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Short Communication

Effect of Agricultural Land Use on the Water Quality of Polish Lakes: a Regional Approach

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Abstract

There is a need to collect and store fast-growing resources of information describing phenomena and processes occurring in the nature, and therefore, databases are increasingly being used in environmental sciences. The possibility of formulating arbitrarily complicated queries enables in the precise determination of the scope and method of analysis using a large amount of historical and actual datasets. This study used a database containing the morphometric parameters of more than 1,000 lakes and their catchments, and basic data describing the quality of water of more than 560 lakes. In the first step of the analysis, the percentage share of agricultural land in the total area of each region was determined. The next stage was to divide the entire set of lakes into equinumerous class breaks based on the values of water quality parameters. Then, the lakes located in individual regions were counted within the groups of low, medium, and high values of studied parameters. Numbers of lakes have been converted to percentages and used to calculate the values of the regional water quality indicator. It was concluded that the values of the indicator are dependent on the type of land use, and in particular, on the percentage of agricultural land that exists within the studied regions.

Keywords: lakes, land use, surface water quality, lakeland, database of Polish lakes

Introduction

During the second half of the 20th century, agricultural productivity increased due to the increased use of irrigation, fertilization, and pesticides [1]. The agricultural sector is the greatest water user in the world [2-3], making this branch of the economy a significant cause of environmental hazards. The main agricultural pollutants are nutrients and pesticides [4-5]. Nutrients limit life in aquatic ecosystems, and their accumulation promotes excessive plant growth. High loads of nitrogen and phosphorus cause eutrophication, hypoxia, and algal blooms in surface water bodies [6]. This is the main reason for the drastic reduction in water quality in the world today. The upper tolerable limit for freshwater eutrophication has already been crossed [7].

The role of catchments in impacting the quality of lake water is important [8-9]. Excess inputs of nutrients to lakes can cause eutrophication and the associated decline of water quality and ecological integrity [10]. The

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poor condition of a lake is a consequence of progressive eutrophication [11]. Effects of this process have been extensively described in the limnological literature [12-13]. Many types of pollutants enter surface waters from urban, industrial, and agricultural land. Due to the use of large areas of arable land, agricultural activity is a major provider of nutrients and harmful chemicals [14]. This leads to the rapid deterioration of lake water quality. The amount of pollution from anthropogenic sources is increasing in some parts of the world and greatly exceeds the natural nitrogen and phosphorus loads in the surface water [15]. Researchers have traditionally focused on the study of in-lake processes [16], but the successful prevention of nutrient pollution is dependent on the nature of the links connecting the lakes and their catchments [17]. Many scientific papers have been written in recent years that indicate an interest in catchment impact on water quality of rivers and lakes. Studies have been conducted on a variety of objects, such as mountain rivers [18], lowland agricultural catchments [19], upland catchments [20], lakes located in national parks and landscape parks of Poland, and many others [21]. However, the problem of agricultural pollution of water should also be seen in a regional context, because "regional" denotes the spatial extent of such factors as soil and climatic conditions, the level of economic development, or agricultural traditions affecting the methods of land cultivation.

The objective of this study was to establish the relationship between the quality of lake waters and agricultural land use in the area of Polish lake districts. The study used the data collected and published by the Polish environmental monitoring services. The analysis was limited to five parameters: Secchi depth, electrolytic conductivity, concentrations of total nitrogen, concentrations of total phosphorus, and content of chlorophyll "A" in water samples. The aim of the investigation has been achieved by demonstrating the existence of significant regional diversity of lake water quality and by collating the calculated values of the water quality indicator with percentages of agricultural land in the regions covered by the study. Analysis of the results helped in identifying the most vulnerable areas and in proposing necessary improvements to environmental management strategy in order to obtain acceptable water quality in Polish lakes.

Material and Methods

Poland is considered to be a lowland country for the most part because more than 70% of its territory lies below an altitude of 200 m a.s.l. The northern and central parts of Poland can be divided into the following zones: coastal lowlands, lakelands, and central lowlands [22]. This terrain forms part of the North European Plain and the East European Plain. The Lakeland areas form a wide strip of land stretching from the western to the eastern border of Poland. A detailed geographic division of the study area is shown in Fig. 1.

Fig. 1. The regions included in the study: 1–West Pomeranian Lakeland, 2–East Pomeranian Lakeland, 3–South Pomeranian Lakeland, 4–Lubuskie Lakeland, 5–Wielkopolskie Lakeland, 6–Leszno Lakeland, 7–Ilawa Lakeland, 8–Chelmno-Dobrzyn Lakeland, 9–Masurian Lakeland, 10–Lithuanian Lakeland, and 11–Western Polesie.

The northern part of Poland is characterized by a specific landscape of glacial relief formed during the Pleistocene. A series of glacial events separated by interglacials occurred during the period from about 2.6 million years ago to the present [23]. The major effects of the ice age are erosion and deposition of material over large parts of Northern Poland, modification of river systems, and the creation of thousands of lakes. The ice sheet left behind physical evidence of its presence in the forms of moraine hills, valleys, local depressions, and fields of glacial mineral deposits. Pleistocene glaciations in Poland were a dominant factor in the creation of the landscapes that exist today. Western Polesie, a region located in east-central Poland, is an area of landscape shaped during older glaciations. The terrain surface is flat and covered with sedimentary rocks of the Pleistocene and Holocene [24]. The lakes of Western Polesie are part of a larger lake district located on the border area of Poland, Ukraine, and Belarus.

There are more than 7,000 lakes in Poland with an area larger than 1 hectare, and their total area is 2,813.77 km^2 [25]. The presence of such a significant number of water bodies makes the northern part of Poland relatively wealthy in water resources. It should be noted, however, that the waters of these lakes are diverse in terms of quality. The research terrain presents both clean lakes that contain water of the highest quality, and heavily contaminated lakes that demonstrate an extremely poor ecological status.

A database of Polish lakes was created to describe the physical and chemical properties of lake waters. The dataset contains information on the climatic, hydrological,

and hypsometric conditions of lakelands, the land use characteristics of catchments, and the quality of lake waters. To create an information system, the digital data available from a variety of sources were used, including meteorological and hydrological data made available by the Institute of Meteorology and Water Management in Warsaw, CORINE Land Cover data derived from the European Environment Agency, topographic digital maps provided by the Documentation Center of Geodesy and Cartography in Warsaw, and information about the lakes published during the period 1981-2012 by the State Inspectorate for Environmental Protection.

Geographic (spatial) data forming the geographic information system (GIS) and descriptive data were used to create the integrated database of Polish lakes. The main selection criterion for lakes included in the database was an area of at least 50 hectares. At the current stage of project development, the information system contains a set of morphometric parameters for more than 1,000 lakes and a basic dataset on water quality of more than 500 lakes. This database can be subjected to all kinds of transformations and analyses using the tools provided by the GIS software and database management system (DBMS). The study involved five parameters, which are used as basic indicators to characterize the quality of lake water: transparency (Secchi depth), electrolytic conductivity, concentration of total nitrogen, concentration of total phosphorus, and content of chlorophyll "A" in the water. The entire set of studied lakes was divided into equinumerous class breaks, according to the values of individual parameters. The classes were defined as groups of objects of small, medium, or large parameter values. Boundary values used in this classification are shown in Table 1. Lakes belonging to the classes designated in this way were counted for individual regions and presented as percentages of the studied statistical populations.

On the basis of the CORINE land cover digital dataset, the percentage share of the two most important forms of land use (agricultural land and forests) in the total area of the regions characterized by the presence of a large number of lakes was fixed. A simple rating system that took into account all the parameters analyzed was used to describe in a synthetic manner the quality of lake water in the regions surveyed. The method worked by allocating evaluation points to individual regions. The number of points (from 0 to 2) depended on which group of parameter values (high, medium, low) most closely described the lakes of the evaluated region. When the basis for the evaluation was Secchi depth, the highest number of points was assigned to those regions where the majority of the lakes were characterized by a high value for this parameter. In other cases, the best assessment was obtained by those regions where the majority of the lakes had low values for the analyzed parameters. The sum of the points allocated to each region is treated as a regional indicator of water quality.

Table 1. Classes of water quality parameters.

Parameter	Parameter value		
	low	medium	high
Secchi depth (m)	<1.15	1.15-2.10	>2.10
Electrolytic conductivity ($\mu S\ cm^{-1}$)	<289	289-402	>402
Total nitrogen ($mg \cdot dm^{-3}$)	<1.04	1.04-1.67	>1.67
Total phosphorus ($mg \cdot dm^{-3}$)	<0.043	0.043-0.08	>0.08
Chlorophyll "A" ($\mu g \cdot dm^{-3}$)	<12.5	12.5-31.5	>31.5

Results and Discussion

The most forested regions are Lubuskie Lakeland and South Pomeranian Lakeland, where forests cover more than half of the area of these regions. The area of land used in these regions for agriculture does not exceed 40% of total area. A significant area of forests (over 35% to almost 40% of the region) also characterized the West Pomeranian Lakeland, Lithuanian Lakeland, and Masurian Lakeland. Agricultural use accounts for about half of the total area of these three regions. A characteristic feature of these lands is the presence of lakes of a large area and significant water capacity. The share of surface waters in the total region area is more than 6.4% in the Masurian Lakeland and approximately 4% in the Lithuanian Lakeland.

The East Pomeranian Lakeland, Leszno Lakeland, and Ilawa Lakeland are regions of strongly marked agricultural character. Cultivated fields account for more than 60%, and forests cover about 25% to 30% of the total area of these regions. However, regions that are predominantly agricultural are the Chelmno-Dobrzyn Lakeland and Wielkopolskie Lakeland, where agricultural use accounts for more than 70% of the total area. Forests cover only about 20% of these regions. Western Polesie is an area of extensive agriculture and forestry, with a large percentage share of meadows, pastures, and peat bogs, which occupy about 20% of the surface area. In the southern part of this region, there is a group of old, gradually disappearing lakes characterized by fairly good water quality.

Several studies carried out throughout the world have shown that nutrient pollution from agriculture has contributed to the eutrophication of many aquatic ecosystems on local and regional scales [26]. It is widely believed that forests moderate climatic extremes and have an effect on important characteristics of surface water, such as the quantity, quality, and thermal regime [27]. In regions that are more forested (Lubuskie Lakeland, South Pomeranian Lakeland) and that have a smaller percentage of land used by agriculture, most of the researched lakes were characterized by high water transparency, low electrolytic conductivity, and low values for the concentrations of nitrogen, phosphorus, and chlorophyll "A." Forested catchments are known worldwide for producing high-quality water [28]. According to Davis [29], nitrogen response in the afforested catchment varied over time, but long-term research has shown a decline

in the concentration of contamination within five years of planting. It is also known [30] that in two or three years after forest harvesting, nitrate concentrations in the stream water of the deforested site exceed the health level recommended for drinking water.

When the information of classified lakes was compared with the data describing the land use in the studied regions, it was easy to notice that there is a relationship between agricultural land use and the quality of lake water in the studied areas. Agriculture is recognized as one of the branches of the economy that has led to major problems in water environments such as eutrophication and ecosystem damage. In European Union countries, various measures have been introduced as part of catchment basin management planning as a means of tackling problems of diffuse pollution from agriculture [31]. In agricultural areas of Poland, a large number of lakes were characterized by high electrolytic conductivity and small Secchi depth as well as high concentrations of nitrogen, phosphorus, and chlorophyll. The results of a study carried out on a regional scale are consistent with the conclusions obtained on the basis of detailed research on individual lakes or river systems [32-33].

The parameters that significantly modify the quality of lake water are the ability to form thermal stratification (related to the depth of the lake) and the value of coefficient calculated as the ratio of drainage basin area to lake volume [34], known as Schindler's ratio. This indicator shows the strength of the impact of catchment on lake water quality. The influence of morphometric parameters of lakes on water quality has been described by many researchers [35-36]. The effect of lake basin and catchment characteristics on the number of lakes described by low, medium, and high values of parameters of water quality has been seen across the Masurian and Wielkopolskie lakelands.

In the region of the Masurian Lakeland, nearly 60% of the lakes described by a low Schindler's ratio were characterized by highly transparent water, and more than 52% of such lakes were distinguished by low concentrations of chlorophyll "A." Almost half of the stratified lakes contain water of high transparency and are characterized by a low content of chlorophyll. Among the shallow lakes, where there is no phenomenon of stratification, it was noticeable that 60% of them were of high concentrations of chlorophyll. Almost 87% of such shallow lakes were characterized by low or medium values for Secchi depth.

In the region of the Wielkopolskie Lakeland, many lakes exhibit poor water quality parameters. In particular, shallow lakes, where there is no stratification phenomenon, were characterized by a low transparency of water (nearly 80% of lakes), a high content of chlorophyll (nearly 76% of lakes), and a high electrolytic conductivity value (over 81% of lakes). It is also possible in this area to identify many examples of the strong influence of the catchment basin on water pollution in many lakes. Among the lakes described by a high Schindler's ratio, the majority were characterized by low water transparency (almost 60% of the surveyed locations), high water electrolytic conductivity (almost 89%), and a high content

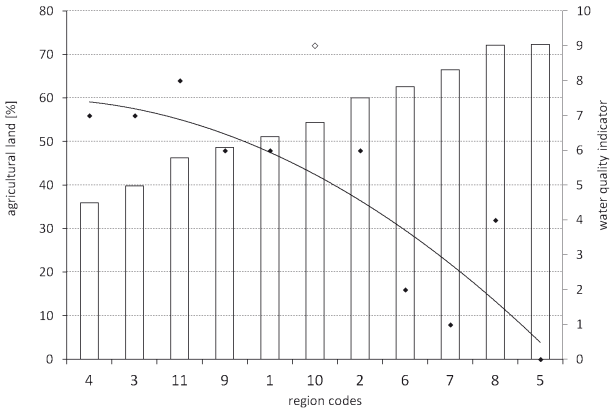

Fig. 2. The relationship between the percentage of agricultural land (bars) and the value of the water quality indicator (points). Region codes are the same as in Fig. 1.

of chlorophyll (almost 65%). Lakes described by a low Schindler's ratio are less susceptible to the impact of the catchment area. A significant number of such lakes (more than 55%) were distinguished by clear water and a small amount of chlorophyll.

The comparison of the percentage of land area used for agricultural purposes and the value of the regional indicator of water quality (*wqi*) has made it possible to determine the relationship between these variables. The final result is presented in the form of a graph (Fig. 2). Low values of *wqi* were assigned to predominantly agricultural regions, namely Wielkopolskie Lakeland, Ilawa Lakeland, Leszno Lakeland, and Chelmno-Dobrzyn Lakeland. Highly ranked were regions with a small ratio of area used for agriculture (Lubuskie Lakeland, South Pomerania Lakeland). Spearman's rank correlation test was used to evaluate the relationship between the variables described. This method of data analysis is appropriate for continuous and discrete variables, including ordinal variables. It assesses how well the relationship can be described using a monotonic function [37]. Spearman's rank correlation coefficient (r_s) is a nonparametric measure of statistical dependence between two variables. Rank correlation test showed that there is a strong inverse relationship between the ratio of agricultural land use and *wqi* value. This is evidenced by the high correlation coefficient $rs = -0.786$ and the level of statistical significance $p = 0.017$.

Lithuanian Lakeland (code 10) stands out clearly against other regions. This is a specific terrain with a significant percentage of the lakes area (about 4%) in the total region area. Numerous deep, stratified lakes are located there. These conditions affect positively the purity of lake water in that region. Spearman's rank correlation test performed for the remaining 10 regions showed that the inverse monotonic relationship between examined variables is very strong ($r_s = -0.911$ and p-level = 0.004). This relationship can be approximated by the exponential function $wqi = -0.0034\ p_a^2 + 0.197\ p_a + 4.7606$ (where p_a is the percentage of a region's land area used for agriculture).

Conclusions

This study performed a classification of regions, taking into account several characteristics of the quality of lake water. The results were compared with the percentages of agricultural land in the area of the regions surveyed. Spatial diversity of lake water quality in the study area is clearly visible. The majority of lakes located in agricultural regions were characterized by low water transparency and a high concentration of nitrogen and phosphorus, as well as a large amount of chlorophyll contained in the water. Examples of such regions include Wielkopolskie Lakeland, Ilawa Lakeland, and Leszno Lakeland. A contrasting situation is observed in areas where there are extensive forests and numerous large and deep lakes. Such conditions occur in the Lithuanian, Masurian, and West Pomeranian lakelands. Water of a large number of lakes located in these regions was characterized by high levels of water transparency, a low content of chlorophyll, low levels of total nitrogen and total phosphorus, and low electrolytic conductivity. The values of the parameters generally regarded as decisive in an assessment of lake water quality were strongly influenced by land use type, and in particular by the proportion of agricultural land within the entirety of a given region.

The majority of polluted lakes exist in agricultural regions. Detailed analysis of the database of Polish lakes indicates that in many cases the water quality of such lakes is very poor. Terrain observations and results obtained from the analysis of information collected in the database led to the conclusion that the most effective way to improve the purity of lakes in Poland is to introduce preventive measures in catchments of lakes located within agricultural regions. The new policy of water quality protection and improvement should be based on proper management of the catchment area, and above all on the introduction of appropriate rules for agricultural production aimed at supporting precision farming. Precision agriculture management practices can significantly reduce the amount of nutrients, pesticides, and other crop inputs [38-39]. Catchment management focused on the introduction of cost-effective ecological agricultural systems and was supported by various measures aimed at lake revitalization that would provide the opportunity to restore the good ecological status of lakes in a relatively short period of time. One of the tools for effective catchment management is a database of historical and contemporary information on rivers, lakes, and catchments. Such a database allows for the analysis of relationships between the different elements of the environment, control over the current situation in the lake basin and catchment area, evaluation of the effectiveness of actions taken to improve water quality, and planning future environmental projects.

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