002-07

Name of lake	Minimum	Maximum
Koprowo	320,0	780,0
Liwia Łuża	90,0	170,0
Resko Przymorskie	1560,0	2700,0
Jamno	70,0	698,0
Bukowo	531,0	1188,0
Kopań	85,2	112,1
Wicko	38,2	66,6
Modła	26,4	152,0
Gardno	13,9	1512,0
Smołdzińskie	81,7	240,0
Dołgie Wielkie	13,0	18,9
Dołgie Małe	9,1	11,9
Łebsko	409,0	1970,0
Sarbsko	21,0	87,7
Kopalińskie	10,0	30,0
Żarnowieckie	8,3	28,6
Pusty Staw	33,4	40,9
Ptasi Raj	2311,0	4090,0
Karaś	1830,0	2703,0
Druzno	39,0	652,0

Table 1. Extreme chloride concentrations in bodies of standing water in 2002-07.

The concentration of chloride did not exceed 200 mg Cl^- dm^{-3} in the following lakes: Liwia Łuża, Kopań, Wicko, Modła, Dołgie Wielkie, Dołgie Małe, Sarbsko, Kopalińskie, Żarnowieckie and Pusty Staw. This indicates that each of the above lakes is being constantly supplied by freshwater from the drainage basin (Tab. 1).

Lake Gardno is yet another type of case of seawater intrusion. The concentration of chloride is very high in Lake Gardno for most of the year. The maximum recorded concentration is 1,512 mg Cl^- dm^{-3}. However, the lake's salinity decreases substantially during certain periods of time and can reach as low as 13.9 mg Cl^- dm^{-3} (Fig. 6). While the Baltic Sea is the dominant factor in the lake's salinity level, freshwater influx from the lake's drainage basin can also play a role in some situations.

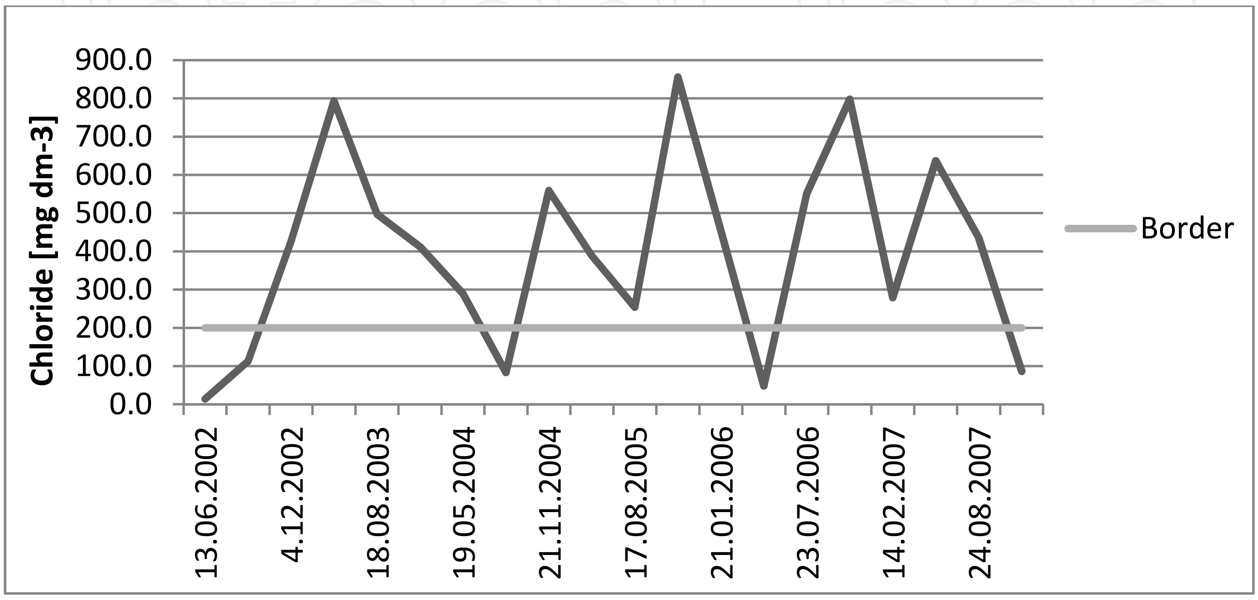


Fig. 6. Changes in chloride concentration in Lake Gardno for the period 2002-07.

The concentration of chloride in Lake Jamno generally remains below 200 mg Cl^- dm^{-3} and freshwater chloride levels tend to be common. The minimum concentration of chloride detected in Lake Jamno was 70 mg Cl^- dm^{-3}. Seawater intrusions in Lake Jamno can cause abrupt increases in chloride concentration across the entire lake or in certain parts of the lake (698 mg Cl^- dm^{-3}).

Two good examples of the Baltic Sea impacting the chemistry of a small lake originating as a puddle due to uneven sediment accumulation in a delta are Lake Ptasi Raj (mean concentration: 3,284 mg Cl^- dm^{-3}) and Lake Karaś (mean concentration: 2,212 mg Cl^- dm^{-3}). The lowest chloride concentration recorded during the summer in Lake Ptasi Raj was 2,311 mg Cl^- dm^{-3}, while the highest concentration was 4,090 mg Cl^- dm^{-3}. The lake is permanently affected by water from the Baltic Sea.

4.3 Canals linking lakes with the sea

Lake Gardno is linked with the sea by a canal 1 km long and 15-20 m wide (gradient: 0.3 ‰) (Fig. 7). The rate of water flow from the lake to the sea ranged from 6.3 to 11.8 m^3 s^{-1} during the study period. The direction of flow becomes reversed with winds from the north and a higher water level in the sea versus the lake. In 15 of 16 cases observed during the 2002-07 study period, the concentration of chloride ranged from 250 mg Cl^- dm^{-3} to just under 2,000 mg Cl^- dm^{-3}, which indicates seawater intrusions (Fig. 8). The chloride concentrations in the lake were close to those in the Baltic Sea itself.

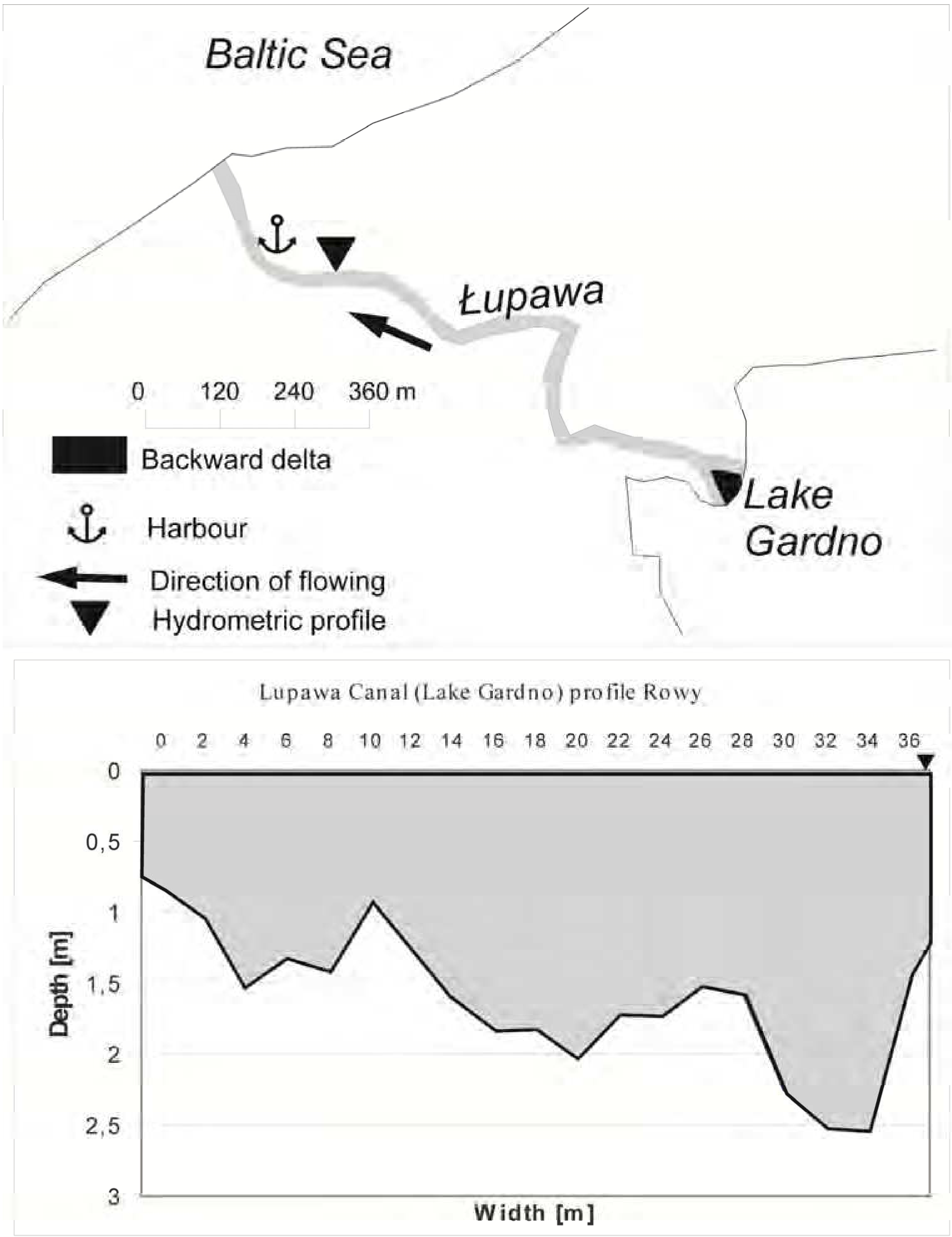


Fig. 7. Łupawa Canal linking Lake Gardno with the Baltic Sea.

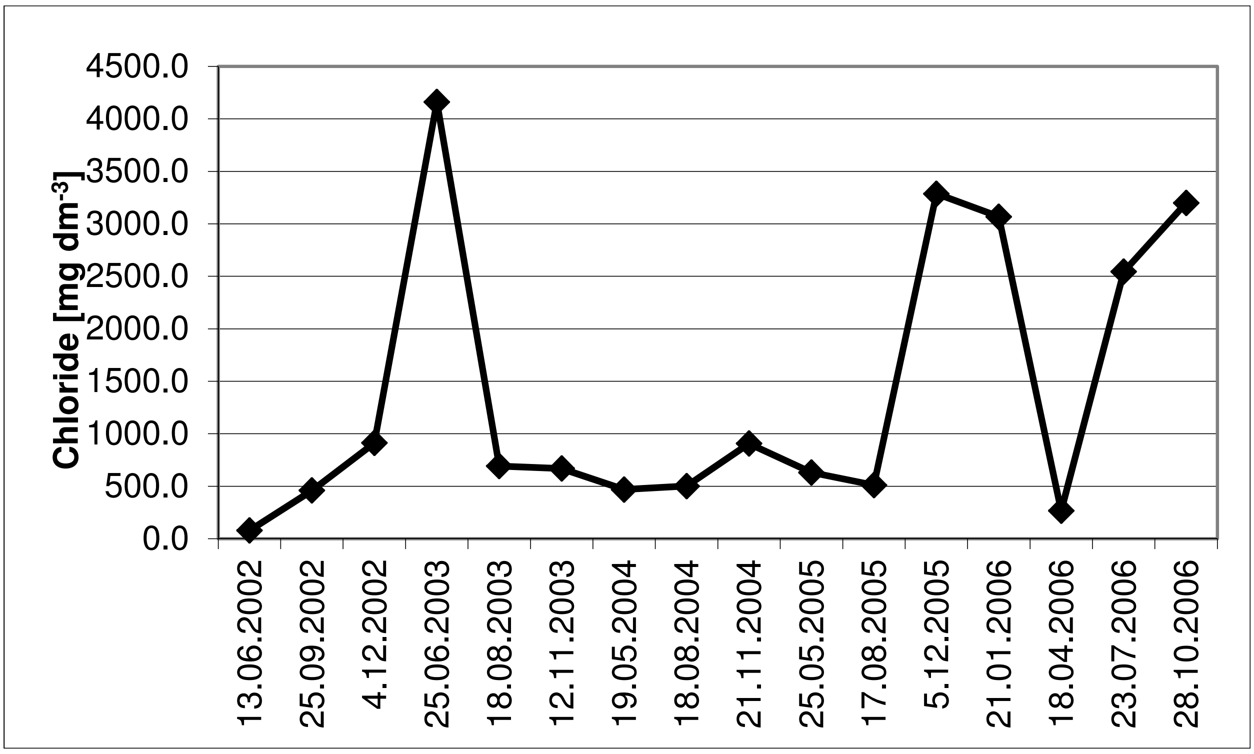


Fig. 8. Chloride concentrations in the canal linking Lake Gardno with the Baltic Sea (2002-06).

Lake Łebsko is linked with the sea by a canal about 2.7 km long and 5-25 m wide (gradient: 0.11‰) (Fig. 9). The rate of water flow from the lake to the sea ranged from 10.2 to 24.3 $m^3 s^{-1}$ during the study period. When the hydrometeorological conditions are right, the direction of flow can become reversed. This occurred on Nov. 10, 2006 with a rate of full channel sea-to-lake water flow of 54 $m^3 s^{-1}$. The concentration of chloride in the Łeba Canal is persistently high, which indicates that seawater intrusions do not occur (16 observations, 2002-07) regardless of hydrometeorological conditions. The seawater effect is more pronounced during sea storms in the autumn and winter and less pronounced at low sea levels in the summer and during snowmelt season. In addition, the concentration of chloride in the canal increases with decreasing distance to the sea (Fig. 10).

4.4 Mouths of small rivers

The Reda River is 45 km long and has a drainage basin of 485 km^2 and empties into Puck Bay – a part of the larger Gdansk Bay. The Reda river channel is 6-13 m wide and 0.5 – 1.0 m deep. Its discharge is 4.1 – 6.3 $m^3 s^{-1}$. The duration of temporary increases in chloride concentration in rivers is related to the duration of favorable winds. The concentration of chloride at the mouth of the river was 1,142.7 mg/dm^3 (Fig 11) on May 20, 2004. The presence of water from Puck Bay can be traced to easterly winds with a speed of more than 10 m s^{-1}.

The Płucnica River is 9.2 km long and has a drainage basin of 85.2 km^2. The river's mean discharge is 0.47 $m^3 s^{-1}$. It empties into Puck Bay. The concentration of chloride did not exceed 100 mg Cl^- dm^{-3} (Fig. 12) during the two-year study period. The concentration of chloride did not fall below 20 mg Cl^- dm^{-3} either. This indicates that the mouth of the river is affected by the sea to some extent but that extent is not significant enough to warrant the conclusion that seawater intrusions are taking place.

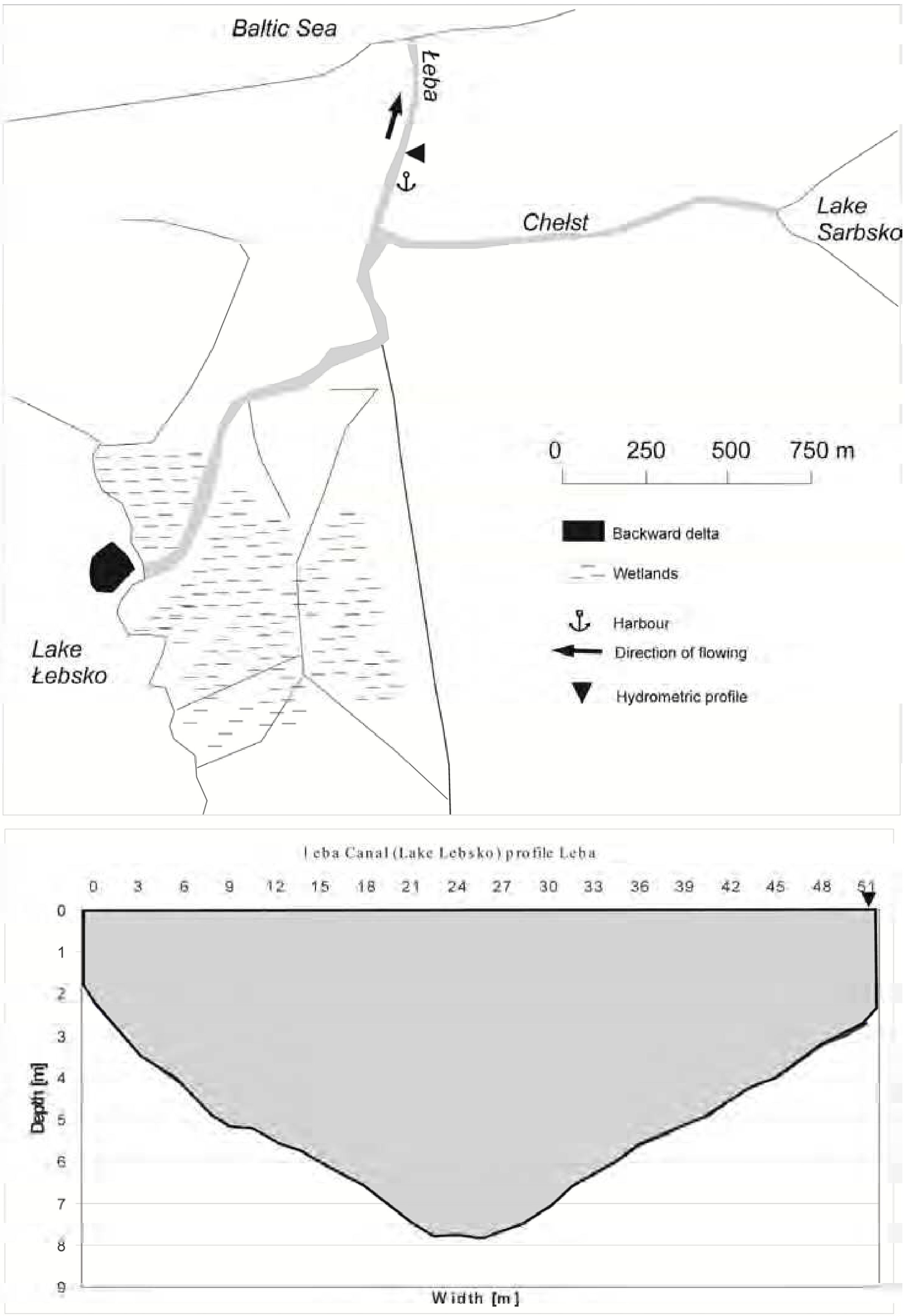


Fig. 9. Łeba Canal linking Lake Łebsko with the Baltic Sea.

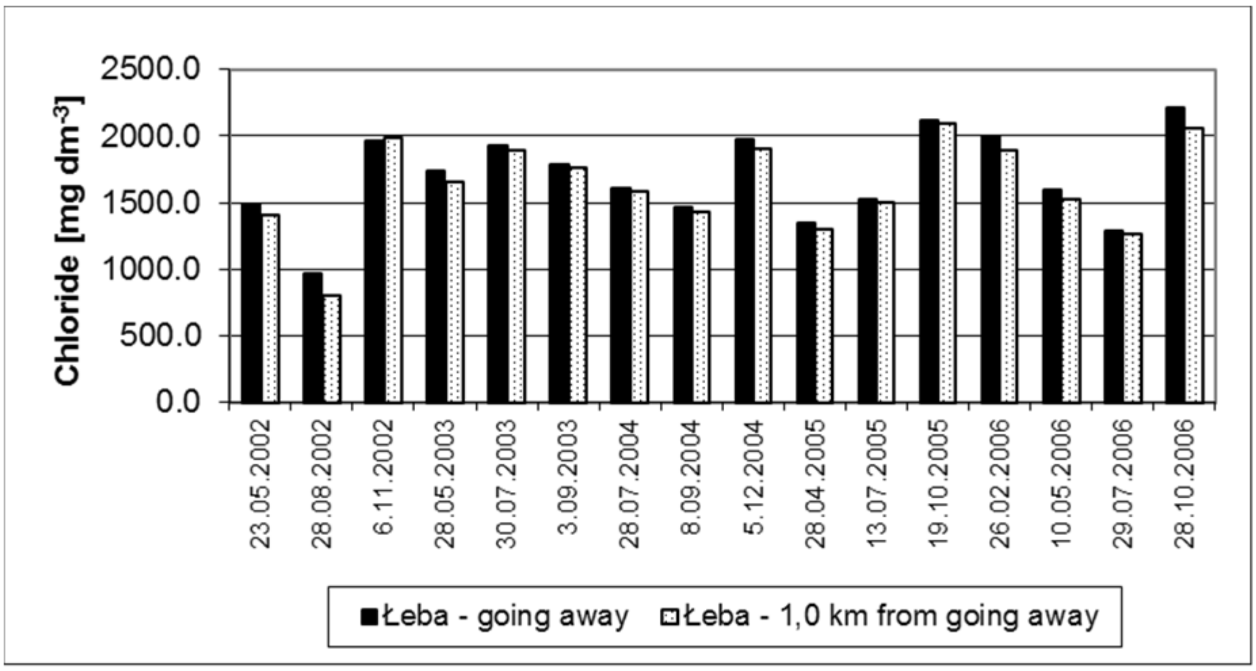


Fig. 10. Concentration of chloride in the Łeba Canal in the period 2002-07.

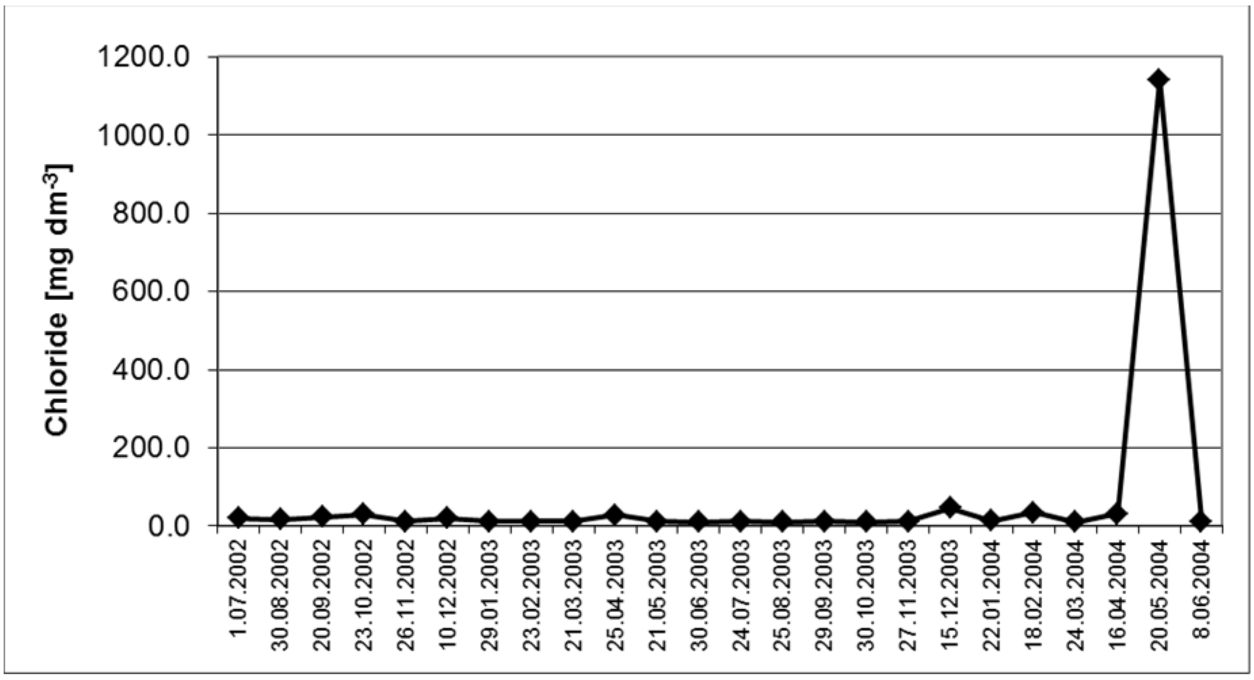


Fig. 11. Concentration of chloride at the mouth of the Reda River in the period 2002-04.

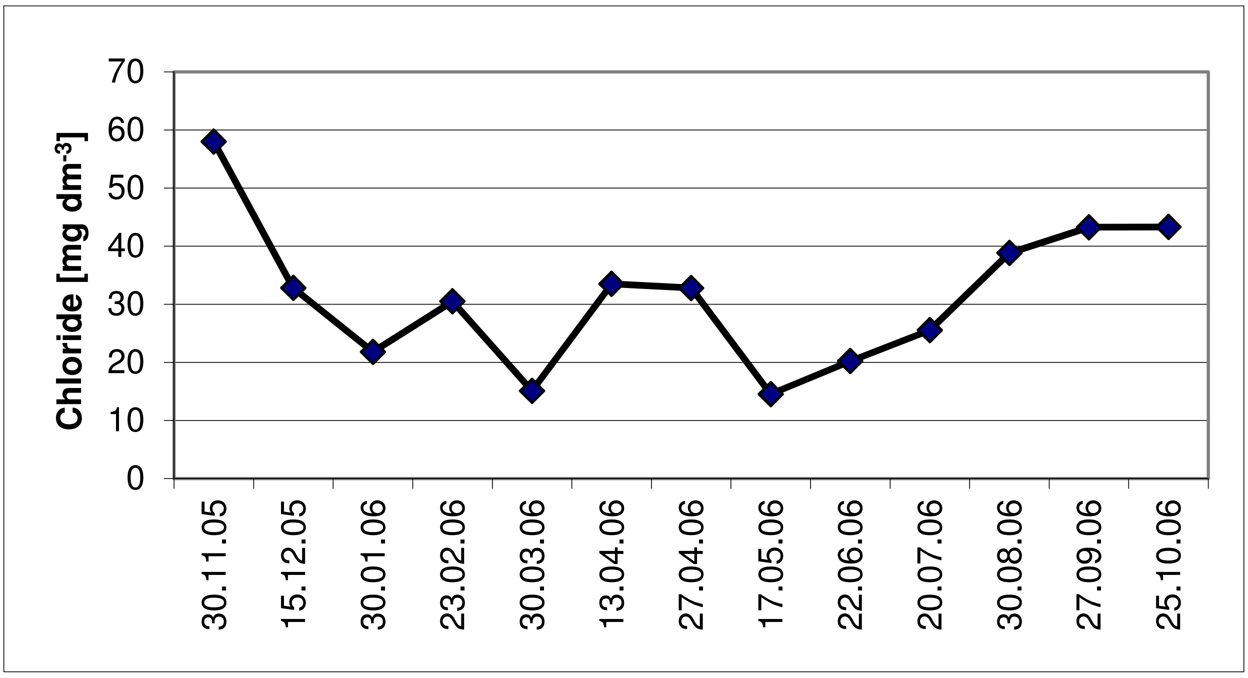


Fig. 12. Chloride concentration in the Płutnica River versus time.

4.5 Wetlands

Wetlands found along the southern coast of the Baltic Sea are unique in that they serve as focal points for seawater intrusions taking place in a variety of bodies of water. Beka Preserve is one such wetland area. The effects of seawater intrusions can be observed here at the mouth sections of the Reda and Zagórska Struga rivers as well as in a dense network of drainage ditches and swamplands. The water balance in Beka Preserve is affected by direct seawater intrusions from Puck Bay, the impediment of surface runoff resulting from temporary increases in base water levels, the flow of seawater over coastal embankments and the influx of brackish groundwater.

This diverse array of water effects divides Beka Preserve into several parts (Fig. 13). The northern part is adjacent to an upland and receives its surface runoff as well as precipitation. Its waters are not very saline. The central part includes a lot of saline puddles and saline groundwater. The western part is affected by freshwater flowing from the interior as well as by brackish water flowing over an embankment from time to time.

Persistently high concentrations of chloride (1,500 to almost 4,500 mg/dm^3) were detected in the Beka Canal, the Unnamed Canal and the Jan Canal during the period 2002-04. Chloride concentrations remained under 20 mg*dm^3 (Fig. 14) in other bodies of water. All of the investigated bodies of water with high chloride concentrations feature stagnant water and do not possess a direct link to the sea. The wetlands also feature puddles of marine water as a result of embankment overflow and wind-carried spray (Fig. 15).

Research data indicates that groundwater is responsible for hydrological differences in Beka Preserve. This is confirmed for the northern part of the preserve (piezometer A) by chloride concentrations ranging from 50 to 80 mg*dm^3 Cl$^-$. This concentration is the result of groundwater flowing down from the upland. The remaining piezometers (B – F) recorded high concentrations of chloride (1,000 – 3,500 mg/dm^3 Cl$^-$), which is a lot higher than the chloride concentrations detected in surface bodies of water. In addition, the fluctuations in chloride concentration in groundwater and the level of groundwater are consistent with fluctuations in Puck Bay. This suggests that seawater from Puck Bay may be encroaching via underground pathways.

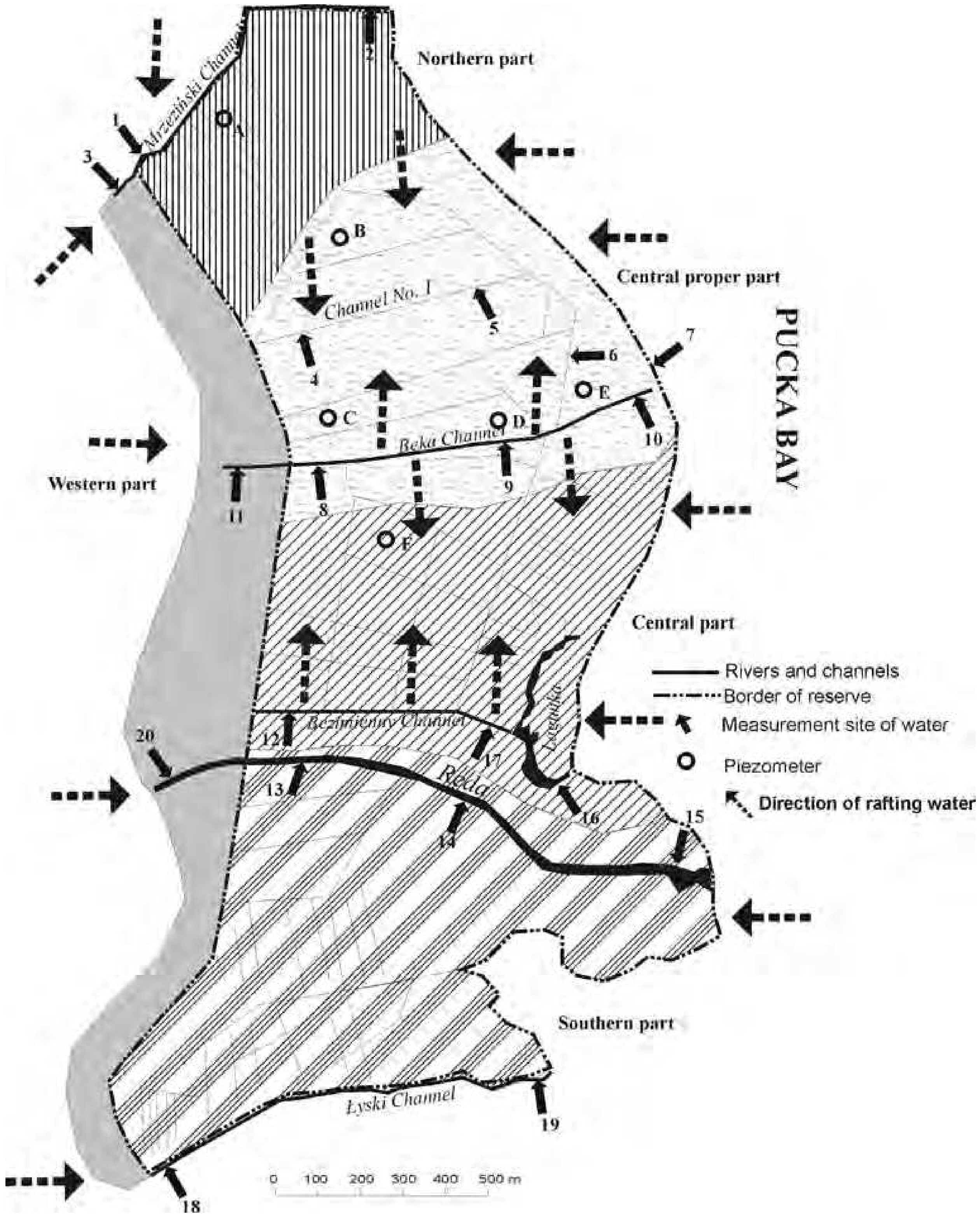


Fig. 13. Differences in water chemistry across Beka Reserve.

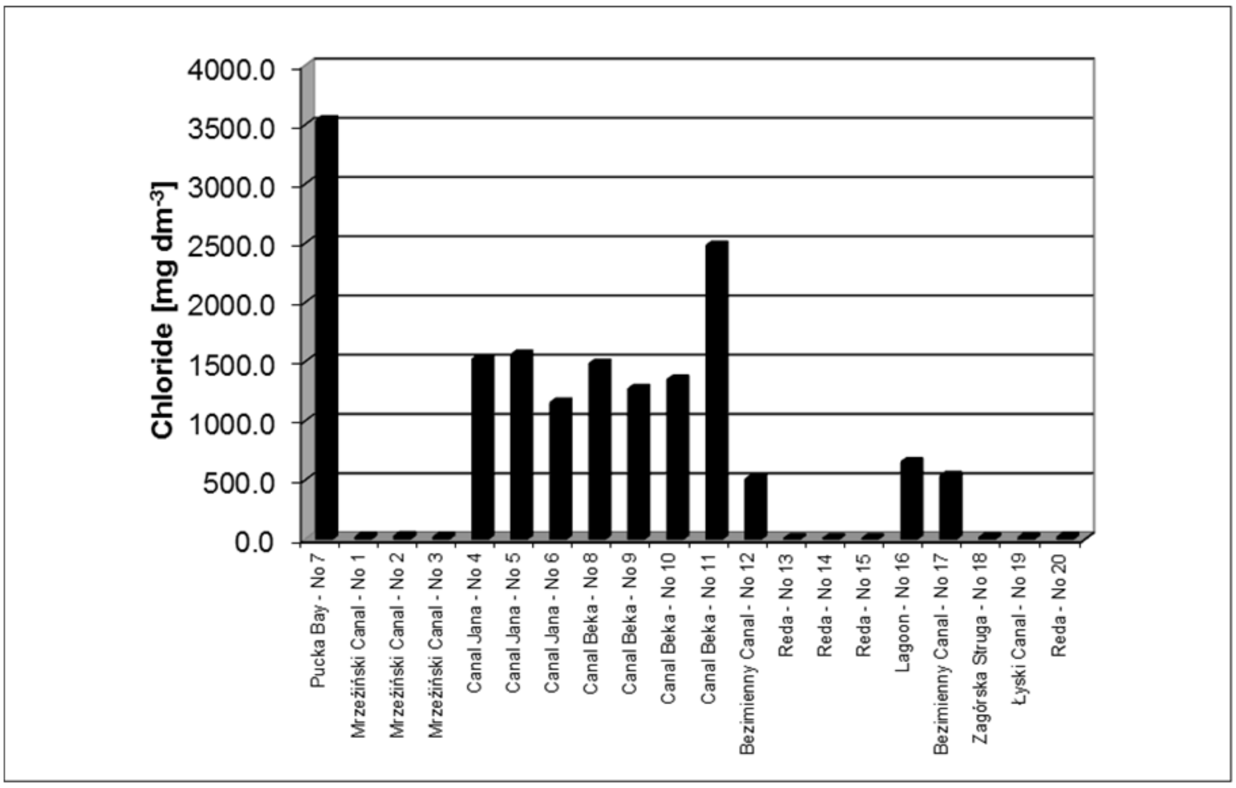


Fig. 14. Concentration of chloride in selected bodies of water on July 15, 2003.

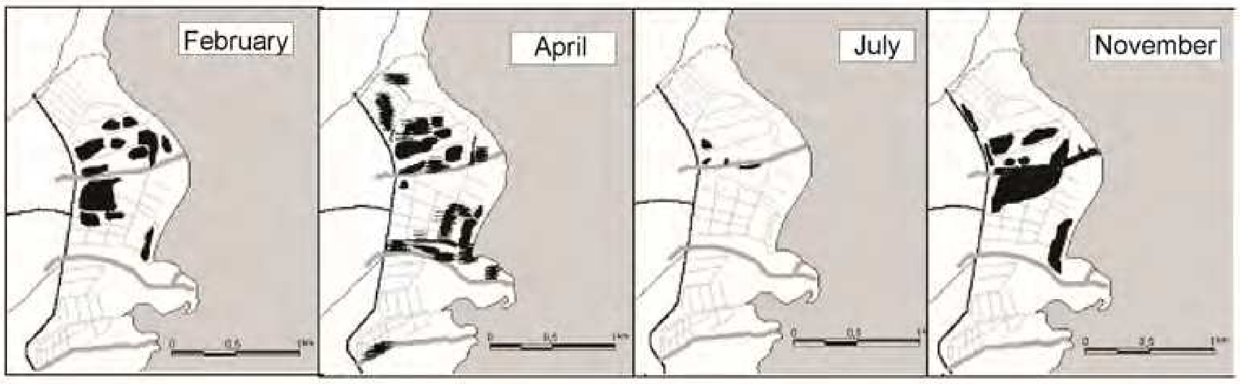


Fig. 15. Changes in wetland surface area on a seasonal basis.

Hence, it may be inferred that this wetland area is affected primarily by periodic seawater intrusions as well as by marine water flowing over coastal embankments and being carried by the wind.

4.6 Hydrographic systems

The extent of seawater impact along the southern Baltic coast is larger in places where bodies of water form hydrographic systems.

The Martwa Wisła River and the Śmiała Wisła River as well as the mouth of the Wisła River (via a sluice) form this type of system. The Martwa Wisła (Fig. 16) is an old arm of the Wisła River and today remains separated from the mouth section of the main river channel. The

Śmiała Wisła is an old breach in a sandbar that occurred in 1840. The Śmiała Wisła is about 2.5 km long and 150-200 m wide.

Today this section of river also connects the Martwa Wisła with the Baltic Sea. The eastern section of the Martwa Wisła remains a flooding arm, whereas the western section serves as a port channel. Discharge in the Martwa Wisła varies substantially as does the direction of flow (Jasińska, 1997). This and the river's direct link with the Bay of Gdansk cause mean annual salinity to remain high where the river meets the sea (6.13‰), somewhat lower in the central part (4.71‰) and the lowest in the western part (3.48‰) (Jasińska, 1997).

This general pattern is interrupted by the influx of river water (salinity in the Motława > 1‰) and seawater via the Śmiała Wisła. Seawater intrusions have been shown to penetrate the river in the period 2002-03 in a manner characteristic of estuaries – a wedge along the bottom (Cameron, Pritchard, 1963; Davidson et al., 1991).

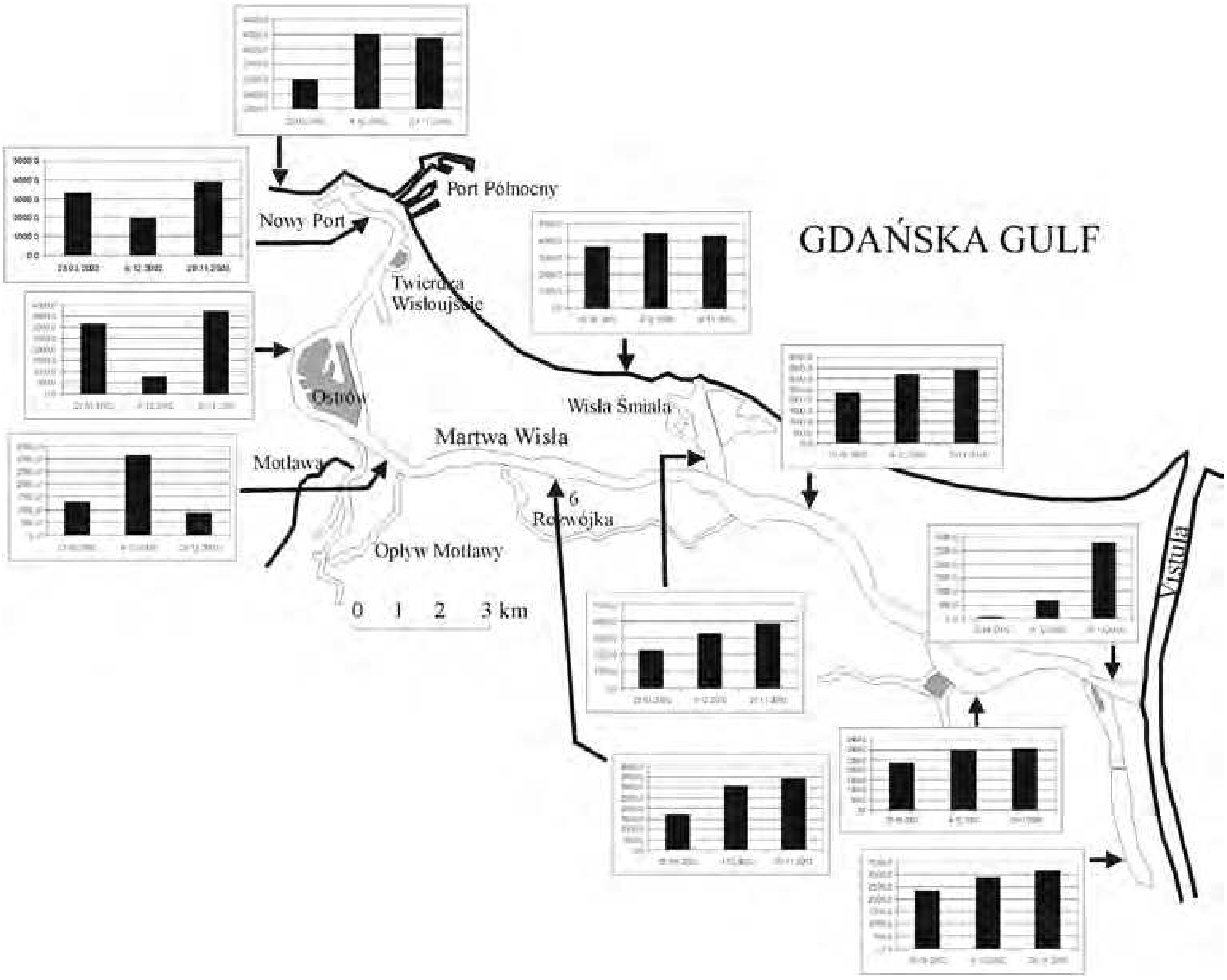


Fig. 16. Chloride concentration in the Martwa Wisła and the Śmiała Wisła in 2002-03.

Elbląg Bay, the Elbląg River and Lake Druzno form yet another hydrograhic system in the eastern Vistula Delta. Lake Druzno is fed by a land drainage basin. Water exits the lake via the Elbląg River, which empties into Elbląg Bay. Seawater periodically enters the lake via this same water route (22 – 33 % of annual discharge).

Mean values of both sea-based and land-based data indicate that the entire system experiences the chemical impact of Vistula Bay. Seawater intrusions were detected in 16 of 35 cases analyzed in 1997-99. Major intrusions were noted on Sept. 24, 1997, Aug. 26, 1998, Feb. 25, 1999 and Oct. 6, 1999. Minor intrusions were noted on July 9, 1997, Oct. 30, 1997 and Jan. 22, 1998.

Mean chloride concentrations were always detected closer to the sea (Fig. 17). It has also been shown that the chloride concentration in the middle part of Lake Druzno is always higher than in the lake's tributaries. This shows that water chemistry in Lake Druzno is substantially affected by seawater intrusions from Vistula Bay.

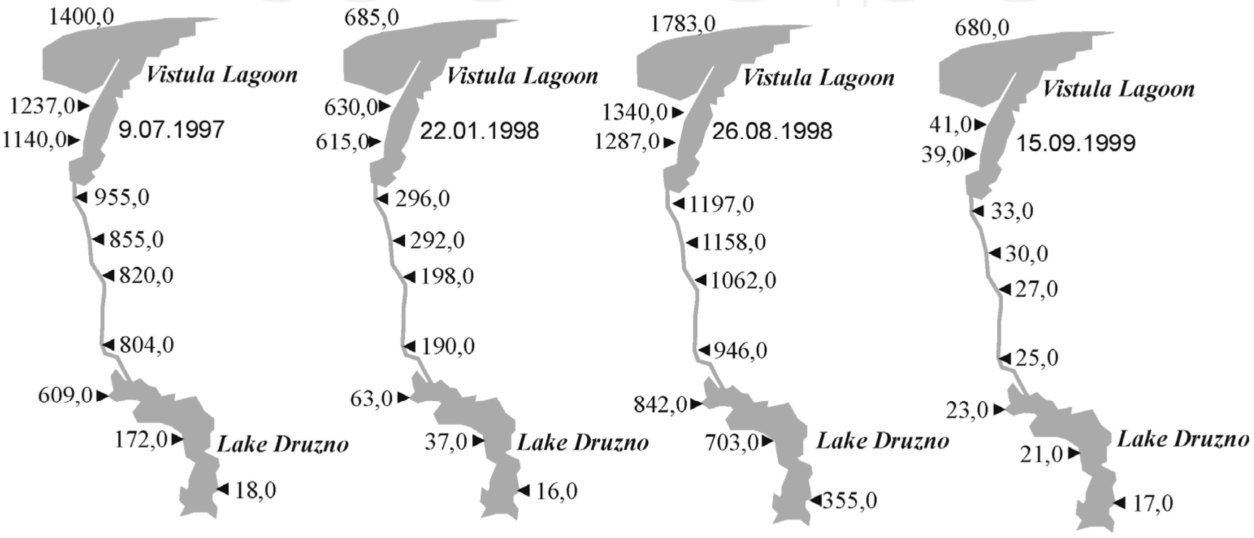


Fig. 17. Chloride concentration in the Elbląg Bay – Elbląg River – Lake Druzno hydrographic system for selected periods.

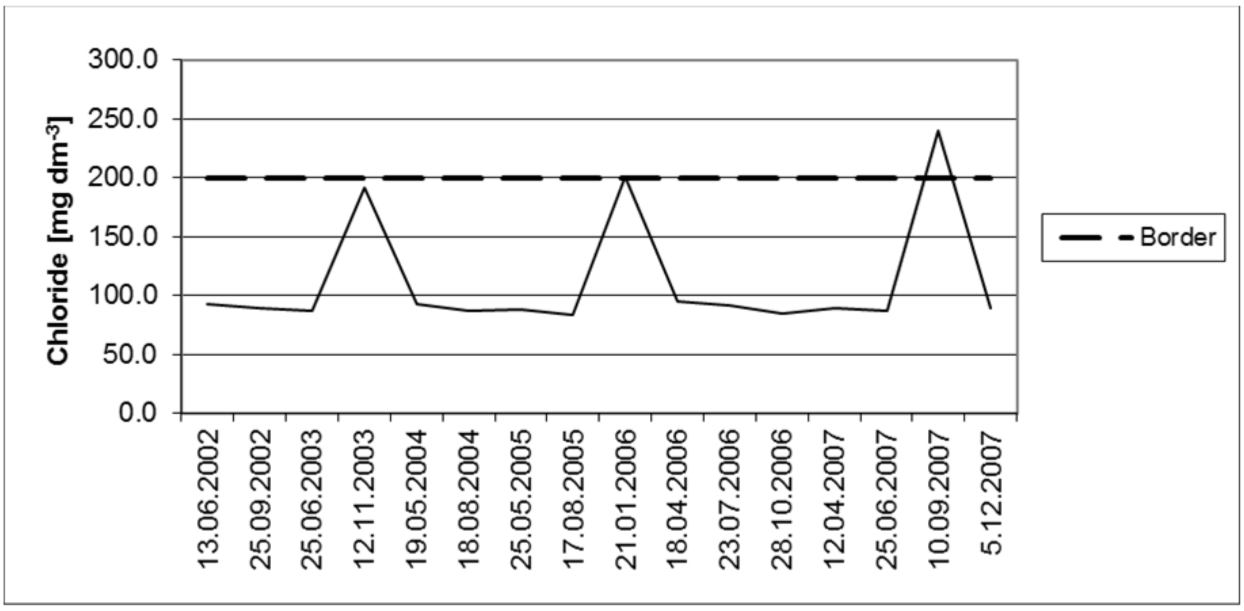


Fig. 18. Chloride concentration in Lake Smołdzińskie in the period 2002-07.

In the period 1996-98, the concentration of chloride ranged from 26 to 1,345 mg/dm^3 in Elbląg Bay, from 15 to 1,197 mg/dm^3 in the Elbląg River and from 12 to 824 mg/dm^3 in the southern part of Lake Druzno.

Another example of a hydrographic system experiencing periodic marine impact is the following system: canal linking Lake Gardno to the sea, Lake Gardno, river linking Lake Gardno with Lake Smołdzińskie, Lake Smołdzińskie. While the concentration of chloride normally does not exceed 200 mg Cl^- dm^{-3} in Lake Smołdzińskie, minor exceptions do exist (Fig. 18).

5. Conclusions

The water balance along the southern Baltic coast is affected by land-based water drainage, seawater intrusions produced by fluctuating sea levels driven by wind surges, hydrographic entity types and the water balance between these types. The stated hypothesis has been shown to be true – the hydrochemical effect of seawater intrusions depends on the type of hydrographic entity and whether that entity is stand-alone or part of a hydrographic system.

Bodies of water such as Vistula Bay experience seawater effects throughout, although their intensity varies spatially. In this case, the coastal zone consists of the surface of Vistula Bay and other bodies of water linked to it.

In bodies of standing freshwater, the hydrochemical effects of seawater vary substantially and depend on the size of the given body of water as well as its location relative to the sea. Large lakes such as Koprowo, Resko Przymorskie, Bukowo and Łebsko constantly exerience seawater intrusions, which makes them similar to lagoons (Drwal, Cieśliński, 2007). Lake Gardno experiences seawater intrusions most of the year but also experiences periods of lower salinity. Gradient appears to play a major role in this case. Nevertheless, all of the studied lakes are affected by seawater intrusions.

Lake Jamno is primarily a freshwater lake but it does experience some seawater intrusions, which cause a sudden rise in chloride concentration in some parts of the lake. Small lakes close to the sea such as Ptasi Raj and Karaś constantly experience seawater intrusions. The extent of the coastal zone is the same for bodies of standing water and lagoons – area of the given body of water plus that of other bodies of water linked to it.

Canals linking the lakes of interest with the sea are the only routes where seawater can travel towards the interior of the coastal zone. Freshwater and seawater can travel either inland or towards the sea via the full cross section of each canal – a classic example of an estuary.

The hydrochemical effect of the sea in the mouths of small rivers is small and not strong enough to be labeled a seawater intrusion. The small cross section of small rivers may help explain this inference. In this case, the coastal zone is virtually limited to the mouth of the given river.

The occasionally elevated concentration of chloride in wetlands may be the result of occasional underground seawater intrusions as well as seawater being carried inland by the wind or simply splashing over embankments. Underground penetration is more likely since surface flow is impeded by coastal infrastructure.

Hence, it may be inferred that wetlands experience periodic seawater intrusions primarily via underground pathways as well as via splashing over embankments and seawater carried by the wind.

Seawater penetrates inland in a classic estuary-type wedge fashion along the bottom in hydrographic systems such as the one formed by the Martwa Wisła and Śmiała Wisła and the mouth of the Wisła River (via a sluice). This system is made up of old flooding arms of the Wisła River and a breach in a sandbar. In other systems – such as the Elbląg Bay, Elbląg River, Lake Druzno system – the coastal zone expands. This happens in areas with lagoons or large bodies of standing freshwater.

Effects associated with marine impact on coastal inland water systems along the southern Baltic Sea – a virtually land-locked sea with negligible tides and a young glacial Pleistocene sediment base – are reminiscent of those taking place along open seas.

6. References

Appelo C.A.J., Willemsen A., 1987, Geochemical calculations and observations on salt water intrusions, a combined geochemical/mixing cell model, J. Hydrology, 94, 313-330.

Bear J., Cheng A.H.-D., Sorek S., Ouazar D., Herrera I. (eds.), 1999, Seawater Intrusion in Coastal Aquifers - Concepts, Methods, and Practices, Kluwer Academic Publishers, Dordrecht/Boston/London, ss. 266.

Beletsky D., Schwab D., McCormick M., Miller G., Saylor J., Roebber J., 1999, Hydrodynamic modeling for the 1998 lake Michigan coastal turbidity plume ewent, [in:] M. Spaulding and H.L. Butler (eds), Estuarine and coastal modeling. American Society of Civil Emgineers, Virginia, 597–613.

Bowden K.F., 1967, Circulation and diffusion, [in:] G.H. Lauff (ed.), Estuaries, AAAS Publ., No. 83, Washington, 15–36.

Cameron W. M., Pritchard D. W., 1963 , Estuaries. The Sea , New York-London, vol. 2.

Cieśliński R., 2004, Application of arithmetic formulae in determining volume of sea waters inflow into Elbląska Bay – river Elbląg – lake Druzno hydrological system, Acta Geophysica Polonica, vol. 52, No. 4, 521 – 539.

Cieśliński R., Drwal J., 2005, Quasi - estuary processes and consequences for human activity, South Baltic, Estuarine, Coastal and Shelf Science, vol. 62, 477 – 485.

Davidson N. C., d'Alaffoley D., Doody J. P., Way L. S., Gordon J., Key R., Pieńkowski M. W., Mitchell R., Duff K. L., 1991, Nature conservation and estuaries in Great Britain, Estuaries Review Chief Scientist Directorate Nature Conservancy Council Northmister House, Peterborough.

Davies S., DeWiest R., 1966, Hydrogeology, Wiley, New York, ss. 245.

Drwal J., 1995, Impact of Baltic Sea on Ground Water and Surface Water in Żuławy Wiślane (Vistula Delta), [in:] Polish Coast: Past, Prezent and Future ed. by Karol Rotnicki, Journal of Coastal Research, Special Issue No. 22 CERF, p. 166-171.

Drwal J., Cieśliński R., 2007, Coastal lakes and marine intrusions on the southern Baltic coast, Oceanological and Hydrobiological Studies, Vol. XXXVI, No. 2 2007, 61 – 75.

Dziadziuszko Z., 1994, Sea-level Fluctuations [in:] Atlas of the Baltic Sea, A. Majewski and Z. Lauer (eds), IMGW, Warszawa

Flynn K. M., McKee K. L., Mendelssohn I. A., 1995, Recovery of freshwater marsh vegetation after a saltwater intrusion event, Journal of Oceanology, vo. 103, No. 1, 63–72.

Folk R.L., 1974, The natural history of crystalline calcium zarbonate: effect of magnesium content and salinity, Journal of Sedimentary Petrology, 44, 1, 40-53.

Foster I.D., 1980, Chemical yields in runoff, and denudation in a small arable catchment, East Devon, England, Journal of Hydrology, 47, 349–368.

Giambastiani B.M.S., Antonellini M., Gualbert H.P., Essink O., Stuurman R.J., 2007, Saltwater intrusion in the unconfined coastal aquifer of Ravenna (Italy): A numerical model, Journal of Hydrology, Vol. 340, Issues 1-2, 91–104.

Glover R.E., 1959, The pattern of fresh water flow in coastal aquifer, J. Geoph. Research, vol. 64, No. 4, 439–475.

Godo T., Kato K., Kamiya H., Yshitobi Y., 2001, Observation of wind-induced two-layer dynamice in lake Nakaumi, a coastal lagoon in Japan, Limnology, vol. 2, No 2, 137–143.

Halbfass W., 1901, Beiträge zur Kenntnis der Pommerschen Seen, Pett. Mitt. Erg. Heft., 36, p. 131.

Halbfass W., 1904, Weitere beiträge sur kerntnis der Pommerschen Seen, Pet. Mitt, p. 154.

Haslett S.K., 2008, Coastal system, Taylor & Francis, ss. 256.

Hem J.D., 1989, Study and interpretation of the characteristics of natural waters, U.S. Geol. Survey, Water Supply Paper, vol. 2254, ss. 263.

Hsing-Juh, L., Xiao-Xun, D., Kwang-Tsao, S., Huei-Meei, S., Wen-Tseng, L., Hwey-Lian, H., Lee-Shing, F., Jia-Jang, H., 2006, Trophic structure and functioning in a eutrophic and poorly flushed lagoon in southwestern Taiwan, Marine environmental research, 62 (1), 61-82.

Ishitobi Y., Kamiya H., Yokoyama K., Kumagai M., Okuda S., 1999, Physical conditions of saline water intrusion into a coastal lagoon, lake Shinji, Japan, Japanese Journal of Limnology, vol. 60, No 4, 439–452.

Jasińska E., 1997, Hydrodynamic and dynamics of salt water In the Martwa Vistula, Hydrotechnical Transactions, Polish Academy of Sciences, No. 61, 31–41.

Kunisch E., 1913, Der Gardensee und Gr. Dolgensee. Mit einem anhang: Ein Beitrag zur Kenntnis des Lebasees, XII Jahresb. Ges. Greiswald, p. 44.

Łomniewski K., Drwal J., Gołębiewski R., Pelczar M., Pietrucień Cz., Szeliga J., Ziółkowski J., 1972, Zasolenie wód w delcie Wisły, Rozprawy Wydz. III, z. 9, GTN, Gdańsk, 263-276.

Macdonald B.C.T., Smith J., Keene A.F., Tunks M., Kinsela A., White I., 2006, Impacts of runoff from sulfuric soils on sediment chemistry in an estuarine lake, Science of Total Environment, vol. 329, no. 1-3, 115–130.

Majewski A., 1972, Charakterystyka hydrologiczna estuariowych wód u polskiego wybrzeża, Prace PIHM , zeszyt 105 , 3-37.

Mikulski Z., Bojanowicz M., Ciszewski R.., 1969, Bilans wodny jeziora Druzno, Prace PIHM 96, 73-88.

Mosquera I., Cosoli S., Gačić M., Mazzoldi A., 2005, Wind forcing and notidal flow In the inlet sof the Venice lagoon, Geophysical Research, vol. 7, European Geosciences Union, 267–278.

Murray E., 2002, Determining the environmental status of coastal lakes: science for estuary management, Coast to Coast 2002, 315–317.

Piasecki M., Sanders B, 1999, Control of estuarine salinity using the adjoint metod, [in:] M. Spaulding, H.L. Butler (eds), Estuarine and coastal modeling, American Society of Civil Emgineers, Virginia, 1–16.

Pulido-Leboeuf, P, 2004, Seawater intrusion and associated processes in a small coastal complex aquifer (Castell de Ferro, Spain), Appl. Geochem., 19, 1517–1527.

Sanderson B.G., Baginska B., 2007, Calculating flow into coastal lakes from water level measurements, Environmental Modelling & Software, vol. 22, no 6, 774–786.

Saeijs H.L.F., Stortelder P.B.M., 1982, Converting an estuary to Lake Grevelingen: Environmental review of a coastal engineering project, Environmental Management, Vol. 6, No. 5, 377–405.

Spagnoli F., Specchiulli A., Sirocco T., Carapella G., Villani P., Casolino G., Schiavone P., Franchi M., 2002, The Lago di Varano hydrologic characteristic and sediment composition, Marine Ecology, 23, supplement 1, 384–394.

Tanaka, H., Takasaki M., Lee H. S., Yamaji H., 2005, Field observation of salinity intrusion into Nagatsura Lagoon, Taylor & Francis, 871–875.

Tiruneh, N. D., Motz, L. H. 2003, Three-Dimensional Modeling of Saltwater Intrusion in a Coastal Aquifer Coupled with the Impact of Climate Change, World Water & Environmental Resources Congress 2003, American Society of Civil Engineers, Philadelphia, PA, June 23-26, 1079–1087.

Tomczak K., 1995, Geological structure and Holocene Evolution of the Polish Coastal Zone [in:] Polish Coast: Past, Prezent and Future ed. by Karol Rotnicki, Journal of Coastal Research, Special Issue No. 22 CERF,p.13-31

Rotnicki K., 1995, The Coastal Zone - Prezent, Past and Future [in:] Polish Coast: Past, Prezent and Future ed. by Karol Rotnicki, Journal of Coastal Research, Special Issue No. 22 CERF, p.3-13

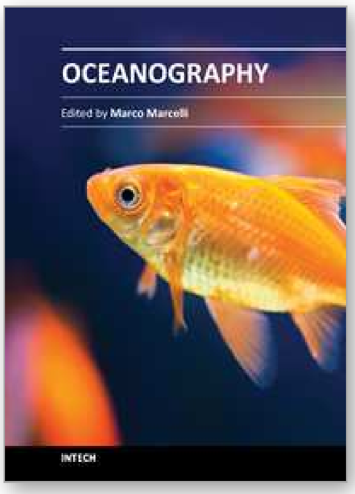
Sztobryn M., Stigge H.J., Wielbińska D., Weidig B., Stanisławczyk I., Kańska A., Krzysztofiak K, Kowalska B., Letkiewicz B., Mykita M., 2005, Storm Surges in the Southern Baltic Sea (Western and Central Parts), Berichte des Bundesamtes für Seeschifffahrt und Hydrographie, Nr. 39

Szopowski Z., 1962, Wybrane zagadnienia związane z wymianą wód pomiędzy jeziorem Łebsko a morzem, Materiały do monografii polskiego brzegu morskiego, z. 3, IBW PAN w Gdańsku, PWN, Poznań, ss. 122.

Van der Thuin H. (ed.), 1990, Guidelines on the study of seawater intrusion into rivers, International Hydrological Programme, UNESCO, Paris, ss. 139.

Zeidler R., Wroblewski A., Miętus M., 1995, Wind, Wale, and Storm Surges Regime at the Polish Balic Coast [in:] Polish Coast: Past, Prezent and Future ed. by Karol Rotnicki, Journal of Coastal Research, Special Issue No. 22 CERF, p. 33-56

Whittecar G.R., Nowroozi A.A., Hall J.R., 2005, Delineation of saltwater intrusion through a coastal borrow pit by resistivity survey, Environmental and Emgineering Geoscience, vol. 11, No 3, 209–219.



Oceanography
Edited by Prof. Marco Marcelli

ISBN 978-953-51-0301-1
Hard cover, 348 pages
Publisher InTech

Published in print edition March, 2012

How inappropriate to call this planet Earth when it is quite clearly Ocean (Arthur C. Clarke). Life has been originated in the oceans, human health and activities depend from the oceans and the world life is modulated by marine and oceanic processes. From the micro-scale, like coastal processes, to macro-scale, the oceans, the seas and the marine life, play the main role to maintain the earth equilibrium, both from a physical and a chemical point of view. Since ancient times, the world's oceans discovery has brought to humanity development and wealth of knowledge, the metaphors of Ulysses and Jason, represent the cultural growth gained through the explorations and discoveries. The modern oceanographic research represents one of the last frontier of the knowledge of our planet, it depends on the oceans exploration and so it is strictly connected to the development of new technologies. Furthermore, other scientific and social disciplines can provide many fundamental inputs to complete the description of the entire ocean ecosystem. Such multidisciplinary approach will lead us to understand the better way to preserve our "Blue Planet": the Earth.

Roman Cieśliński and Jan Drwal (2012). Bodies of Water Along the Coast of a Tideless Sea in Areas with Young Pleistocene Accumulation from Scandinavian Glaciers (Baltic Sea), Oceanography, Prof. Marco Marcelli (Ed.), ISBN: 978-953-51-0301-1, InTech, Available from: http://www.intechopen.com/books/oceanography/inland-waters-in-coastal-areas-of-tideless-seas-in-regions-with-young-accumulation-from-scandinavian

INTECH
open science | open minds

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821