Short-term changes in specific conductivity in Polish coastal lakes (Baltic Sea basin)

doi:10.5697/oc.55-3.639
OCEANOLOGIA, 55 (3), 2013.
pp. 639–661.

KEYWORDS
Specific conductivity
Short-term changes
Increase
Decrease
Intrusion

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Received 5 November 2012, revised 8 January 2013, accepted 29 April 2013.

Abstract

The paper discusses hourly changes in specific conductivity in two lakes and compares them to changes over longer time intervals. The short time intervals between measurements are designed to help assess the course of seawater intrusions. Two lakes on the Polish coast were selected for research purposes – Lakes Gardno and Łebsko. Specific conductivity was measured using an automatic YSI Sontek 6920V2 probe. It was shown that Lake Łebsko has a permanently elevated specific conductivity, whereas Lake Gardno experiences episodes of fluvial influence. The specific conductivity was shown to change constantly in both lakes, as evidenced by multi-day, daily and hourly data.

1. Introduction

The Baltic Sea is located in the temperate climate zone. It is almost wholly surrounded by land and is almost completely tideless. The freshwater influx averages 470 km^3 year^{-1} and the ocean water influx averages 430 km^3 year^{-1}, which makes the Baltic a brackish water body (Thulin & Andrushaitis 2003). The average salinity along its southern shore is 75 g kg^{-1}, with a range between 20 g kg^{-1} and 90 g kg^{-1}. Storms at sea as well as low freshwater levels on land cause periodic intrusions of brackish water into freshwater bodies (Jasińska 1997, Pitkänen 2001, Cieśliński & Drwal 2005, Drwal & Cieśliński 2007, Gamo et al. 2007, Tarkhov & Treivish 2007).

Not only do intrusions cause the influx of seawater into coastal freshwater bodies, they also halt the flow of water from land-based sources. This results in both large- and small-scale flooding (Hall & Andersen 2002, Pizarro et al. 2007), and increases the salinity of freshwater bodies and wetlands (Cieśliński & Drwal 2005, Drwal & Cieśliński 2007). Given their sporadic nature, major intrusions must be treated as extreme events; these, too, are characteristic of the southern Baltic shore (Van den Brink et al. 2005).

The southern Baltic shore is a location where early water relationships were shaped by the sedimentation effect of Scandinavian Pleistocene glaciers and their meltwaters. Since the 17th century these relationships have been affected by intense human pressure, though to varying degrees. Periodic intrusions of brackish water in open bodies of water along the southern Baltic coast resemble estuarine processes driven by low and high tides. Yet this is not a cyclic phenomenon. Seawater and freshwater chemical data were used in conjunction with water level fluctuation data to identify intrusion events lasting from several days to several weeks (Chlost & Cieśliński 2005). Intrusions several hours in duration were identified only sporadically because of the incomplete monitoring methods used in the study.

The paper attempts to assess the impact of short-term (several hours) seawater intrusions on the chemical composition of coastal lakes along the Baltic Sea.

2. Material and methods

The research was carried out on two lakes (Gardno and Łebsko) located in the central section of Poland's Baltic Sea coast (Figure 1). Both lakes lie in the immediate vicinity of the open sea and are separated from it by sandbars from 200 to 1 000 m in width. Each lake is connected to the sea by a canal (Figures 2a and 3a). Lake Gardno is 24.7 km^2 in area, has a maximum depth of 2.6 m, a volume of 30 950 000 m^3, and is fed by the River Łupawa with an average discharge rate of 8.2 m^3 s^{-1}. Lake Łebsko has an area of 71.4 km^2, a maximum depth of 6.3 m, a volume of 117 521 000 m^3, and is fed by the River Łeba with an average discharge rate of 11.8 m^3 s^{-1}.

Specific conductivity (SC) was selected as the indicator of the presence of seawater intrusions and was measured using an automatic YSI Sontek 6920V2 probe that acquires a continuous stream of data. Each probe was anchored at a depth of about 0.5 m in each of the two lakes in close

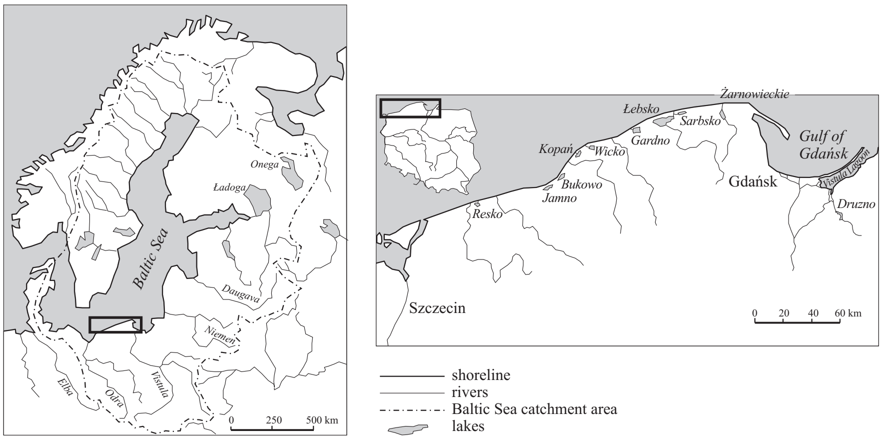


Figure 1. Location of the lakes

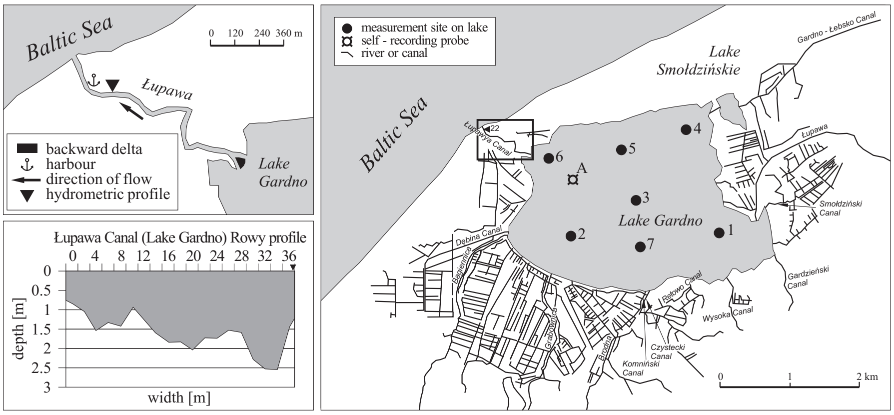


Figure 2. Location of the automatic probe and water sampling sites on Lake Gardno

proximity to the canals linking the lakes to the sea (Figures 2 and 3). Hourly measurements were acquired between July 2008 and April 2009.

In order to learn whether continuous SC measurement could be used as a means to identify the presence of seawater intrusions, SC data were compared to chemical composition data for the two lakes. The chemical data were gathered all the year round by the Department of Hydrology of the University of Gdańsk between 2002 and 2007. SC data were also compared to changes in seawater levels measured daily at a hydrometric site in the port of Łeba. In order to assess whether the recorded seawater intrusions were detectable across each lake, specific conductivity was measured once a month at seven sites on Lake Gardno (Figure 2) and eight sites on Lake Łebsko (Figure 3) using a WTW 350i conductometer.

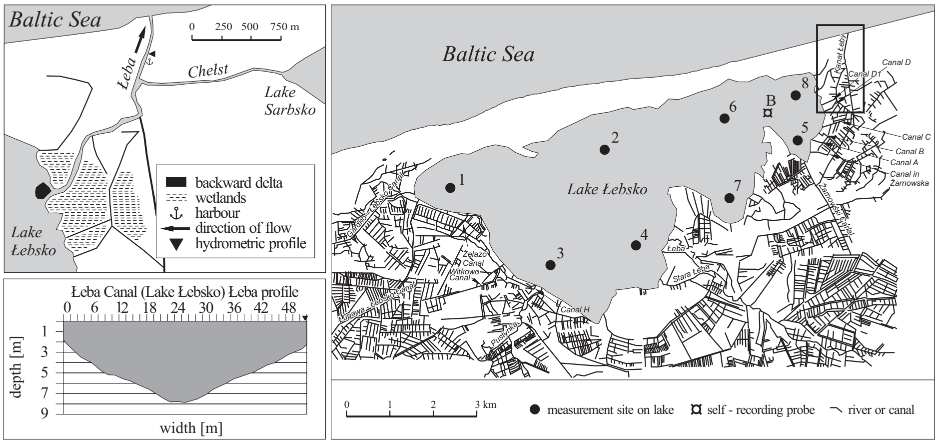


Figure 3. Location of the automatic probe and water sampling sites on Lake Łebsko

The study also used the data on salinity given in g kg^{-1} according to TEOS-10 (Millero et al. 2008). In most cases, the conductivity results refer to a salinity of < 2, which is off the PSS-78 scale (Lewis & Perkin 1978). Only a few values are in the 2–42 range, i.e. on the PSS-78 scale (BIPM 2006).

Measurements of discharge in rivers and canals connecting the lakes with the sea were performed using a StreamPro ADCP Acoustic Doppler Current Profiler (Teledyne RD Instruments) with a depth range from 0.15 to 4.2 m and a Workhorse Rio Grande 1200 ZedHed ADCP (Teledyne RD Instruments) with a depth range from 0.3 to 21 m. In order to obtain results from the ADCP by radio, a GPS – EKO-GIS Services ROMAR measurement kit was used together with a receiving aerial based on a MLR GA24X receiver. The results are presented graphically using the WinRiver program.

3. Results

3.1. Short-term changes in specific conductivity

Large fluctuations in SC were detected in both lakes across a 4–48 hour time range. The SC fluctuation amplitude reached 11 509 μS cm^{-1} in Lake Gardno (Figure 4) and 8 575 μS cm^{-1} in Lake Łebsko (Figure 7; see p. 644).

Lake Gardno experienced periods of several days when SC fluctuated between 200 and 400 μS cm^{-1} (Figure 5a), periods of two and three days when it varied between 1 000 and 2 000 μS cm^{-1} (Figure 5b), and periods of several hours when it rose as high as, and even exceeded, 10 000 μS cm^{-1} (Figure 5c). For example, SC rose and fell 1 898 μS cm^{-1} (6b1) once

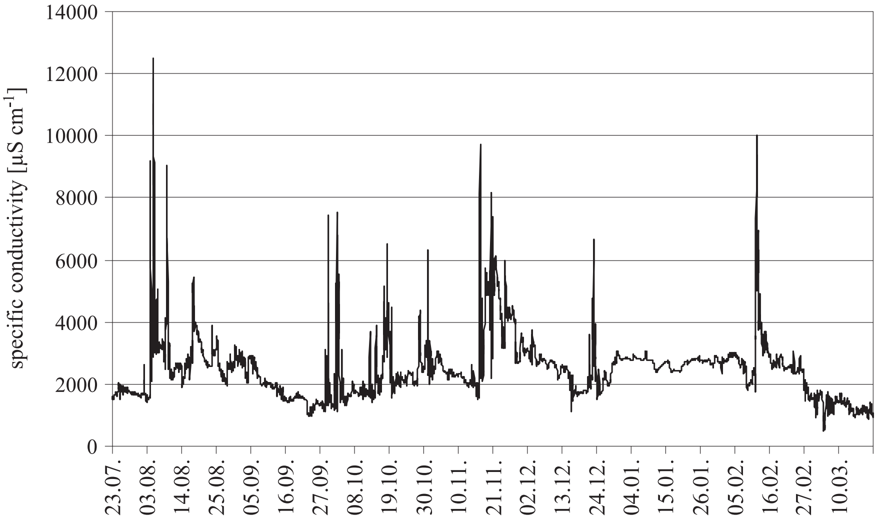


Figure 4. Changes in specific conductivity in Lake Gardno between July 2008 and March 2009

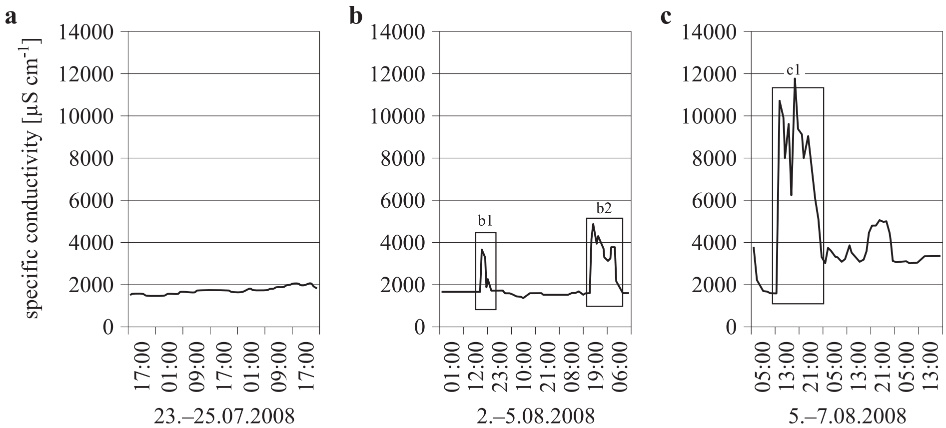


Figure 5. Periods of variable specific conductivity in Lake Gardno: a) multi-day periods with small changes, b) several-hour periods with appreciable changes, c) several-hour periods with very large changes

over the course of four hours between 2 and 5 August 2008. It then rose and fell 3 129 μS cm^{-1} (6b2) a second time during 13 hours. Finally, it rose and fell 9 618 μS cm^{-1} (6c) over the course of 14 hours between 5 and 8 August 2008.

A similar variability was observed in Lake Łebsko (Figure 7). In addition to the several-day periods when SC ranged from 200 to 500 μS cm^{-1} (Figure 8a), there were two- and three-day periods featuring several increases

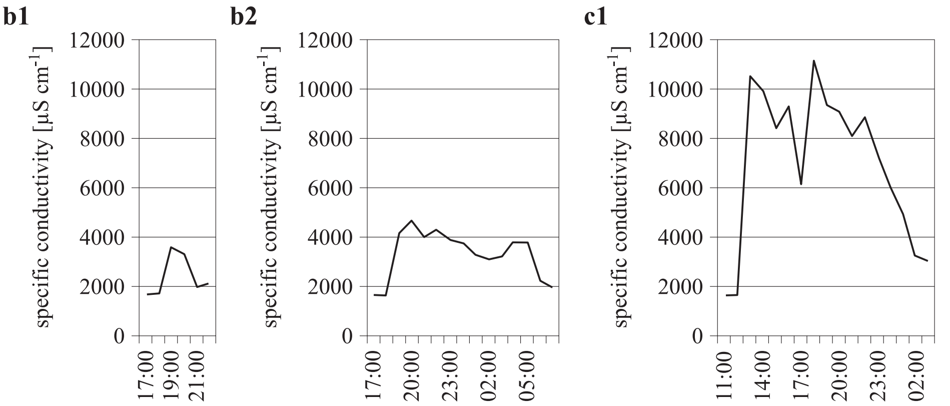


Figure 6. Selected hourly changes in specific conductivity in Lake Gardno: appreciable (b1 and b2); large (c1)

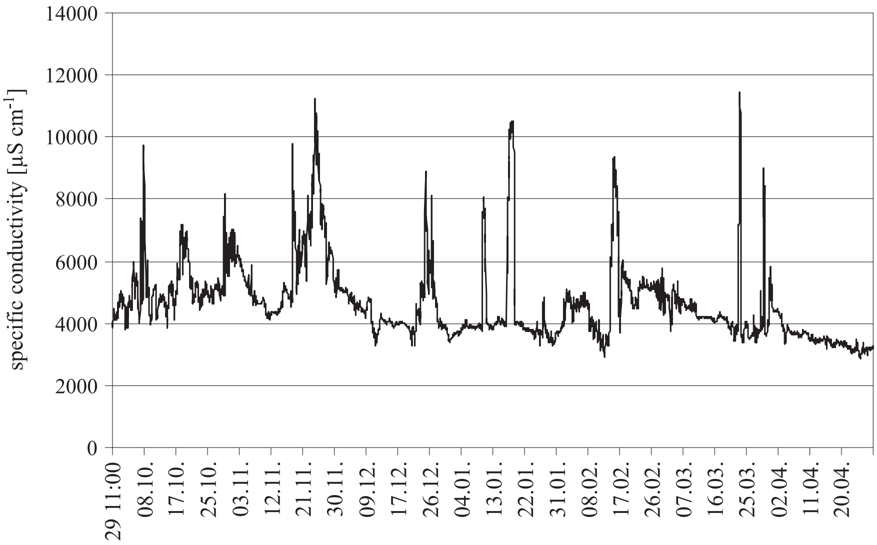


Figure 7. Changes in specific conductivity in Lake Łebsko between September 2008 and April 2009

and decreases of 2 000–3 000 μS cm^{-1} (Figure 8b) as well as several-hour periods when SC rose between 6 000 and 7 000 μS cm^{-1} (Figure 8c). For example, SC rose and fell 3 385 μS cm^{-1} (9b1) once over the course of nine hours between 5 and 7 October 2008, and it rose and fell a second time (2 709 μS cm^{-1} (9b2) over the course of five hours during the same period. Between 16 and 18 November 2008 it rose and fell 5 087 μS cm^{-1} (9c1) during four hours.

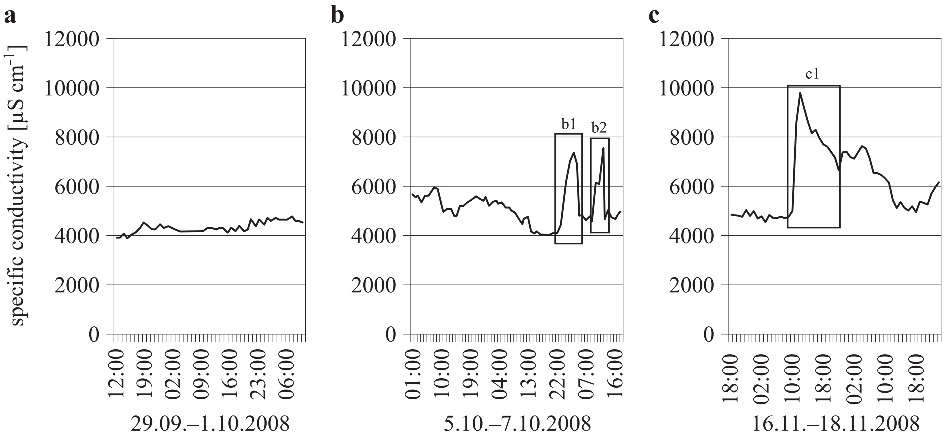


Figure 8. Periods of variable specific conductivity in Lake Łebsko: a) multi-day periods with small changes, b) several-hour periods with appreciable changes, c) several-hour periods with very large changes

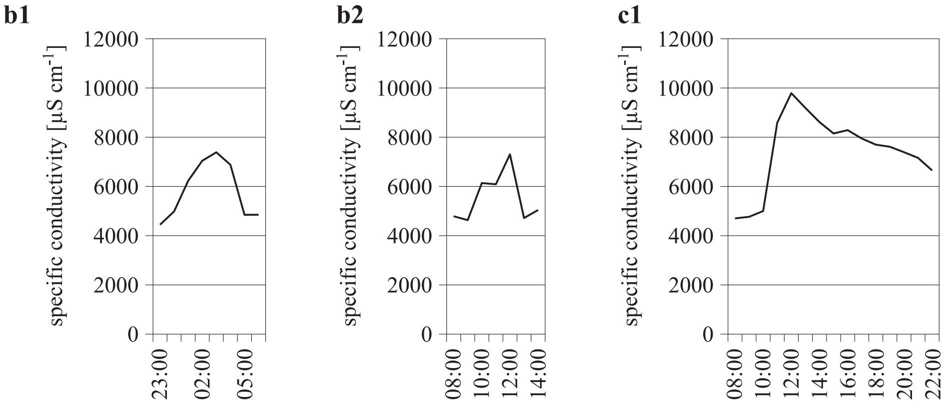


Figure 9. Selected hourly changes in specific conductivity in Lake Łebsko: appreciable (b1 and b2); large (c1)

SC increased and decreased for several hours regardless of the average SC of the lake in question and was detected prior to an increase. The average SC in Lake Gardno was 2 539.1 μS cm^{-1} for the entire research period, with a maximum of 11 048 μS cm^{-1} and a minimum of 490 μS cm^{-1}. In Lake Łebsko, the average SC was 5 460.0 μS cm^{-1} for the entire research period, with a maximum of 11 449 μS cm^{-1} and a minimum of 2 874 μS cm^{-1}. The maxima for the two lakes were quite similar.

A quick comparison of data collected for both lakes between July 2008 and April 2009 shows that both bodies of water experienced a similar several-hour pattern of changes in SC, although the magnitude of the changes was different. Figures 4 and 8 show that several-hour changes were detected in Lake Gardno with SC in the 2 000–4 000 μS cm^{-1} range and in Lake Łebsko with SC in the 2 000–7 000 μS cm^{-1} range. The amplitude of the changes ranged from 1 000 to 2 000 μS cm^{-1} in the former lake, and from 2 000 to 3 000 μS cm^{-1} in the latter.

86 such cases were recorded in Lake Gardno and 63 in Lake Łebsko. Periods of large several-hour changes in SC were observed in Lake Gardno when this varied between 4 000 and 11 000 μS cm^{-1}; in Lake Łebsko, the corresponding range was 7 000–11 000 μS cm^{-1}. In the case of the former, the amplitude of the changes was 6 000–7 000 μS cm^{-1} in the former lake, and 4 000–5 000 μS cm^{-1} in the latter. 34 such cases were recorded in Lake Gardno and 20 in Lake Łebsko.

3.2. Effect of topography on lake water salinity

One reason for the variability in salinity in these lakes could be the morphometry of their basins. However, literature data (Cieśliński 2011) indicates that in the case of the lakes situated in the Polish coastal zone of the southern Baltic Sea, the impact of the surface area and depth of the lakes on salinity is minimal. This is evidenced by the calculated correlation coefficient R^2, which was 0.0003 for the correlation between mean chloride concentrations and the surface area of the lake, and 0.0366 and 0.0401 for the respective correlations between the average and maximum depths and mean chloride concentrations.

However, a closer look at the bathymetry of both lakes reveals some local properties that could facilitate the easier penetration of seawater into the lake basins. An old river bed (thalweg) crosses the Lake Łebsko basin (Figure 10), whereas the bathymetry of Lake Gardno varies only slightly, with numerous shallows (Figure 11).

Another important issue concerning the morphometry of these lakes is the potential impact of external factors on these features, predominantly wind action. The exposure index for these lakes, which allows the impact of wind to be defined, varies: it is 4 462.5 for Lake Łebsko and 1 898.5 for Lake Gardno. This difference is due to the different surface areas with similar average depths.

The elevation of the water level in relation to the Baltic Sea is also important in the context of marine and lacustrine water exchange. The water level of Lake Łebsko is only 0.1 m above sea level, while that of Lake Gardno is 0.3 m above sea level. Theoretically, therefore, the influx of water from the sea should be easier and more frequent in the former case.

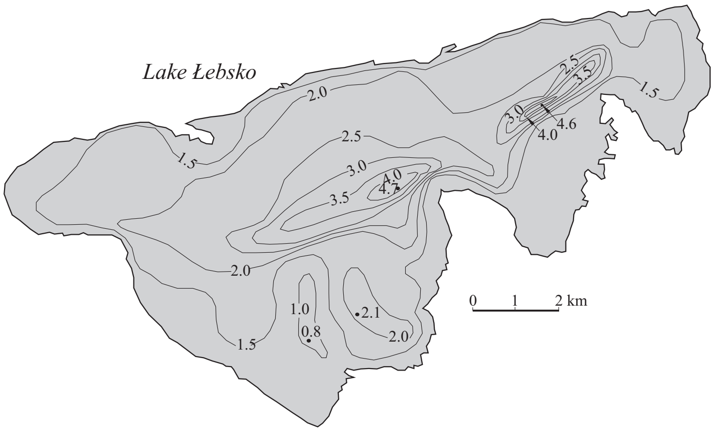


Figure 10. Bathymetric plan of Lake Łebsko

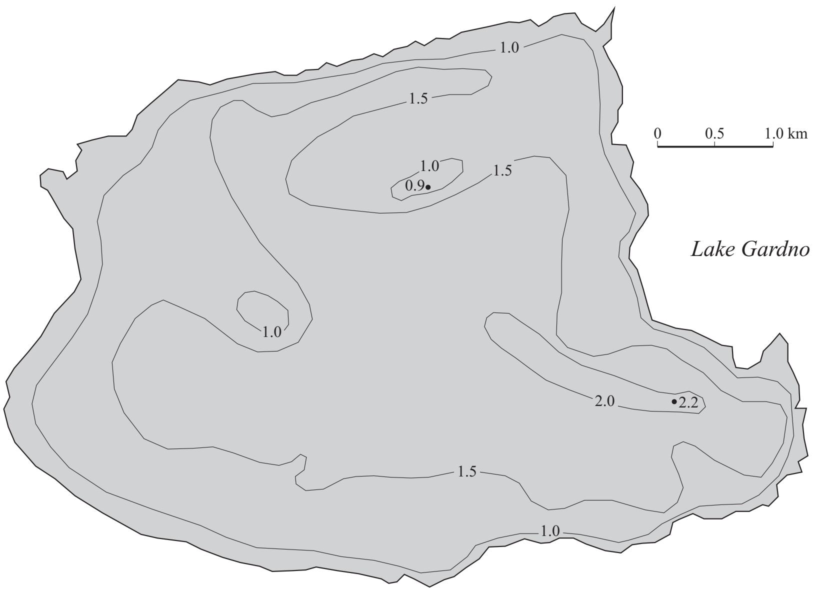


Figure 11. Bathymetric plan of Lake Gardno

3.3. Impact of hydrology on lake water salinity

The underground impact of the sea on these two lakes can be assumed to be minimal (Pietrucień 1983), as is the case in most lakes in the southern Baltic Sea coastal zone. The boundaries of underground direct drainage to the sea coincide with the surface watershed between rivers flowing into the Baltic Sea (ibid.). Ziętkowiak (1983) believes that there is a direct and significant impact of the sea on changes in groundwater levels, which is limited to a narrow strip of land 100–150 m wide, as in the case of the Łeba Spit. He associated the changes in water levels and groundwater chemistry of the Łeba Spit with changes in sea level and rainfall, and delimited three hydrodynamic zones and concordant hydrochemical zones of the same range.

In the first zone, a narrow strip about 100–150 m wide directly adjacent to the sea, the groundwater level is closely related to changes in sea level. In the second one, which is isolated from the sea shore and from the lake by high dune ramparts, groundwater level changes are long-term and are related to seasonal changes in sea level. Precipitation makes itself felt mainly through a build-up of high sea water, by increasing its amplitude and extending its duration. In the third, lake-side zone, the groundwater level changes are governed by the sea level, acting indirectly through changes in lake water levels. The result of this indirect action is a reduction in the amplitude of the groundwater table as well as delayed damming and a lowered water table in relation to the first zone.

The Holocene-Pleistocene level of the coastal Gardno-Łebsko Lowland is directly connected with the water-bearing deposits of the Reda-Łeba Spillway. It is fed by rainwater infiltration and lateral inflow from the plateau. The water table is no deeper than 3 m below ground level. This level includes groundwater of the carbonate-sodium and sulphate-sodium groups. The periodically changing type of water (from SO_4-Na to HCO_3-Na and vice versa), observed in the coastal zone of the lake, is associated with fluctuations in its level. It can be assumed that the sea, a factor governing the type of groundwaters, is of little importance. The direct influence of the sea on the changes of groundwater chemistry is limited to a narrow strip of land (of accumulative character) adjacent to the coast (Kozerski 1981, Kozerski & Kwaterkiewicz 1984, Piekarek-Jankowska 1996).

The law of Ghyben-Herzberg suggests that groundwaters in spits and areas adjacent to them depend on the dynamics of sea and lake water levels as well as the different densities of water, as their drainage areas stretch along sea and lake shorelines. Drainage along the entire Polish coast is free; only in the delta of the River Vistula is there additional artesian drainage (Pietrucień 1983). The salinity of underground water is sometimes high. Groundwater salinity in the catchments of coastal lakes, such as Lake Jamno, is often polygenetic, i.e. it is derived from marine and deep waters (Choiński 1981). In the case of coastal lakes, however, no supply of water through artesian drainage was recorded.

Lake Łebsko shows consistently high concentrations of marine-borne indicators, while Lake Gardno does so only periodically. The distance of these lakes from the coastline excludes the possibility of an underground inflow of marine waters. Using the formula of Ghyben-Herzberg, adapted to the salinity conditions prevailing in the Baltic Sea, Ziętkowiak (1983) calculated the depth of the lower limit of the fresh water lens in the coastal zone of the Łeba Spit.

The results indicate that only in the case of a significant lowering of the groundwater table can the right conditions occur for the periodic penetration of saline water at a depth of about 30 m below sea level to the profile closest to the sea (zone up to 150 m). The further penetration, as well as the longer presence of saline waters at this depth, is prevented by the substantial retention of groundwater that forces out saline water from the water-bearing sandy sediments overlying non-permeable sediments at a depth of ca 30–40 m below sea level.

Similar conditions exist in Lake Łebsko, where groundwater flowing into the lake from the interior of the spit limits the penetration of lake water in the sandy deposits of the spit to a narrow low-lying coastal zone. In this situation it can be assumed that the fresh water contained in the sandy sediments of the spit, besides the narrow marginal zones, does not have any contact with saline water.

These assumptions were confirmed by the results of chemical analyses, which allowed the water to be divided into three types: carbonate-sodium, sulphate-sodium and chloride-magnesium-sodium (Ziętkowiak 1983).

Groundwater chloride concentrations in Lakes Gardno and Łebsko decreased with increasing distance from the coastline (towards the lake). The chemical composition of the groundwater along the northern shores of these lakes showed a low concentration of chloride (Table 1).

Table 1. Groundwater chloride concentrations in the coastal zone between the sea and two coastal lakes

Name of lake	Measuring station	Distance from the sea [m]	Distance from the lake [m]	Chloride concentration [mg dm^{-3}]
Gardno	Rowy	100	1300	246.0–440.0
Gardno	Rowy	1200	200	63.0
Łebsko	Łeba	150	550	192.2
Łebsko	Łeba	600	100	7.8

3.4. Effect of wind speed and direction on the salinity of the lake water

Wind speed and direction are the conditions that can affect the variability of the chemical composition of coastal lake waters, including, according to Jankowski (2000), the spatial variability of their salinity. This can lead to the so-called support of free riverine water runoff. The result of this phenomenon is a situation in which seawater, under the influence of wind, forms a natural barrier that prevents the free drainage of water from the lake to the sea. We then have a situation where not only outflow is prevented, but water is pushed back into the lake. Another effect of the wind on the coastal lakes is the formation of wind damming. This happens when strong winds are blowing from the northerly sector, when masses of seawater are pushed towards the southern Baltic coast. This leads to local water damming, as a result of which seawater can be pushed into the lake basin through an existing connection. In the canal connecting the lake with the sea we then see the water flowing in the opposite direction to the usual one. This is a particularly frequent occurrence when the sea is stormy: the volume of water builds up very rapidly and is referred to as storm damming. What is also relevant is the angle at which waves approach the canal entrances. They arrive from the north-east in the case of Lake Łebsko and from the north-west in the case of Lake Gardno. The angle at which the waves are incident to the coastline is thus closely related to the location of the canals connecting the lakes with the sea.

Yet another example of the effect of wind on the hydrochemical diversity and variability of coastal lake water is the phenomenon of wind waves. The result is the complete mixing of the lake water in shallow basins. This causes small differences in the levels of physicochemical indices between the individual layers of water and ultimately the total disappearance of these layers. Wave action can also cause sediment resuspension. Cyberski & Jędrasik (1992) used a barotropic model for Lake Gardno to identify level differences in the lake basin, depending on the direction of the wind: they range from 0.4 to 0.6 m. These values were obtained for a wind speed of 20 m s^{-1}. However, wind speeds may exceed 30 m s^{-1}. Damming of the lake waters triggers a circulation that involves the entire mass of lake water. The model shows that after 24 h of the wind blowing at a speed of 20 m s^{-1}, the velocity of the water flow is significant and can reach up to 30 cm s^{-1}. This type of circulation has a huge impact on the physicochemical parameters of the water as well as its hydrobiological conditions. The lake water circulation depends not only on the wind speed and direction and the flow rate in the River Łupawa, but also on the volume of the seawater influx.

When northerly winds are blowing, there is an intrusion of seawater into the coastal lakes, whereas when winds are from the south, water flows out of the lake. The maximum flow rate (51 m^3 s^{-1}) on the Łeba Canal, which connects Lake Łebsko with the sea, was recorded by Szopowski (1962) during an the intrusion caused by N winds, when the initial difference in water level in relation to the sea was +43 cm. Given the same difference in water levels but a NW wind, the water flow rate in the canal was 32 m^3 s^{-1}. In the case of S winds, the fastest average flow rate was 50 m^3 s^{-1}. This was caused by a S wind, with an initial difference in water level of +66 cm between lake and sea. For the same water level difference but a SE wind, the flow rate was 36 m^3 s^{-1}.

The dominant wind direction causing seawater influxes into Lake Łebsko was SW–W. Between 1966 and 1970 this sector accounted for 58.0% of all directions (Weber 1973). Southerly winds made up 16.4%. These winds dammed up the water off the north-eastern shore of the lake. This was no obstacle, however, to the formation of a seawater influx as the winds were weak: their speed was 2–3 m s^{-1}. The temporarily lowered sea level was quickly compensated for by counter-currents.

The largest seawater intrusions into Lake Gardno occur during winds from the N (29.7% of intrusions), NW (26.0%) and W (13.5%) sectors (Balicki 1977). This is due to the alignment of the shoreline in relation to north. The percentage of seawater intrusions was the smallest for winds blowing from the E (4.3% of intrusions) and SE (1.1%) sector (ibid.). Of particular importance are winds blowing from the SW. According to Szmidt (1967), winds from this latter direction blow over the lake water perpendicularly to the currents of the River Łupawa. This generates damming-lowering movements. As a result of prolonged winds, the outflow of the Łupawa from the lake is weakened, thereby creating a situation conducive to seawater inflows.

The magnitude of the specific conductivity during the study period in the waters of Lake Łebsko was strictly dependent on wind direction. High conductivities ($> 2\,000$ μS cm^{-1}) were closely related to westerly and northerly winds (Figure 12). The same applied to the waters of Lake Gardno, except that the prevailing wind direction was from the north (Figure 13). The lowest conductivities (< 500 μS cm^{-1}) were measured in both lakes when winds were blowing from the southerly sector.

3.5. Effect of sea level changes on lake water salinity

The relevant literature indicates that the rhythm of water level fluctuations in the Baltic Sea and the two lakes takes a similar course, highlighting the dominance of higher water levels in the lakes (Figure 14).

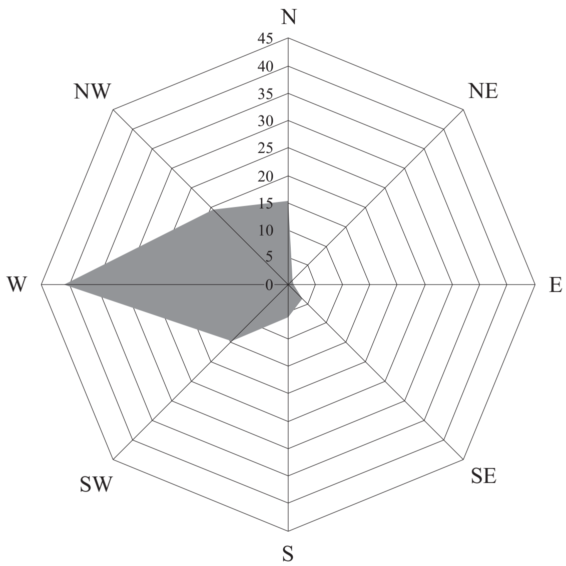


Figure 12. Distribution of wind directions at high conductivities ($>2\,000\,\mu S\,cm^{-1}$) in the waters of Lake Łebsko

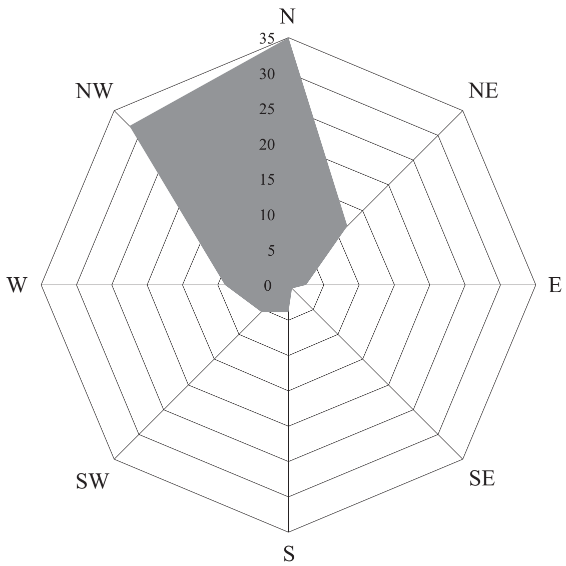


Figure 13. Distribution of wind directions at high conductivities ($>2\,000$ μS cm^{-1}) in the waters of Lake Gardno

One of the conditions that may affect the magnitude and diversity of the chemical composition of lake waters are changes in water level difference between the two lakes and the Baltic Sea. When the water level in the sea is higher than in the coastal lakes, there is an influx of brackish water. Szopowski (1962) found that brackish water readily enters the Lake Łebsko basin when the water level in the Baltic Sea is higher than that in the lake by at least 17 cm. He found that the number of intrusions is the largest when the water level difference between the sea and

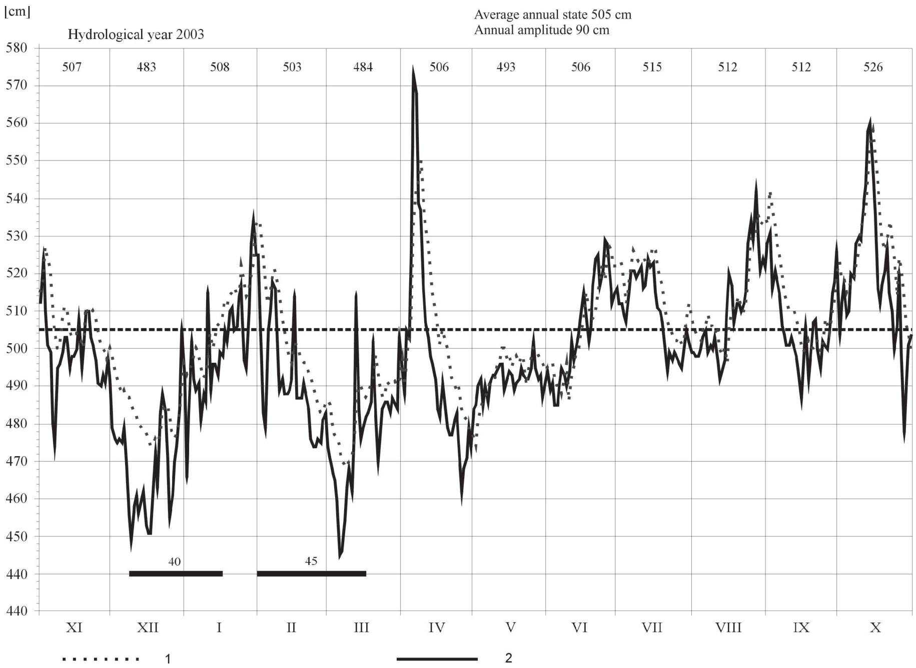


Figure 14. Comparison of fluctuations in Lake Łebsko water levels with Baltic Sea levels during the hydrological year 2003 (Chlost & Cieśliński 2005, altered); 1 – water state in Lake Łebsko, 2 – water state in the Baltic Sea

a coastal lake is approximately 0 to −10 cm and decreases with both rising and falling water levels. On the other hand, Drwal & Cieśliński (2007) consider that such inflows to Lakes Łebsko and Gardno can occur as soon as the water level difference is 1–2 cm. This may also apply to other coastal lakes with a surface connection with the sea. In the case of Lake Gardno, Jasińska (1990) observed that even with a difference of water levels between the sea and the lake of +5 cm an intrusion of seawater into the lake may occur at the mouth of the Łupawa.

In order to determine the impact of the changes in the water level differences between the Baltic Sea and the two lakes, the mean concentrations of chloride ions during higher and lower water levels of the Baltic Sea were compared. When water levels were higher in the sea than in Lake Gardno, the average chloride concentration at all measurement points was higher by approximately 230 mg Cl^- dm^{-3} (Figure 15). In the case of Lake Łebsko the average chloride concentration at all measurement points was higher by 230 to 398 mg Cl^- dm^{-3} (Figure 16).

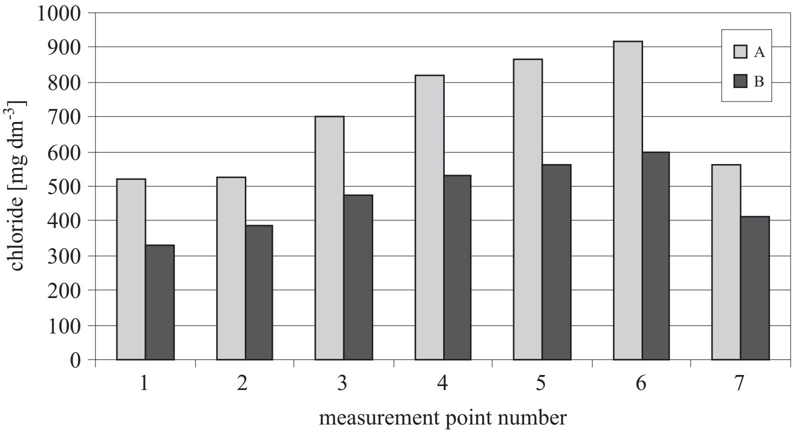


Figure 15. Average chloride concentration for water levels lower (A) and higher (B) in Lake Gardno than in the Baltic Sea

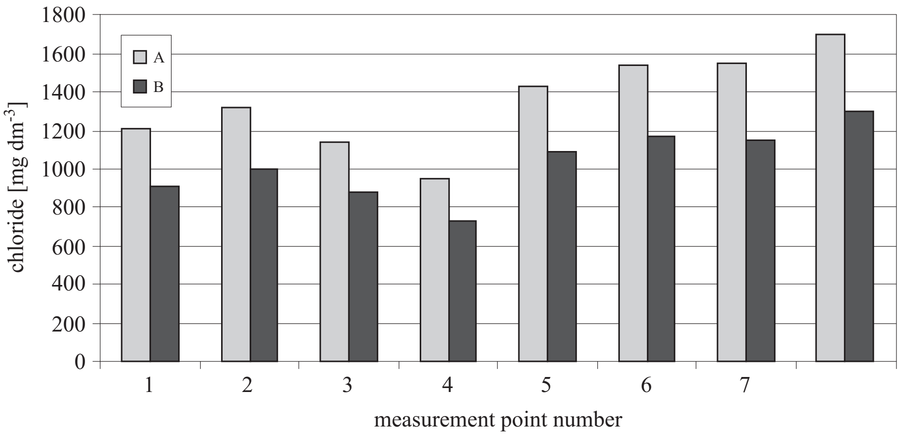


Figure 16. Average chloride concentration for water levels lower (A) and higher (B) in Lake Łebsko than in the Baltic Sea

3.6. Correlation between several-hour changes in specific conductivity and concurrent changes in sea level

Several-hour changes in specific conductivity in Lakes Gardno and Łebsko were compared to the sea level data available in the literature on seawater intrusions into the aforementioned bodies of water (Figures 17 and 18).

The correlation between all 120 recorded several-hour changes in specific conductivity (both large and medium) in Lake Gardno and the changes in sea level is weak (Figure 17). The corresponding correlation for Lake Łebsko,

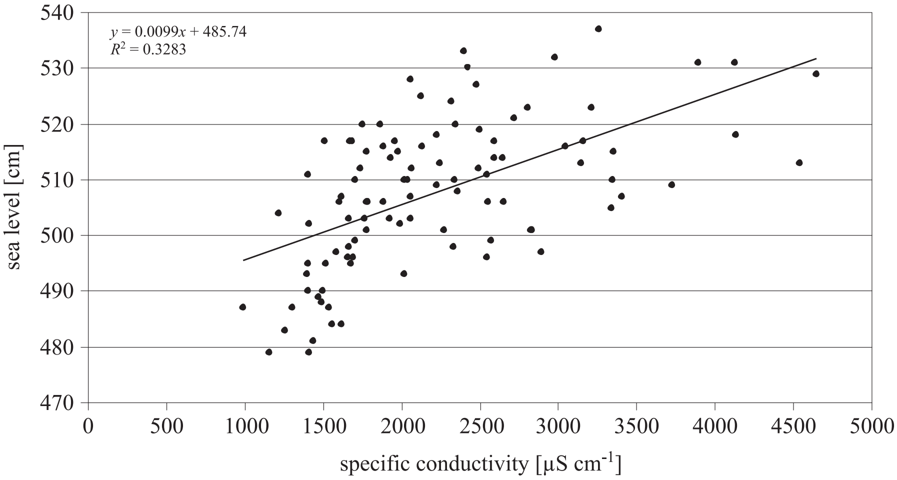


Figure 17. Relationship between sea level and specific conductivity in Lake Gardno

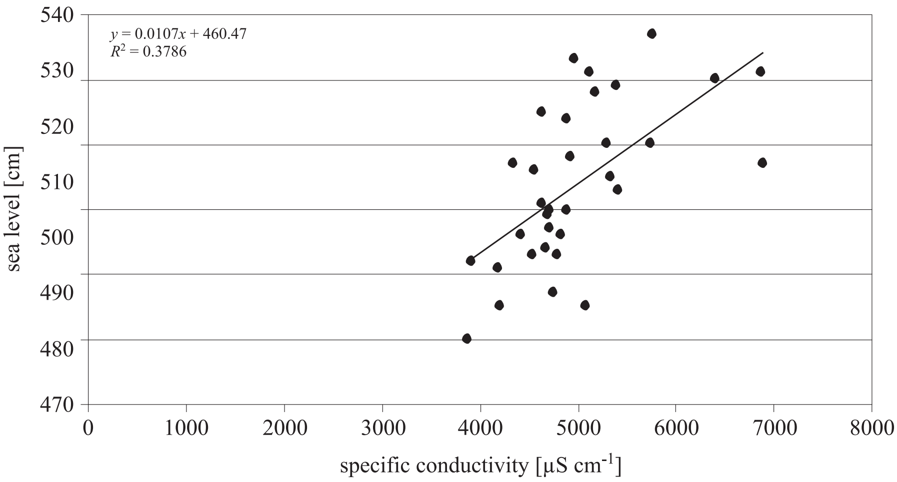


Figure 18. Relationship between sea level and specific conductivity in Lake Łebsko

based on 83 recorded changes in specific conductivity, is somewhat stronger (Figure 18).

3.7. Flows

In order to confirm the more or less substantial influence of seawater on the waters of the two lakes, flow rates were recorded at the hydraulic structures located at the sea ends of the lake-sea connections. The most variable of the flow rates, recorded over a longer period of time, occurred in the Łeba Canal, which connects Lake Łebsko to the sea. 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}. Minimum flow rates were around 10 m^3 s^{-1} whereas maximum values were around 54 m^3 s^{-1}.

Under normal circumstances, sea-bound flow rates in the Łupawa Canal (Lake Gardno) ranged from 10 to 20 m^3 s^{-1}, whereas lake-bound flows attained a maximum rate of 30 m^3 s^{-1}.

4. Discussion

4.1. The possible proliferation of seawater intrusions driven by several-hour episodes

As mentioned earlier, specific conductivity was measured continuously only at one site per lake. Previous research showed that the effects of seawater intrusions were more pronounced in the northern parts of coastal lakes (Drwal & Cieśliński 2007, Cieśliński 2009).

Several series of concurrent control measurements were performed each season in each lake. The purpose of this was to see whether the several-hour changes in specific conductivity, recorded in each lake near the canals linking the lakes to the sea (Figures 2 and 3), could be detected in other parts of the lakes in question. The control measurements obtained indicate that this is so. In each lake, the average specific conductivity (SC) was lower in its southern part than in its northern part. In Lake Gardno (Figures 19 and 20), SC in its southern part was roughly half the value recorded in the northern part.

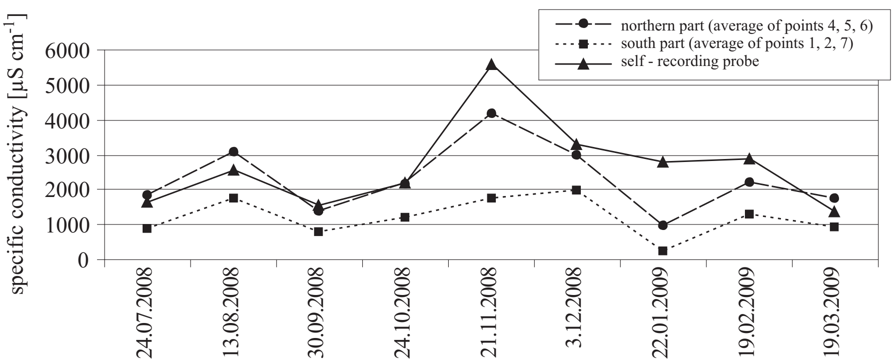


Figure 19. Specific conductivity in different parts of Lake Gardno in different seasons

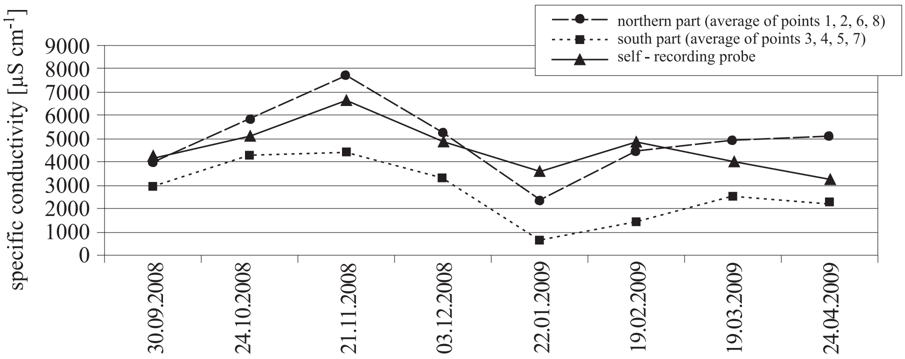


Figure 20. Specific conductivity in different parts of Lake Łebsko in different seasons

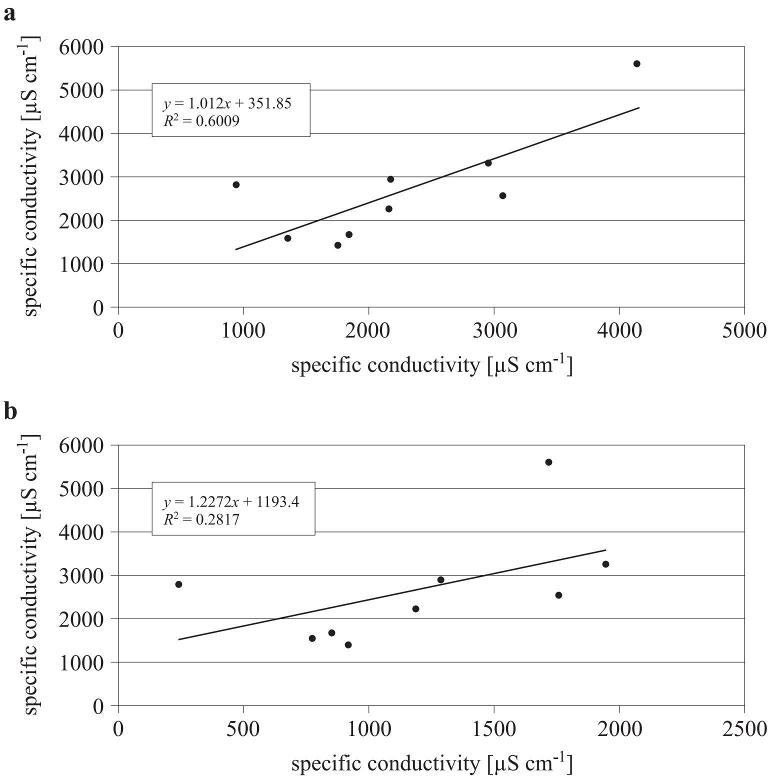
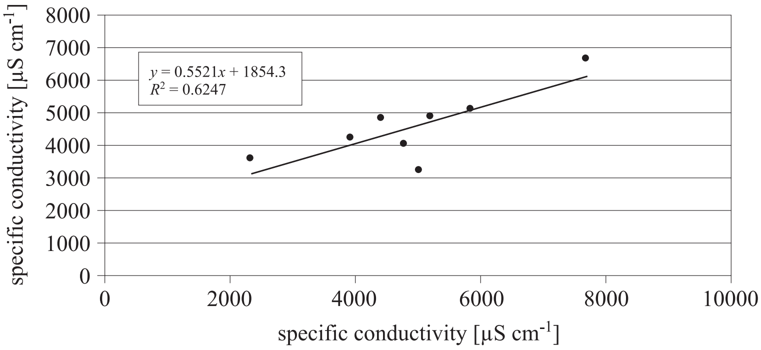


Figure 21. Relationship between specific conductivities in Lake Gardno, as measured by an automatic probe (OX axis) and at other sampling sites (OY axis): north (a) and south (b)

Measurements of specific conductivity (SC) made in different seasons have shown that a higher or lower SC recorded by an automatic probe would

a



b

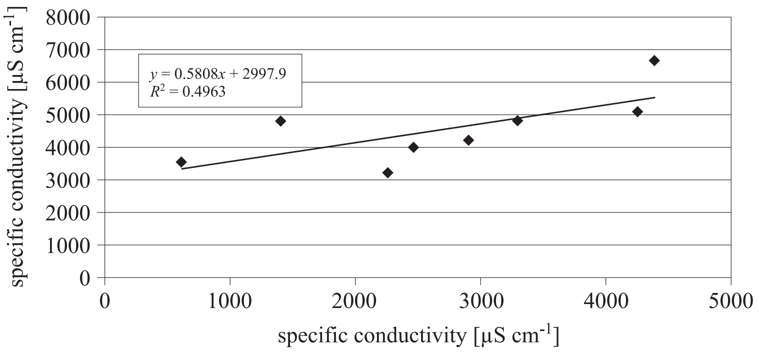


Figure 22. Relationship between specific conductivities in Lake Łebsko, as measured by an automatic probe (OX axis) and at other sampling sites (OY axis): north (a) and south (b)

be mirrored at other locations on the lake. However, specific conductivity was generally higher in the northern part of each lake (Figures 21 and 22).

5. Conclusions

The occurrence of several-hour periods of increasing and then decreasing specific conductivity in Lakes Gardno and Łebsko can be associated with high Baltic Sea levels observed at the same time (winter) and low water levels in the two lakes (summer). The phase resemblance indicates that the changes were caused by the same external factor – seawater intrusions – as shown by earlier research on the chemical composition of seawater and freshwater. This factor is separate from the cyclicality of low and high tides.

Thus far, water analysis has been done just once a season or once a month. Hence, we cannot state with any certainty that the samples collected represent the peak of a given event or its duration. However, the recording of specific conductivity on an hourly basis using automatic probes affords far greater accuracy. Events previously interpreted as one-off events have now been identified as sets of consecutive events. Such sets of events can include anywhere from several to several dozen small events.

The magnitude of the changes driven by seawater intrusions in each lake studied depends on the level of salinity in each lake as well as the relationship of the lake with its drainage basin. In the case of Lake Gardno, where the average salinity is 6 g kg^{-1}, several-hour increases and decreases in specific conductivity are larger than in the case of Lake Łebsko, where the average salinity is 12 g kg^{-1}. In addition, seawater intrusions proliferate across Lake Gardno with greater difficulty than is the case for Lake Łebsko. Lake Gardno experiences a stronger 'drainage basin effect' than does Lake Łebsko. The water exchange[1] rate for the two lakes is estimated at 9.3 (Lake Gardno) and 4.4 (Lake Łebsko).

The ability to continuously monitor specific conductivity affords a more accurate look at the extreme phenomena that occur sporadically along the southern shore of the Baltic Sea. This includes strong seawater intrusions into open freshwaters and wetlands.

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[1]The water exchange rate is defined as the ratio of the volume of water flowing out of the lake to the volume of water in the lake.

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