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The Role of Confluence in Shaping Water Quality Parameters on Example of the Flow-Through Lake Bikcze (Eastern Poland)

Beata Ferencz [1,*] **and Jarosław Dawidek** [2]

[1] Department of Hydrobiology and Protection of Ecosystems, University of Life Sciences, 13 Akademicka St., 20-950 Lublin, Poland
[2] Department of Hydrology, Maria Curie-Skłodowska University, Aleja Kraśnicka 2 cd, 20-718 Lublin, Poland; jaroslaw.dawidek@poczta.umcs.lublin.pl
* Correspondence: beata.ferencz@up.lublin.pl; Tel.: +48-814-610-061

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Abstract: The role of confluence (flowability) in shaping the concentration of dissolved oxygen (DO), chlorophyll-a (chl-a) and pH was determined using a model approach. The calculations considered both horizontal and vertical variability of parameters. There was a general tendency for the pH and oxygen to increase along the transect connecting the place of surface water inlet, deepest point of the lake basin and the place of water outlet, and the reverse tendency for chlorophyll. The average gradient for particulate radius was calculated as arithmetic mean value of six partial gradients (corresponding to individual depths, every 0.5 m). Values of average gradients indicated high dynamics of DO and pH concentration changes as well as low chlorophyll-a variability. A slight inclination of the final resultant vector gradients of DO and pH from the surface water inlet, deepest point of the lake basin and the place of water outlet transect indicated the dominant role of confluence in these parameters variability (values amounted to 6.08 mg·km^{-1} and 3.34 pH units·km^{-1}, respectively). The value of the chlorophyll-a gradient vector (1.86 µg·km^{-1}) indicated a slight differentiation of the parameter in the basin, independent of the hydrological conditions. The concentration of chl-a in the polymictic Lake Bikcze resulted from the effect of the limnic conditions; the flowability of the lake was just one of many factors affecting the variability of the parameter.

Keywords: polymictic lake; confluence; modeling approach; tributaries input; limnetic conditions

1. Introduction

Surface waters, especially shallow polymictic lakes, are dynamic systems. They are known for a high degree of heterogeneity in both space and time. Multicoreality of components of these systems bring about the variation of physicochemical properties of water, as well as determine the growth and changes, both temporal and spatial, of aquatic life [1]. Thus, to assess water quality of lakes, physicochemical and biological parameters are usually observed [2]. Chlorophyll concentration is an indirect estimation of the biomass of phytoplankton and the photosynthesis rate of the primary producers. Chlorophyll-a (chl-a) is usually considered to be surrogate and an important biological parameter indicating eutrophication of water [3]. Phytoplankton biomass (measured as chlorophyll) in freshwater lakes is usually limited by phosphorus and nitrogen. The more intense is the human pressure on the catchment, the higher is the nutrient input into the lake basin [4,5]. Increase in chlorophyll concentration may also be brought about by changes in water temperature, water level, flushing time, or intense precipitation [6,7].

Seasonal and spatial variability of the quality of lake waters has been previously confirmed [8]. One of the most important factor determining the water quality of shallow lake waters is temperature. It may hinder many chemical and biological processes and influence living conditions and spatial distribution of aquatic life [9]. Dissolved oxygen (DO) concentration and the pH are important parameters for determining the quality of aquatic systems. Dissolved oxygen is considered to be the most important parameter in natural or semi-natural aquatic systems for determining the health of the ecosystems [10]. The DO concentration in lakes is controlled by interaction of three main processes: (1) Consumption of oxygen by respiration; (2) production of oxygen by photosynthesis; and (3) gas exchange with the atmosphere, mainly due to wind explosion [11]. Ecosystem respiration as well as primary production are determined by various physical, chemical and biological factors, whereas gas exchange in the atmosphere is a physical process [12]. The photosynthesis can also shape pH and dissolved oxygen concentration. Thus, the relationship between pH and DO also indirectly influence phytoplankton photosynthesis [13]. Variation in pH is usually generated by factors such as photosynthesis since CO_2 assimilation increases pH values [14,15]. Water quality monitoring (both spatial and temporal) is essential not only to evaluate the impacts of pollution sources, but also to maintain water resources protection and proper management of lake catchments [16].

The aim of the study was to estimate the rate and the direction of changes in the important water quality parameters, namely oxygen, pH, and chlorophyll-a concentration, both horizontally and vertically. Both the pace and directions of changes were determined using the model approach, in the context of the role of confluence of the lake. The proposed method presents the relative variability of the analyzed parameters in all dimensions of the lake basin, such as horizontal isobaths systems, vertical values for radiuses, and a synthetic index (final gradient) taking into account both dimensions. We hypothesized that: (i) Oxygen concentration in a shallow polymictic lake is determined mostly by the gas exchange with the atmosphere; and (ii) inflow of stream waters determine the size and direction of pH as well as the chlorophyll-a variability.

2. Study Area

Lake Bikcze is one out of around 70 lakes located in the Łęczna-Włodawa Lake District. The group of lakes is located in Eastern Poland, outside the zone of the last glaciation. The flow-through, shallow Lake Bikcze is supplied with water of one inflow, from the south, and drained toward the north by one outflow (Figure 1). The water body is polymictic in nature. The area of the lake is 759,038 m^2, and the volume is 988,482 m^3. Basic morphometrical parameters are presented in Table 1. The confluence of the lake results from the implementation of the drainage system related to the construction of the Wieprz-Krzna canal in the 1950s. Currently, the lake basin is diked, and thus it has been cut off from the surface supply of the basin. Groundwater recharge has been hindered due to construction of the drainage ditch along the western lake shore (Figure 1).

Table 1. Selected morphometric characteristic of Lake Bikcze.

Parameter	Area m^2	Volume m^3	Length m	Width m	Depth Max m	Shoreline m	Mean Depth m
Value	759,038	988,482	1206	860	2.7	3351	1.3

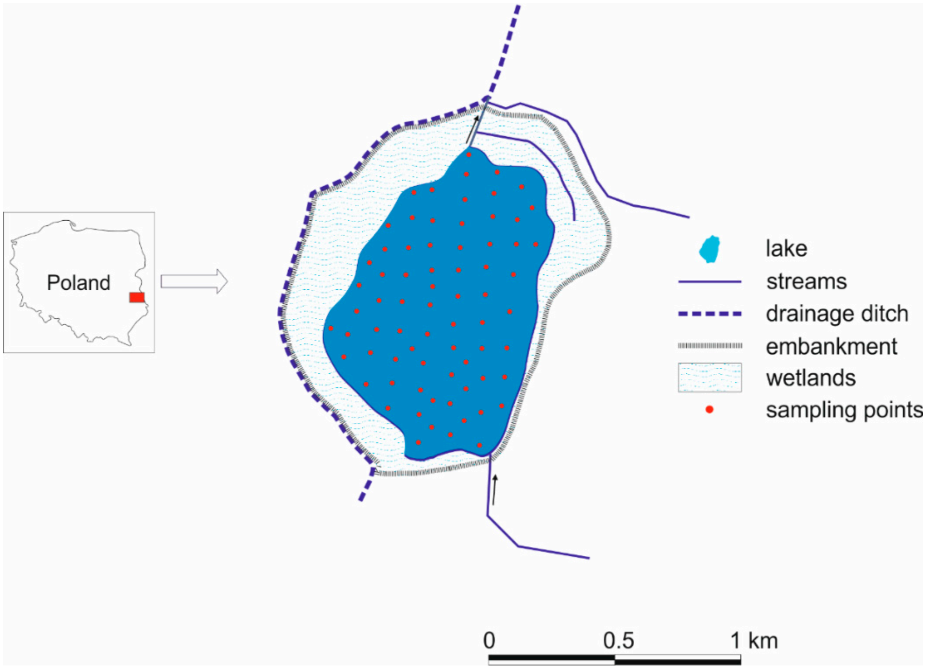

Figure 1. Location of the lake under study.

3. Materials and Methods

Bathymetric measurements were conducted in the winter of 2016, using Garmin GPS MAP 64S receiver (Garmin International, Inc., Olathe, KS, USA). Depth measurements were tested using the weight probe. Golden Software Didger 5 (Golden Software LLC, CO, USA) as well as Surfer 8 was used to prepare bathymetric scans. Measurement points of the depth measurements were downloaded from the GPS to the Didger program, in which the corresponding depth values were assigned to them. Then, the data were exported to the Surfer program for interpolation and preparation of bathymetric scans.

In May 2016, spatial measurements of physicochemical parameters were conducted along the transects. Parameters (chlorophyll, DO concentration, and pH) were measured optically, with YSI 6600 V2-4 Multi-parameter Water Quality Sonde (YSI Incorporated, Yellow Springs, OH, USA). The major advantage of the method is that both oxygen and chlorophyll in this procedure are measured in-situ, without disrupting the cells, as in the extractive analysis. Chlorophyll fluorescence measurements were compared with extracted chlorophyll-a, to calculate chl-a concentration according to standard methods of chlorophyll quantification. A total of 72 probes were performed in the water column, every half a meter in depth. Measuring points were evenly distributed, considering all parts of the lake basin. The measurement of the analyzed quality parameters took place in the situation of confluence (active inflow and outflow of the lake basin). Chemical analyses were performed using a LF300 photometer (Slandi, Michałowice, Poland). Samples were collected using 250-mL flasks and then transported to the laboratory where the concentrations of NO_2, NO_3, NH_4, PO_4, TP, and TN were measured. Samples were preserved using sulfuric acid to determine the TP and TN concentration. In the laboratory, the samples were mineralized in the microwave oven for 30 min before the measurements.

Isarithmic maps of the spatial variability of the parameter (chl-a, DO, and pH) were constructed for each measured depth (SL (surface layer), 0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m). The transfer of parameter values from the measurement point to the space was made in the ARCGIS ArcView 9.1 software (ESRI, Redlands, CA, USA) and inverse distance weighted (IDW) interpolation method (Figure 2).

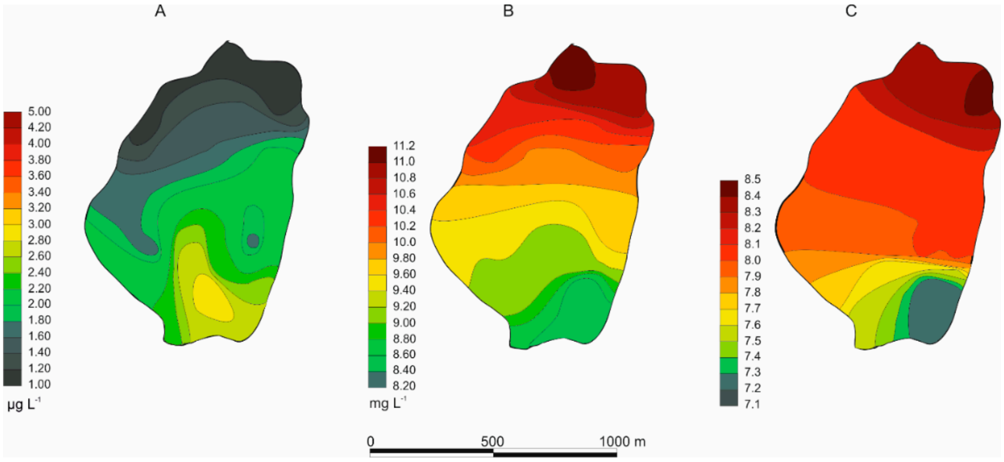

Figure 2. Exemplary maps of the spatial variability of the studied parameters for the surface layer: (**A**) Chl-a; (**B**) dissolved oxygen; and (**C**) pH.

To analyze an effect of confluence on the quality parameters of waters, a transect connecting water inlet, the deepest point of the lake and the outlet was established. The transect line determined the zone of the highest confluence of the lake. Two additional radiuses, angularly dividing the bowl into equal parts, were determined on both sides of the main transect. The aim of introducing additional radii was to consider all the zones of the lake basin to make the analysis more detailed (Figure 3). The values of the partial gradient of the relative variability of parameters (unit·km^{-1}) were calculated on each radius of the designated isobaths. The value of partial gradients was always calculated as the difference between the value recorded in the deepest part of the lake basin (D) and the points of radiuses intersection with the isobath, according to Equation (1). In this way, 36 partial gradients (6 radii times 6 isobaths) were obtained. For example, 6 partial gradients of radius 1 were calculated as follows:

$$Gp1 - 6_{0\ldots n} = \frac{v_{0\ldots n} - vD}{\Delta L} \tag{1}$$

where: $Gp1 - 6_{0\ \ldots\ n}$ are the partial gradients for radiuses from 1 to 6 for particulate lake depths, $v_{0\ \ldots\ n}$ re the parameter values for particulate lake depths, vD is the parameter values for the deepest point of the lake, and L is the distance from the deepest point of the lake to the point on the isobath.

In the next step, 6 average gradients were calculated. The average gradient ($\overline{G}$) of particular radius (from 1 to 6) was calculated (Equation (2)) as arithmetic mean value of the six gradients describing the vertical (surface, 0.5, 1.0, 1.5, 2.0, and 2.5 m deep) variability of oxygen conditions, pH and chlorophyll-a (Figure 3).

$$\overline{G} = \frac{Gp1 + Gp2 + \ Gn}{N} \tag{2}$$

where: $\overline{G}$ is the average gradient, $Gp1\ \ldots\ Gn$ are the partial gradients, and N is the number of partial gradients

The system of six average gradients was used to determine the resultant vector of the final gradient of relative values of the examined parameters (graphical method of vector addition, presented in Figure 4). Compatibility of the direction and the sense of the resultant vector with the course of the transect inflow–depth–outflow indicates the dominant role of confluence in shaping the parameter variability.

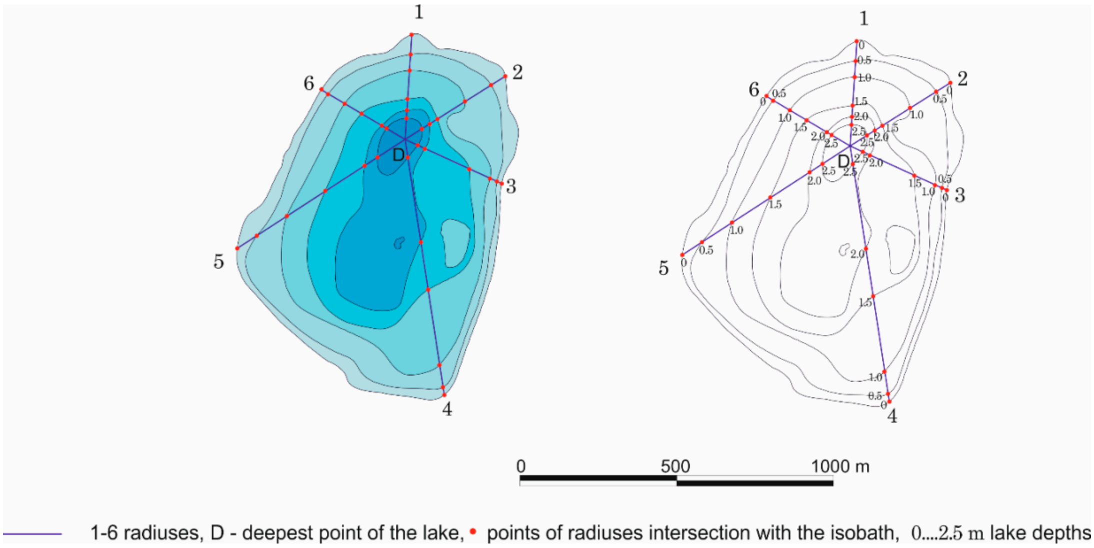

Figure 3. Radiuses used for partial gradients calculations.

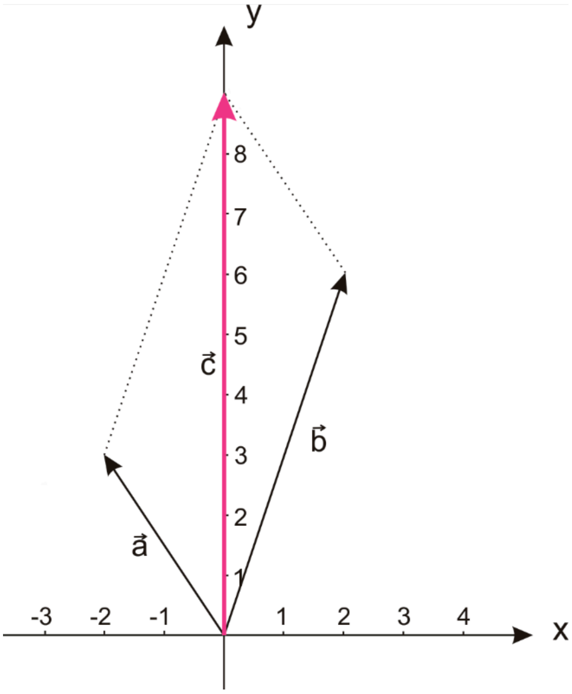

Figure 4. An example of average gradient addition: (**a**,**b**) average gradients; and (**c**) resultant gradient.

4. Results

Homogeneous conditions of water temperature and electrical conductivity was observed in the lake basin. Both horizontal and vertical temperature and EC values amounted from 15.5 to 16.6 °C and from 237 to 247 μS·cm^{-1}, respectively. Hydrochemical conditions of inflow and outflow waters are presented in Table 2. Flushing time, calculated as a lake volume and Q of the outlet (one the day of sampling) amounted to 780 days.

Table 2. Hydrochemical conditions of water of inflow and outflow waters, Q, discharge.

Parameter	Q $L{\cdot}s^{-1}$	NO_2^- $mg{\cdot}L^{-1}$	NO_3^- $mg{\cdot}L^{-1}$	NH_4^+ $mg{\cdot}L^{-1}$	PO_4^{3-} $mg{\cdot}L^{-1}$	TP $mg{\cdot}L^{-1}$	TN $mg{\cdot}L^{-1}$
Inflow	13.7	0.002	0.005	0.056	0.115	0.4	0.33
Outflow	14.8	0.012	0.036	0.106	0.048	1.3	0.31

The oxygen conditions of lake waters on the surface water inlet, deepest point of the lake basin and the place of water outlet transect, expressed by the concentration of DO ($mg{\cdot}L^{-1}$), was characterized by distinct variability (Figure 5B). In the zone of 200 m from the place of an inflow of waters supplying the lake, dissolved oxygen concentration fluctuated in a relatively narrow range from 8.4 to 8.8 $mg{\cdot}L^{-1}$. Depending on the place of measurement, water DO changed slightly: on the surface and at a depth of 0.5 m it increased by about 0.1 $mg{\cdot}L^{-1}$ at 200 m, while at a depth of 1 m by about 0.35 mg per 100 m distance. Intensive changes of oxygen concentration were recorded in the entire vertical section on the section 200–300 m from the place of water inflow to the basin. The clear enrichment of water with dissolved oxygen was 0.8 $mg{\cdot}L^{-1}$ on average. A step DO increase by about 1.1 $mg{\cdot}L^{-1}$ was observed in the zone of 1 m to the depth from the surface of the lake. The most even course of this parameter variability occurred on the section from 400 m from the lake deepest point (820–835 m of the transect). The concentration of DO in water increased by a similar value, about 0.5–0.6 $mg{\cdot}L^{-1}$ at all measured depths. Oxygen concentration of waters over the deepest point of the basin decreased with the depth to about 9.1 $mg{\cdot}L^{-1}$. The last fragment of the cross-section (to water outflow from the lake) was characterized by an increase in waters DO. In the surface and sub-surface layer (0.5 m), there was a step increase in the parameter, by about 1 $mg{\cdot}L^{-1}$ per 200 m of transect. Comparing the oxygen conditions of the inflow and outflow of lake waters, the observed difference should be emphasized. Higher stabilization of oxygen parameters distribution was noted on the inflow to the basin. In the outflow zone, there was a slightly higher variability of the parameter in a clearly higher range.

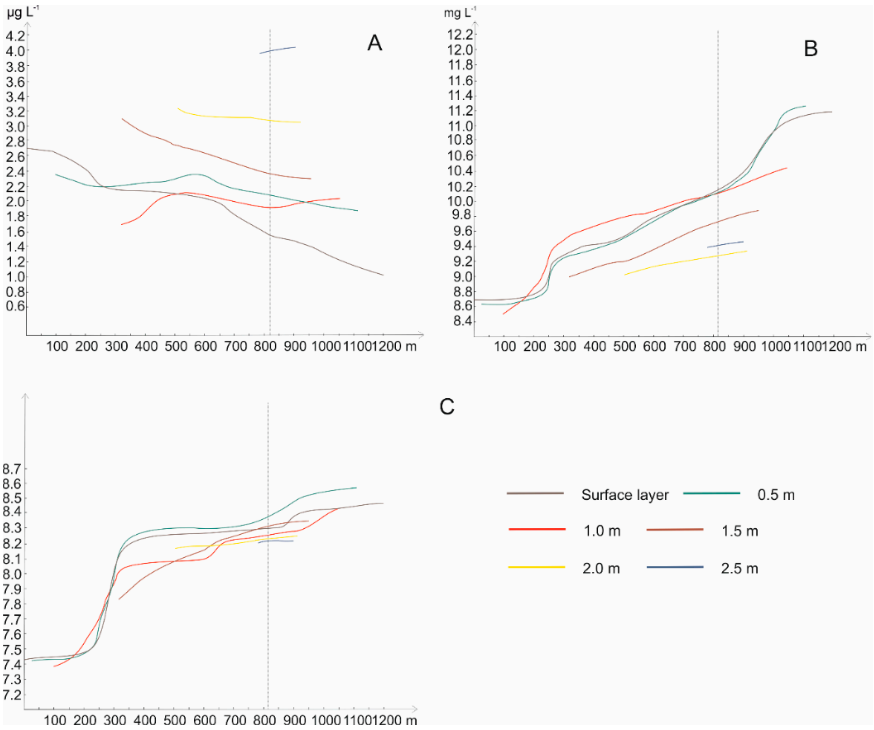

Figure 5. Variability of: (**A**) Chl-a; (**B**) DO; and (**C**) pH conditions along the main inlet–deepest point of the lake–outlet transect.

pH value in the waters of Lake Bikcze was differentiated along with the distance and depth of the lake (Figure 5C). Weak alkaline conditions were constantly maintained where the basin was supplied with the waters of the catchment, and the pH value ranged from 7.42 at a depth of 0.5 m to 7.45 at the surface. Surface waters had a slightly higher pH than subsurface waters (pH 7.35) up to 1 m, and such distribution of the parameter concerned the first 180 m of the transect. An increase in the dynamics of pH changes in lake waters was recorded in the zone of 200–400 m of the transect. The measurements of pH at all depths were characterized by a step increase. The highest amplitude of increase (0.85 pH on average) was recorded in surface and subsurface waters, from about 7.45 to 8.3 pH. The next part of the transect, to the basin depth, was characterized by a relative stabilization of pH in the mass of water. The range of vertical variation was moderate, 0.37 pH on average. In the depth zone, the conditions of water pH changes could be described as low-variable. In the part of the cross-section from the depth to the place of water outflow from the lake, the alkalinity of waters (from 8.4 to 8.5.5 pH on average) and the variability range were again a subject to an increase. An inverse distribution (in relation to the inflow zone) of the vertical parameter was also recorded. Surface waters had a lower pH than deeper waters. The pH value of water in the whole basin is constantly increasing along with the distance.

Chlorophyll concentration in the waters of Lake Bikcze was characterized by a distinct variability, both with the distance on the great axis of the lake and depth, from about 1.05 to 4.1 $\mu g \cdot L^{-1}$. The general tendency in the decrease in chlorophyll concentration on the line of the examined transect, from 2.55 to 1.68 $\mu g \cdot L^{-1}$ on average, was observed (inversely to the changes in pH value and DO of waters). At the place of an inflow of the watercourse feeding the basin, surface waters were characterized by a higher concentration of chlorophyll (2.71 $\mu g \cdot L^{-1}$ on average) than deeper water (2.38 $\mu g \cdot L^{-1}$ on average). In the zone of the strongest influence of fluvial conditions on the chlorophyll distribution (the first 350 m of cross-section), the decreasing tendency was subject to change in the zone of 400–700 m (Figure 5A). A decrease in the role of fluvial conditions and the increase in the significance of limnetic conditions resulted even a temporary increase in this parameter concentration in the case of a depth of 0.5 m (up to 2.4 $\mu g \cdot L^{-1}$). The depth zone was not modified in the general course of chlorophyll-a concentration change. Changes in the concentration of the analyzed photosynthetic dye in the vertical direction were increasing with depth (from 1.5 $\mu g \cdot L^{-1}$ on the surface to 4.1 $\mu g \cdot L^{-1}$ at the bottom). The decreasing tendency in chlorophyll concentration was maintained until the end of the examined transect.

Oxygen showed the highest variability of partial gradients, expressed as standard deviation (SD) value, which was always above 1, whereas pH was the lowest (Table 3). In vertical terms, the highest variability of all parameters was observed at the deepest point.

Table 3. Values of partial gradients of DO, pH and chlorophyll, expressed as relative values ($unit \cdot km^{-1}$).

Gradient	DO [†]			pH [‡]			Chl [§]		
	min	**max**	**SD**	**min**	**max**	**SD**	**min**	**max**	**SD**
Surface	−2.69	1.65	1.61	−0.82	0.97	0.56	−1.78	1.23	1.27
0.5 m	−4.15	1.81	2.14	−0.95	1.11	0.67	−0.94	0.80	0.69
1.0 m	−1.68	1.85	1.18	−0.84	1.23	0.68	−4.06	0.00	1.68
1.5 m	−1.06	2.06	1.16	−0.96	1.44	0.89	−2.68	0.35	1.09
2.0 m	−1.41	3.08	1.45	−0.94	1.85	0.96	−1.08	1.41	0.75
2.5 m	−1.41	6.06	2.54	−1.33	1.54	1.06	−1.33	4.53	1.76

[†] $mg \cdot km^{-1}$, [‡] pH $units \cdot km^{-1}$, [§] $\mu g \cdot km^{-1}$.

The average gradients of the analyzed parameters for the isobaths (SL, 0.5, 1.0, 1.5, 2.0, and 2.5) in the vertical planes of six highlighted partial radiuses are shown in Figure 6. The highest variations of the average gradients were observed in the case of DO (from −1.94 on radius 6 to 2.52 on radius 4) (Figure 6B), the smallest for chlorophyll-a (from −1.17 on radius 3 to 0.07 on radius 2) (Figure 6A). The variation occurred in the case of average pH gradients amounted from −0.84 on radius 1, to 1.4

on radius 4. The arrangement of average DO and pH gradients showed similarity (Figure 6B,C). The arrangement of the chlorophyll-a gradients was different.

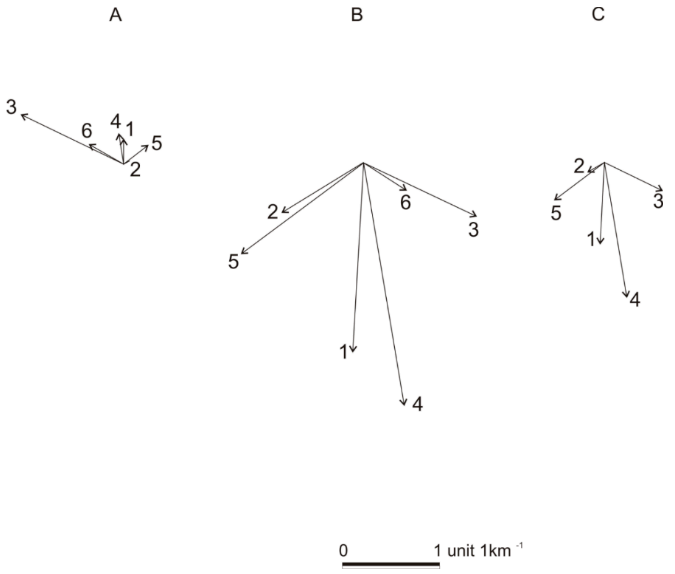

Figure 6. Average gradients of: (**A**) Chl-a; (**B**) DO; and (**C**) pH.

The final resultant vector gradients showed the influence of Lake Bikcze's confluence on shaping the pH and DO variability of the water, as evidenced by the turn of the vectors (Figure 7). The DO and pH vector gradients amounted to 6.08 and 3.34, respectively. The direction of vectors of the pH and DO gradient was characterized by a slight inclination on the inflow–deepest point–runoff transect (small deflection angle testifies to the large role of water inflow from the catchment). The variability of the chl-a gradient was the smallest (value 1.86) and independent of the hydrological conditions. The turn and direction of the chlorophyll vector gradient indicated the dependence of the parameter on the limnetic conditions, while the lake's confluence was only one of the many factors shaping the chlorophyll variability.

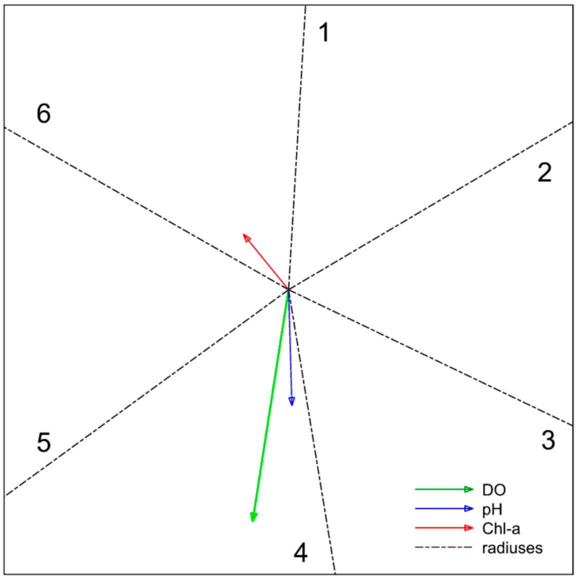

Figure 7. The final resultant vector gradients.

5. Discussion

Sampling was conducted under intensive mixing conditions, which reflect the stability of vertical and horizontal temperature and EC conditions. The lake presented a stage of output prevalence over input, which was a short-termed. Two weeks before the sampling, the inverse situation was observed, and inflow was several times higher than outlet (data not presented). Both input and drainage force water movement in the lake basin (mostly due to piston flow of water [17]), thus role of confluence can be estimated in various hydrological conditions. Flushing time that amounted to over two years on the day of sampling vary in Lake Bikcze from 42 days to 146,636 days. Limnologists nowadays refer to Tf rather as theoretical value, due to its uncertainty [18,19].

Investigations of statistical relationships among physicochemical, hydrological or biological factors are usually based on seasonal approach [20–22]. This paper introduces a new method of estimating role of confluence, based on lake water condition at a specific time. Determination of the impact of seasonality of environmental conditions (i.e., precipitation, evaporation, rate of exchange, temperature, vegetation, etc.) on seasonality of quality parameters of lake waters has not been presented, as it is irrelevant for this approach. Case study papers, assessing spatial distribution of parameters or modeling approach, often lack seasonal perspective [23–25].

This paper focuses on the impact of Lake Bikcze's confluence (inflow–outflow transect) on DO, pH, and chlorophyll-a distribution. These three parameters are the most important in lakes, because DO concentration and pH values determine the temporal distribution of aquatic organisms, including algae, which is also presented as the chlorophyll-a concentration. Other limnological factors, such as transparency, total dissolved solids, or conductivity, directly depend on the DO and pH [26].

General increase of DO concentration that was observed along the transect inflow–outflow indicated the role of external processes. The lower DO concentration in a lake is often a result of elevated oxygen-demanding substances, such as total suspended solids and algal bloom [27], thus lower values and variability of the parameter in the zone of inflow. Further in the lake water from the inflow has higher DO variability. It shows alteration of conditions, from fluvial to limnetic one, and the decreasing role of surface input, which was different from the one reported in Romanian Lake Rosu [28].

Water mixing due to the inflow has favored a uniform oxygen condition in the water column [29,30]. Dissolved oxygen concentration is often the result of wind, increasing rate of gas exchange predisposed to wind impact [31], as it was in the shallow Lake Bikcze, and the oxygen exchange with the atmosphere. Therefore, the highest variability (expressed as the gradient value) among all the analyzed parameters were observed in DO. In a zone of fluvial impact, from the inflow to the deepest point of the lake, the highest variability of the parameter was observed. As inflow water mixes with lake water, changes in main physical parameters of lake water may be more pronounced in this part of the lake basin [2].

pH usually shows similar distribution to DO [29], which was confirmed in Lake Bikcze. In the zone from the tributary to the deepest point of the lake, the alkalinity of waters was lower, but the rate of pH changes was significantly higher compared to the limnetic zone (from the deepest point of the lake to the outflow). The pattern of pH changes along the transect inflow–outflow was characterized by the higher pH in the outlet than in the inlet, which was consistent with other studies [32]. Heini et al. [21] reported on a temperate lake (Lake Vanajanselkä) that chlorophyll, pH, and oxygen concentration were higher in the upper layers of the water column. This was confirmed in Lake Bikcze in the event of DO and pH.

The spatial heterogeneity of phytoplankton distribution observed in Lake Bikcze has been previously reported in other lakes [33]. It may result from physical, chemical, and biological factors, for example, due to horizontally and vertically unequally distributed conditions, both physical and chemical [34]. It may also be a result of inflowing water impact. General decrease of chlorophyll-a concentration along the gradient was observed, and the highest values were found in the zone of the inflow mouth that delivers waters abundant with nitrogen (0.7 $mg \cdot L^{-1}$ NO_3 on average) and phosphorus (3.13 mg·L^{-1} PO_4 on average). High concentration of nutrients in this zone of the lake favors phytoplankton development. Although the depth of the lake was low, the chl-a vertical variability showed clear parameter increase in the 2.5 m depth layer. Maximum abundance of algae at a certain depth, far from the surface, is often described in temperate lakes of North America and Central and Northern Europe [35,36].

In the case of chlorophyll-a, the variability in the parameter was not related to the confluence of the lake. The very low final vector gradient value indicated the aligned conditions of the spatial distribution. Slightly higher chl-a variability was recorded in the part between the deepest point of the lake and the outflow; the direction and the orientation of the vector was consistent with the wind direction (SW), during the measurement period. Wind may influence the phytoplankton distribution (expressed as chlorophyll) [37,38].

As final resultant gradients have shown, the DO and pH correspond to the confluence of the lake, whereas chlorophyll-a does not. It corresponds to results of Thomaz, Bini and Bozelli [39] that lakes are also affected by local functioning forces, such as inputs from small tributaries. Chlorophyll or phytoplankton's community are affected by many environmental factors [40], and thus inflow of stream waters has not determined the size and direction of chlorophyll variability in Lake Bikcze. Both direction and orientation of pH vector showed the strongest relationship with the confluence of the lake among the studied parameters, which confirmed the aforementioned hypothesis.

Shallow polymictic Lake Bikcze showed variability of the measured parameters in both horizontal and vertical directions. pH and DO values showed general increase along the inflow–outflow transect, indicating external impact on shaping the parameters. Reverse situation was observed in terms of chlorophyll. The results have shown that both pH and DO conditions are determined by the lake confluence, whereas chlorophyll-a is prone to other environmental factors.

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