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The simplistic nitrogen input and output balance in Lake Łebsko – case study

by

Roman Cieśliński*

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Department of Hydrology, Institute of Geography, University of Gdańsk, ul. Jana Bażyńskiego 4, 80-952 Gdańsk, Poland

Abstract

The paper is based on the hypothesis that coastal lakes significantly affect changes in the quality of freshwater coming from catchments, which is best reflected in the reduction of biogenic loads. Some of the main reasons for this phenomenon include unique geographic locations of coastal lakes and physical and chemical properties of their waters as well as other hydrographic determinants that affect water circulation in catchments. The study area covered the direct drainage basin of Lake Łebsko, which is located in Słowiński National Park in northern Poland, on the coast of the southern Baltic Sea. The study was conducted from June 2008 to October 2010. Fieldwork was the main part of the research project and included hydrographic mapping, water sampling for laboratory analysis, and measurement of the discharge in all tributaries and outflows of the studied lake. Water chemistry data for Lake Łebsko indicate a significant accumulation of biogenic materials in the lake, which proves a strong effect exerted by the lake on the incoming water. This is true for both total chemical loads per year as well as concentrations of selected ions over short time intervals. This standard pattern may be interrupted by seawater intrusions that alter water chemistry in the whole lake.

Key words: coastal lakes, nitrogen load, hydrochemistry, Baltic coast

* Corresponding author: *georc@univ.gda.pl*

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Introduction

The response of aquatic ecosystems to nutrient enrichment and altered nutrient ratios varies along the continuum from freshwater to estuarine, coastal, and marine systems. Within the estuarine to coastal continuum, multiple nutrient limitations occur along the salinity and seasonal gradient, however, nitrogen is generally considered to be the primary limiting nutrient for phytoplankton biomass accumulation. In some cases, however, the load of nutrients into estuarine, coastal and marine systems exceeds the capacity of systems for assimilation of nutrient-enhanced production, and the degradation of the water quality occurs (Rabalais 2002).

Coastal lakes act as a natural filter for waters from drainage basins reaching the sea. This is important, as lakes located in the lower parts of drainage basins serve as the last collection point for most waters leaving the drainage basins. Lakes are bodies of standing (lentic) water where load reduction (debris, biogenic substances) is a common phenomenon. This is a typical result of physical, chemical, and biological processes occurring in standing water (Christia et al. 2014). In the case of coastal lakes, however, these processes are periodically interrupted and altered by the intrusive action of seawater. There are several causes of seawater intrusions, including high tides in the case of open seas (Otsmann et al. 1998; Beckers et al. 2002) and gales in the case of landlocked seas and semi-landlocked seas. Summertime low water stages in drainage basins may also prompt a seawater intrusion (Dailidiene et al. 2006; Drwal & Cieśliński 2007).

Agriculture and urban activities are major sources of nitrogen in aquatic ecosystems. Atmospheric deposition further contributes as a source of N. These nonpoint inputs of nutrients are difficult to measure and control, because they derive from activities dispersed over large areas of land and are variable in time due to weather effects. These nutrients cause diverse problems in aquatic ecosystems such as toxic algal blooms, loss of oxygen, fish kills, loss of biodiversity (including species important for commerce and recreation), loss of aquatic vegetation and other problems. Nutrient enrichment seriously degrades aquatic ecosystems and impairs the use of water for drinking, industry, agriculture, recreation, and other purposes (Carpenter et al. 1998). The effect of agriculture is reflected in rapid vegetation growth in most tributaries in spring and summer seasons leading to limited potamic flow from drainage basins and changes in water quality. This is particularly applicable to biogenic substances. Fertilizers and pesticides are used in a repeatable annual cycle, which is why coastal lakes are constantly affected by agriculture. Another effect of agriculture is eutrophication of lakes, which leads to excessive vegetation growth along lake shores. It can therefore be concluded that nitrogen compounds are the primary cause of rapid lake eutrophication (Vollenweider 1979). Most lakes in the world are currently affected by eutrophication (Vollenweider 1989).

What is important is the export of nitrogen from diffuse and point sources and its retention in the major river and lakes basins. According to Lepistö et al. (2006), agriculture contributes 38% of the total nitrogen export in Finland and forestry contributes on average 9%. Of the total N input to Finnish river systems, on average 22% was retained in surface waters and/or peatlands. The highest retention of N (36-61%) was observed in the basins with the highest percentage of lakes. The lowest retention (0-10%) of N was in the coastal basins with basically no lakes. In the total N balance, lake retention was estimated at 32% and peatland retention at 3% (Lepistö et al. 2006). The removal of N in a lake, which in most cases is dominated by denitrification, seems to be controlled by organic matter. If no major N fixation takes place, the concentration of total N in the epilimnion during summer is proportional to the load of N. N fixation occurs in some lakes (Hellström 1996).

A lake is supplied with water and nutrient material by its drainage basin. Together with its tributary streams, a lake forms a network characterized by a dynamic exchange of waters, transformation and retention of allochthonous matter caused by water (Knuth & Kelly 2011). This is a spatial system of two types of ecosystems that coexist and are connected by water transport – rivers and lakes. Streams that flow into a lake bring nutrient materials, chemical compounds, and suspended matter which directly affect the quality of lake water by increasing the concentration of nutrients or indirectly by initiating or accelerating processes that reduce the quality of water and inhibit the proper functioning of the lake ecosystem. Depending on many factors, lakes not only retain nutrients, but also supply them to rivers (Bajkiewicz-Grabowska & Zdanowski 2006). In many cases, functions of lakes in the circulation of nutrients may vary in different years (Jańczak et al. 2007).

The paper is based on the hypothesis that coastal lakes significantly affect changes in the quality of freshwater in catchment areas, which is best illustrated by the reduction of nutrient loads. This is due to i.a. unique geographic location of coastal lakes and physical and chemical properties of their waters as well as other geographic and hydrographic factors that affect water circulation in catchments. The nature and intensity of this transformation are determined by morphometric parameters as well as key characteristics and functions of coastal lakes. Other key factors include the hydrography and land use of drainage basins in question as well as their trophic status. The purpose of this research is the qualitative and quantitative determination of the range of changes in nutrient loads occurring in coastal lakes. The most important objective was to determine the simplistic balance of nitrogen reaching and leaving a coastal lake, based on the example of Lake Łebsko. The choice of the subject was dictated by the deterioration of the quality and progressive eutrophication observed in coastal lakes worldwide, including the Polish coast of the southern Baltic. It is known that one of the main causes is excessive inputs of nutrients from different point and nonpoint pollution sources.

Materials and methods

The study area covered the direct drainage basin of Lake Łebsko, which is located in Słowiński National Park in northern Poland (Fig. 1). The study was conducted from June 2008 to October 2010.

Fieldwork was the main part of the research and included hydrographic mapping, water sampling for laboratory analysis, and measurements of the discharge in all tributaries and outflows of the studied lake.

The discharge was measured in large streams using an acoustic Doppler current profiler made by Teledyne RD Instruments – StreamPro ADCP (depth range: 0.15 to 4.2 m). Another acoustic Doppler current profiler manufactured by Teledyne RD Instruments was also used in the course of research – Workhorse Rio Grande 1200 ZedHed ADCP (depth range: 0.3 to 21 m). In addition, small and medium-sized streams were analyzed using an Argonaut discharge meter made by YSI Sontek, while very shallow streams were analyzed using a VALEPORT electromagnetic discharge meter. Figure 1 shows the location of hydrometric profiles on the studied streams.

The continuous water-level measurements were performed using a 6920V2 automatic probe made by YSI Sontek. The probe was installed in the northeastern part of Lake Łebsko at the point where a canal exits the lake before reaching the Baltic Sea (Fig. 1). The measurements were performed at one-hour intervals.

The measurements were performed at 8 sites (Fig. 1). Water samples were collected from the surface and the midsection of the lake. Lacustrine bottom sediments were also collected. In addition, a number of measurement sites were selected in streams flowing into the lake and in the canal which is the only connection of Lake Łebsko with the Baltic Sea. Additional sites were established in the Baltic Sea (Fig. 1). Water and sediment sampling was performed once a month from June 2008 to October 2010.

Surface water samples were collected using a 3 dm^3 collection vessel. Water at middle depths was sampled using a Burke bathymeter. Lacustrine bottom sediments were collected using a pipe vessel designed by Kajak (1983) and a collection vessel designed by Eijelkamp (sandy sediment). Samples of active sediment were collected from the 25-30 cm thick layer (Engstrom & Swain 1986; Rainey et al. 2000). An MPW-340 centrifuge was then used to remove interstitial water from the sediment. The water was analyzed for the presence of selected chemical substances.

Laboratory analysis was designed to measure the concentration of main ions, which could then be used to identify the hydrochemical type of Lake Łebsko. A Dionex ICS 1100 ion chromatograph was used for this purpose. Nitrate was determined via colorimetry using sodium salicylate using a DR 890 photometer manufactured by HachLange. Standard laboratory methods were employed to determine total nitrogen using a VIS NOVA 400 spectrophotometer manufactured by Merck.

Raw physical and chemical data, including N, on atmospheric precipitation were obtained from the Air Monitoring Station in the town of Łeba, while hydrological data were obtained from the Institute of Meteorology and Water Management in Gdynia.

Biogenic compounds were characterized based on the measured loads, monthly averages and annual averages.

Nitrogen compounds were characterized on the basis of the value of instantaneous, average monthly and annual average loads.

Momentary loads were calculated according to the formula:

$$L_i = C_i \times Q_i$$

where:

L_i – momentary loads [g s^{-1}],

C_i – instantaneous concentration [mg dm^{-3}],

Q_i – water flow [m^3 s^{-1}].

Average monthly loads are calculated based on instantaneous loads in a given month:

$$L_m = \frac{\sum_{i=1}^{n} L_i}{n}$$

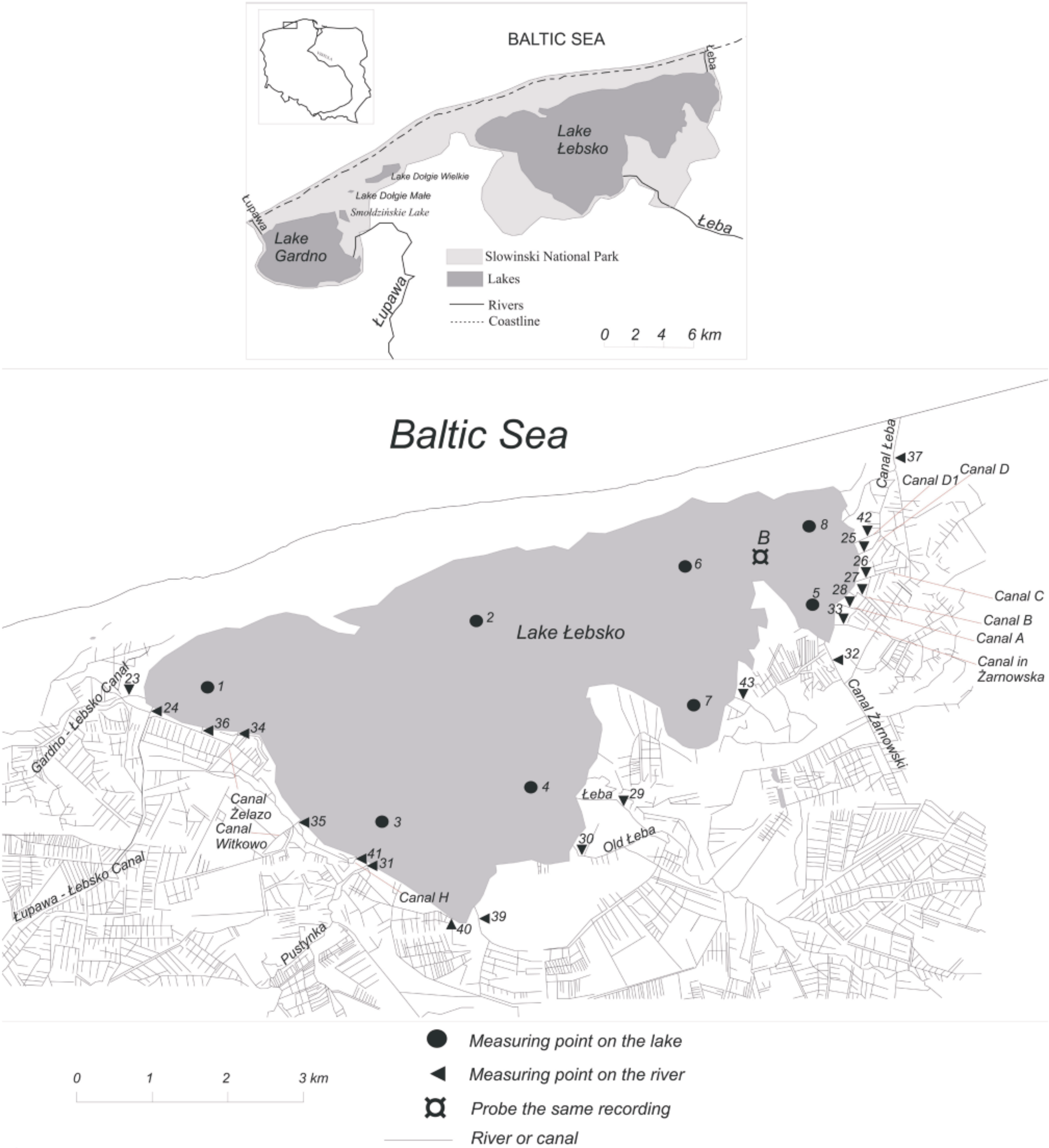

Figure 1

Location of Lake Łebsko in the Polish coastal zone and location of measurement sites

where:

L_m – average monthly loads [g s^{-1}],

n – the number of measurements (per month)

The average annual loads are calculated based on average monthly loads, taking into account the different number of days in each month of the year:

$$L_r = \frac{1}{365}\sum_{i=1}^{12} m_i \times L_{m_i}$$

where:

L_r – the average annual load [g s^{-1}],

m_i – the number of days in a month.

The study determined the relationship between the annual N load into and from the lake and the mass of N stored in the lake waters. The following formula was used:

$$N_{in} - N_{out} = \Delta N$$

where:

N_{in} – input of total N [tons month^{-1}]

N_{out} – output of total N [tons month^{-1}]

Further, the following was established:

$$\Delta N < N_{ret}\ ,\ \Delta N > N_{ret}\ ,\ \text{or}\ \Delta N \approx N_{ret}$$

where:

N_{ret} is the actual mass of N stored in the lake [tons × month^{-1}] and was calculated as follows:

$$N_{ret} = N_{tot} \times V_{lake}\ [\text{tons}]$$

where:

N_{tot} – indicate N concentration in the lake [mg dm^{-3}],

V_{lake} – lake volume [dm^3]

Results

Morphometry and hydrography

One of the main determinants of the transformation in lakes is the lake basin morphometry, especially the lake depth and the degree of water mixing induced by wind. Both factors are very important in the case of coastal lakes, as most of them are characterized by a small average and maximum depth. Most coastal lakes do not have a well-developed epilimnion and are very sensitive to wind effects. As a consequence, water in coastal lakes tends to be well mixed. Lake Łebsko follows this well-established pattern. Its average depth is 1.6 m, while its maximum depth is 6.3 m. It is a shallow lake (Cieśliński 2007) and according to the Berger formula (1955), its maximum mixing depth is about 9 meters. The calculations indicate that stratification cannot occur in this lake and instead the complete mixing is a key characteristic.

The exposure index for Lake Łebsko is 4462.5, which is a measure of the impact of wind on a given lake. This high value suggests that the lake is strongly affected by the wind. For comparison, the average for lakes in Poland is 30.

Lake Łebsko is a body of water exposed to inflows of fresh and sea water. The lake receives water from its direct drainage basin and the basin of the Łeba River. In addition, when the hydrometeorological conditions are favorable, the lake also receives water from the Baltic Sea. In short, there is a strong connection between each element of the hydrographic network. The catchment size is one of characteristics affecting the water circulation. The total area of the drainage basin of Lake Łebsko is 1,594.0 km^2, while the area of its direct drainage basin is 322.0 km^2, which is 20.2% of the total drainage basin of the Łeba River.

When assessing the impact of a catchment area on a lake, it is important to compare the size of a given lake with the size of its catchment. Ohle's index is a useful measure of this relationship. It is 22.3 for Lake Łebsko, which is a relatively high value and indicates a relatively strong impact of the catchment on the lake. Another measure is the Schindler index (ratio of the total surface of the lake and its catchment area to the volume of the lake), which is 13.6 for Lake Łebsko.

One key difference between coastal lakes in northern Poland is the way they are connected with the Baltic Sea. Lake Łebsko is connected with the sea by the Łeba Canal (2.6 km long). Such connections facilitate seawater intrusions from time to time. The longitudinal gradient of the Łeba Canal is 0.12‰.

Water exchange

The average water exchange index reported in the literature for Lake Łebsko is 3.6. What is important here is the range of this index, which can be illustrated by the lowest annual, highest annual, and average annual discharge for the period of 1961-2005. The water exchange index for Lake Łebsko can vary from 2.44 to 4.24, with an average value of 3.16. The result is a hypothetical exchange of water in the lake from 2.5 to more than 4 times a year. The average value suggests an average rate of water exchange in the lake.

However, the index does not illustrate how water exchange rates will change when affected by periodic seawater intrusions. A discharge measurement performed on November 10, 2006 illustrates such an intrusion. The discharge was measured in the canal connecting the lake with the sea. Water from the sea was shown to flow toward the lake via the full profile of the canal. The discharge was measured to be about 54 m^3 s^{-1}, which produced a water exchange index of 14.5. Assuming no inflow of freshwater, it would take about 25 days to fill the lake with seawater. An intrusion this long has never been recorded and freshwater does always enter the lake from its catchment. However, in this purely theoretical scenario, the lake would be filled with seawater after a longer period of time.

Freshwater inflow to Lake Łebsko

The main tributary of Lake Łebsko is the Łeba River. Data collected by the Polish Institute of Meteorology and Water Management suggest that the Łeba River is characterized by relatively small differences in the annual discharge. The mean value for the period of 1961-2000 is 11.7 $m^3 s^{-1}$, while the highest values are noted for the autumn and winter seasons. The mean discharge in the Łeba River fluctuated from 9.08 $m^3 s^{-1}$ in June to 14.2 $m^3 s^{-1}$ in March in the 1961-2000 period. The lowest discharge values ranged from 4.3 $m^3 s^{-1}$ in August to 7.9 $m^3 s^{-1}$ in December. The highest discharge values ranged from 22.9 $m^3 s^{-1}$ in August to 45.9 $m^3 s^{-1}$ in July. In addition, raw data on extreme discharge were also collected for the Łeba River in 1961-2000. The lowest discharge on record was noted on August 10, 1992: 4.3 $m^3 s^{-1}$. The highest discharge on record was noted on July 13, 1980: 45.9 $m^3 s^{-1}$.

The second largest tributary of Lake Łebsko – the Pustynka River – supplied water to the lake at a mean rate of 2.2 $m^3 s^{-1}$ in 2003-2007. Its mean discharge values fluctuated between 1.6 $m^3 s^{-1}$ in 2007 and 2.6 $m^3 s^{-1}$ in 2004. The maximum value was noted in March (3.8 $m^3 s^{-1}$), while the minimum value was noted in July and August (1.3 $m^3 s^{-1}$). The discharge varied from 0.9 $m^3 s^{-1}$ to 5.1 $m^3 s^{-1}$ in the study period. TMaximum values were always noted in March (spring snowmelt), while minimum values were noted in July and August and sporadically in September.

In addition to the two larger rivers, Lake Łebsko also receives water from more than a dozen smaller rivers, streams, and drainage canals, which constitute the direct drainage basin of the lake. The research in 2008-2010 has shown that discharge from the direct drainage basin of the lake averaged 1.13 $m^3 s^{-1}$.

Polder management

The polder system of Lake Łebsko consists of 13 polders located in close proximity of the lake and the downstream part of the Łeba Valley. The polders are located on a plain in three regions – the southwest, southeast, and east of the lake. The total area of the polders near Lake Łebsko is 5480 ha. The output rate of pumps is 8.48 $m^3 s^{-1}$, which translates into 267.5 M m^3 per year, assuming that all pumps work all year round, 24 hours a day. The actual rate depends on hydrometeorological conditions and varies from year to year. The polder system supplied an average of 14,579,000 m^3 of water per year in the period of 2003-2007, which is equivalent to 5.5% of the available pump capacity. This is also equivalent to a 204.2 mm layer of water per year.

Discharge in canals connecting Lake Łebsko with the Baltic Sea

The Łeba Canal is the only surface link between Lake Łebsko and the nearby Baltic Sea. Water in the canal can flow either way – in the standard direction from the lake to the sea as well as in the opposite direction (referred to as negative) from the sea to the lake. The latter is known as a seawater intrusion.

Both types of flow were observed in the course of the study period. The proper flow (to the sea) was noted on 18 occasions, while the negative flow (to the lake) was noted on 11 occasions (Fig. 2). The mean discharge from the lake to the sea was recorded at 13.7 $m^3 s^{-1}$ and ranged from 10.2 (April 2009) to 20.3 $m^3 s^{-1}$ (March 2010). The mean discharge from the sea to the lake was recorded at 18.2 $m^3 s^{-1}$ and ranged from 14.8 (November 2009) to 25.8 $m^3 s^{-1}$ (December 2008).

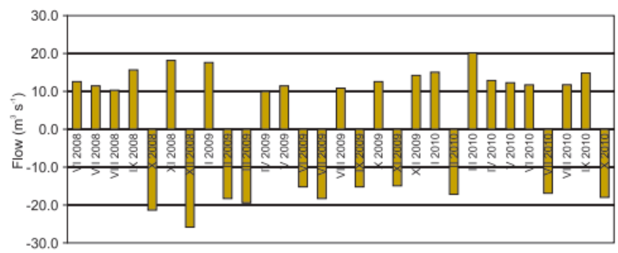

Figure 2

Discharge in the Łeba Canal between June 2008 and October 2010. Negative values indicate the sea-lake flow direction, while positive values indicate the lake-sea flow.

Net surface flow

The net surface flow was determined for Lake Łebsko based on the discharge from the rivers Łeba and Pustynka, other watercourses that constitute the direct drainage basin of the lake, the water inflow from polders, as well as estimates of the brackish water amount reaching the lake from the nearby Baltic Sea. This dataset was used to determine a mean discharge for the Łeba River at 11.7 $m^3 s^{-1}$, which translates into an annual inflow of 369 M m^3 of water into Lake Łebsko. The second river – the Pustynka River – has a mean annual inflow of 69.4 M m^3 of water into Lake Łebsko. The total annual value for both contributing rivers is 438.4 M m^3 of water. In addition, other watercourses in the direct drainage basin of the lake yield a discharge of 1.13 $m^3 s^{-1}$, which translates into an annual inflow of 35.7 M m^3 of water. Finally, the polder system yields about 15 M m^3 of water per year, which is roughly 5.5% of the pump capacity.

The average inflow of seawater to the lake per year was also determined (159 M m^3). The flow in the lake-to-sea direction via the Łeba Canal was measured at 707.6 M m^3 per year.

The research data show that the total gravitational and forced surface flow reaching the lake yields about 650 M m^3 of water per year. The total N has four components: two large tributaries – the Łeba (56.8% of the total surface water inflow) and the Pustynka (10.7%), the inflow of seawater (24.6%), the inflow of water from polder pumps (2.4%), and the inflow of additional water from the direct drainage basin of the lake (5.5%). Figure 3 lists and quantifies sources of the surface water reaching Lake Łebsko.

Differences in the concentrations of nitrogen compounds

The nutrient substances analyzed in this study in Lake Łebsko were characterized by significant changes in concentration, often due to changing seasons or the direct or indirect effects of human impact.

Table 1 shows changes in the concentration of nutrient substances in Lake Łebsko.

The highest mean concentration of nitrogen in surface water was determined at Site No. 4 (1.39 mg N dm^{-3}) in Lake Łebsko. This is the location of the Łeba River mouth, i.e. the largest tributary. The two lowest mean concentrations of nitrogen were determined at Site No. 2 (1.11 mg N dm^{-3}) and Site No. 8 (1.12 mg N dm^{-3}). The former site is located in the northern part of the lake, while the latter site is located close to the canal connecting the lake with the sea. At other sampling sites on the lake, the mean concentration of nitrogen varied from 1.21 to 1.36 mg N dm^{-3}.

The distribution of nitrate in Lake Łebsko was somewhat different, with the highest concentration determined at Site No. 3 (0.85 mg NO_3^- dm^{-3}). This site is located across the lake from the locations where

Table 1

Concentrations of nutrient substances in Lake Łebsko in the study period

Indicator [unit]	Minimum	Maximum	Average
Total nitrogen [mg N dm^{-3}]	0.31	3.08	1.25
Nitrates [mg NO_3^- dm^{-3}]	0.05	1.94	0.58
Ammonium [mg NH_4^+ dm^{-3}]	0.90	3.90	2.20

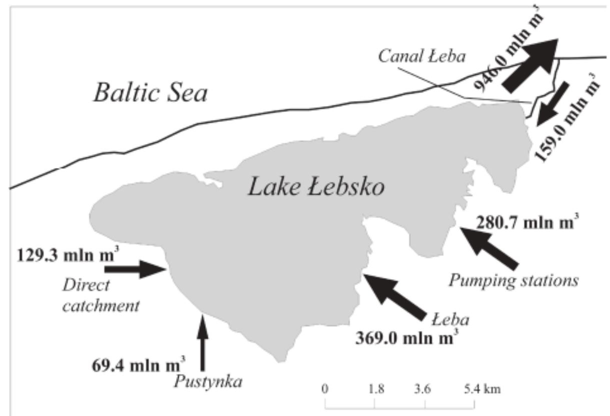

Figure 3

Inflow of surface water into Lake Łebsko

the rivers Łeba and Pustynka flow into the lake. As in the case of total nitrogen, the lowest concentration of nitrate was determined at Site No. 8 (0.50 mg NO_3^- dm^{-3}). The mean concentration of nitrate at the other sampling sites on the lake ranged from 0.53 to 0.69 mg NO_3^- dm^{-3}.

The highest mean concentrations of ammonium were determined at Site No. 3 (3.4 mg NH_4^+ dm^{-3}) and Site No. 4 (3.6 mg NH_4^+ dm^{-3}). The lowest mean concentration of ammonium was determined at Site No. 8 (1.3 mg NH_4^+ dm^{-3}) (Fig. 4). Mean concentrations at other sites on the lake ranged from 1.5 to 3.0 mg NH_4^+ dm^{-3}.

Analysis of total nitrogen concentrations over time reveals a similar pattern at all sampling sites. The highest concentrations were determined in winter, while the lowest in autumn (Fig. 5). The highest nitrate concentrations were determined in winter and spring, while the lowest in summer and autumn (Fig. 6).

Changes in the concentration of ammonium over time followed a slightly different pattern. The highest concentrations were recorded in summer, while the lowest in winter. The main most likely reason was the accumulation of organic waste produced by water birds that breed in the vicinity of both lakes in the summertime (Jarosiewicz 2009) and degradation of organic matter in the water column. The production of bird waste leads to an increased water ammonium content. Another reason for this increase is a larger number of tourists in Słowiński National Park in summer (10-fold increase). Visitors produce much more wastewater in the summer than during the rest of the year. Waste water from the sewage treatment plant in the town of Łeba is discharged into the Łeba Channel Leba. The other four sewage treatment plants discharge into rivers and canals, which then flow into Lake Łebsko.

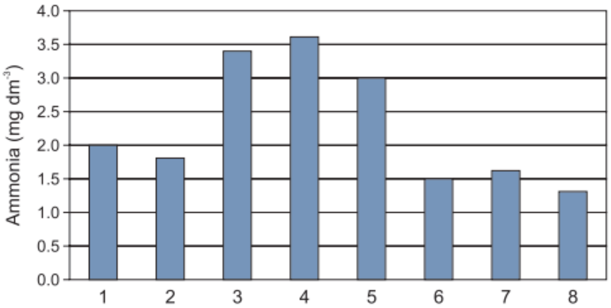

Figure 4

Mean concentrations of ammonium in Lake Łebsko at selected sampling sites

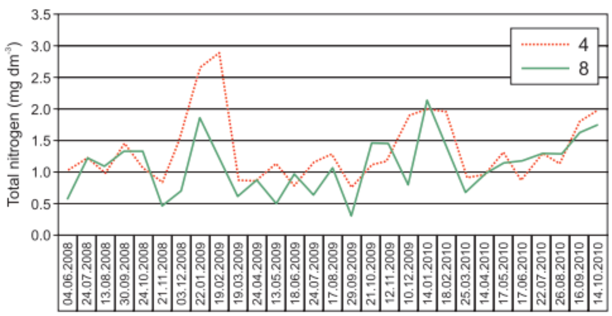

Figure 5

Changes in the concentration of total nitrogen in Lake Łebsko – two sampling sites. Two sampling sites: Site No. 4 – located in the southern part of the lake; Site No. 8 – located in the northern part of the lake

The largest differences in the concentration of total nitrogen between lake near-bottom water and interstitial water reached 30% in Lake Łebsko. In the case of ammonium and nitrate, the differences were below 10% (Table 2). The concentrations of all three ions increased with lake depth.

The concentrations of the analyzed nutrient substances were higher in the majority of watercourses

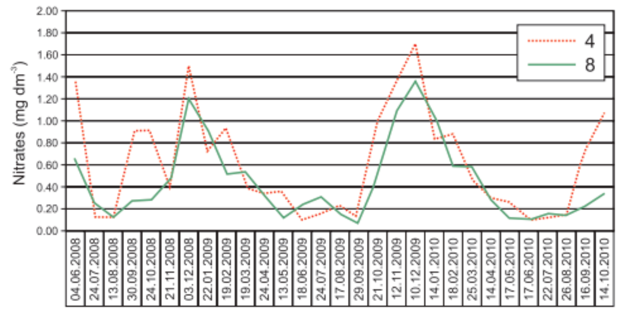

Figure 6

Changes in the concentration of nitrates in Lake Łebsko. Two sampling sites: Site No. 4 – located in the southern part of the lake; Site No. 8 – located in the northern part of the lake

reaching Lake Łebsko compared to the lake itself (Table 3).

The concentration range for total nitrogen in the watercourses reaching Lake Łebsko ranged from 0.45 mg N dm^{-3} to 7.38 mg N dm^{-3}. Mean concentrations ranged between 1.44 mg N dm^{-3} and 3.20 mg N dm^{-3}. In addition, Paturej and Goździejewska (2005) estimated the concentration of total nitrogen reaching Lake Łebsko via the Łeba River at 4.4 mg N dm^{-3}.

The concentration of nitrate in the watercourses reaching Lake Łebsko ranged between 0.01 mg NO_3^- dm^{-3} and 5.21 mg NO_3^- dm^{-3}. This indicates large differences in the nitrate content in the studied water bodies. The rates of changes in the nitrate concentration were also quite significant. Changes in the concentration followed a different pattern in the rivers Łeba and Stara Łeba compared to all other studied watercourses. In this case, mean concentrations determined in the study period ranged from 0.69 mg NO_3^- dm^{-3} to 1.64 mg NO_3^- dm^{-3}.

Lake Łebsko is supplied with biogenic substances by rivers and streams, atmospheric precipitation, and seawater intrusions that occur periodically when the hydrometeorological conditions are favorable.

Table 2

Mean concentrations of nutrient substances in lake surface water, lake bottom water, and lake interstitial water for Lake Łebsko from June 2008 to October 2010

Indicator [unit]	Layer	Point							
		1	2	5	6	8	3	4	7
Total nitrogen [mg N dm^{-3}]	Surface	1.36	1.11	1.21	1.34	1.12	1.33	1.39	1.33
	Near-bottom	1.34	1.16	1.28	1.40	1.16	1.39	1.41	1.41
	Interstitial	1.77	1.64	1.49	2.13	1.67	1.95	1.76	1.62
Nitrates [mg NO_3^- dm^{-3}]	Surface	0.67	0.53	0.67	0.69	0.50	0.85	0.68	0.56
	Near-bottom	0.67	0.54	0.71	0.64	0.59	0.79	0.79	0.65
	Interstitial	0.79	0.72	0.77	0.86	0.74	0.96	0.78	0.80
Ammonium [mg NH_4^+ dm^{-3}]	Surface	2.0	1.8	3.0	1.5	1.3	3.4	3.6	1.6
	Near-bottom	2.1	1.8	3.2	1.6	1.5	3.5	3.6	1.7
	Interstitial	2.2	1.9	3.3	1.9	1.6	3.8	3.8	1.9

Table 3

Mean concentrations of nutrient substances in river and stream water reaching Lake Łebsko between June 2008 and October 2010

Name	Total nitrogen [mg N dm^{-3}]	Nitrates [mg NO_3^- dm^{-3}]	Ammonium [mg NH_4^+ dm^{-3}]
Gardno – Łebsko Canal	1.44	0.69	2.48
Łupawa – Łebsko Canal	2.04	0.89	2.66
Łeba	1.85	1.41	2.25
Old Łeba	1.92	1.02	2.28
Pustynka	2.37	1.64	2.95
Canal Żarnowski	3.20	1.29	3.16
Canal Żelazo	1.64	1.18	2.67
Canal Witkowo	1.85	1.05	2.44
Canal Izbicki	1.97	1.03	3.15
Lake Łebsko	1.27	0.64	2.20

Brackish water may enter the lake in the course of seawater intrusions and provide a supply of nitrogen compounds. In most cases, the concentration of total nitrogen was higher in Lake Łebsko. However, higher concentrations were determined in the Łeba Canal in the case of three study intervals, ranging from 0.74 to 1.26 mg N dm^{-3}, while total nitrogen concentrations in Lake Łebsko ranged from 0.62 to 1.07 mg N dm^{-3}. In the case of all other study intervals, the concentration of total nitrogen ranged between 0.20 and 1.27 mg N dm^{-3} in the Łeba Canal and between 0.31 and 1.78 mg N dm^{-3} in Lake Łebsko.

In four cases, higher nitrate concentrations were determined in the Łeba Canal than in Lake Łebsko. Concentrations ranged from 0.79 to 1.20 mg NO_3^- dm^{-3} in the canal and from 0.28 to 0.59 mg NO_3^- dm^{-3} in the lake. At other times, the nitrate concentration ranged from 0.00 to 0.87 mg NO_3^- dm^{-3} in the canal and from 0.07 to 1.19 mg NO_3^- dm^{-3} in the lake.

The ammonium concentration was higher in Lake Łebsko than in the Łeba Canal throughout the study period and ranged from 0.9 to 3.3 mg NH_4^+ dm^{-3}. The range was much smaller in the Łeba Canal. Finally, the concentration of ammonium in the Łeba Canal ranged from 0.5 to 2.0 mg NH_4^+ dm^{-3}.

The research has shown that Lake Łebsko is supplied with seawater from the Baltic Sea (via the Łeba Canal) from time to time, but also delivers water to the Baltic Sea. Significant changes in the concentration of selected nutrient compounds have been observed during each period of the lake-to-sea flow.

During periods of the lake-to-sea water flow, total nitrogen concentrations in the Łeba Canal ranged from 0.48 to 1.86 mg N dm^{-3}. The average for the entire period was 1.13 mg N dm^{-3}. Total nitrogen concentrations varied significantly over time, but were much lower than those determined for Lake Łebsko. Some of the reasons for this included the effect of the sea, even when the brackish waters are not readily detectable, as well as biochemical and transformational processes occurring in the lake basin itself. Such processes included the absorption of total nitrogen by plants and deposition in lake bottom sediments.

The concentration of nitrate in the Łeba Canal was also much lower than that in Lake Łebsko. The concentration range for the Łeba Canal during periods of the lake-to-sea water flow was 0.02 to 1.22 mg NO_3^- dm^{-3}, while the mean for the entire period was 0.43 mg NO_3^- dm^{-3}. The concentration of total nitrogen and that of nitrate significantly fluctuated over time. The pattern for ammonium was quite similar to that for other nitrogen compounds, but changes were smaller over time. The mean concentration of ammonium in the study period was 1.36 mg NH_4^+ dm^{-3} and the concentrations varied between 0.50 and 2.30 mg NH_4^+ dm^{-3}.

The size of the load of nutrients discharged into Lake Łebsko

The Łeba River supplies the largest load of total nitrogen to Lake Łebsko. It is several times larger than that supplied by other watercourses (Fig. 7) in the drainage basin. The Pustynka River periodically supplies a larger than usual load of total nitrogen, but it is still several times smaller than that delivered by the Łeba River. The largest total nitrogen concentration in the Łeba River was recorded in July 2010 (81.43 tons), while the smallest was determined in July 2009 (8.82 tons). In addition to the Łeba and Pustynka rivers, smaller rivers also contribute total nitrogen to Lake Łebsko – 4.03 tons in July 2010 and 2.02 tons in July 2009. This is equivalent to one fourth to one twentieth of the load supplied by the Łeba River. For comparison,

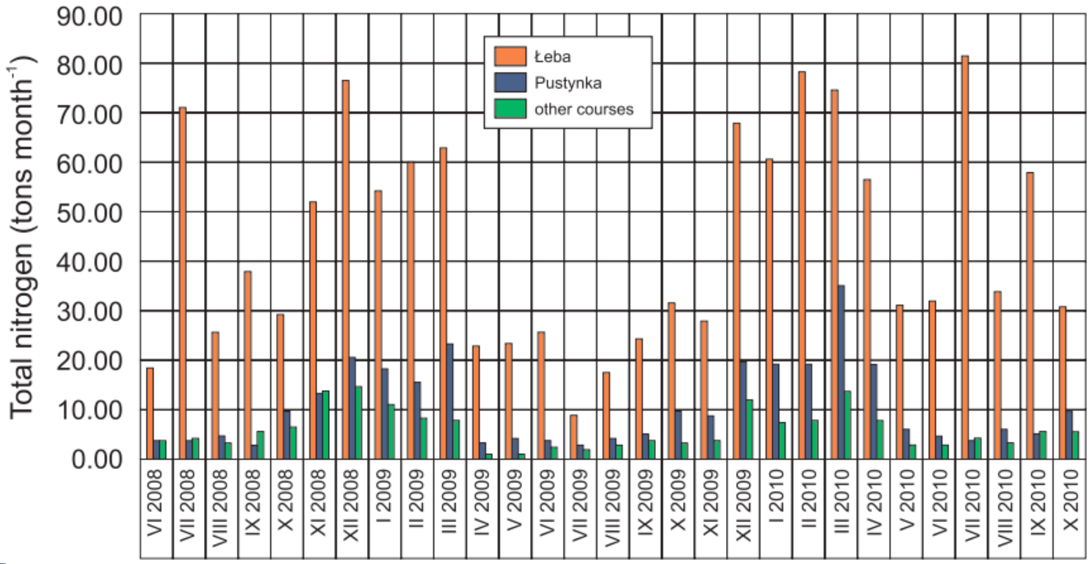

Figure 7

Total nitrogen load supplied to Lake Łebsko by rivers and canals in 2008-2010

the Pustynka River supplied 2.82 tons of total nitrogen in September 2008 and 34.96 tons in March 2010. According to Bogdanowicz (2004), the inflow rate for total nitrogen supplied by the Łeba River ranged from 10.7 to 170.6 g s^{-1}, with an average of 42.9 g s^{-1}. Table 4 lists mean monthly total nitrogen loads that vary quite significantly from year to year.

The total nitrogen load reaching Lake Łebsko from the Baltic Sea ranged from 8.14 t $month^{-1}$ in September 2009 to 59.43 t $month^{-1}$ in December of 2008. The average load that arrives in Lake Łebsko via seawater intrusions is 36.01 t $month^{-1}$. The largest total nitrogen loads were determined in winter, which is associated with the strongest seawater intrusions that occur via the Łeba Canal.

Table 4

Mean monthly total nitrogen load, nitrate load and ammonium loads (tons per month) for watercourses flowing into Lake Łebsko in 2008-2010

Name	2008	2009	2010
total nitrogen load			
Łeba	44.27	35.39	53.55
Pustynka	8.18	9.81	12.64
Other courses	7.27	4.84	6.03
nitrate load			
Łeba	35.41	29.64	36.77
Pustynka	6.36	7.82	7.59
Other courses	4.69	2.65	3.16
ammonium loads			
Łeba	64.84	51.19	62.43
Pustynka	7.91	7.27	9.18
Other courses	8.83	4.81	6.65

The largest nitrate loads supplied to Lake Łebsko arrived via the Łeba River whose highest nitrate concentration was determined in July 2010 (67.27 tons), while the lowest in July 2009 (5.88 tons). The second largest contributor of nitrate to Lake Łebsko – the Pustynka River – supplied between 0.24 tons in July 2008 and 26.69 tons in March 2010. Other watercourses supplied a total of 0.38 tons in June 2009 (the lowest value) and 9.40 tons in December 2008 (the highest value). Table 4 lists mean monthly nitrate loads for selected years.

The inflow of nitrate from the Baltic Sea to Lake Łebsko ranged from a value of zero in the Łeba Canal in September 2009 to 60.12 t $month^{-1}$ in December 2008. The largest loads were detected in autumn and winter.

The Łeba River is also the primary contributor of ammonium to Lake Łebsko, with the highest concentration in the river recorded in September 2010 (85.74 tons) and the lowest in April 2009 (24.05 tons). The second largest contributor – the Pustynka River – supplied between 2.07 tons in April 2009 (the lowest value) and 17.50 tons in March 2010 (the highest value). Other watercourses in the drainage basin of the lake contributed a total of 0.92 tons in April 2009 and 10.76 tons of October 2008. Table 4 lists mean monthly concentrations of ammonium calculated for selected years.

The ammonium load reaching Lake Łebsko during seawater intrusions was quite high, often exceeding 100 tons per month, ranging from 27.80 t $month^{-1}$ in February 2010 and 135.79 t $month^{-1}$ in July 2010. The mean for the study period was 82.56 t $month^{-1}$.

Large ammonium loads were determined not only in the autumn and winter storm season, but also at low water stages in summer.

More than 70% of the biogenic materials reaching Lake Łebsko by watercourses are supplied by the Łeba River, which supplied 73.0% of total nitrogen, and the second largest contributor was the Pustynka River (17.0%). Other watercourses provided between 0.08 and 1.8% of the total nitrogen inflow to the lake.

The nitrate inflow followed a similar pattern in Lake Łebsko where the Łeba River once again served as the primary inflow route (75.8%) and the Pustynka River served as the second major inflow route (7.4%). Other watercourses provided between 0.09 and 3.0% of nitrate.

The largest contribution made by the Łeba River was that of ammonium (80.1%). The Pustynka River contributed another 11.1%, while the other watercourses contributed only 0.1 to 3.1% of ammonium.

The research has shown that the Łeba River is the primary source of total nitrogen for Lake Łebsko – estimated at more than 51%. The Pustynka River is a secondary source at 14% and atmospheric precipitation contributes about 12%. Finally, seawater intrusions contribute about 11%. Other sources did not exceed 7% of the total nitrogen supply (Fig. 8).

Table 5 shows absolute values of total nitrogen supplied per year to Lake Łebsko. In 2009, about 840 tons of total nitrogen reached Lake Łebsko from a variety of sources. The lake also released about 305 tons of total nitrogen in 2009. Consequently, about 63% of the total nitrogen load reaching Lake Łebsko remained in the lake.

Analysis of the input and output of the total nitrogen load to Lake Łebsko in each month revealed higher values for the input throughout the study period. The size of the monthly total nitrogen load flowing into the lake ranged from 29.73 tons month^{-1}

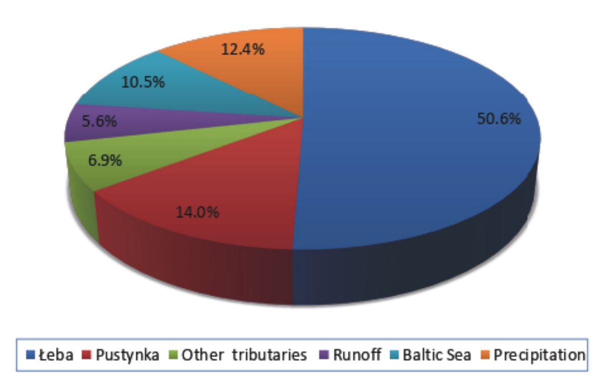

Figure 8

Percentage contribution of selected sources of the total nitrogen load supplied to Lake Łebsko in 2009

Table 5

Size of total nitrogen loads discharged into Lake Łebsko in 2009 via various routes

Name	Annual load in tons
Łeba	424.72
Pustynka	117.70
Other courses	58.07
Runoff	47.00
Baltic Sea	87.81
Precipitation	104.30
Total	839.60
Outflow to the sea	304.65

in July 2009 to 139.17 tons month^{-1} in March 2010. The size of the monthly total nitrogen load leaving the lake ranged from 11.97 tons month^{-1} in July 2009 to 75.22 tons month^{-1} in February 2009 (Fig. 9). As a result, the difference between the input and output loads of the lake varied from 4.11 tons in August 2009 to 108.22 tons in March 2010. The actual mass of *N* stored in the lake (retention) ranged from 87.47 tons month^{-1} in September 2009 to 271.11 tons month^{-1} in January 2009 (Fig. 10). The difference between the actual mass of *N* stored in the lake (N_{ret}) and the annual N load into and from the lake (ΔN) ranges from -11.32 tons in March 2010 to 245.70 tons in January 2009. In all the analyzed months, except March 2009, higher values were obtained for the actual mass of *N* stored in the lake. In March, a higher value of approximately 11 tons was obtained for ΔN.

An extremely important issue for the water quality in Lake Łebsko is agricultural runoff, the size of which depends on the structure of land use in drainage basins. The highest agricultural runoff occurs in basins with a significant contribution of arable lands and pastureland (Ferrant et al. 2011). Arable lands cover 12% and pastures 23% of the drainage basin of Lake Łebsko. The research by Kajak (1983) on the migration of nutrient material to watercourses with respect to land use suggests that – hypothetically – more than 6500 kg km^{2} yr^{1} of nitrogen is supplied to Lake Łebsko (Table 6).

Arable lands and pastureland occupy about one third of the drainage basin of the lake, which results in a significant use of fertilizers and plant protection products. Surface runoff carries these chemical substances to lake waters, which leads to elevated concentrations of biogenic substances, excessive plant growth in the aquatic environment, and increased eutrophication in water bodies. It was therefore

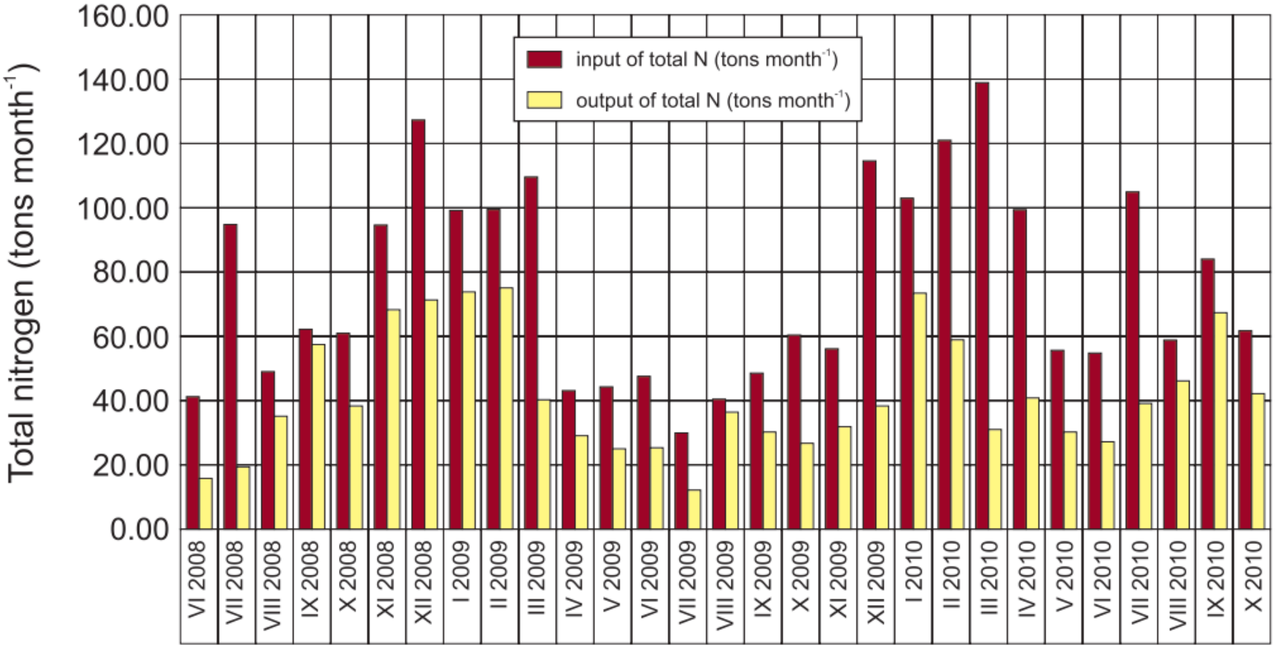

Figure 9

Monthly inputs and outputs of total nitrogen [tons month^{-1}] in Lake Łebsko in 2008-2010

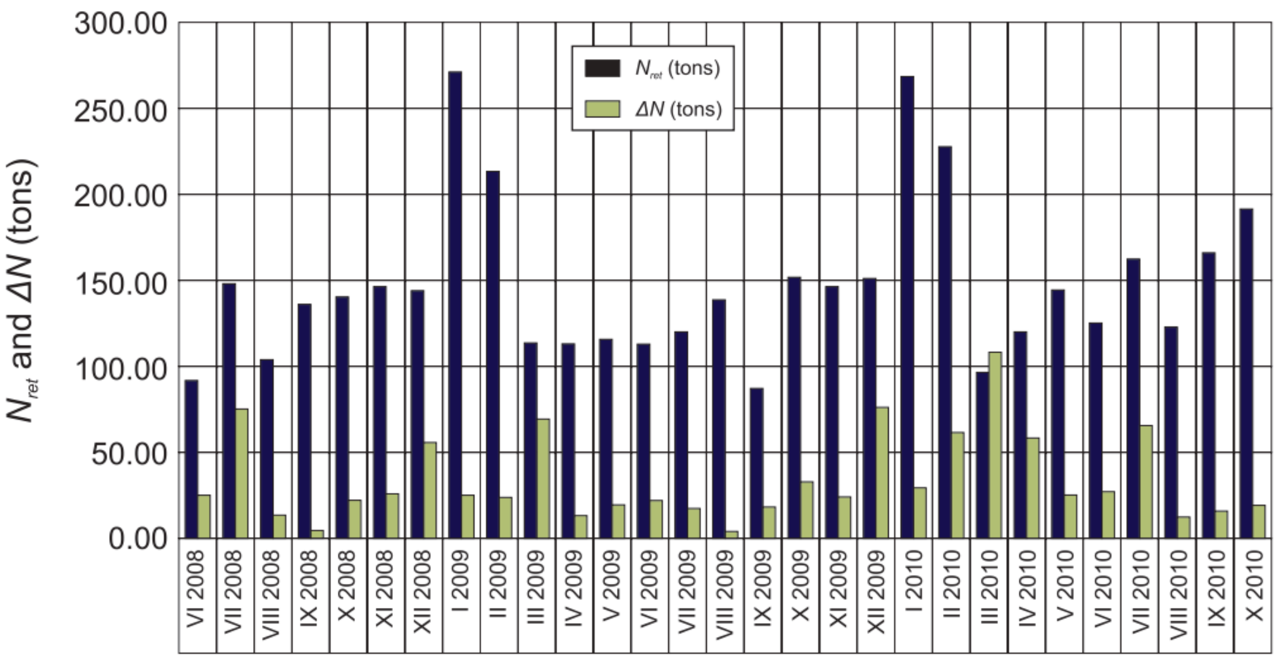

Figure 10

Monthly size of N_{ret} and ΔN in Lake Łebsko in 2008-2010

decided to determine what amounts of each type of fertilizer are used in agriculture.

Data from the Central Statistical Office of Poland show that the use of nitrogen-based fertilizers has increased from about 60 kg per hectare of farmland in 2003 to about 70 kg per hectare. On the other hand, the use of phosphorus and potassium fertilizers has decreased in the same period from about

Table 6

Hypothetical migration of nutrient material into Lake Łebsko from its drainage basin (kg km^2 yr^{-1}) based on research by Kajak (1983)

Type of use	Nitrogen
Forests	258.2
Arable land	2295.4
Meadows and pastures	4032.8
Total	**6586.4**

32 kg per hectare to 25 kg per hectare in the case of phosphorus-based fertilizers and from about 42 kg per hectare to 32.5 kg per hectare in the case of potassium-based fertilizers. In addition, the use of calcium-based fertilizers declined from about 110 kg per hectare in 2003 to about 40 per hectare in 2009.

The impact of agriculture can be manifested in the rapid vegetation growth in most tributaries of Lake Łebsko in the spring and summer seasons leading to a limited potamic flow from drainage basins and changes in the water quality. This is especially applicable to biogenic substances. Fertilizers and pesticides are used in a repetitive annual cycle. Therefore, the impact of agriculture is characterized by a constant influence on the water of coastal lakes (runoff of nutrients). Another effect of agriculture is eutrophication of lakes, which leads to the excessive vegetation growth along the lake shores. Hence, it may be inferred that nitrogen and phosphorus compounds constitute the primary cause of rapid lake eutrophication.

Pumps collecting water from lakeside polders also tend to affect the physical and chemical properties of water in coastal lakes. The effect of the pumps resembles that of watercourses flowing into coastal lakes.

Lakes also receive pollution from illegal point sources in local towns and villages. It is difficult to estimate the volume of this type of pollution. One way of estimating such pollution is via the number of residents in a given drainage basin. Assuming that several hundred people live in a given drainage basin, then each analyzed lake receives about 20,000 m^3 of illegal wastewater per year (data obtained from the Regional Inspectorate for Environmental Protection). This relies on the assumption that one person produces about 36 m^3 of wastewater per year.

Analysis of key changes in the water quality of watercourses flowing into Lake Łebsko began with the determination of chemical loads entering and leaving the lake. In the case of Lake Łebsko, the inflow of nutrient substances was always greater than the outflow. These differences were significant – as much as 300% in the case of nitrate. The differences were smaller for total nitrogen (approx. 30%) and very small for ammonium (less than 5%) (Table 7).

Water chemistry in Lake Łebsko indicates certain local patterns and conditions that illustrate changes in the water quality in the system of connected water bodies. The concentration of certain substances increases, while the concentration of other substances decreases. These changes may be analyzed in the seasonal or spatial context.

Discussion

The transformation of the water quality is caused by both natural and anthropogenic factors (Allanson 2001), and the most important effects are changes in the water chemistry, ion balance, water physical properties, the size of nutrient loads (incoming and exiting), and the activity of lacustrine bottom sediments (resuspension).

These factors are mostly related to the local environmental conditions around the lake and its basin, in particular the morphometry of the lake basin, and they determine the types of physical and biochemical changes occurring in a lake. Each of the factors directly affects the properties of the lake water as well as patterns and rates of changes (Carstensen et al. 2011). As a result, we can observe the eutrophication process, a good example of which is Lake Łebsko. The ratio of total nitrogen to phosphorus indicates the degree of eutrophication of a lake. On the basis of the limit, i.e. 20 as given by Wetzel (2001), it can be

Table 7

Mean loads of nitrogen compounds (tons per month) entering and leaving Lake Łebsko

Ion	Inflow from the catchment	Outflow from the lake	Odds	% amount of load remaining in the lake	Inflow from the sea
N_{total}	60.03	41.16	18.87	31.43	36.01
$N\text{-}NO_3$	44.20	16.50	27.70	62.50	30.16
$N\text{-}NH_4$	72.86	67.02	5.84	8.02	82.56

concluded that Lake Łebsko is greatly affected by eutrophication processes.

The elementary mass balance and export models are explored in relation to eutrophication caused by nitrogen. The results suggest that lakes having a long water renewal time are much more sensitive to nitrogen loading than would appear from a mean depth only (Vollenweider 1975). This is confirmed by the results for Lake Łebsko. The lake has a long recharge time and at the same time is sensitive to nitrogen load. Furthermore, from comparison of the relative residence time of nitrogen, it is deduced that with increasing eutrophication the nitrogen metabolism is accelerated beyond the point of simple proportionality. The variable nutrient dynamics observed among the lakes appears to be typical of shallow lake systems. This indicates that a greater reliance on lake-specific research may be required for effective management, and a lesser role of inter-lake generalization than is possible for deeper, dimictic lake systems (Havens et al. 2001). The last statement is also confirmed by the results obtained for Lake Łebsko, which is one of the shallow lakes.

In the context of the retention capacity of lakes, the aforementioned factors interfere with the transport of the matter. In the case of a decrease in the kinetic energy of water, lakes tend to accumulate the allochthonous matter in the form of bottom sediments, which for Łebsko is about 5-6 m.

The mass balance for total nitrogen (N) in 16 shallow, mainly eutrophic Danish lakes was calculated by Windorf et al. (1996). N input and output were calculated using daily data on discharge (Q), the latter being obtained either from the Q/H relationship based on automatic recordings of the water level (H) for the main in- and outlet, or from Q/Q relationships for the minor inlets. Annual mean N retention in the lakes ranged from 47 to 234 mg N m^{-2} d^{-1}, and was particularly high in lakes with high N loading. Annual percentage retention (N_{ret} – y%) ranged from 11 to 72%. By analyzing the size of the input and output of the total nitrogen load into Lake Łebsko, it has been shown that the size of the monthly total nitrogen load flowing into the lake ranged from 29.73 to 139.17 tons $month^{-1}$. The size of the monthly total nitrogen load discharged from the lake ranged from 11.97 to 75.22 tons $month^{-1}$. As a result, the difference between the input and output loads of the lake varied from 4.11 in August 2009 to 108.22 tons. The actual mass of N stored in the lake (retention) ranged from 87.47 to 271.11 tons $month^{-1}$. The difference between the actual mass of N stored in the lake (N_{ret}) and the annual N load into and from the lake (ΔN) ranges from -11.32 to 245.70 tons. In all the analyzed months, except March 2009, higher values were obtained for the actual mass of N stored in the lake. In March, a higher value of approximately 11 tons was obtained for ΔN. In 2009, about 840 tons of total nitrogen was delivered to Lake Łebsko. On the other hand, about 305 tons of total nitrogen left the lake. As a result, Lake Łebsko retained about 63% of the total nitrogen load per year.

One of the key factors in the conversion of biogenic compounds in lakes is the interaction at the interface between the lacustrine bottom sediment and the lake near-bottom water and the lake surface water. This interaction is generated by the intensity of wind and changes in the intensity of wind (Vicente et al. 2010), which it is clearly visible in Lake Łebsko. Strong and very strong winds dominate, and the silence is below 2%. The mutual exchange of ions occurs between the mineral phase and the aqueous phase via adsorption and desorption. This often leads to unpredictable increases and decreases in the concentration of biogenic materials in the lake. This mutual exchange of ions is also a likely cause of changes in the water chemistry in the studied lake, which is the outcome of the controlled inflow of pollutants from local water treatment plants as well as the uncontrolled inflow of wastewater produced by households located at the lake. In the case of Lake Łebsko, this is very important because a large amount of impurities is deposited in the sediments, and and at the same time the phenomenon of re-suspension of bottom sediments is observed.

Pollution released by the Łeba water treatment plant is also pushed back into the lake during seawater intrusion events. This is important because the plant was designed to handle wastewater produced by city residents, but it has to handle ten times more waste produced by people during the summer tourist season (Cieśliński & Olszewska 2012). Biological activity and the equilibrium between two phases are associated with the depth, lake bottom currents, primary production, and external sources of organic matter. In addition, the size and density of particles in sediment are also important (Daumas 1990). Henriksen and Brakke (1988) argue that an increase in the concentration of biogenic ions in the water may be due to decreased absorption by sediment. This may further lead to a reduction in lake water pH. No abrupt pH decreases were observed for the studied lake whose pH tended to remain close to neutral.

The amount of nitrogen in the sediment of a lake can significantly affect its water chemistry. However, the concentration of nitrate in sediment does increase with depth due to nitrification and denitrification. Yang et al. (2015) were able to show that the maximum rate of nitrogen ion release from sediment occurs in the first five minutes, reaching 94% of the maximum value within the first ten minutes. The authors obtained these values based on the results of laboratory experiments with N cycling. Another possibility, as discussed by Zhang et al. (2008), is the regeneration of nitrogen compounds induced by oxidation at the sediment-water interface. The researchers also found that ammonia is the dominant component of pore water in sediment, while nitrate is the dominant ion in lake near-bottom water.

In the case of shallow lakes, the inflow of biogenic material can also occur via exchange at the water-atmosphere interface. Important in this case is the input of nutrients and aerosols. Greenwood Lake is one of the examples of this process – 42% of its nitrogen comes from the air above the lake (Imboden et al. 2002). According to Loÿe-Pilot et al. (1990), the amount of total nitrogen delivered to surface waters by atmospheric precipitation ranges between 10% and 25% of total nitrogen in the lake. This is also confirmed by the research on Lake Łebsko, which receives about 12% of its total nitrogen from atmospheric precipitation. According to Falkowska and Korzeniowski (1988), Lake Łebsko receives about 40 tons of nitrogen per year. However, both amounts strongly depend on air circulation patterns and tend to significantly vary from year to year. He et al. (2011) reported that the inflow of nutrient material from aerosols is much larger during humid periods than dry periods, which is also the case with the studied lake. This is especially true of nitrate and ammonia.

On the other hand, the exchange of nutrient material at the groundwater and surface water interface is negligible. Groundwater mostly serves as a diluter of lake water. In some cases, some nitrogen is absorbed from lake water by shallow groundwater (Einstein et al. 2011). One should remember about the possible impact of marshes that surround Lake Łebsko from the south, east and west, and which can release some N into the lake. However, one should assume that it is a small value, because it is balanced by the underground drainage and runoff.

Significant seasonal changes in chemistry are also the result of changes in the leaching rate of nitrogen ions from the ground as well as variable rates of intake by plants and bacteria (Neff et al. 2003). The research by Ruiz and Velasco (2010) serves as a good example of scientific studies on changes in the nitrogen content in water bodies due to the vegetation growth. The study concludes that the annual cycle of changes in the nutrient material content is due to the growth of reeds and their harvesting. Reed flowers in early spring and is then cut down, and flowers again in late summer to be cut down again. The study found that the maximum nutrient levels in reed were determined in the early growth stages of autumn vegetation as well as in the spring and summer, which is also when a corresponding decline in nutrient concentration was determined in the water. This is an important source for Lake Łebsko, which results from the fact that the lake is overgrown with reeds in around 20%.

The research by Kansiime et al. (2007) has shown that plants floating on the water surface can easily absorb nutrients owing to certain hydrological and climate conditions. This leads to a change in water quality in the lake. According to work by Cieśliński and Olszewska (2012), Lake Łebsko is affected by this problem to a substantial degree, as floating plants cover about 15% of its surface every year. Another potential source of biogenic material is wetlands in the vicinity of the lake, which are strongly connected with the lake in various ways (Herdendorf et al. 1986). At the same time, wetlands found near coastal lakes can also absorb some of the nutrient material making its way from lakes to the sea. The modeling work carried out by Arheimer and Wittgren (2002) shows that wetlands reduce nitrogen transport to coastal areas by about 6%. However, point values depended on variables such as residence time, the size of wetland area, and land-water linkages. The research in Sweden has shown that wetlands can reduce the inflow of biogenic material to coastal lakes by about 27% (Thiere et al. 2011). It is an important source of nutrients into Lake Łebsko because the lake is surrounded by wetlands from the south, east and west and occupy about 30% of the total catchment area of Lake Łebsko.

Given the relationship between temperature and seasonal changes in runoff, substantial loss of nitrogen was recorded mainly in the summer months. Yet another source of biogenic material for lakes was pollution produced by tourist traffic and agriculture (Ruiz and Velasco 2010). The catchment of Lake Łebsko is considered large by Polish standards. Its sources of nutrient material can be classified using a system created by Lepistö et al. (2001) for large catchments. In this case, agriculture is noted to yield 17% of total nitrogen, while forests yield about 16%.

Research on mass balance and "sensitivity analysis" has shown that large catchments yield 5 to 10 kg ha^{-1} yr^{-1} of total nitrogen. Wetlands absorb less than 1 kg ha^{-1} yr^{-1} nitrogen. In addition, Helliwell et al. (2001) found that woodland areas significantly help to reduce the amount of total nitrogen in a catchment. Consequently, lakes and other water bodies gain less nitrogen. The opposite is true of moors (wetlands), which are characterized by strong leaching of nitrogen compounds that eventually migrate into surface waters.

Voss et al. (2010) argue that total nitrogen concentrations can decline partly due to the denitrification of nitrate in water bodies located near the sea or ocean. Mathematical models make it possible to determine the amount of nitrogen compounds, their sources, and amounts lost. The study by Valiela et al. (1997) shows that the largest source of nitrogen in the catchment studied is wastewater (48%), followed by atmospheric precipitation (30%) as well as fertilizers (15%). Nitrogen loads are transported to water bodies by inhabited areas (39%, primarily via wastewater), natural vegetation (21%, via atmospheric precipitation), and peat (16%, due to atmospheric precipitation and the use of fertilizers). The main source of nutrients in Lake Łebsko is the inflow of rivers (70%), precipitation (14%), surface runoff (9%) and the inflow from the sea (7%).

It is important to note that the most intensive processes occur about 200 meters from the water body receiving the nitrogen. Furthermore, Xie et al. (2008) believe that the most important source of biogenic material for lakes is an artificial fertilizer. Both the quantity and time of its application are relevant. Vicente et al. (2006) believe that the conversion of nutrient material in lakes strongly depends on local hydrology. In such cases, sediment begins to play a key role in nutrient concentration changes. The return of nutrients from the bottom sediment to surface waters is closely associated with the local hydrological regime, morphometry of the basin, and sediment grain size. This is very important because the areas around Lake Łebsko are fertilized with nitrogen, phosphorus and potassium fertilizers.

The release of nitrogen compounds stored in sediment is determined by wind effects (resuspension) and yields limited results due to the roughness of the sediment. The studied lake in this case (Lake Hondo) experienced nutrient exchange at the water-sediment interface driven by chemical processes. This exchange also tends to favor rapid increases in calcium content. In Lake Łebsko, dynamic changes are indicated by the water exchange rate of more than four as well as the ability of the wind to freely accelerate across the lake's surface.

Coastal lakes, in direct or indirect contact with seawater, need to be treated differently. The inflow of nutrient material to such lakes depends on many interrelated processes such as hydrodynamics and morphology, freshwater inflow rates, runoff rates, and biogeochemical processes. In some systems, the mixing of freshwater and seawater may also be important (Statham 2012). According to Hartzell and Jordan (2012), increases in the concentration of biogenic material in coastal areas may be due to increased salinity levels. On the other hand, the study by McCrackin and Elser (2010) suggests denitrification associated with microbiological processes that remove excess nitrogen. Lake Łebsko is a brackish lake, where salinity is above 2000 mg dm^{-3}, which certainly affect the volume of total nitrogen.

According to McGuirk-Flynn (2008), water bodies located along the coast serve as the last collection point for pollutants including biogenic materials washed across the land into the sea. As a result, about 50% of pollutants are deposited in coastal lakes. Lake Łebsko is located in the lower part of the catchment receiving water from the entire catchment which covers an area of more than 1500 km^2. The study also found that increases in nitrogen concentration occur in the spring, summer, and autumn months, with the maximum in early spring and summer. Climate change may also bring some changes in the coastal lake hydrology.

It will also affect the inflow of nutrient materials and their conversion in lake water via changes in temperature, wind power, sea water levels, and the hydrologic cycle. This will lead to coastal flooding and changes in stratification as well as changes in runoff patterns, phytoplankton productivity, more extreme phenomena, changes in ecosystems, and changes in the functioning of selected species (Statham 2012). The rate of eutrophication is also likely to increase (Schindler et al. 2012), which has already been observed in the case of Lake Łebsko. However, Paerl (2009) argues that these problems can be controlled to some extent.

Harrison et al. (2009) describe coastal lakes as perfect collection vessels for nitrogen compounds and their reduction via denitrification. Lakes with an area of 50 km^2 or less are problematic to some extent, but still collect about 50% of total nitrogen.

Finally, it is important to note that the magnitude of nitrogen inflow remains uncertain due to ongoing climate change, which is likely to significantly affect the nitrogen transport totals, changes in nitrogen concentration in lakes, and resulting rates of lake eutrophication. Already at this time, the nitrogen content of lake water is increasing despite limits on external sources (Jeppesen et al. 2011).

In conclusion, water quality in the drainage basin of Lake Łebsko has undergone multiple changes caused mainly by human impact. This effect is readily apparent in surface water enriched with nutrients coming from the surface runoff. A large amount of nutrients, mainly nitrogen and phosphorus, introduced into local waters with industrial and municipal wastewater and agricultural runoff contributes to the growth of biogenic production in local waters and consequently their eutrophication (Howarth et al. 1996). Other effects of the inflow and spreading of nutrients in the natural environment include the size of retention of some nutrients in river systems, emission in drainage basins, as well as local (Howarth et al. 1996; Behrendt, Opitz 1999; Behrendt et al. 2003; Bogdanowicz 2005) and global diffusion of these compounds (Billen et al. 1995), and natural and anthropogenic sources of water pollution causing eutrophication (Vollenweider, Kerekes 1982; Howarth et al. 1996; Bogdanowicz 2005).

Lakes are an excellent place to observe the presence of nutrient compounds (Wolin, Stoermer 2005) as a relative lack of water movement and certain physical properties (e.g. elevated temperature) facilitate the rapid growth of biomass. In the context of the eutrophication problem, the analysis of lake contamination levels should involve the determination of concentrations of biogenic materials and the determination of biogenic loads reaching the lake via overland flow from its drainage basin. According to Bachmann et al. (2012), about half of the biogenic material load of total nitrogen and phosphorus comes from surface runoff – mostly from agricultural land.

Summary

- Lakes are water bodies that significantly affect the circulation of water and matter in a drainage basin. The standing water of lakes enables a temporary retention of excess water in a drainage basin or resupply of other water bodies in the drainage basin. Coastal lakes are often the last receivers of water flowing into the sea.

- The role of a lake in the circulation of water and other matter largely depends on its location in the spatial hydrographic system and the linear lake-river system. In the former, lakes transform the water circulation by including the groundwater in the circulation system as well as by retention, regulation, and transfer of the discharge. In the latter, lakes tend to interrupt the continuity of flow and the potamic transport of matter. A lake defined as part of the system is located inside it (within a drainage basin), which results in a close relationship between a lake and the level of organization of the system in which it is located.

- Lakes are objects that quantitatively and qualitatively transform the flowing through water and other matter. Qualitative changes are affected by internal structure of a lake. The development of internal structure and the lack of stratification determine the intensity and direction of changes in lake ecosystems. Hydrochemical properties of lakes indicate how lakes are recharged – precipitation, river flow, groundwater – and do not always reflect the hydrographic location of a given lake. Quantitative changes are significantly affected by a drainage basin and its ability to deliver chemical substances as well as the capacity of a lake to retain these substances in the bottom sediments and suspended matter. Other factors relevant in quantitative changes include the ability to transform the chemical substances into biomass and the rate of water flow from the lake into the sea, which helps to carry part of the chemical load away from the lake. Finally, the lake water exchange rate also appears to be important, as it illustrates the general rate of changes possible in a given lake.

- There are about 7000 lakes in Poland with an area of one hectare or more. About 30 of them can be defined as coastal lakes based on their origin, including Lake Łebsko. Analysis of the role of lakes in the transformation of the water quality is quite difficult, partly due to multiple competing effects of the drainage basin and the sea (in the case of coastal lakes). In this case, many processes occur that are unique to coastal lakes. Rates of changes are also different, which generates something that can be described as transient waters. The primary difference in the case of coastal lakes is the presence of seawater intrusions that supply some brackish water as well as biogenic substances common in freshwater. This results in either permanent or temporary changes in the water chemistry of coastal lakes.

- Water chemistry data for Lake Łebsko indicate significant accumulation of biogenic materials in the lake, and hence a strong effect of the lake on the incoming water. This is true of both total chemical loads per year as well as concentrations of selected ions over short time intervals. This standard pattern may be interrupted by seawater intrusions, which alter water chemistry throughout the lake.

- The nutrient substances analyzed in this study and present in Lake Łebsko were characterized by significant changes in concentration, often due to changing seasons or direct or indirect effects of human impact. More than 70% of the biogenic materials reaching Lake Łebsko via watercourses are supplied by the Łeba River, including 73.0%

of total nitrogen, while the second largest contributor was the Pustynka River (17.0%). Other watercourses provided between 0.08 and 1.8% of the total inflow of nitrogen into the lake.

- The analysis of the input and output of the total nitrogen load into Lake Łebsko showed that the size of the monthly total nitrogen load flowing into the lake ranged from 29.73 to 139.17 tons month^{-1}. The size of the monthly total nitrogen load flowing from the lake ranged from 11.97 to 75.22 tons month^{-1}. As a result, the difference between the input and output loads of the lake varied from 4.11 in August 2009 to 108.22 tons. The actual mass of N stored in the lake (retention) ranged from 87.47 to 271.11 tons month^{-1}. The difference between the actual mass of N stored in the lake (N_{ret}) and the annual N load into and from the lake (ΔN) ranges from -11.32 to 245.70 tons. In all the analyzed months, except March 2009, higher values were obtained for the actual mass of N stored in the lake. In March, a higher value of approximately 11 tons was obtained for ΔN. In 2009, about 840 tons of total nitrogen was delivered to Lake Łebsko. On the other hand, about 305 tons of total nitrogen was discharged from the lake. As a result, about 63% of the total nitrogen load per year remained in Lake Łebsko. Based on these results we can say that Lake Łebsko is a system producing mineral and organic substances. Periodically, it may also be classified as a mixed system where production of organic substances and absorption of minerals occur.

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