Spatial variability of nutrients (N, P) in a deep, temperate lake with a low trophic level supported by global navigation satellite systems, geographic information system and geostatistics

Michał Łopata, Dariusz Popielarczyk, Tomasz Templin, Julita Dunalska, Grzegorz Wiśniewski, Izabela Bigaj and Daniel Szymański

ABSTRACT

We investigated changes in the spatial distribution of phosphorus (P) and nitrogen (N) in the deep, mesotrophic Lake Hańcza. The raw data collection, supported by global navigation satellite system (GNSS) positioning, was conducted on 79 sampling points. A geostatistical method (kriging) was applied in spatial interpolation. Despite the relatively small area of the lake (3.04 km^2), compact shape (shore development index of 2.04) and low horizontal exchange of water (retention time 11.4 years), chemical gradients in the surface waters were found. The largest variation concerns the main biogenic element – phosphorus. The average value was 0.032 at the extreme values of 0.019 to 0.265 mg L^{-1} (coefficient of variation 87%). Smaller differences are related to nitrogen compounds (0.452–1.424 mg L^{-1} with an average value of 0.583 mg L^{-1}, the coefficient of variation 20%). The parts of the lake which are fed with tributaries are the richest in phosphorus. The water quality of the oligo-mesotrophic Lake Hańcza has been deteriorating in recent years. Our results indicate that inferences about trends in the evolution of examined lake trophic status should be based on an analysis of the data, taking into account the local variation in water chemistry.

Key words | eutrophication, GNSS positioning, in-lake gradients, kriging, nitrogen, phosphorus

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INTRODUCTION

In an aquatic ecosystem, water quality depends upon physical, chemical, and biological factors. The qualitative characteristics of the surface water of lakes are generally largely determined by the climatic, geomorphological and geochemical conditions. Natural processes (soil erosion in the catchment basin, precipitation rate, weathering processes, surface and groundwater supply) and human-related transformation of land use have a strong influence on the environmental conditions of freshwater ecosystems (Carlson 1977; Lijklema 1998). In recent decades, urban, industrial, and agricultural activities have increased organic supply, especially main nutritive elements phosphorus (P) and nitrogen (N), in water bodies, resulting in an excess of eutrophication processes in rivers and lakes (Cooke *et al.* 2005). Deterioration of surface water quality has become a common, serious environmental problem in many countries. Enrichment of nutritive salts can rapidly involve nuisance algal blooms, which destabilize the ecological balance and hinder the recreational use of water bodies.

Attempts to manage lake eutrophication have most frequently involved controlling nitrogen and phosphorus loads from external (watershed) and internal (water, bottom sediments, biota) sources (Gulati & van Donk 2002; Cooke *et al.* 2005; Łopata & Gawrońska 2006). Therefore, accurate data of their abundance all over the ecosystem are crucial for making decisions about further conservation and restoration steps.

Surface waters in large, especially multi-basin, shallow lakes are characterized by a high degree of spatial heterogeneity (Gruendling & Malanchuck 1974; Kangur & Möls 2008). Differences in the natural conditions and human impact between parts of a lake can lead to prominent lake-wide gradients of water quality. For deeper lakes with a

doi: 10.2166/wst.2014.084

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compact shape and greater stability of water masses, it can usually be assumed that these variations are insignificant. Water quality analysis is carried out on the basis of measurements at a representative point, usually in the centre, the deepest part of the lake. This may be too simplistic for flow-through lakes with varied shoreline and sophisticated bottom shape. The dynamic growth of global navigation satellite systems (GNSS), hydroacoustic measurement technology and the increasing availability of measuring devices and geographic information system (GIS) software provide new potential to develop integrated measurement solutions. This provides an opportunity to reduce data acquisition costs and improve the quality of new developments in water management.

MATERIAL AND METHODS

Study area

Lake Hańcza (Figure 1) is located in the north-eastern part of Poland, in the catchment area of the Baltic Sea, in the basin of the Niemen River. It is the deepest glacial lake in the central part of the European Depression and one of the largest reservoirs in the Lithuanian Lake macro region. Its surface covers an area of 304.4 ha. The lake is situated in a deep glacial trough surrounded by the Suwałki Landscape Park. According to the limnological typology, Lake Hańcza is a eumictic water body with spring and autumn circulation periods, summer thermal stratification and a winter ice-cover period.

Due to the unique nature of the geomorphological and limnological features and the presence of rare species of flora and fauna, the lake has been a protected nature reserve for 50 years. As in many lakes under anthropopressure, eutrophication has become the most serious environmental problem for Lake Hańcza. In previous studies (1925–2004) it was classified as oligo-mesotrophic, but in recent years (2005–2007) a deterioration of water quality has been observed (Zdanowski *et al.* 2008).

The maximum depth and basic morphometric parameters differ depending on the bibliography. The first measured maximum depth of 104.5 m has been described by Śledziński in 1927 (Śledziński 1927). The next bathymetric survey was conducted by Rühle in 1930. He reported that the maximum depth was 108 m with a water level of 227.2 m above sea level (Rühle 1932). According to the latest hydrographic and geodetic survey, the maximum depth located in the central part of the lake is 105.7 m with 227.6 m of the water level above sea level (Popielarczyk & Templin 2013).

Despite the unique ecological nature of this lake, little information is known about its overall limnochemistry. The aim of this study was to describe the spatial variations of nutrients in Lake Hańcza with the support of GNSS positioning and spatial analysis and compare them with the locations of possible sources of pollution. The basic hydrological, limnometric and morphometric parameters are presented in Table 1.

The total catchment area of the lake tributaries is small with an area of 41.4 km^2. This includes hilly regions with a distinct moraine terrain (denivelations reach 40–50 m). The geological structure of the basin is dominated by clay, with less sand and gravel. This favors the occurrence of numerous outlet depressions. The catchment area drained surface is only 30% (Bajkiewicz-Grabowska 2008) and the main watercourse, discharging yearly 4.2 million m^3, is the Czarna Hańcza river (A, Figure 1), flowing into the lake from the north. In addition, the lake is continuously fed through the inflow from Przełomka (B) draining the south-western part of the catchment (1.4 million m^3 per year) and a number of periodic watercourses and groundwater flows. Excess water is discharged through the Czarna Hańcza river to the south (C).

The catchment area of the lake is primarily used by agriculture. Arable land constitutes 58%, meadows and pastures occupy almost 15%, and forests cover around 23%. A small part of these areas is rural housing (4%). Several small villages are located in the immediate vicinity of the lake. Housing wastewater management is individual, based on domestic wastewater treatment plants or septic tanks. There are no effectual point sources of pollution.

The structure of the phytoplankton is dominated by *Bacillariophyceae*, *Cryptophyta*, *Chlorophyta* and *Cyanobacteria*, represented with species characteristic for moderately fertile waters. Contemporary studies of Hutorowicz & Napiórkowska-Krzebietke (2008) and the Regional Inspectorate for Environmental Protection in Bialystok (RIEP 2011) indicate that during the past decades there was an approximately twofold increase in biomass of algae (up to 2–2.5 mg L^{-1}) while increasing the share of blue-green algae in the summer.

In Lake Hańcza there is a moderate amount of macrophytes. Submerged plants occupy more than 85% of the phytolittoral (occur to a depth of 5.5–6 m). In the southern part of the lake macrophyte coverage is less – an average of 4.5 m (RIEP 2011). The total area of macrophyte occupancy is low – approximately 40 hectares (13% of surface

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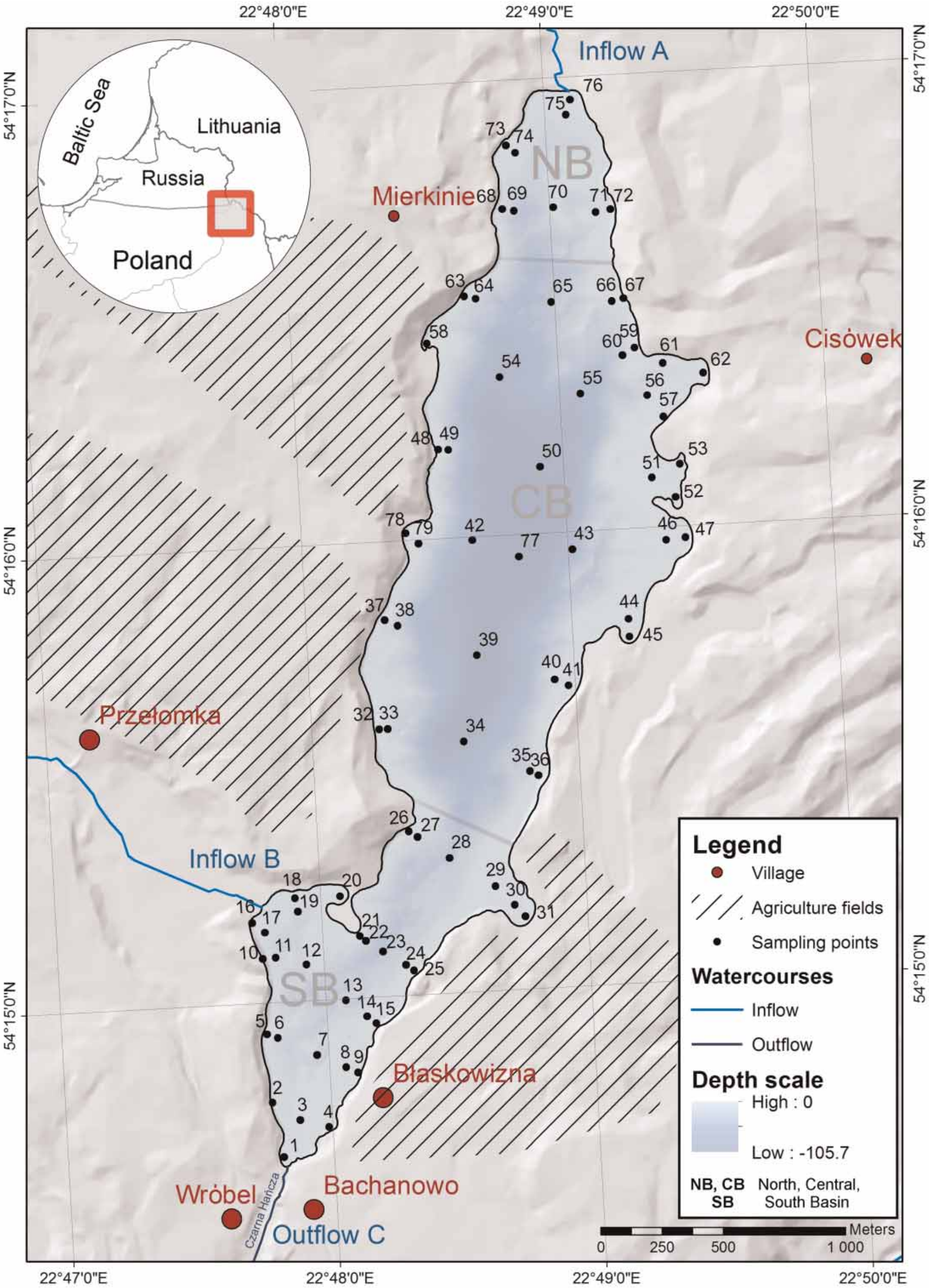

Figure 1 | Lake Hańcza – the location of study area and sampling points.

area). The species composition is strongly dominated by *Charophytes*. In the northern and southern parts of the lake there are also beds of *Potamogeton* spp. In the vicinity of the inlet B commonly occur *Nuphar lutea* and *Elodea canadensis* – species characteristic in eutrophic waters. Near both inlets there are some reed areas, as well as in shallow bays along the east coast.

Lake basin morphometric features, large water resources and a relatively small catchment cause the low susceptibility to eutrophication. Currently, the lake is still characterized by low primary production, lack of oxygen depletion above the bottom during summer stagnation periods and relatively good transparency of water (Zdanowski *et al.* 2008). Nevertheless, the multi-year

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Table 1 | Selected hydrological, morphometric, and water quality characteristics of Lake Hańcza

Characteristic	Parameter	Lake	NB	CB	SB
Watershed area	km^2	41.4	–	–	–
Surface area	km^2	3.04	0.28	2.04	0.72
Maximum depth	m	105.7	51.8	105.7	58.2
Mean depth	m	38.7	19.4	48.2	21.2
Water volume	thous. m^3	120,360	5,648	99,073	15,639
Residence time	years	11.4	–	–	–
Shore development index	–	2.04	–	–	–
Water quality parameters[a] – annual means		**1925–1973**	**1977–2002**	**2005–2010**	
Total phosphorus	mg L^{-1}	–	0.037 (0.020–0.063)	0.050 (0.013–0.087)	
Total nitrogen	mg L^{-1}	–	1.00 (0.33–1.42)	0.68 (0.46–0.91)	
Chlorophyll a	mg m^{-3}	<3	3.0 (1.0–8.1)	3.5 (2.7–4.2)	
Secchi disk visibility	m	7.3 (5.0–8.2)	5.9 (5.2–9.0)	4.5 (3.5–5.5)	

[a]According to Zdanowski *et al*. (2008) and RIEP (2011).
NB – north basin, CB – central basin, SB – south basin.

observations show that the effects of human impact on the trophic status of lakes are increasing.

Data collection

The physico chemical properties of the water of Lake Hańcza have been studied in May 2011 during spring water circulation. Raw physicochemical data collection was performed on the basis of water sampling points distributed evenly around the lake. The 79 points were designed on the background of the new bathymetric map of Lake Hańcza. The coastal sampling points were located at a higher frequency (about 3 and 30 m from the shoreline). The bathymetric spatial database of the lake was based on the new, integrated hydroacoustic and GNSS measurements carried out in 2010–2011. Bottom topography presented as a digital elevation model was also considered in designing water sampling point locations.

The process of defining raw water sampling points on the lake was supported by real-time GNSS navigation between each designed point. The locations of the stations were obtained by using a Topcon HiPer Pro geodetic GNSS receiver. The differential GPS positioning technique with 1 m horizontal accuracy was used.

Water samples for laboratory analyses were collected during a cloudy, windless day (it took 8 h) from the surface layer (0.5 m below the water table) and secured in a portable refrigerator. Samples were delivered to the laboratory within 12 h.

Water quality investigation

The concentrations of total phosphorus (TP) and mineral phosphorus ($P_{\min}$) were measured using the molybdenum blue method (*Standard Methods* 1998). Total nitrogen (TN) was determined by a Hach IL 550 TOC-TN analyzer. Ammonium (N-$_{NH4}$) and nitrate (N-$_{NO3}$) nitrogen were examined by ion chromatography using a Dionex analyzer – ICS 5000. Due to the trace amount of nitrite in water (below 0.005 mg L^{-1}), it was assumed that organic nitrogen is the difference between TN and the sum of ammonia and TN. Temperature (T), dissolved oxygen (DO) and the reaction of water (pH) were analyzed *in situ* using a WTW Multiline P4 multi-parameter sensor and a YSI ProODO optical oxygen sensor. Additionally, water transparency was measured using a Secchi disc (SD) in 11 points on the longitudinal cross-section of the lake. The same areas were taken to determine the water content of chlorophyll 'a' (Chl *a*) using the spectrophotometric method after extraction with acetone (*Standard Methods* 1998).

To determine the spatial variability of the parameters and the relationships between them, a one-way analysis of variance (ANOVA) and variation coefficients were used with the Statistica 10.0 Software (StatSoft, Inc., Tulsa, OK, USA).

One of the most common methods of expressing the progress of eutrophication of water bodies is the Trophic Status Index (TSI). TSI is based on regression equations developed for the main indicators of water quality: TP, Chl *a*,

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SD (Equations (1)–(3) based on Carlson (1977)) and TN (Equation (4), Kratzer & Brezonik 1981).

$$TSI_{(TP)} = 4.15 + 14.42\ln(TP)\left(TP \text{ in } \mu g\, L^{-1}\right) \quad (1)$$

$$TSI_{(Chl\,a)} = 30.6 + 9.81\ln(Chl\,a)\left(Chl\,a \text{ in } \mu g\, L^{-1}\right) \quad (2)$$

$$TSI_{(SD)} = 60.0 - 14.41\ln(SD)(SD \text{ in m}) \quad (3)$$

$$TSI_{(TN)} = 54.45 + 14.43\ln(TN)\left(TN \text{ in mg}\, L^{-1}\right) \quad (4)$$

In general, the level of 40 units as the average TSI is considered as the threshold between oligotrophy and mesotrophy, while the level of 50 units indicates eutrophic conditions of an aquatic environment.

Spatial interpolation of water quality parameters

The standard version of the kriging interpolation method was used to calculate the spatial distribution of water quality parameters. The spatial variations of nutrients were elaborated on the basis of 79 water sampling points. The ArcGIS 10.0 software package and the Geostatistical Analyst extension function were chosen for interpolation of spatial distribution maps of TN, TP, etc.

The sampling point results were converted into an Esri (Environmental Systems Research Institute) vector point feature class. This geometric type contains the X and Y horizontal coordinates and depth values associated with each collected point. The spatial location of all sampling points is presented in Figure 1. All processed data sets such as TN, N_{-NH3}, N_{-NH4}, TP, P_{org}, $P_{min,}$ pH, and temperature (°C) values were joined in the point feature class and recorded in the attribute table.

The multistep kriging process included exploratory statistical analysis of data, variogram modelling, creating the surface and exploring the variance surface (Kitanidis 1997). Several properties of the output data were first explored, including data distribution, anisotropy and extreme values (outliers).

Normality of the distribution was tested using the histogram tool and normal QQPlots tool. Exploration of water quality parameters showed that points number 16 and 17 (located in the south-east part of the lake) have enormous values, that were much higher than the rest of the data.

This caused a problem with building a valid kriging model. Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. It fits a function to a specified number of points or all points within a specified radius to determine the output value for each location (Childs 2004). Recently, several authors have suggested various ways to work with outliers. One of the simplest approaches was described by Krivoruchko and Krause (Krivoruchko 2011; Krause 2012). Their method removes the outliers for the variogram modeling, and then uses the whole dataset (including outliers) in the prediction step.

The data without outliers were examined again and log-transformed if they did not fit a normal distribution for statistical analysis. For each water quality parameter, an analysis trend was made and removed from all parameters. Kriging has a number of functions (linear, spherical, exponential, circular, Gaussian, Bessel, power, etc.) to fit the theoretical models to empirical semivariograms (Isaaks & Srivastava 1989; Cressie 1991). The ESRI Geostatistical Analyst extension has ability to build most of them (circular, spherical, tetraspherical, pentaspherical, exponential, Gaussian, rational quadratic, hole effect, k-bessel, j-bessel, stable). All these models have been tested for each water parameter. After cross-validation prediction performances the stable model was chosen. In this model, parameters were optimized with focus on the estimation of the range. Table 2 shows prediction error values for each parameter. The model provides accurate predictions when the standardized mean error is close to 0, the root-mean-square error and average standard error are as small as possible, and the root-mean-square standardized (RMSS) error is close to 1. For water quality parameters the stable model RMSS error ranges from 0.82916 to 1.06054.

The ordinary kriging interpolation method was used to elaborate the thematic maps indicating the spatial distribution of TN, N_{-NO3}, N_{-NH4}, TP, P_{org}, P_{min}, pH, and temperature (°C). The spatial distribution of water quality parameters in Lake Hańcza are shown in Figures 2–4.

RESULTS AND DISCUSSION

Phosphorus and nitrogen variability patterns

An analysis of water quality data indicated that the total concentration of the main nutrients remained at levels characteristic of temperate eutrophicated lakes. Phosphorus was present in amounts of 0.019 to 0.265 mg L^{-1} (average 0.032 mg L^{-1}), and nitrogen from 0.452 to 1.424 mg L^{-1} with an average value of 0.583 mg L^{-1}. In accordance with

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Table 2 | Fitted parameters of the theoretical variogram model for water quality parameters

Parameters	Prediction errors				
	Mean	**Root-mean-square**	**Average standard error**	**Mean standardized**	**Root-mean-square standardized**
TN	−0.00036	0.05372	0.05460	−0.00634	0.98302
N_{-NO3}	−0.00017	0.01007	0.01130	−0.03458	0.97673
N_{-NH4}	−0.00001	0.00278	0.00284	−0.03219	0.97499
TP	0.00001	0.00600	0.00545	0.00176	0.99302
P_{org}	0.00009	0.00413	0.00442	−0.01640	0.97202
P_{min}	0.000004	0.00113	0.00155	−0.00231	0.82916
pH	−0.00090	0.02855	0.02809	−0.02138	1.02584
°C	−0.01671	0.39341	0.36550	−0.04946	1.06054

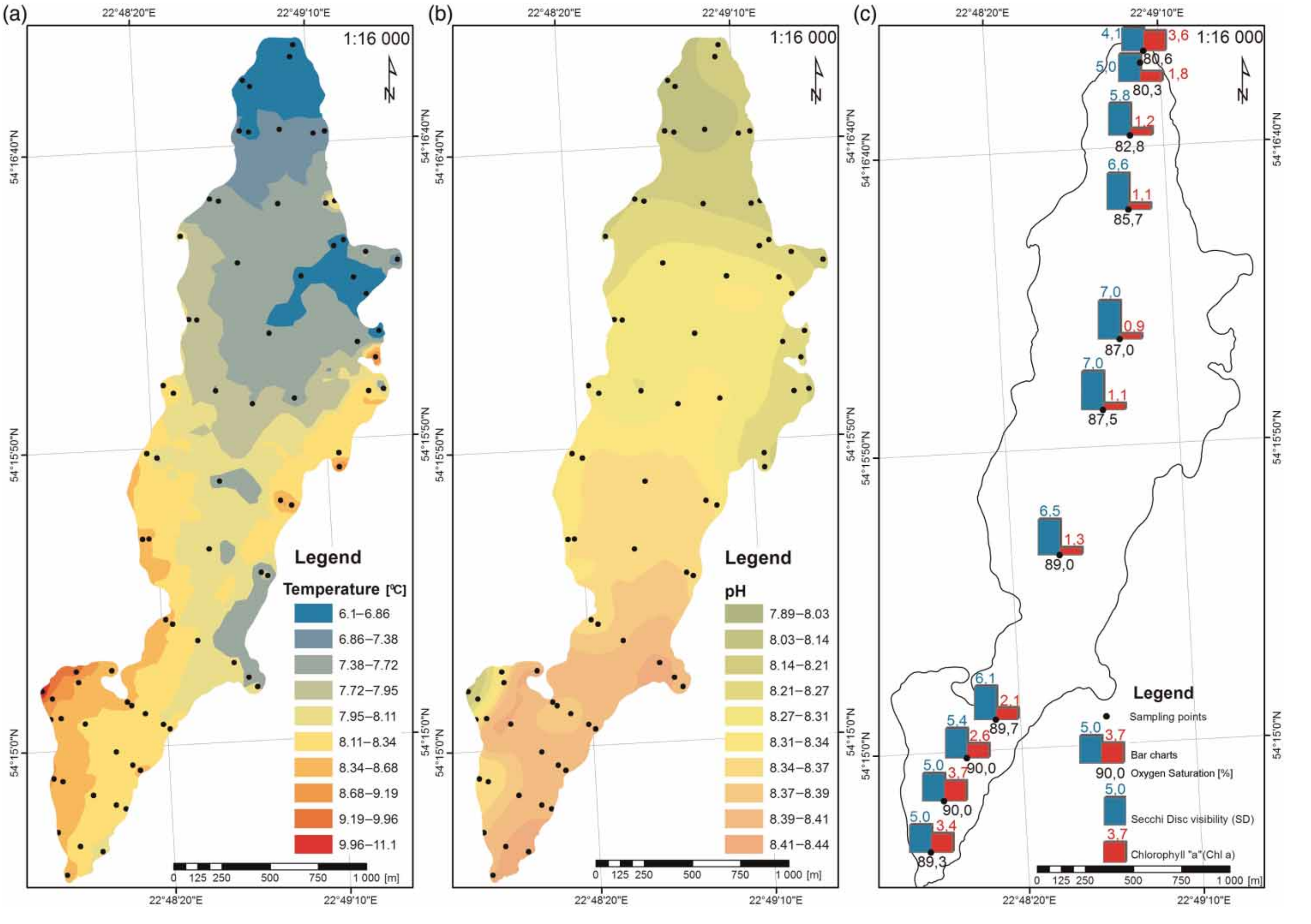

Figure 2 | The spatial distribution of temperature (a), pH (b), SD visibility, DO and Chl *a* (c).

generally accepted classifications (Carlson 1977; Kratzer & Brezonik 1981; OECD 1982), the average content of these components correspond to mesotrophy. However, comparing the distribution of P and N concentrations, different patterns can be observed – a much greater spatial differentiation characterized by phosphorus (coefficient of variation for phosphorus 87.01%, and for nitrogen 19.97%).

In order to more accurately determine the level of variation in water quality, the sampling point area was divided into three groups: the north basin (NB – sampling points

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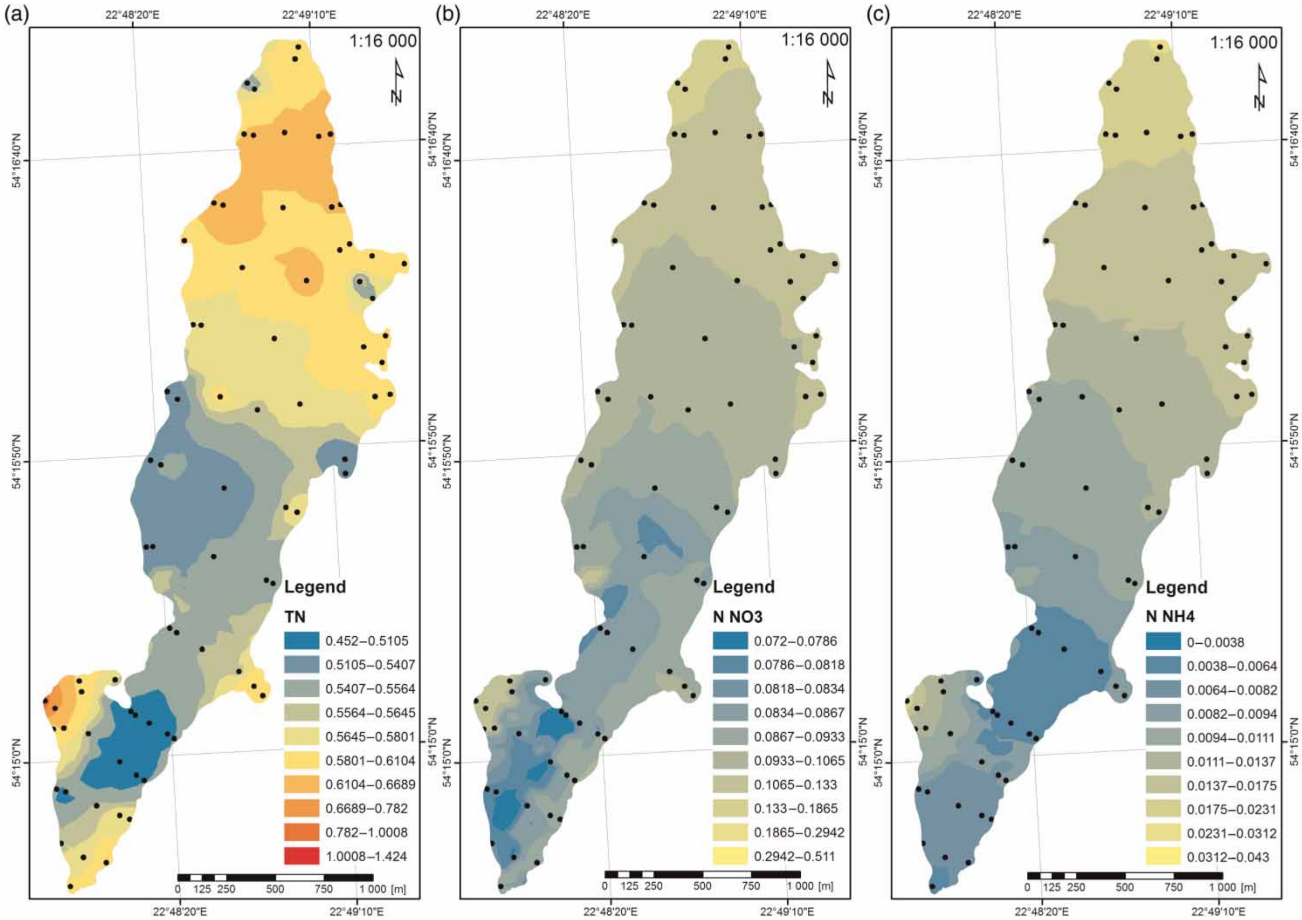

Figure 3 | The spatial distribution of nitrogen compounds TN (a), $N_{\text{-NO3}}$ (b), and $N_{\text{-NH4}}$ (c) (mg L^{-1} N).

no. 68–76) in the vicinity of the main tributary, Czarna Hańcza; center basin (CB – sampling points no. 32–67, 77); and the south basin (SB – sampling points no. 1–31), located in adjacent buildings, receiving water from the second largest constant supply. The nutrient contents in the different parts of the lake are presented in Figure 5. The significance of differences between the measured parameters is given in Table 3.

The highest concentrations of phosphorus are present in the southern basin (Figure 5(a)). The average abundance of this element was 0.037 mg L^{-1} and it was significantly higher than the average level of 0.023 mg L^{-1} observed in the central part of the lake (Table 3). The concentrations at the southern stations are approximately twice the CB values. This is the greatest difference in compounds that has been observed in our study. The variation of results was also the highest in this part of the lake (coefficient of variation 94.3%). As can be seen from the distribution of the amounts presented in Figure 3, the main reason seems to be the water supply of the watercourse draining the western part of the catchment (B). The significant burden of nutrient salts at this location has been reported in recent years (RIEP 2011). SB is much more insulated from the CB than NB, so the horizontal transport of matter to the north is less likely (the shape of the coastline, the dominance of the northwestern winds). Therefore, with comparable loads of TP in both tributaries, in the southern part of the lake can be maintained higher content of this element. Furthermore, in SB we found significantly lower concentrations of P_{min} than in the rest of the lake (Table 3, Figure 5(c)). This phenomenon indicates the increased activity of phytoplankton – phosphates are the main nutritive element for photosynthetic organisms in the growing seasons. The result of the intense absorption of phosphates could be a drop in their level in the water until it is completely exhausted, as observed in eutrophic ecosystems. The largest and deepest central basin, not directly exposed at the point input of pollutants, was characterized by the lowest amount of phosphorus (an average of 0.023 mg L^{-1}) and the differences in the concentrations of

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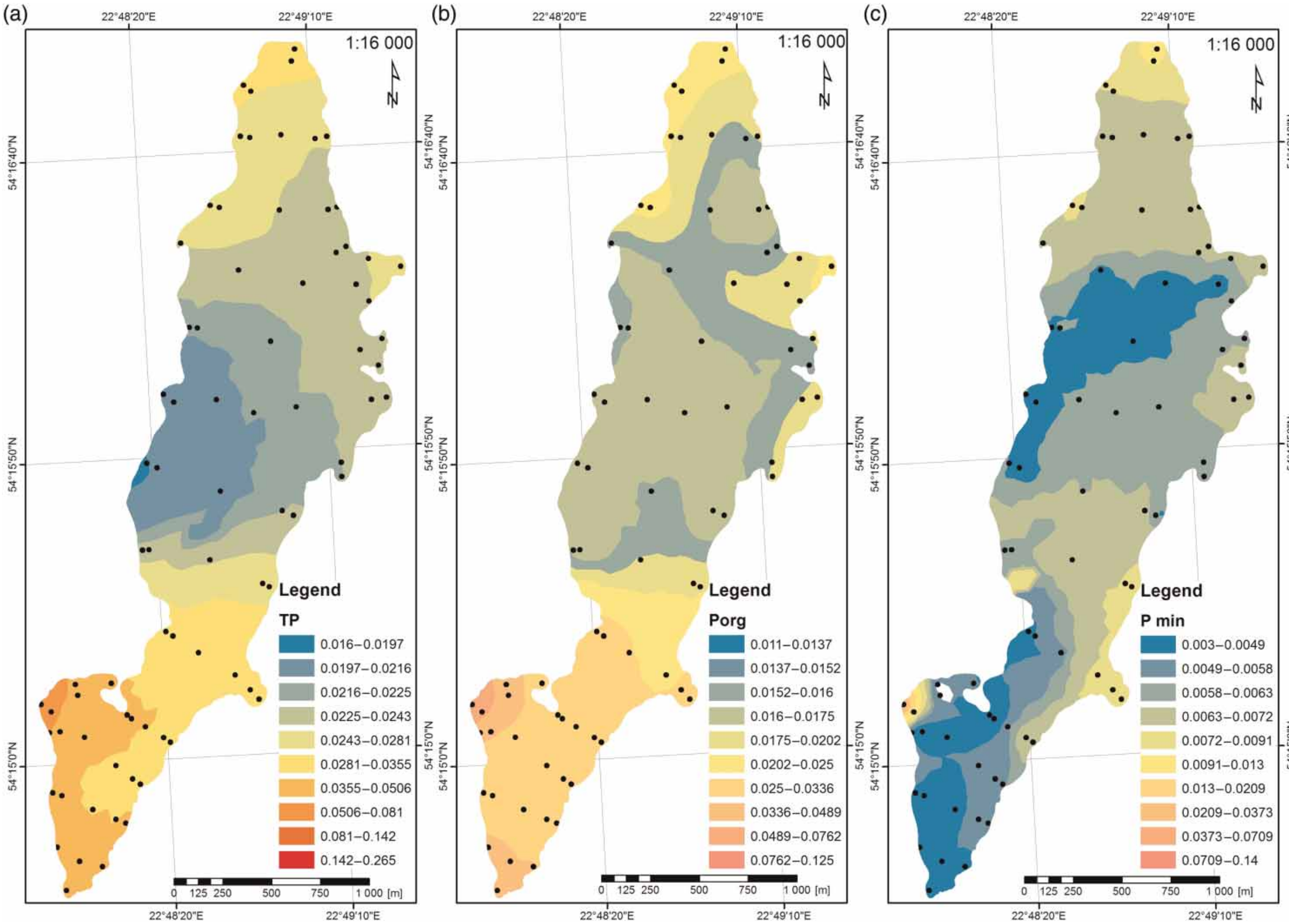

Figure 4 | The spatial distribution of phosphorus compounds TP (a), P_{org} (b), and P_{min} (c) (mg L^{-1} P).

this element (coefficient of variation 15.0%), which indicates the highest capacity for buffering the impact of external factors. In the northern part of the lake, a greater amount of phosphorus (0.027 mg L^{-1}) was found, at a slightly greater variability in the concentration (19.7%). These differences were related to both organic and mineral forms. The highest concentrations of this element were located directly in the mouth of Czarna Hańcza (Figure 4), confirming the negative impact of its main surface inflow on the lake water quality.

Nitrogen values were characterized by a more equalized distribution (Figure 5(d)). Coefficients of variation in individual basins (SB, CB and NB) had a smaller dispersion (28.1, 12.5 and 11.2%, respectively) and, as in the case of phosphorus, the greatest variability was related to the south bay of the lake.

Among the investigated nitrogen compounds, the greatest dynamics were related to the mineral forms (Figure 5). Their presence in the water is generally limited by autotrophic plankton and macrophytes. As in the case of phosphates, the diversity of mineral nitrogen during the growing season in eutrophic lakes is commonly observed. George (1981) reported high horizontal variation of phosphates and ammonia in the South Basin of Windermere (England) with coefficients of variation exceeding 100%. In our examinations, the lowest contents (an average of 0.01–0.02 mg L^{-1}, Figure 5(f)) were characterized by the form of ammonium, commonly considered to be the most easily digestible by phytoplankton. Nitrate nitrogen was present in somewhat larger quantities (from 0.08 mg L^{-1} in the SB to 0.13 mg L^{-1} in the northern part of the lake – Figure 5(e)).

In the case of the mineral forms of both N and P there was some regularity observed in the increased quantities towards the north. Such spatial distribution may indicate the uneven rate of biological production processes.

This phenomenon may be related to differences in the thermal water properties (Figure 2(a)). During the study period (at the end of spring water circulation) the temperature gradient between the examined fragments of the lake was over 3.0 °C. This was a significant variation in habitat conditions for the metabolism of phytoplankton.

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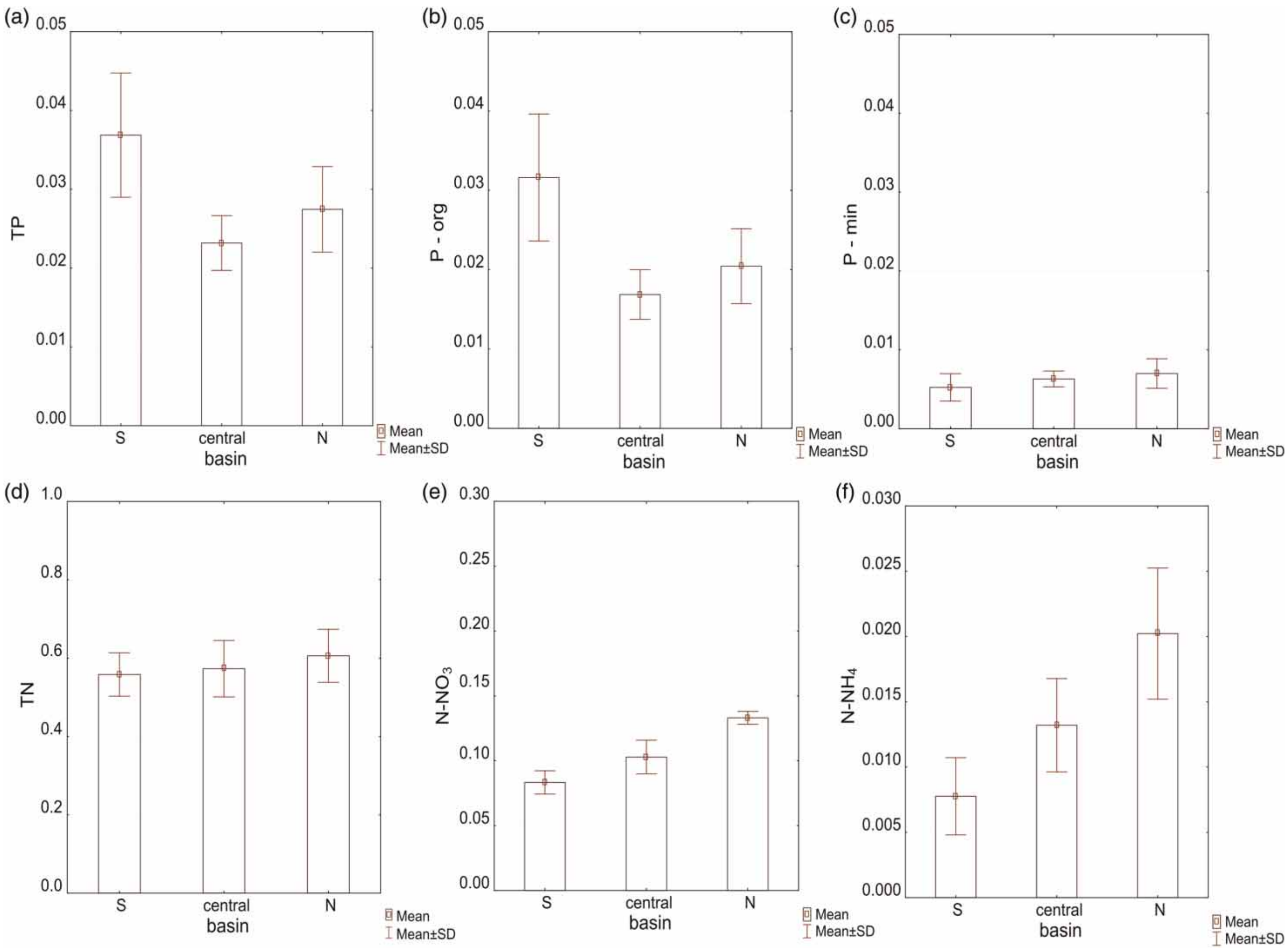

Figure 5 | Changes in phosphorus and nitrogen compounds in three basins of Lake Hańcza (mg L^{-1}).

Higher activity of primary producers in the warmer, southern part of the lake was also reflected in an increase of the pH values (Figure 2(b)), affected by the uptake of CO_2 during photosynthesis processes. The oxygen values varied between 9.5 and 11.7 mg L^{-1} with average about 10.5 mg L^{-1}. Previous studies (Zdanowski *et al.* 2008) showed that the oxygen conditions in the lake are good, without phenomena characteristic of eutrophicated ecosystems such as an anoxic period in the hypolimnion and high supersaturation in the trophogenic, surface layer of water. In our study the oxygen values, expressed as saturation level, were between 80 and 99% and clearly raised to the south (Figure 2(c)). It confirms the higher potential of primary producers in south basin.

The ecosystem response to the more favourable environmental conditions occurred also in fluctuations of phytoplankton biomass, determined as Chl *a*. High correlation between Chl *a* content and water transparency ($r = -0.86$, $n = 11$, $p < 0.05$) shows that deterioration of water quality in the spring period is connected with algae development. Additionally significant dependency between Chl *a* and TP ($r = 0.87$, $n = 11$, $p < 0.05$) indicates a limiting role of phosphorus in primary production processes. In contrast, correlation between Chl *a* and TN is negligible ($r = 0.21$, $n = 11$, $p = 0.53$). Relative deficiency of phosphorus is also reflected in the lake N/P ratio, usually exceeding factor 20.

Our results demonstrate that the patterns of spatial distribution of TN and TP in the lake are dissimilar on a short-term scale. Nitrogen shows a much more balanced concentration. Similar relationships were also presented by other authors. Kangur & Möls (2008) reported that in north-temperate Lake Peipsi more homogeneous nitrogen content could have resulted from internal processes such as bacterial denitrification and N_2 fixation by heterotrophic bacteria and cyanobacteria. However, Lake Hańcza is a rather low-trophic ecosystem and it is unlikely that biochemical activity could result with such a deep impact on

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Table 3 | The significance of differences between the nutrient contents in examined lake parts computed with one-way ANOVA analysis

Parameter	Central vs south basin					Central vs north basin					South vs north basin				
	SS	MS	df	*F*	*p*	SS	MS	df	*F*	*p*	SS	MS	df	*F*	*p*
TN	0.285	0.0042	67	0.872	0.354	0.234	0.005	46	1.39	0.245	0.126	0.0034	37	4.64	0.038
N_{org}	0.266	0.0040	67	0.254	0.615	0.226	0.005	46	0.012	0.91	0.119	0.0032	37	0.128	0.722
N_{NO3}	0.012	0.0002	67	21.37	<0.0001	0.008	0.0002	46	32.07	<0.0001	0.0056	0.00015	37	92.47	<0.0001
N_{NH4}	0.006	0.00009	67	1.81	0.183	0.0007	0.00002	46	25.64	<0.0001	0.0005	0.00001	37	88.50	<0.0001
TP	0.002	0.00003	67	94.20	<0.0001	0.0006	0.00001	46	13.30	<0.001	0.0020	0.00005	37	11.16	0.002
P_{org}	0.002	0.00003	67	110.91	<0.0001	0.0005	0.00001	46	10.93	0.002	0.0020	0.00005	37	15.71	<0.001
P_{min}	0.0001	0.000002	67	10.15	0.002	0.00006	0.000001	46	4.59	0.037	0.0001	0.000003	37	6.80	0.013

SS – sum of squares; MS – mean square; df – degrees of freedom; *F* – statistic value; *p* – probability value.

water chemistry. It indicates the presence of different causative factors – external loading pathways. A relatively low content of TN in the tributary waters (Table 4) is only two (inflow A) or less than three (inflow B) times higher than in-lake concentrations. In contrast, the same ratio for phosphorus is near 4 and 10, respectively. Simultaneously, supply of nutrients from surface runoff shows the opposite tendency – it is relatively rich in nitrogen. Taking into account the flow rate and concentration in watercourses, the total annual load of N reaching the lake from tributaries is about 7,300 kg (A – 5,100 kg, B – 2,200 kg) while the spatial loading, estimated on the basis of runoff coefficients, is about 6,500 kg. What is important, it reaches the central basin mainly (Figure 1). Thus, the whole nitrogen external loading is relatively homogeneous. In the case of phosphorus the surface runoff contribution only about 250 kg, while both watercourses supply more than 850 kg (with the ratio near 1:1) – over three times more. Such proportions of external nutrient loading seem to explain the different spatial distribution of biogenic compounds in the lake.

Horizontal heterogeneity of water chemistry is supported also by hydraulic factors. In reference to observations of Rueda & MacIntyre (2009), simple geometry of inlet basins in combination with a relatively small but stable water flow results in limited depth of penetration of the incoming water. Additionally, maintaining spatial gradients in surface water is facilitated by sheltering the lake from the wind (by natural terrain culminations), limiting horizontal and vertical water movements.

The eutrophication processes are the most intensive in the southern basin of the lake, with almost doubled TP and chlorophyll contents, increased pH as well as lower transparency, which indicates an increase in the trophic conditions of this part of Lake Hańcza. The progressive input of TP content involves the primary eutrophication phenomenon in the lake, which points to the urgent need for preventive measures.

Trophic status of Lake Hańcza

The calculated TSI values indicated that Lake Hańcza was found to be in an oligo- or mesotrophic stage during the study period (Table 5). Although the presented results are for only part of the growing season, they indicate the possibility of periodic variations in water quality at the trophic level categories in different parts of the lake. It is important to mention that this variability could be reported only in the case of detailed study of spatial distribution of water quality parameters. It should be noted that

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Table 4 | Content of nutrients in investigated tributaries (yearly ranges, mg L^{-1}), according to Zdanowski *et al*. (2008) and authors' examinations

Site/parameter	TN	$N_{\text{-NO3}}$	$N_{\text{-NH4}}$	TP	P_{min}
Inflow A	0.32–2.23	0.00–0.82	0.10–0.38	0.04–0.19	0.02–0.08
Inflow B	1.24–2.30	0.34–1.17	0.14–0.31	0.17–0.40	0.11–0.26

Table 5 | Mean values of eutrophication parameters and calculated TSI of Lake Hańcza during the study

Parameter	Unit	South basin		Central basin		North basin	
		Mean	TSI	Value	TSI	Value	TSI
TP	μg m^{-3}	36.9	56.2	23.2	49.5	27.4	51.9
Chl *a*	μg m^{-3}	2.9	41.0	1.1	31.5	2.2	38.3
SD	m	5.4	35.8	6.8	32.4	5.0	36.9
TN	mg L^{-1}	0.56	46.1	0.57	46.4	0.60	47.2
Average TSI			44.8		39.9		43.6
Trophic status		Mesotrophic		Oligotrophic		Mesotrophic	

the present TSI values were calculated on the basis of the spring surveys, at the beginning of the growing season, before the peak of activity of primary producers. It is possible that the lake (especially its southern parts) supplied with biogenic matter will fall into a state of eutrophy during summer periods.

TSI (TP, TN) was found to be greater than TSI (Chl *a*, SD). This indicates the status of an excess of nutrients in the water compared to the potential for growth of phytoplankton. A similar lack of consistency of indices of biogenic elements (especially TP) relative to the index of chlorophyll content and visibility was also demonstrated in the studies of other limnetic ecosystems (Nas *et al*. 2008; Zdanowski *et al*. 2008). The cause of this phenomenon is the presence of phosphorus forms connected with calcium and iron and the embedding of both nutrients in the structure of the organic matter. Such conditions occur in the main inflow of Lake Hańcza which is rich in calcium (60–80 mg L^{-1}) and iron (0.2–0.4 mg L^{-1} (Zdanowski *et al*. 2008)). Moreover, numerous bogs and swamps in the catchment make the water of Czarna Hańcza river ('Black Hańcza') rich in humic substances (mean total organic carbon is about 15 mg L^{-1}, which is almost 2.5 times higher than in-lake values (Dunalska 2011)). These factors provide the opportunity to delay the process of eutrophication of the lake, despite the increasing level of human impact. However, it does not relieve the need for protective measures, especially reducing the level of pollution of surface tributaries.

CONCLUSION

Lake Hańcza, the deepest inland reservoir of the central part of the European Depression, has steadily been losing its oligotrophic character. The results of this study show that current abundance in nutrients, especially phosphorus, locally reaches, and even exceeds, the eutrophic level.

Recommendations made on the basis of previous studies carried out only in the central part of the lake indicated that there is no risk of eutrophication. Our research, based on a multi-point, detailed study of water quality parameters showed significant differences in trophic conditions in examined parts of the lake and a greater impact of catchment on the development of water quality than previously thought.

The case study of Lake Hańcza indicates that in designing programs for the protection of water bodies, there is a need for a holistic approach which takes into account the environmental conditions of the whole ecosystem, especially spatial nutrient dynamics. Modern measuring techniques, such as GNSS, hydrographic systems, radar and laser scanning, bring new opportunities for the acquisition and limnometric raw data processing. The example of Lake Hańcza shows that the newly collected raw data, analyzed and visualized in GIS software, can be used in further scientific studies by researchers. One of the advantages of GNSS positioning is not only the navigation support during sample collection but also the chance to provide further study in the same sampling points. It is especially important to monitor the changes in the quality of the environment under the influence of external factors, such as the results of conservation measures taken in water management.

REFERENCES

Bajkiewicz-Grabowska, E. 2008 Water balance of Lake Hańcza. In: *Environment and Ichtiofauna of Lake Hańcza* (J. Kozłowski, P. Poczyczyński & B. Zdanowski, eds). Institute of Inland Fisheries, Olsztyn, Poland, pp. 25–36.

Carlson, E. R. 1977 A tropical state index for lakes. *Limnology and Oceanography* **22** (2), 361–369.

Childs, C. 2004 Interpolating surfaces in ArcGIS Spatial Analyst, *ArcUser*, July–September, pp. 32–35.

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Cooke, G. D., Welch, E. B., Peterson, S. A. & Nichols, S. A. 2005 *Restoration and Management of Lakes and Reservoirs*. Taylor & Francis/CRC Press, Boca Raton, FL, USA.

Cressie, N. A. C. 1991 *Statistics for Spatial Data*. Wiley, New York.

Dunalska, J. A. 2011 Impact of morphometric and catchment variables on summer organic carbon richness in deep temperate lakes. *Knowledge and Management of Aquatic Ecosystems* **403**, 1–11.

George, G. 1981 The spatial distribution of nutrients in the South Basin of Windermere. *Freshwater Biology* **11**, 405–424.

Gruendling, G. K. & Malanchuck, J. L. 1974 Seasonal and spatial distribution of phosphates, nitrates, and silicates in Lake Champlain, U.S.A. *Hydrobiologia* **45** (4), 405–421.

Gulati, R. D. & van Donk, E. 2002 Lakes in the Netherlands, their origin, eutrophication and restoration: state-of-the art review. *Hydrobiologia* **478**, 73–106.

Hutorowicz, A. & Napórkowska-Krzebietke, A. 2008 Phytoplankton communities in lake Hańcza. In: *Environment and Ichtiofauna of Lake Hańcza* (J. Kozłowski, P. Poczyczyński & B. Zdanowski, eds). Institute of Inland Fisheries, Olsztyn, Poland, pp. 93–102.

Isaaks, E. H. & Srivastava, R. M. 1989 *An Introduction to Applied Geostatistics*. Oxford University Press, New York.

Kangur, K. & Möls, T. 2008 Changes in spatial distribution of phosphorus and nitrogen in the large north-temperate lowland Lake Peipsi (Estonia/Russia). *Hydrobiologia* **599**, 31–39.

Kitanidis, P. K. 1997 *Introduction to Geostatistics*. Cambridge University Press, Cambridge, UK.

Kratzer, C. R. & Brezonik, P. L. 1981 A Carlson-type trophic state index for nitrogen in Florida lakes. *Water Research Bulletin* **17**, 713–715.

Krause, E. 2012 Dealing with extreme values in kriging. http://blogs.esri.com/esri/arcgis/2012/05/07/dealing-with-extreme-values-in-kriging/.

Krivoruchko, K. 2011 *Spatial Statistical Data Analysis for GIS Users*. Esri Press, Redlands, CA, USA.

Lijklema, L. 1998 Dimensions and scales. *Water Science and Technology* **37** (3), 1–7.

Łopata, M. & Gawrońska, H. 2006 Effectiveness of the polymictic Lake Głęboczek in Tuchola restoration by the phosphorus inactivation method. *Pol. J. Nat. Sci.* **21** (2), 859–870.

Nas, B., Karabork, H., Ekiercin, S. & Berktay, A. 2008 Assessing water quality in the Beysehir Lake (Turkey) by the application of GIS, geostatistics and remote sensing. In: *Proceedings of Taai 2007: The 12th World Lake Conference*, Jaipur, India (M. Sengupta & R. Daiwani, eds), pp. 639–646.

OECD 1982 *Eutrophication of Waters – Monitoring, Assessment and Control*. The Organisation for Economic Cooperation and Development (OECD), Paris.

Popielarczyk, D. & Templin, T. 2013 Application of integrated GNSS/hydroacoustic measurements and GIS geodatabase models for bottom analysis of Lake Hancza: the deepest inland reservoir in Poland. *Pure and Applied Geophysics*, doi 10.1007/s00024-013-0683-9.

RIEP (Regional Inspectorate for Environmental Protection in Białystok) (Poland) 2011 *The Study Report and Preliminary Assessment of Lake Hańcza in 2010*. Bulletin no. 2, Delegacy in Suwałki, Poland.

Rueda, F. J. & MacIntyre, S. 2009 Flow paths and spatial heterogeneity of stream inflows in a small multibasin lake. *Limnology Oceanography* **54** (6), 2041–2057.

Rühle, E. 1932 Der Hancza See auf der Suwalken-Seeplatte (Lake Hańcza in the Suwalki Lake District). *Geographic Messaging Service* **6** (4), 422–455.

Śledzinski, J. 1927 The lakes of Suwalki district. *Archives of Hydrobiology and Fisheries* **3** (1–2), 340–309.

Standard Methods for the Examination of Water and Wastewater 1998 20th edn, American Public Health Association/ American Water Works Association/Water Environment Federation, Washington, DC, USA.

Zdanowski, B., Stawecki, K. & Pyka, J. 2008 Abiotic environment of Lake Hańcza. In: *Environment and Ichtiofauna of Lake Hańcza* (J. Kozłowski, P. Poczyczyński & B. Zdanowski, eds). Institute of Inland Fisheries, Olsztyn, Poland, pp. 59–74.

First received 20 September 2013; accepted in revised form 4 February 2014. Available online 19 February 2014

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