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Coastal lakes and marine intrusions on the southern Baltic coast

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Abstract

In particular branches of the Earth sciences the term ***estuary*** is used with various meanings. The term *estuary* is applied to objects that often differ from the original geographic meaning of the word. The phenomena that accompany them and processes that cause them are called also estuary phenomena and processes. The aim of the study is to describe, in a geographic context, the range in meaning of both the term and names of phenomena and processes derived from it. In the years 2002 – 2005, a survey of the distribution of chloride concentrations was conducted on five lakes characteristic of the southern Baltic coast: Jamno, Bukowo, Wicko, Kopań and Łebsko. It was observed that seawater intrusions into the coastal lakes only resembles those that occur in classic estuaries, though the results are similar to seawater intrusion processes. In the Polish section of the southern Baltic coast, coastal lakes are not the only places where these phenomena are observed. We suggest that all inland water bodies that are under the influence of marine intrusions should be called coastal waters, instead of the misleading term estuary.

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INTRODUTION

In particular branches of the Earth sciences the term **estuary** is used with various meanings. This term is applied to objects that often differ from the original geographic meaning of the word. Descriptions of the phenomena that occur in such objects and processes that cause them are called **estuary** phenomena and processes. The use of the same terms for objects that differ in origin and or describe different phenomena or causal processes may lead to misunderstanding. What, then, is the original meaning of the term estuary, and what are the appropriate derived terms that describe related phenomena and causal processes?

The aim of the study is to explore, in a geographic context, the range in meaning of both the term and the derived names of phenomena and processes that cause estuaries. Additionally, another aim is to address the question of whether the coastal lakes that occur along the southern coast of the Baltic can be called estuaries. The initial assumption is that the phenomena observed there and the processes that cause them are only similar to those occurring in classic estuaries, as the water bodies in which they occur are not estuaries in the geographic sense of the term.

DEFINING ESTUARIES

In geography, the term estuary has traditionally been applied (Bajkiewicz-Grabowska and Mikulski 2006) to a marine bay or even the outlet region of a river, in which cyclic tides prevent the formation of deltas. Herschy and Faibridge (1998) concisely define an estuary as „... a river outlet that connects it with the sea where tides contact river current" (p. 720). This water body is usually shaped like a funnel that broadens towards the sea, hence it has traditionally been called a funnel-shaped river outlet or simply a river estuary. Thus, in the classic approach, the basis for distinguishing an estuary is the shape of the outlet region of a river (funnel-shaped), which exists at a given site on the coast due to the occurrence of tides. However, if the same approach is maintained, information on the mutual penetration of marine and river waters, which is mentioned in recent geographic definitions (Jackowski 2004), should be treated only as additional information on the effect caused by tides.

The term estuary, as used in the above context, was satisfactory as long as the basis for distinguishing the types of river outlets was only the shape on small scales. The moment interest shifted to the origin of the forms, causes (hence processes) and consequences of the observed phenomena (hence features), and also due to the fact that research developed on estuaries that occur in various geographic environments, the classic definition of estuaries became

insufficient. This insufficiency became especially clear when the geographic term started to be used, sometimes uncritically, in other disciplines of the Earth studies or even by researchers for whom the term geographic environment is limited to the location of the objects of research.

The diversity of definitions of estuaries in Earth science literature was noted previously by Majewski (1972) and explained as a transformation of the definition. Later (Majewski 1992), he introduced a transformation of the definition to the canon of Polish oceanographic nomenclature. In other words, the author suggested that the former classic definition was being replaced with new meanings, whose scope also encompassed oceanographic research. From the perspective of the last 30 years, this suggestion seems premature. Estuary is still defined classically (Stevenson 1998). There have also been attempts to broaden the meaning of the term estuary so that it would encompass the subject matter of geological, physical, hydrochemical or hydrobiological research.

There are definitions of estuaries that emphasise the origin of the form. Estuaries have been demonstrated to have formed as a result of a relative rise in sea level (Monkhose and Small 1978), e.g. after the termination of Pleistocene glaciations or as a result of global warming.

According to such a criterion, the boundaries of the present estuary are determined by the former width of the sunken river valley flowing into the open sea, and its length by the extent of the maximum discharge (Fairbridges 1980). In other definitions the only criterion is the extent of the zone of fresh and marine water contact. Already cited here, Majewski (1972) even suggested the term estuary waters instead of an estuary. Thus defined, the estuary is determined by the extent of the spread of waters of inland origin into the sea, and of marine waters into open water bodies. Pritchard's (1967) definition is an example of the emphasis on describing features, in this case on the quality of water. He described an estuary as a half-closed inland water body with a free connection to the open sea, in which the proportion of seawater to fresh water is measurable. This is the definition that Majewski adopts in his later paper (1992) as the official one for oceanography. There is only a small step from such a definition to the emphasis on process in the statement that "There are no formal obstacles to treating the Baltic as an estuary as… it is not the area but processes that decide on the classification of a given water body as an estuary." (Cyberski 1995; p.50, l.8-11). The author proceeds to classify „... areas of river outlets, lakes, lagoons, bays as lower order…" estuaries. (p.52, l.3-4). Whereas, an example of the emphasis on consequences, in this case biological, is Davidson's definition (1991), according to which estuaries are wetlands that occur on the borderline between land and the sea.

In view of the above ambiguity in defining estuaries, two basic questions can be asked: how should the phenomena that occur on the southern coast of the

Baltic and their causal processes be called? and are the forms in which they occur estuaries?

BALTIC WATER INTRUSIONS INTO COASTAL LAKES

The Baltic is a half-closed inland sea, in which cyclically repeated tides do not play any role in the aspect of interest here. However, at its southern shores there are periodic storm swellings of seawater and on the coast there are also periodic low stages of inland waters, which together cause intrusions of Baltic waters into the waters of the southern coastland. Sea coasts situated in areas of young accumulation of Pleistocene Scandinavian continental glaciers, such as the southern coast of the Baltic, are characterised by a high diversity of hydrographic objects, including coastal lakes. As a result, the course of the phenomena of the seawater intrusion into the water coastal lakes and their effects are conditioned by the relationships between local water bodies. Descriptions of places where such phenomena occur in particular sections of the coast (fig. 1) can be found in a rich Polish literature on the subject.

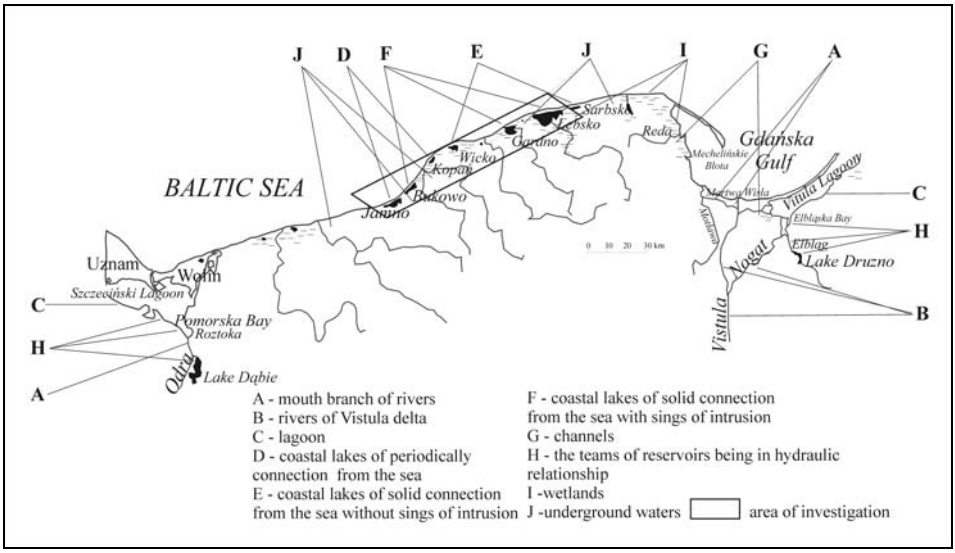


Fig. 1. Known locations of seawater intrusions into coastal waters.

The multitude of cases described in the literature and highly varied geographic conditions under which the phenomena occur, as well as the variety of approaches and research methods applied by individual authors, make comparative studies very difficult. Results of earlier studies (Szopowski 1962; Szmidt 1967; Drwal 1968; Łomniewski et al. 1972; Cyberski, Mikulski 1976;

Cyberski, Jędrasik 1992; Buchholz 1999; Cieśliński 2000; Cieśliński and Drwal 2005) reveal that only chloride ion is appropriate as an indicator of the impact of seawater on inland waters in such studies. This ion does not participate in oxidation-reduction reactions and is nearly non-reactive in absorption – exchange processes, due to which it is one of the best indicator seawater migration (Burchard et al. 1990).

STUDY OBJECTS

The authors performed surveys between April 2002 and December 2005 on five lakes situated in the central coastland (fig. 2). These were lakes of varied size, with hydrographic conditions characteristic of the southern Baltic coastland. The chosen lakes include: Jamno, Bukowo, Wicko, Kopań and Łebsko. On each lake, 8-12 surveys were performed, which included measurements of chloride concentrations at several sites most representative of particular water bodies.

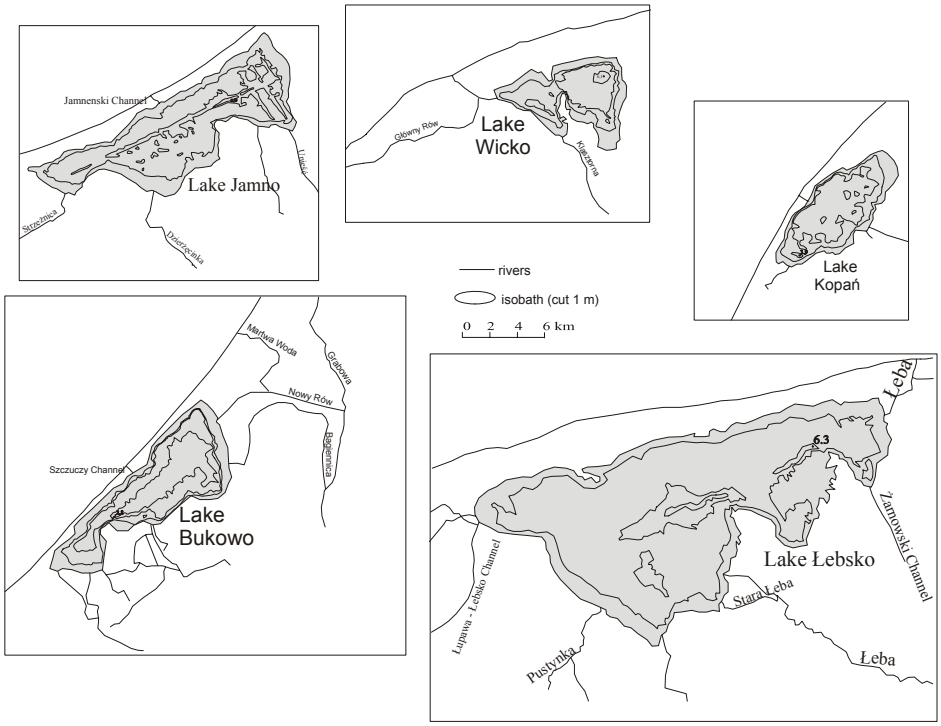


Fig. 2. Coastal lakes selected for research.

Lake **Jamno,** with 22.4 km^2 in area and a catchment of 510.6 km^2, is an example of a large lake with only periodic connection to the sea. The mean depth of the reservoir is 1.4 m, and the cryptodepression reaches the depth of -3.8 m. The lake is connected to the sea by the wide Jamno Canal, which is about 500 m in length. This canal is filled with debris for about 80 days a year on average (Szwichtenberg 1989). Annual inflow is estimated at 136 million m^3 (Mikulski 1970). It is estimated that the proportion of inflow from the catchment in the water balance is 70 – 90% (Szmidt 1967). Whereas the inflow of sea waters into the lake can reach 25 million m^3 (Łomniewski 1962). The research conducted in 2002 – 2005 revealed that increased chloride concentrations are observed continuously in Lake Jamno (Cieśliński 2004), and that concentrations are many times higher than those observed in waters of inland lakes. They ranged from 22.5 to 2337 mg dm^{-3}. Moreover, the research revealed that chloride concentrations decrease with increasing distance from the sea, primarily from the canal that connects the lake with the sea (fig. 3).

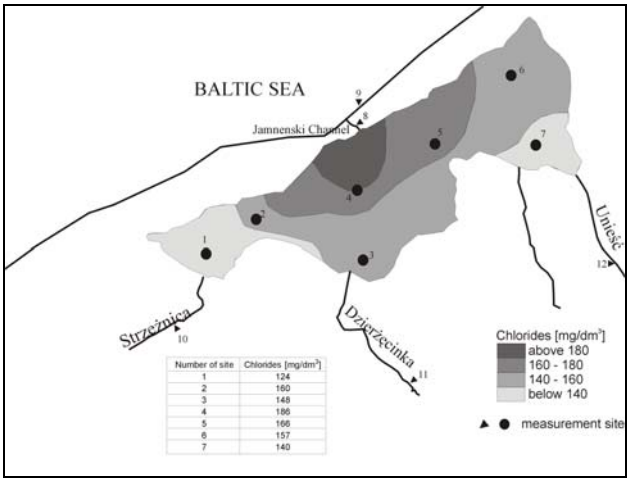


Fig. 3. Distribution of chloride concentrations in waters of Lake Jamno on 15.10.2002.

Lake **Bukowo** experiences different hydrographic conditions. The lake area is 17.5 km^2, with a catchment of 102.8 km^2. The cryptodepression reaches the depth of -2.7 m. This lake is connected with the sea via a wide artificial canal, about 300 m long. The annual potamic inflow is 30 million m^3 (Mikulski 1970). Extreme observed chloride concentrations ranged from 531 to 1179 mg dm^{-3}. A clear tendency of decreasing values with increasing distance from the coast was observed. The highest values were recorded opposite the canal connecting the lake with the sea (fig. 4).

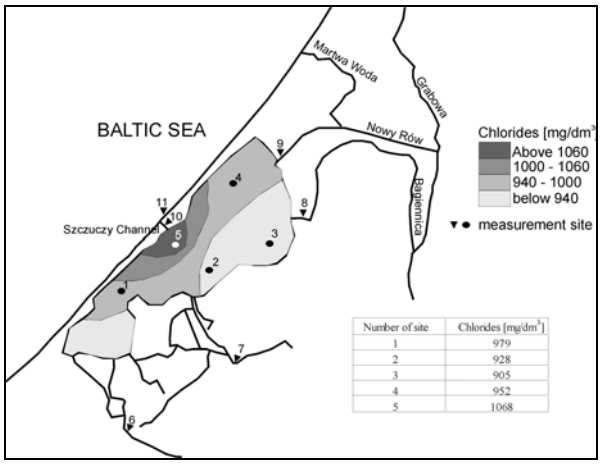


Fig. 4. Distribution of chloride concentrations in waters of Lake Bukowo on 25.05.2005.

Lake **Wicko** also experiences distinct hydrographic conditions. The lake is 10.6 km^2 in area and has a catchment region of 107.7 km^2. The cryptodepression reaches the depth of -5.9 m. The lake also has a permanent connection with the sea via a canal about 2 km long. Annually, 32.1 million m^3 of water flow into the lake (Mikulski 1970). Extreme recorded chloride concentrations ranged from 66 and 36 mg dm^{-3}. Chloride concentrations increased from east to west (fig. 5).

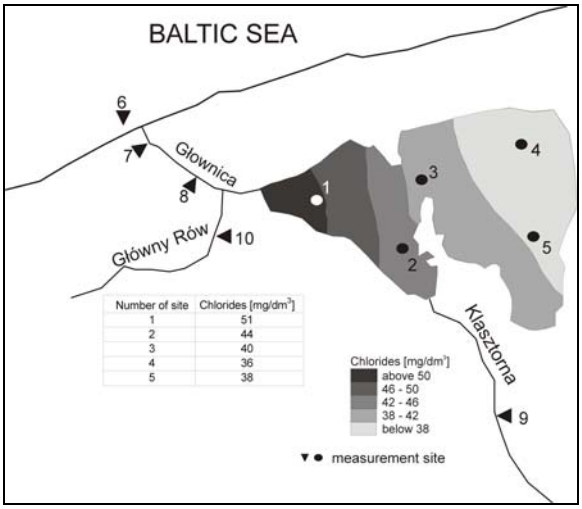
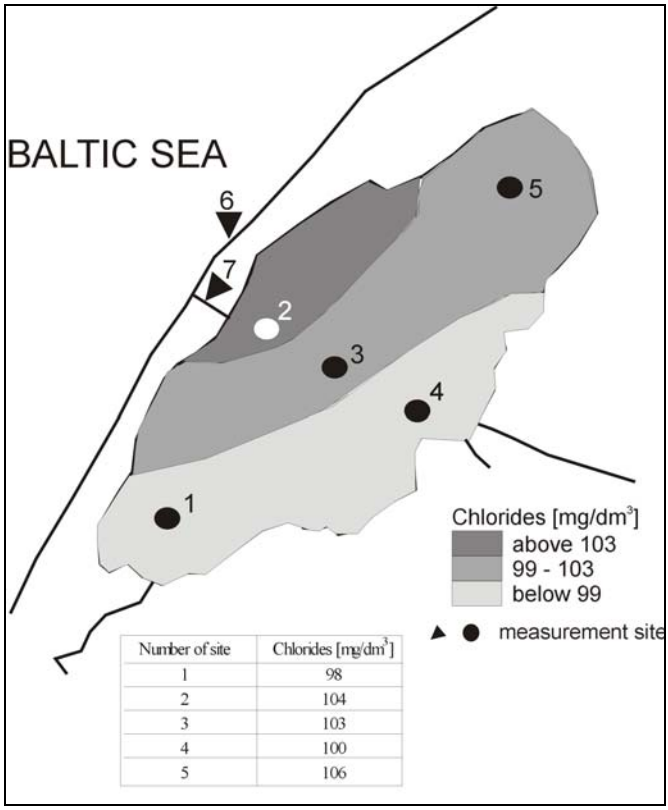


Fig. 5. Distribution of chloride concentrations in waters of Lake Wicko on 25.10.2002.

Yet another hydrographic condition for a coastal lake is represented by Lake **Kopań,** with a much smaller area than the previously discussed lakes, i.e. 789.7 ha and with a catchment of just 38.5 km^2. The cryptodepression reaches the depth of -3.8 m. The lake is connected with the sea via a periodic canal about 300 m long and 20 m wide. The annual inflow to the lake from the catchment is 11.5 million m^3. Intrusions of sea waters into the lake were recorded as early as the 1960s (Drwal 1968). The research performed in 2002 – 2005 revealed that extreme recorded chloride concentrations ranged from 142 to 86 mg dm^{-3}. Their values increased from east to west and north to south (fig. 6).



Number of site	Chlorides [mg/dm^3]
1	98
2	104
3	103
4	100
5	106

Fig. 6. Distribution of chloride concentrations in waters of Lake Kopań on 23.05.2005.

The last hydrographic condition is represented by Lake **Łebsko** with 71.4 km^2 in area and catchment of 1594 km^2. The cryptodepression reaches the depth of -6.0 m. The lake is connected with the sea by an anthropogenically modified channel of the River Łeba, about 2.7 km long. Annual potamic inflow is 524

million m^3 (Mikulski 1970). Intrusions of sea waters into the lake were observed in the 1950s and the beginning of the 1960s in situations when the sea level was higher by 17 cm than the water level in the lake (Szopowski 1962). The research performed in 2002 – 2005 showed that extreme recorded chloride concentrations ranged from 2772 – 250 mg dm^{-3}. The highest concentrations were recorded in the region with a direct connection to the sea via the outlet section of the Łeba (fig. 7).

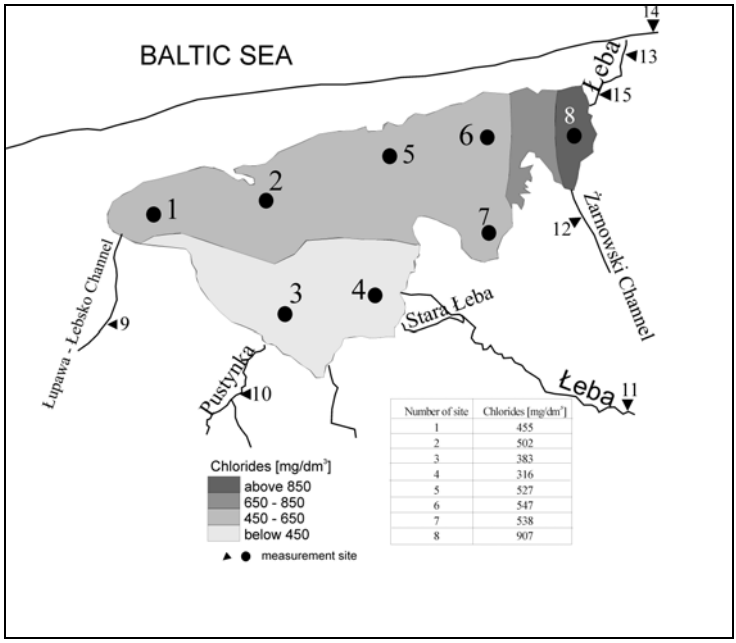


Fig. 7. Distribution of chloride concentrations in waters of Lake Łebsko on 23.05.2002.

DIVERSITY OF CHLORIDE CONCENTRATIONS

The obtained results of chloride concentration measurements in all cases and in each of the investigated lakes were higher than those that occur in inland lakes, even those of the polish Lakeland, where average chlorides concentrations have values on the level of 20 – 25 mg dm^{-3}. These values are lower than chloride values observed in coastal lake water, from 80 to 1200 mg dm^{-3}.

However, significant differences were recorded between particular coastal lakes or particular dates as well as in the distribution of concentrations in each of the lakes.

The highest concentrations were recorded in Lakes Łebsko and Jamno with values twice as low in Lake Bukowo. In the remaining two lakes: Kopań and Wicko, maximum concentration of chlorides was low but clearly higher than concentrations observed in inland lakes, cited here for comparison. The lowest chloride concentrations recorded in lakes Bukowo, Wicko and Kopań, however, were not higher than the concentrations of inland lakes. On the other hand, the lowest values for lakes Łebsko and Jamno were many times higher. There is no indication that these differences could be due to the length of the channels, as their lengths differ. Of the two lakes in which the highest concentrations were observed (Łebsko and Jamno), one has a channel length of 2700 m and the other is only 500 m (table 1). Whereas the lake in which the lowest chloride concentrations were recorded, Kopań, is connected with the sea by a channel of just 300 m of length.

A clear relationship between chloride concentration and lake depth was not observed in the studied coastal lakes. All the lakes are shallow, and their mean depth ranges from 1.4 m (Jamno) to 2.7 m (Wicko). Each of the investigated lakes is situated in a cryptodepression, which reaches several metres in deepest place (table 1). For example, in Lake Bukowo, which is the shallowest lake, chloride concentrations did not fall below 531 mg dm^{-3}. On the other hand, in Lake Wicko, which together with Lake Łebsko is among to the deepest, chloride concentrations fell to 36 mg dm^{-3}. However, in deepest place of Lake Łebsko the differences between chloride concentrations in water at the surface and at the bottom reached over 170 mg dm^{-3} (fig. 8), which was determined by performing this measurement in only this lake.

Table 1

Selected hydrological measures of investigated lakes

Lake	Maximum depth [m]	Volume [thousand m^3]	Coefficient of exchange*	Relation of surface catchment to lake	Tributary from catchment [mln m^3]
Jamno	3.9	31528	4.4	22.5	136
Bukowo	2.8	32072	0.9	5.9	30
Łebsko	6.3	117521	4.4	22.3	524
Wicko	6.1	28495	8.0	10.2	32
Kopań	3.9	14773	0.7	4.9	11.5

* ratio of river inflow to lake capacity

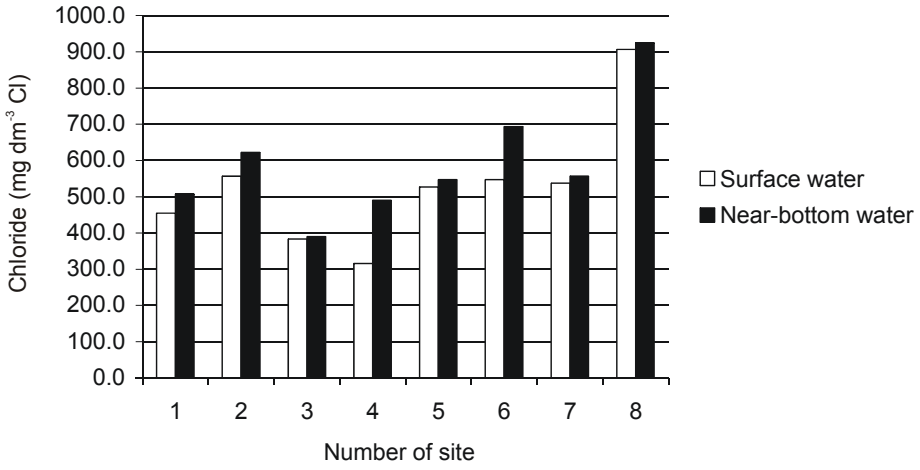


Fig. 8. Chloride concentrations in surface and near-bottom waters of Lake Łebsko on 23.05.2002.

Moreover, in the waters of the investigated coastal lakes no seasonal variability in chloride concentration was observed that would result from transformations occurring in the reservoir or from inflow from the catchment (fig. 9). For Lake Jamno, Bukowo and Łebsko, irrespective of the season (spring, summer, autumn), large differences in concentrations can occur, which indicates the occurrence of periodic intrusions from the Baltic. On the other hand, in waters of Lake Wicko and Kopań, small seasonal variability in chloride concentrations was observed, though variability is clearly influenced by the stronger impact of waters from the catchments.

During each survey on each of the lakes, a characteristic distribution of chloride concentrations in the near-surface water layer was observed (fig. 3-7). The highest concentrations occurred in the area where the channel connects the lake with the sea and decreased from there. However, in each of the reservoirs the distribution of concentrations had individual characteristics. A quick examination of the distribution would indicate a relationship between the distribution and the shape of the lake and general topography of the bottom. However, a closer analysis reveals also a clear relationship of the chloride concentration distribution in a lake with its capacity, water exchange capability, detailed bottom topography as well as the hydrographic conditions in the catchment area.

The volume of potamic inflow is criticial to chloride concentrations in each lake (table 1). Lakes Łebsko and Jamno, in which the highest chloride concentrations and largest differences between maximum and minimum

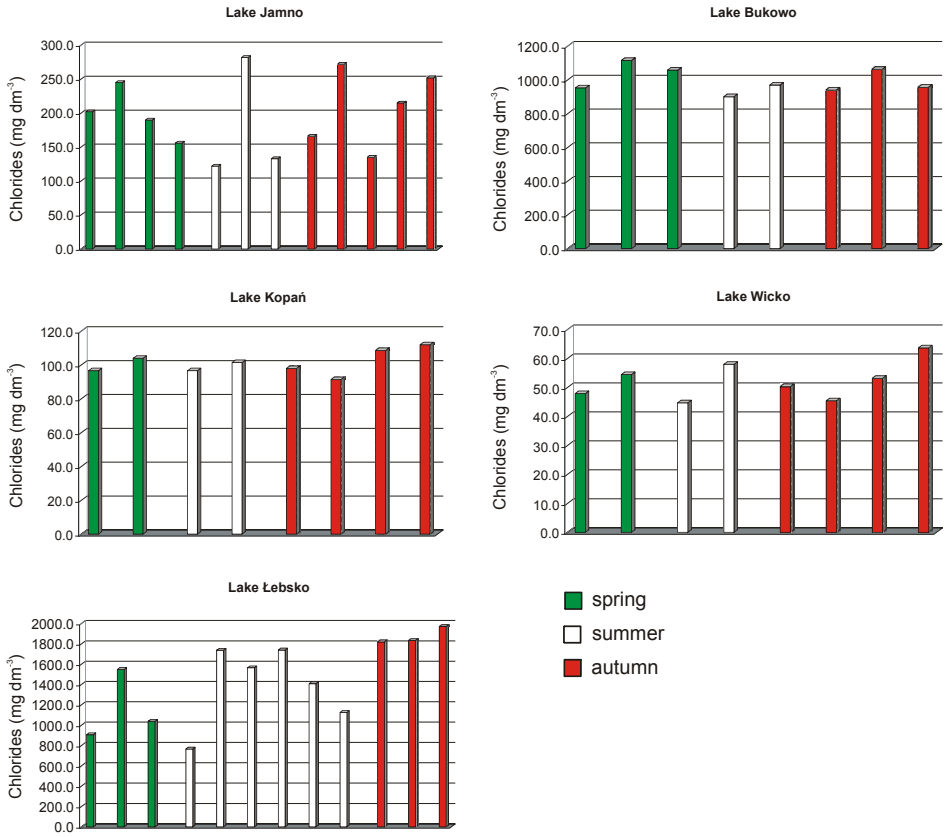


Fig. 9. Recorded chlorides concentrations in each lake in spring, summer, and autumn.

recorded values were observed, also have the largest potamic inflow of 524 and 136 million m^3/yr respectively. On the other hand, in Lake Bukowo, in which chloride concentrations were twice as low and extreme concentrations were smaller, the inflow in the first case is smaller by over 17 times, and in the second case by almost 5 times. However, in Lake Wicko, in which the potamic inflow is almost the same as in Lake Bukowo, chloride concentrations were very small. In Lake Kopań, which has still three times lower potamic inflow, chloride concentrations and their extreme records were higher.

Another important influence on the variability of chloride concentrations in coastal lakes is exerted by the potential capability of water exchange, expressed as the exchange coefficient (table 1). High values of the coefficient characterise both of the lakes in which the largest differences between extreme chloride

concentrations also were recorded (Łebsko and Jamno). Lake Bukowo, in which, as was mentioned above, both the maximum and range of concentrations were smaller, is characterised by an exchange coefficient of only 0.9. On the other hand, in Lake Wicko, which is characterised by the lowest chloride concentrations, this coefficient is the highest.

In view of the above, the observed differences in chloride concentrations between the near-surface and near-bottom water in Lake Łebsko are the effect of stagnation of waters coming from intrusions in deepest place while at the surface, water is coming in via potamic inflow. This is suggested by the location of measurement sites (deepest places are situated on the talweg line of the River Łeba flowing through the lake).

GEOGRAPHIC INTERPRETATION OF THE SEAWATER INTRUSION PHENOMENON

In classic estuaries, seawater flows in through the funnel-shaped river outlet and flows out according to the rhythm of the tides. The inflow fills the water body, which in oceanography is called a bay and in hydrography a river outlet, and during outflow the water is replaced with river water. Seawater flows into coastal lakes only incidentally during favourable anemobaric or hydrological conditions through channels that connect them with the sea. After the inflow ceases the water does not recede, but rather remains in the lake. Then, as a result of potamic inflow, the water is successively replaced with river water. The stagnation and exchange period depends on the topography of a given reservoir, its area, and the volume and location(s) of potamic inflow. This process is the slowest in lakes with a low exchange coefficient and small potamic inflow. The last to exchange is water in deepest place. Thus, seawater intrusions into coastal lakes only resembles those processes that occur in classic estuaries, but the results of these processes in coastal lakes are similar in classic estuaries.

In coastal lakes of the southern Baltic, the terrestrial hydrological regime dominates. The incidental seawater intrusions contribute to the uniqueness of these reservoirs, among other lakes. Moreover, in the Polish section of the southern Baltic coast, coastal lakes are not the only places where seawater intrusions are observed. The widespread nature and richness of types of intrusions accompanied by the domination of the terrestrial hydrological regime lead to the suggestion that all inland water bodies that are under the influence of seawater intrusions should be called **coastal waters** instead of by the misleading term **estuaries**.

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