Oceanological and Hydrobiological Studies

International Journal of Oceanography and Hydrobiology

Volume 43, Issue 2

ISSN 1730-413X (178–184)
eISSN 1897-3191 2014

VERSITA

DOI: 10.2478/s13545-014-0131-1
Original research paper

Received: *February 26, 2014*
Accepted: *March 25, 2014*

Present-day evolution of coastal lakes based on the example of Jamno and Bukowo (the Southern Baltic coast)

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Key words: coastal lakes, changes in the surface area, bathymetry, Baltic Sea

Abstract

This study presents the directions and the rate of changes occurring in the coastal lakes Jamno and Bukowo, located in northern Poland. Based on the cartographic materials and aerial photographs of those water bodies, it was established that in 1909-2012, the area of the lakes decreased by 183.6 ha (7.7%) and 250.7 ha (13.6%) for Jamno and Bukowo, respectively. Another component of lake disappearance − shallowing of lake basins − was analyzed using bathymetric plans. It turned out that water supplies of Jamno during more than 100 years decreased by 2.4 million m^3 (5.9%), while in the case of Bukowo, it was 5.9 million (17.5%). Unfavorable location (inflow of pollutants from the basin) and morphometry of both lakes should be considered as the main causes of such major changes. The lakes are polymictic with a considerable area of the shallowest zone (1 m depth). This favors the vegetation succession and, consequently, shallowing of the lake basins. Moreover, direct connection with the Baltic Sea contributes to the fact that the materials of marine origin deposited in the form of a reverse delta also contribute to a decrease in the open water surface area.

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INTRODUCTION

Lakes located in the area of the last glaciation belong to the least stable elements of the natural environment. They undergo a continuous evolution which eventually leads to their disappearance. According to Choiński (2007), the expected life span of lakes in the area of Poland (affected to a considerable extent by the Scandinavian glacier) is around 2000 years, which is not long from the geological perspective. The rate and the scale of lake disappearance can vary depending on many factors (e.g. genetic type of a lake, lithology, development of lake catchment area). According to Lange (1993), the evolution of water bodies depends on their size and the development of their internal structure, which can be understood as all processes of energy and mass exchange between a lake and its surrounding occurring through a water table, lake shore and bottom. The slowest rate of changes is usually observed in the deepest lakes with a high contribution of hypolimnion. Shallow, polymictic lakes are usually at advanced stages of their development since nearly the whole volume of water takes part in most of the phenomena and energy processes. Lakes located along the southern coast of the Baltic Sea can be classified into this type. Small depths combined with relatively large areas can be regarded as their characteristic feature. Data on changes in the lake area and volume of their basins are reliable indicators of lake evolution. Analyses of present-day transformations of lakes (not based on methods established in paleolimnology) are mainly based on the first factor (Marszelewski and Adamczyk 2004, Ma et al. 2007, Carroll et al. 2011, Gao 2011, Bai et al. 2012, etc.). However, one should remember that the lake basin is three-dimensional and evolves not only horizontally but also vertically. Comparisons of bathymetric plans from different periods can be found in the investigations carried out by for example Wiśniewski and Wolski (2005), Choiński and Ptak (2009), Ławniczak et al. (2011), Ptak and Ławniczak (2011), Ptak (2013). Such an approach, considering the last one hundred years, can be an alternative for methods applied in paleolimnology (precise assessment of changes in lake basins but much more time-consuming and expensive). According to Teresmaa (2011), proper interpretation should not be based on one bottom core (usually sampled at the deepest site of a lake), since adjacent areas are often characterized by different sedimentation conditions.

This study presents the evolution of two coastal lakes – Jamno and Bukowo – located in the southern coast of the Baltic Sea (Fig. 1). The main objectives of the study were to (1) assess the direction and the rate of changes occurring in those neighboring water bodies over the last 100 years and (2) to determine the main causes of their transformations.

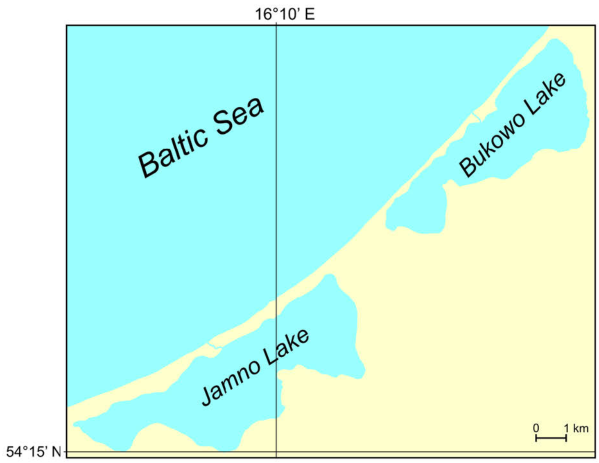

Fig. 1. Location of the studied coastal lakes

MATERIALS AND METHODS

The investigation was carried out in two stages. First, the changes in lake areas were analyzed on the basis of cartographic materials and aerial photographs. The second stage consisted in the analysis of changes in the basin volume of the lakes based on bathymetric plans. Two time-slices over the period of 100 years were selected.

The area of lakes was estimated from geological maps (Geologische Karte von Preussen und benachbarten Bundesstaaten) published in 1915, for which field photographs were taken in 1889, 1907 and 1909. The year 1909 was assumed as the first time-slice. In spite of earlier cartographic materials available, e.g. Karte des Königl. Preuss... (1789) (Fig. 2), they were not included in this study because those materials are not cartometric and only illustrate the study area.

Despite the fact that the map in Figure 2 is not precise enough to calculate the lake areas, it clearly shows that the shape of the lakes was completely different comparing to the present-day situation (Fig. 1). This may indicate considerable transformations that occurred in the last centuries.

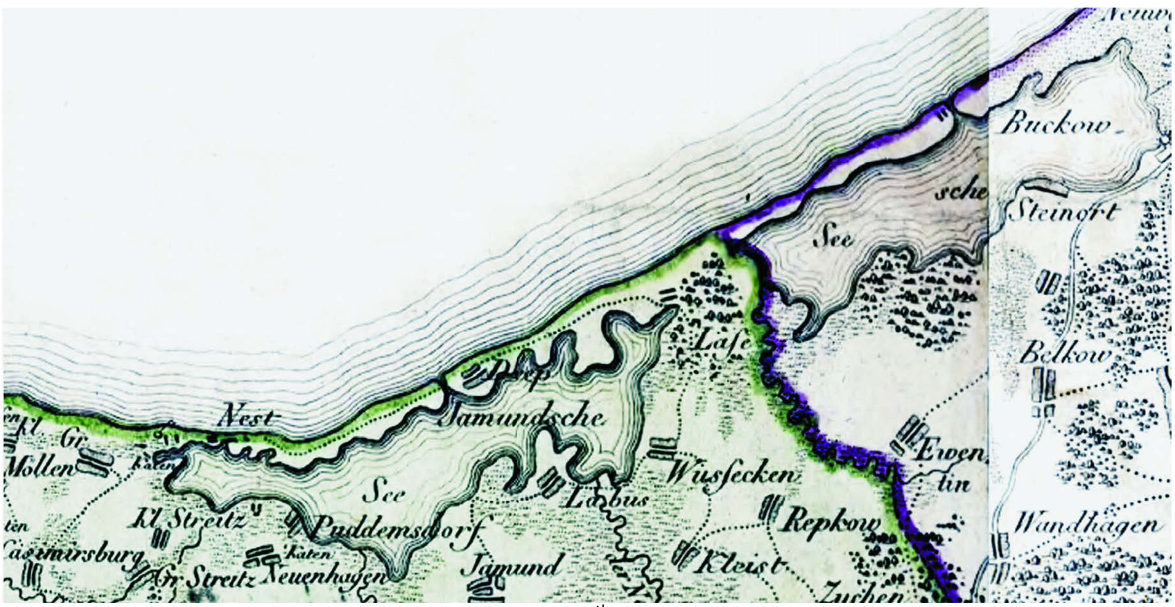

Fig. 2. Lakes Jamno and Bukowo in the second half of the 18th century (map Karte des …)

Current information on the areas of the lakes were obtained from orthophotomaps (resolution 0.5 m per pixel), taken at the beginning of the 21st century (2010). Calculations of the area for both time-slices were performed with the MapInfo 6.0 software. For each time-slice the area was calculated two times and the arithmetic mean was regarded as a representative value.

The volume of lake basins and their shape at the beginning of the 20th century were determined on the basis of bathymetric plans included in the geological maps. The present-day situation was obtained from measurements performed in September 2012 using the echo sounding Garmin Fishfinder 100 equipment and Garmin GPS 12 receiver. Taking into account the fact that the measurements in the first time-slice were performed from ice using a weighted rope, their compatibility with the echo sounder were verified in a comparative study. The depths measured with a weighted rope (regarded as more reliable) at several dozen sites were around 10 cm larger than the measurements from echo sounding. Therefore, the results for the second time-slice bathymetric plan were corrected and 10 cm were added to each measurement. The volume of lakes were assessed according to Penck's method (lake basin was regarded as a set of truncated pyramids closed with cones).

RESULTS AND DISCUSSION

Results of the calculated lake areas, volumes and depths are presented in Table 1. The analysis of data for the period of over 100 years revealed unfavorable changes in the functioning of the studied lakes. The area of the water bodies decreased by 7.7% for Jamno and 13.6% for Bukowo. A similar trend was observed in the case of lake water volume – it decreased by 5.9% (Jamno) and 17.5% (Bukowo). Taking into account the whole time span, the average decrease in the lake area amounted to 1.6 ha year^{-1} for Jamno and 2.0 ha year^{-1} for Bukowo. The volume of lake basins decreased with the rate of 0.02 million m^3 year^{-1} and 0.05 million m^3 year^{-1} for Jamno and Bukowo, respectively. Such transformations should be linked to the relationships between lakes and their drainage area, as well as morphometric parameters of the lake basins.

Direct connection between a lake and its catchment area can be expressed with the use of two coefficients: Ohle's and Schindler's. Both of them indicated unfavorable influence of lakes' catchments

Table 1

Changes in the area and volume of lakes Jamno and Bukowo between 1909 and 2012

Lake	1909			2012		
	Area (ha)	Vol. (m m^3)	Mean depth (m)	Area (ha)	Vol. (m m^3)	Mean depth (m)
Jamno	2390.9	40.7	1.7	2207.3	38.3	1.7
Bukowo	1853.0	33.8	1.8	1602.3	27.9	1.7

on the quality of lake waters. However, their values classified the lakes differently. Schindler's coefficient for Jamno was 11, which placed this lake in category II of susceptibility to degradation. The value of 2.4 was obtained for Bukowo and this lake was classified into category I, which indicated slight susceptibility of the lake to degradation caused by the inflow of pollutants from its catchment area. The values of Ohle's coefficients were 20.6 and 4.3 for Jamno and Bukowo, respectively. Location of both lakes in their basins is presented in Figure 3.

The main source of pollutants in Lake Jamno (according to the Report on the state of the environment in the West Pomerania Province for 2006 – 2007 and the Report on the state of the environment in the West Pomerania Province for 2008 – 2009) is the direct inflow of waste water from the sewage treatment plant in Unieście, which receives sewage from the nearby villages and towns.

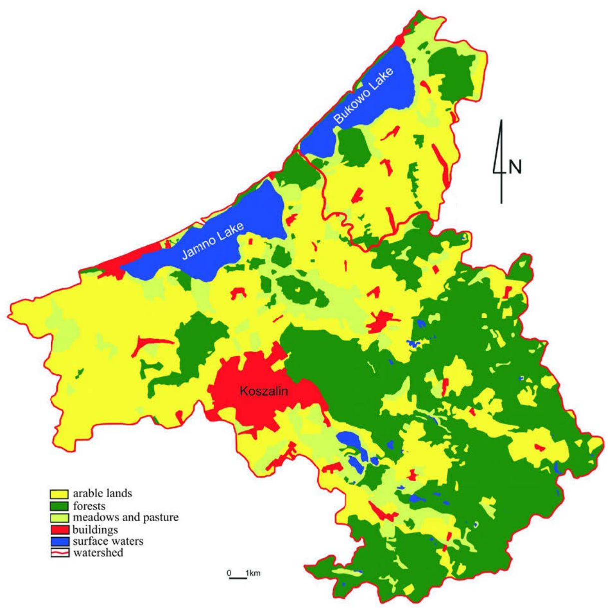

Fig. 3. Catchment areas of lakes Jamno and Bukowo and the land-use structure

Rain water from the coastal places and cooling water from the distillery in Osieki are also piped directly to the lake. Moreover, Jamno is indirectly influenced by sewage from the municipal sewage treatment plant in Koszalin, rain water from this city and sewage from the sewage treatment plant in Bonin, which flow into the discussed water body through the Dzierżęcinka River. Another source of pollutants is the sewage from the town of Sianów, which flows into Lake Jamno through the Unieść River. The run-off from arable lands is also a threat to the lake. Obolewski (2009) investigated macrozoobenthos in Lake Jamno and assessed that water quality in the northern and southern part was very low and low in the central zone. The quality of water in Lake Jamno can also be influenced by natural factors, e.g. the presence of cormorants. Klimaszyk (2012) assessed for Lake Chrzypsko that those birds can considerably contribute to the increase in the concentrations of nitrogen and phosphorous compounds as well as to the presence of *E. coli* bacteria. Lake Bukowo is mainly polluted by waste water from the mechanical-biological sewage treatment plant in Dąbki, which receives sewage from the surrounding villages and towns. Seaside resorts at the eastern part of the lake and surface run-off from arable lands also contribute to the contamination of lake waters. Moreover, fishponds and a pig farm in Bukowo Morskie are also a potential threat. Considerable accumulation of nutrients in bottom sediments of both lakes (Trojanowski and Bruski 2000, Choiński and Gogołek 2005) also increases their trophic status.

Bottom sediments play an important role in the accumulation of nutrients (Kowalczewska-Madura et al. 2010). Nitrogen and phosphorus compounds accumulated in sediments can be released as a result of water overturn caused by wind waves (de Vicente et al. 2009, Tammeorg et al. 2013) as well as by human activity. Yousef et al. (1980) proved that mixing of water above sediments and disturbances in their structure induced by cabin cruisers sailing on shallow lakes (average depth 1.8 – 4 m) increased the release of orthophosphates from bottom sediments and their concentration was by 16 – 73% higher. It should be emphasized that both lakes are often used for motor boating. Moreover, ichthyofauna also plays an important role in the reactivation of organic compounds (Zambrano et al. 2001, Søndergaard et al. 2008, etc.).

According to Łukasiewicz (1995), the rate of water exchange in both lakes (calculated as the ratio of the total lake water supplies to the water inflow) is similar and close to 5.2 for Jamno and 4.9 for Bukowo.

Considering the relationships between lakes and their catchments, Bukowo was in better situation since the loss of lake area and lake volume were smaller comparing to Jamno. In the light of those observations, changes in morphometric parameters of both lakes were particularly interesting.

Since the average depths of both lakes were similar, the most shallow zones (down to 1 m) were analyzed based on bathymetric plans. The calculations showed that the area bounded by the 1 m isobath was 18.1% for Jamno and 24.8% for Bukowo. Shrinking of the discussed lakes had probably two causes: encroachment of the vegetation along the whole shoreline and accumulation induced by the sea (formation of reverse deltas in the vicinity of channels connecting the lakes with the Baltic Sea). A considerable area of the shallow zones in lake basins had been a great place for the development of emerged plants for the last one hundred years. Only 10.2% of Jamno and 5.1% of the Bukowo shoreline was devoid of aquatic vegetation. Apart from vegetation encroachment, their direct connection with the Baltic Sea is another important issue. The length of the connecting channel is around 500 m for Jamno and 300 m for Bukowo (Drwal and Cieśliński 2007). Periodic intrusions of sea water during heavy storms contributed to the deposition of sediments near connecting channels, which is clearly visible as reverse deltas (Fig. 4). The area of the reverse delta in

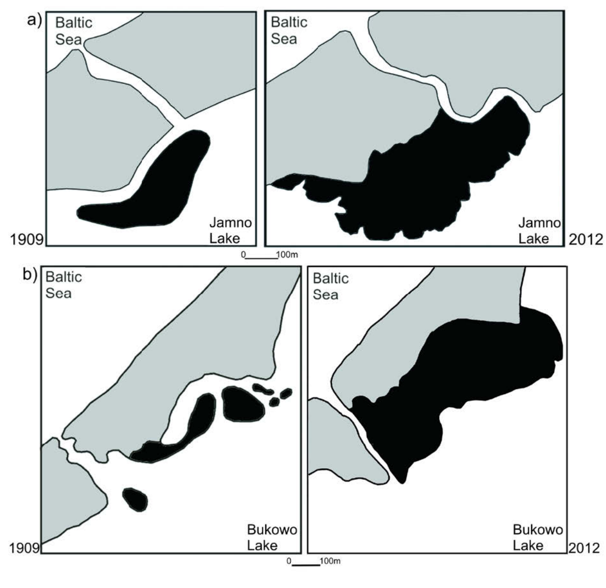

Fig. 4. Formation of reverse deltas: a) Lake Jamno, b) Lake Bukowo

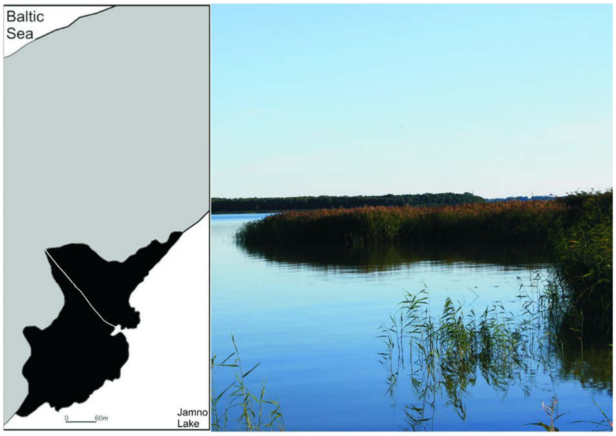

Fig. 5. Reverse delta within the area of Lake Jamno: the former mouth of Jamno – the Baltic Sea channel

Jamno had increased from 5.1 ha in 1909 to almost 15 ha (14.8 ha) in 2012, while in Bukowo from 4.3 ha to over 16 ha (16.6 ha).

The contribution of the sea in the shrinkage of Lake Jamno is also visible at another site. The former channel connecting the lake with the Baltic Sea was located around 1000 m to the south-west from the present-day channel. A relatively large delta is also the result of accumulation caused by the sea in this part of the lake (Fig. 5).

Apart from a horizontal decrease in lake areas, visible to the naked eye, also another process occurred in the studied lakes. Deposition of auto- and allochthonous matter had led to the shallowing of lake basins. Changes in their morphometry are presented in Figure 6.

Comparison of bathymetric plans for both lakes (Fig. 6) indicated transformation of lake basin morphometry. Over a considerable area of Lake Jamno, the 1 m isobath shifted toward the shoreline. Vegetation encroachment (terrestrialization) was the most likely cause of such a situation. Whereas in the north-eastern part of the water body – relatively resistant to succession – 1 m and 2 m isobaths moved toward the centre of the lake. A characteristic shape of the 2 m isobath (semicircle, the central part) reflected the influence of the sea (extension of the reverse delta). The distribution of isobaths in Bukowo was simpler. In general, the isobaths shifted toward the centre of the lake, which was accompanied by vegetation encroachment and, as a result, the 1 m isobath moved toward the shoreline.

Deposition of matter contributed to the decrease in the area of both lake basins and, consequently, to the decrease in water supply. However, the topography of lake bottoms has varied in time. Spatial distribution of bottom sediments, their

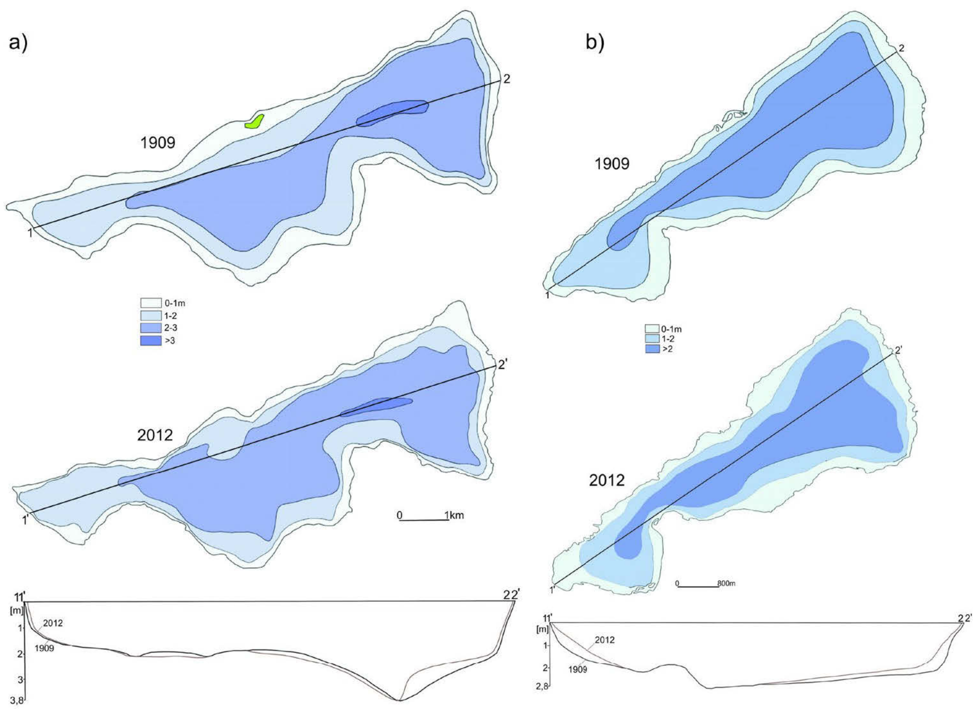

Fig. 6. Changes in the bathymetry of lakes Jamno and Bukowo between 1909 yr and 2012 yr: a) Lake Jamno, b) Lake Bukowo

composition and structure reflected the lake-catchment interactions as well as morphometric parameters of the lakes and other processes affecting the studied water bodies (Gilbert 2003). Dislocation of bottom sediments is caused by many factors (Hakanson 1982), e.g. wind direction, duration of windy weather and wind velocity, the presence of thermocline, the content of water and organic matter in sediments, the type and abundance of benthic fauna etc. The thickness of bottom sediments in Jamno ranged from 0.0 to 7.9 m and increased in an easterly direction (Szwichtenberg 1989). Such a distribution may reflect the prevailing wind direction which, according to Cieśliński (2011), is mostly from the south-west on the Polish coast. Location of both Jamno and Bukowo on the SW-NE axis favors the formation of high waves, which leads to higher deposition in the eastern part of the water bodies. The range of water mixing assessed with Patalas' formula (1960) amounted to 5.4 m and 5.1 m for Jamno and Bukowo, respectively. Those numbers considerably exceed the mean depths (and even the maximum depths) recorded for the lakes. Woszczyk et al. (2013) established that the depth of vertical mixing of sediments in Lake Sarbsko − another coastal lake located ca. 100 km east of Bukowo (with a similar average and maximum depth as Jamno and Bukowo) – was up to 40 cm and increased along the lake axis. Therefore, one can conclude that the vertical range of sediment mixing in the case of the studied lakes is similar. Whereas Chróst (2012) reported (based on the example of Lake Śniardwy characterized by the deepest range of water mixing compared to an average lake depth) that lake morphology may change as a result of wind influence – the circulating water carries bottom sediments, gravel and fine stones.

The results obtained in this study revealed differences in the distribution of isobaths in the analyzed bathymetric plans of lakes Jamno and Bukowo during ca. 100 years. This indicates the need of further detailed research on sediment resuspension and transport in both lakes. This kind of research would bring interesting conclusions and reveal the influence of not only the prevailing wind direction but also its velocity and frequency of occurrence. The vicinity of the Baltic Sea favors the strong wind (above 10 m s^{-1}) for a considerable number of days – according to Trzeciak (2001) around 55 days per year in the central part of the coast. This fact, combined with a small depth of the lakes and semi-fluid character of the upper layer of bottom sediments, might contribute to the transport of sediments.

CONCLUSIONS

Transformations of two coastal lakes – Jamno and Bukowo – discussed in this study should be regarded as unfavorable in the context of their existence in the future. The dynamic economic and industrial development in the 20th century has brought large amounts of nutrients into these water bodies from various sources (surface run-off from arable lands, sewage discharge etc.). Protection of surface waters through, for example development of sewage treatment plants, is nowadays a very important issue. However, it is very difficult or even impossible to completely eliminate the inflow of pollutants into the studied lakes from external sources. Moreover, compounds deposited in the lake sediments still greatly influence the water quality and contribute to eutrophication. This, in turn, is reflected in the quick reduction of lake areas and the shallowing of lake basins. The prevailing wind direction was the same as the longitudinal axes of both lakes, which favored the sediment resuspension and the processes transforming the lake bottom. Moreover, the direct connection with the Baltic Sea contributed to the gradual decrease in the lake areas as a result of sediment deposition of marine origin and the formation of deltas.

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