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Geographic Information Systems (GIS) as Supporting Tools in the Monitoring and Water Management of Lakes in Poland: A Review

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Geographic Information Systems (GIS), lakes, monitoring, water management, databases, modeling

Abstract
A multitude of spatial relations between the lake and its catchment prompts both water managers and scientists to use Geographic Information Systems (GIS). The paper presents the possibility of using GIS systems in the monitoring and management of Polish lakes, taking advantage of the dynamic development of geoinformatics. The focus is on the possibility of using GIS systems when creating documents necessary for the implementation of subsequent water management plans, as required by the Water Framework Directive. This review presents the currently existing spatial databases of Polish lakes and discusses the impact of the use of morphometric data of lakes on the process of water monitoring. Attention was paid to the problem of delimiting the catchment areas of lakes and the legal consequences of determining their boundaries. Tools used in the interpolation of limnological parameters and the models most often used in GIS software for water quality prediction are discussed.

1. INTRODUCTION

The world's water resources are under constant pressure from economic activity, population growth, and urbanization processes. On a global scale, the main problem is the dwindling land water resources and their significant deterioration [Kundzewicz et al. 2010]. Standing waters are particularly affected by shallowing and overgrowing [Gutry-Korycka et al. 2014], which can be accelerated by hydrological and morphological modifications and water pollution, mainly from agricultural sources [Hillbricht-Ilkowska 1997]. The European Union's response to these problems is the Water Framework Directive [WFD; Directive… 2000], which sets the framework for controlling and managing the quality of surface and groundwater and obliges member states to prepare River Basin Management Plans (RBMPs, Water Plans). This piece of legislation is the basis for making decisions shaping the condition of water resources and the principles of their management. Water Plans are reviewed and updated every six years. Water Plans are created on the basis of a number of planning documents, such as updating the typology of water bodies, environmental objectives, water monitoring program. While creating the RBMPs, the DPSIR model consisting of five elements is used [Carr et al. 2007]:

- Driving forces (or Drivers) – causative factors of environmental changes;
- Pressures – pressures affecting the environment;
- State – environmental condition;
- Impact – the effect of pressures on the environment;
- Response – activities aimed at improving the condition of the environment.

This model enables environmental diagnosis which indicates the causes of existing conditions, designs adequate measures for action, and determines their effectiveness. The elaboration of this information requires analysis at the catchment level.

The WFD introduces the concept of the Water Bodies (WBs), that is, units of surface and groundwater that are subject to monitoring and planning. WBs and their catchments are spatial. The diversity of WBs and the multitude of relationships between the environmental components within them support employment of digital tools for collecting, storing, analyzing, processing, and imaging data, such as a Geographic Information System (GIS) in water management, which have become indispensable [Urbański, Kryla-Straszewska 2010]. Through the dynamic development of geoinformatic sciences, the use of a

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GIS can significantly contribute to the improvement of the planning, monitoring, and the creation of planning documents.
The aim of the study is to identify the benefits from using GIS for water monitoring and the elaboration of planning documents resulting from the provisions of the WFD in Poland. This paper reviews the literature on the possibility of acquiring, processing, and analyzing the environmental data of lakes with the use of GIS tools.

2. METHODS

The study employed an extensive literature review using web-based scientific database research, library queries, and analysis of both Polish and European legal acts. A wide scope of various sources was analyzed, including scientific articles (40), academic publications (1), monographs and books (27), legal acts (6), industry-specific websites (13), and other documents (8). Keywords used to search scientific databases included: GIS, Geographic Information Systems, limnology, hydrology, water management, spatial analysis, Water Framework Directive, and others, specific to the topics of sections of this paper. In total, 95 sources were explored to prepare this review.

3. SPATIAL DATABASE OF POLISH LAKES

In Poland, there are over 7,000 lakes with an area of more than 1 ha [Choiński 1995]. They cover about 0.9% of the area of the country, and their distribution is uneven. Cataloging all lakes is an essential task that enables the rational management of their waters and the organization of their monitoring. The first complex information about the Polish lake resources came mainly from the *Atlas of Polish Lakes* [Jańczak 1996; 1997; 1999] and the *Catalog of Polish Lakes* [Choiński 2006]. Both registers contain information on the morphometry of the lakes. Additionally, the atlas includes bathymetric plans prepared by The Inland Fisheries Institute in Olsztyn and the Institute of Meteorology and Water Management in the 1960s.
In 1991, at the Institute of Environmental Protection, the first digital database on lakes was created, under the name LAKES. The database collected the results of monitoring surveys from the years 1989 to 2006 (data on physicochemistry and biology of lakes), as well as morphometric, hydrographic, and catchment data. Until 1999, this database operated under the DOS system. In 1999, at the request of the Chief Inspectorate of Environmental Protection, it was adapted to the Windows system [Cydzik 2004].
A continuation of the database LAKES was the spatial database LAKES 2, which was developed in 2013 at the Institute of Environmental Protection – National Research Institute. The new database included information and data about lakes monitored under State Environmental Monitoring (SEM) since 2007. It consists of two modules: a tabular (attribute) module in MS Access 2007 software and a graphic module in ArcGIS for Desktop v. 10.1 software. Data in the LAKES 2 database are grouped into related thematic blocks, that is, basic information on the lakes (morphometric data of the lake and its catchment area, the inspectorate conducting the research, geographical location, affiliation to a voivodeship (province), river basin, water region), results of field surveys and laboratory tests, as well as the assessment of the ecological state based on the biological elements (Figure 1).
The spatial component of the LAKES 2 database, the lake geometry, was derived from the Hydrographic Map of Poland in scale 1:50,000 (HMP50) [Kutyła, Pasztaleniec 2013]. The lakes' shorelines in HMP50 were marked based on topographic maps in the scale 1:50,000, in the "1942" coordinate system. The maps were obtained from the resources of the Topographic General Staff of the Polish Army. Additionally, in any case where the course of the shoreline was uncertain, it was verified in the field [Piórkowski et al. 2013]. In the years 2012–2013, at the request of the National Water Management Authority, a Hydrographic Map of Poland at the scale of 1:10,000 [HMP10; Barszczyńska et al. 2013] was developed as a continuation of the HMP50 project. Since then, the HMP10 has become the reference hydrographic dataset in Poland. This map, in addition to many thematic layers covering catchments and rivers, also includes a layer dedicated to lakes and reservoirs larger than 50 ha (constituting WBs *sensu* WFD) and smaller reservoirs (< 50 ha).
In 2017, the first version of the HMP10 was verified, and some inconsistencies in lake shoreline delimitation identified within the first years of its use were corrected [Hobot et al. 2015; Grela et al. 2017]. For updating the lake shoreline determination in HMP10, the Digital Surface Model (DSM, pixel 1x1 m) and orthophotomaps obtained from the Central Geodetic and Cartographic Documentation Center, and satellite images of the Copernicus program were used. The water line and plant communities included in the lake littoral zone were identified based on the Normalized Difference Vegetation Index developed using multi-channel images taken by the Sentinel-2A remote sensing satellite. The course of the shoreline obtained at the final stage was verified against DSM. In doubtful cases, field verification was also performed [Grela et al. 2017]. As part of the HMP10 update, layers depicting the direct and total catchments of the lakes were also developed, which, due to changes in the geometry of the lakes, also had to be improved in order to maintain the topology rules [Grela et al. 2017]. During the update of the shoreline, remote-sensing vegetation analysis and a numerical model of land cover were used, which allowed for a precise determination of the shorelines of overgrown lakes. The precise delimitation of watersheds was obtained by using the data from laser scanning. As a result, it was possible to accurately determine the range of the lakes' catchment area, which may translate into, among other things, a more detailed analysis of area pressures related to surface runoff.
The updated HMP10 database is now a reference source of data used in the preparation of documents necessary

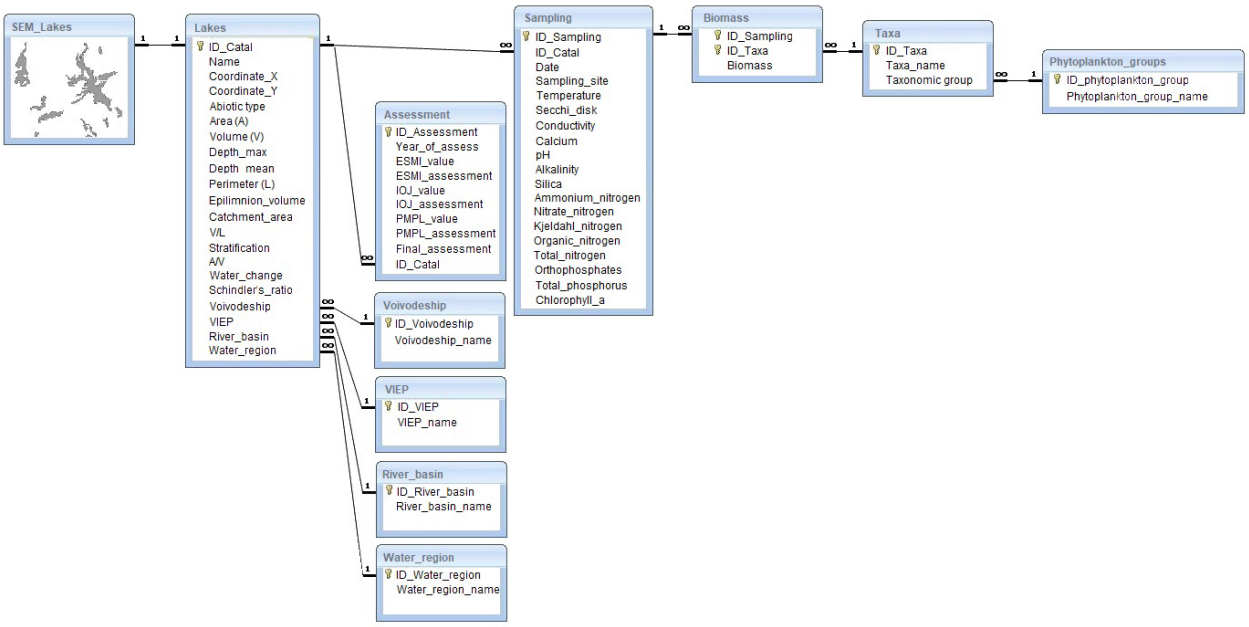


Figure 1. Scheme of the relationship between tables in the database LAKES 2 [after Kutyła, Pasztaleniec 2013]

for the implementation of the third Water Plan, also in the field of lakes. The HMP10 is therefore a data source essential for designing activities aimed at maintaining or improving the ecological conditions of lakes.

4. MORPHOMETRY OF THE LAKE AND CATCHMENT

4.1. Lake Morphometry Analysis

The bathymetric plan, that is, a map showing the shape of the bottom of the lake through isolines (isobaths) is the basic source of data that enables the analysis of the lake's morphometry. Creating a bathymetric plan requires data on the depth of the lake and its geolocation [Bajkiewicz-Grabowska et al. 1994]. In the times preceding the development of GIS tools, such measurements were performed using a calibrated rope with a weight, lowered in geodetic nodes of a square or triangular grid [Gutry-Korycka, Werner-Więckowska 1996]. Measurements were conducted in winter, from above the ice cover, and holes were drilled in each site. Georeferencing of measuring sites was also problematic before introduction of the Global Positioning System (GPS). The measurement position was determined based on its relation to the lake shore, by measurements of a geodetic grid in the case of ice cover measurements [Bajkiewicz-Grabowska et al. 1994]. Prussian bathymetric plans from the nineteenth century were created based on measurements from the boat, and the boat's position was determined based on paddle movement [Schütze 1920], which lacks the precision possible now.

Creating bathymetric plans manually, with analog field measurements was time-consuming, and the field work took place in unfavorable weather conditions. In Poland, bathymetric plans for over 2,400 lakes are available, all elaborated in the years 1950–1960 at the Inland Fisheries Institute in Olsztyn. Measurements were made in a 50-, 100-, or 200-m grid, depending on the lake's size [Hutorowicz et al. 2018]. In the deepest parts of the lake and in places where slopes were steep, the measurement grid had a higher resolution [Piasecki, Krąż 2015]. For example, the Legińskie lake with an area of 2.3 km^2 was sampled at 400 points [Hutorowicz et al. 2018]. The largest lake in Poland, Śniardwy (110 km^2), was sampled with this method for three winter seasons, between 1960 and 1962, with about 20 people working every day during each season [Szostak 1967].

The ultimate bathymetric plan was prepared by manually placing a measurement grid or an echogram on the contour of the lake, then interpolating the measurements and drawing isobaths [Bajkiewicz-Grabowska et al. 1994]. This plan can be further employed for calculating the approximate volume of a lake, for example, from the batigraphic curve or the Penck method [Penck 1894]. Both of these methods are time-consuming because they require the calculation of the area of individual isobaths, which is complicated, as the natural, irregular shapes of the lakes differ from the standard geometric figures.

Among the most important limitations of the above methods are the low precision of measurements, the large amount of labor required, and the strong dependence on weather conditions. Moreover, lake shoreline in these plans is often distorted, which makes it difficult to fit isobaths to the map. Currently, when winters are milder

and periods of full ice cover less frequent, the safe use of bottom sampling from the ice cover has become virtually impossible. Moreover, the manually drawn hard-copy bathymetric plans are static and not editable, hence unchangeable.

Currently, depth measurements are greatly facilitated and partially automated by the use of GPS-related sonar. In this method, measurements are made from a boat moving in profiles, forming a grid that covers the entire surface of a lake. Ultimately, an echogram along with the geolocation of individual measurement points is created. For the already mentioned Legińskie lake, bathymetric measurements carried out in 2018 with this method lasted two days. There were 97 profiles covered in sonar measurements. In total, 5,400 points were registered, which is over 13 times more than when using analog measurements in the 1960s [Hutorowicz et al. 2018].

A more advanced method is the use of a bathymetric laser scanner, which can be used to perform depth measurements from the air (Light Detection and Ranging – LiDAR) [Quadros et al. 2008]. The scanner sends out two laser beams, infrared and blue-green. The infrared beam is reflected from the surface of the water, while the blue-green beam penetrates the water and reflects off the bottom. The lake depth is computed from the difference of these two measurements. Depth and/or turbidity of water as well as the shore zone and the breaking-wave zone limit the scanner's operation. For coastal waters, the scanner range is determined to be up to a maximum of 50 m, whereas it is much smaller for inland waters and strongly depends on the transparency of the water. The scanner penetrates a depth of 1–3 times the visibility of the Secchi disc [Kurczyński 2014].

The processes of plotting measurements, interpolating and plotting contours using GIS tools are largely automated, faster and simpler than manual methods. The standard algorithm of the procedure for creating a bathymetric plan in GIS has been developed by the International Institute for Geo-Information Science and Earth Observation (ITC) in the Netherlands [Dost, Mannaerts 2008]. It includes the following steps:

- obtaining the lake contour from satellite images, automated classification using the Normalized Difference Water Index (NDWI) – is recommended because manual digitization is associated with a high risk of error [McFeeters 1996];
- combination of the sonar measurement layer and the lake contour that serves as isobath 0;
- interpolation of measurements;
- clipping the interpolated raster layer with the mask obtained in the first step.

From a raster generated in the GIS environment in this manner, a vector layer with any cut of isobaths can be created. For Polish lakes, the first step, i.e., determination of the shoreline can be omitted, as this information is available from the HMP10.

Obtaining new data from depth sounding is not possible in all cases. In those cases where it is not possible, archival bathymetric plans can be digitized: however, it is necessary to first "stretch" the shoreline and isobaths from the bathymetric plan to the shoreline from the reference point. This process is particularly important as the manually designed bathymetric plans by the Inland Fisheries Institute in Olsztyn were made in winter, when precise delineation of the shoreline is difficult [Gutry-Korycka, Werner-Więckowska 1996]. Therefore, isobaths were stretched to the reference shoreline from topographic map [Piasecki, Krąż 2015]. To prepare the hydrological Digital Terrain Model (DTM), the Topo to Raster tool in ArcGIS software can be used, which is based on ANUDEM program [Hutchinson 1988; 1996; Hutchinson et al. 2011]. This tool interpolates a hydrologically correct raster surface from point (the deepest point in the lake) and line (isobaths) data. It prevents creating incorrect pits in output raster layer. It is worth emphasizing that a bathymetric plan prepared this way is a hybrid of the current contours of the lake and the archival course of the isobaths, that is, it takes into account the changes in the shoreline related to, for example, the bank overgrowing, but does not take into account the dynamics of the bottom, for example, lake shallowing processes.

The advantage of using GIS systems over manual/traditional methods in creating and analyzing bathymetric plans is the speed and automation of the process. Moreover, it also provides more flexibility, as the product obtained is editable. The GIS user can test many interpolation methods and choose the most appropriate ones [Šiljeg et al. 2015], as well as the isobath cut and the possibility of a smooth transition between the forms of spatial information (raster or vector: lines or polygons) depending on which form is more suitable for the analysis or visualization. A raster bathymetric map makes it possible to read the depth at any point in the lake, without the need to interpolate from isobaths. Moreover, such a map can be the basis for an attractive 2D and 3D visualization (Figure 2). There is also possibility of plotting lake area and lake volume curves using GIS tool Storage Capacity (Spatial Analyst Supplemental Toolbox). This tool determines table and plots the area and volume of water at specific elevations. This function can be used, for example, for modeling potential area and volume of dam reservoirs [Rajasekar 2007].

Since the emergence of databases containing the lake geometry in the form of a vector (polygon) and lake raster models, most of the analyses employ simple spatial queries in the GIS environment. Urbański and Kryla-Straszewska [2010] showed that most of the morphometric indicators (related to the lake surface) can be calculated using the GIS software functions (Table 1), and only the maximum length (l), maximum breadth (b), and the derived morphometric characteristics (mean breadth and elongation index) require additional scripts in the Python programming language. A number of significant characteristics

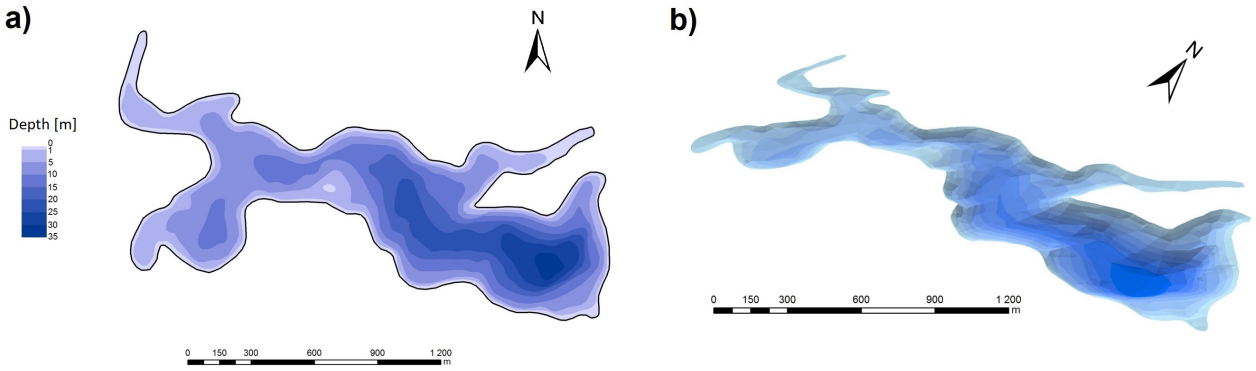


Figure 2. Lake basin visualization: (a) 2D bathymetric plan (b) 3D model [authors' own elaboration based on data from Inland Fisheries Institute in Olsztyn]

Table 1. Calculation of lake surface characteristics using GIS tools [after Urbański, Kryla-Straszewska 2010; modified]; N/A – not applicable

Parameter	Definition	Formula	Necessary layers	Determination method in GIS
Lake area characteristics				
Height above sea level	The location of the lake above sea level (m a.s.l.)	N/A	Digital Terrain Model and a polygon layer with the lake area	Zonal Statistics
Area (A)	Water surface area without taking the area of islands into account	N/A	Polygon layer with the lake area	Option calculate geometry area (in the attribute table)
Maximum length (l)	The shortest distance between the most distant points of the lake shore when measured along the line, without extending beyond the lake's boundary	N/A	Polygon layer with the lake area	Requires a Python script
Maximum breadth (b)	The greatest distance between opposite shores measured along a line perpendicular to the maximum length of the lake	N/A	Polygon layer with the lake area	Requires a Python script
Mean breadth ($\overline{b}$)	The ratio of the lake area to the maximum lake length	$\overline{b}=A/l$	Polygon layer with the lake area	Requires a Python script that counts l and the calculate option (in the attribute table)
Perimeter (L)	The length of the lake shoreline measured along the 0 isobath	N/A	Polygon layer with the lake area	Option calculate geometry perimeter (in the attribute table)
Elongation index (λ)	This parameter gives an overview of the shape of the lake surface. The greater its value, the more elongated the lake is	$\lambda=l/\overline{b}$	Polygon layer with the lake area	Requires a Python script that counts l and the calculate option (in the attribute table)
Shoreline development (D_L)	This parameter shows how close the shape of the shoreline is to the shape of a circle	$D_L=L/(2\sqrt{\pi \cdot A})$	Polygon layer with the lake area	Options of calculation several geometric and algebraic parameters (in the attribute table)

Table 2. Calculation of morphometric characteristics related to lake bathymetry using GIS tools [after Urbański, Kryla-Straszewska 2010; modified]; abbreviations – see table 1, N/A – not applicable

Parameter	Definition	Formula	Necessary layers	Determination method in GIS
Bathymetric characteristics				
Volume (V)	Lake volume	$V = A \cdot \overline{Z}$	Polygon layer with the lake shoreline	Calculation option within the attribute table
Maximum depth (Z_m)	Depth at the deepest point of the lake	N/A	Polygon layer with lake shoreline and raster bathymetry map	Zonal Statistics
Mean depth ($\overline{Z}$)	The ratio of the lake's volume to its area	$\overline{Z} = V/A$	Polygon layer with lake shoreline and raster bathymetry map	Zonal Statistics
Exposure or openness (W_o)	Indicator that allows assessing the intensity of the impact of external factors on the lake	$W_o = A/\overline{Z}$	Calculation option within the attribute table	Calculation option within the attribute table
Relative depth (Z_r)	The ratio of the maximum depth to the diameter of a circle equal to the area of the lake, expressed as a percentage	$Z_r = 50 \cdot Z_m \cdot \sqrt{\pi} \cdot (\sqrt{A})^{-1}$	Calculation option within the attribute table	Calculation option within the attribute table
Littoral zone	The percentage of the lake area covered by macrophytes	N/A	Raster bathymetry map	Reclassification of the bathymetric plan into two depth classes depending on the depth of the macrophyte occurrence. Then, calculation of the percentage of the class in the attribute table

describing the capacity, depth, and bottom of the lake can be derived from a bathymetric plan prepared in the GIS (Table 2) including, for example:

- number and location of the deepest points (parameter essential for phyto- and zooplankton sampling),
- shape of the lake (allows analysts to determine the degree of water mixing and indirectly model the spread of pollutants),
- the bottom area contacting the epilimnion layer, the so-called "active bottom", which is required to understand the thermal stratification; important in the analysis of the production and decomposition processes and in determining the potential for nutrient release from bottom sediments,
- slope (may be important for modeling the distribution and taxonomic composition of macrophytes).

Physical and biological processes in the lake affected by the bottom shape include, among others, resuspension of sediments, formation of thermal stratification, mixing intensity, and the type and manner of vegetation overgrowing. Because lakes are subject to dynamic changes in morphometry related to natural factors such as erosion, sedimentation, fouling or anthropogenic disturbance of these processes, bathymetric plans should be systematically verified to track these changes [Choiński, Ptak 2009]. Thus, it is vital to develop a fast and efficient workflow, in which GIS tools are very helpful.

4.2. Delimitation of the Catchment Area of Lakes

Topographic catchments are the basic spatial units used in all hydrological studies [Gutry-Korycka, Soczyńska 1990]. The correct determination of their boundaries determines the results of hydrological and hydraulic calculations that are used in the planning processes by the government administration. Until recently, catchments were marked out on topographic maps and then digitized and entered into GIS systems. The intensive development of agriculture and settlements in the last few decades has influenced the topographic watersheds, which has made it necessary to verify their course in planning works.

The first use of DTMs for water flow modeling appeared in the 1980s [Ufa 2013]. Only recently, however, has the

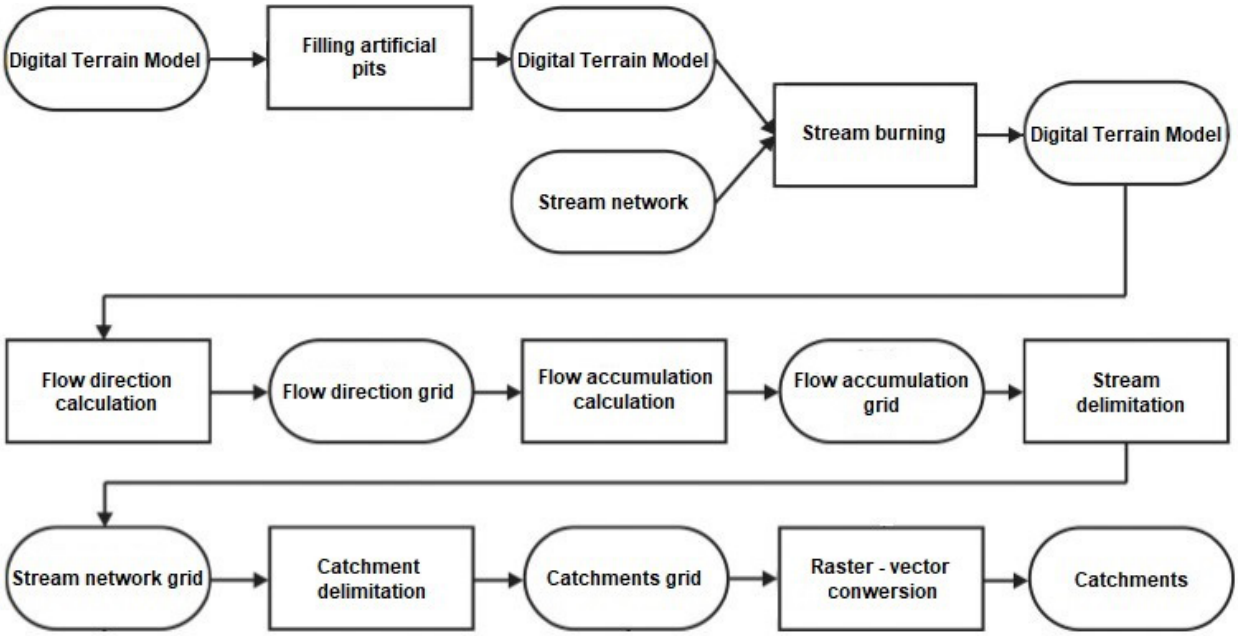


Figure 3. Scheme of the analysis of the delimitation of the catchment area based on the Digital Terrain Model in GIS systems [after Gudowicz, Zwoliński 2009; modified]

emergence of a high-resolution DTM made it possible to designate reliable watersheds for Young Glacial areas. In Poland, high-resolution DTMs have been developed using Airborne Laser Scanning, its spatial resolution is 1 m and average height error under 0.2 m [http://www.gugik.gov.pl]. It should be noted that each DTM must be pre-processed to fill in the spurious pits. Such pits are created by pixels, which are attributed to a height value smaller than the value of the surrounding pixels [Gudowicz, Zwoliński 2009]. A lack of pre-processing may result in the interruption of surface runoff modeling [Urbański 2012].

Any layer showing a river network should be burned on the DTM to increase the compliance of the generated river network with the actual terrain situation and, hence, increase the accuracy of calculations [Gudowicz, Zwoliński 2009].

Then, a flow direction grid defining one of the eight possible directions should be created. This grid is the basis for creating a flow accumulation grid. One of the final stages of this work is the generation of a stream network grid from the runoff accumulation map, based on which the raster layer consisting of an elementary catchments grid will be created (Figure 3). This raster can be easily converted into a vector form [Gudowicz, Zwoliński 2009; Ufa 2013].

5. DATA ANALYSIS AND INTERPOLATION

5.1. Measurement Interpolation

Physicochemical sampling of waters using *in situ* methods are carried out in a limited number of sites on the lake, as they are usually costly and time-consuming. For monitoring purposes, sampling is usually performed at one point (the deepest point of the lake). In scientific research, sampling design is adjusted to the study aims and is usually carried out at a few/dozen points located in characteristic places of the water body or points that are evenly distributed on the surface of the lake. To correctly interpret the field measurements, it is reasonable to recognize the distribution of the values of the tested parameters (in a continuous form) over the entire surface of the lake. For this purpose, interpolation techniques are employed that provide the transformation of point measurements to continuous surfaces [Longley et al. 2006; Urbański 2012].

Formerly, various manual interpolation methods were used in hydrological studies [e.g. Delhomme 1978], which were tedious as well as time- and work-consuming. The development of computer science and new software tools, dated at its earliest stage in 1950s and 1960s [Waters 2018], significantly improved and accelerated the interpolation of measurements. At present, the use of GIS software enables the generation of a map with the spatial distribution of the examined parameter in several seconds. However, the interpolation methods still involve some simplifications, limitations, and assumptions. Therefore, these methods require professional experience in data processing and interpretation. Thus, the interpolation may still take hours or even days if it is not a repetitive project related to the same types of observations and lakes (this issue will be continued in the end of this subsection). The selection of the interpolation method depends mainly on the data specification, that is, spatial distribution, type (scalar or vector), quality (certain or uncertain), environmental barriers (permeable, semi-permeable, impermeable),

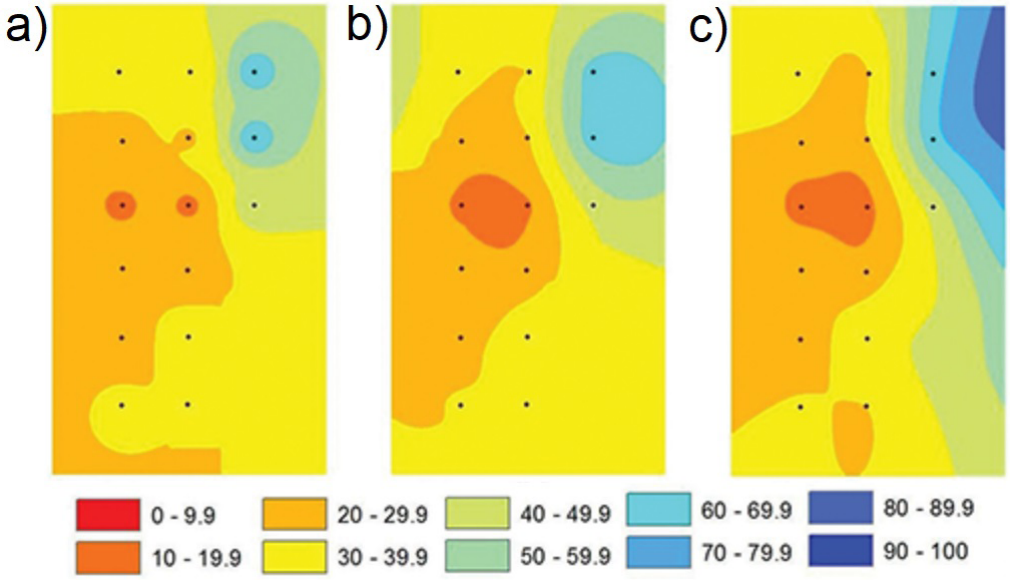


Figure 4. Interpolation of an example parameter using various methods: (a) IDW, (b) kriging, (c) spline [after Wu, Hung 2016]

extent (global trends, local trends). The most frequently used interpolation methods in limnology include: Inverse Distance Weighted (IDW), spline, and kriging (ordinary) [Kowalczak et al. 2006].

The IDW method calculates a value for each cell based on the value of the distant points, weighted with the reciprocal of their distance. Consequently, the farther away the point is located, the weaker its effect on the interpolated value. The weight of the points is established using the argument of the power exponent [Shepard 1968]. In the spline method, the interpolating polynomial is created separately for each segment between two consecutive nodes. The coefficients of the polynomials valid for individual segments are determined in order to ensure the continuity of the nodes of the interpolating function and its derivatives up to the $1 - n$ degree, providing that the degree of the interpolating polynomial is equal to n [Pazdanowski 2016]. In short, this method consists of plotting the smallest possible curvatures passing through the measurement points [Urbański 2012]. Ordinary kriging is a method that assigns appropriate kriging weights (coefficients) to the measurement data inside the estimation area in such a way as to reduce the mean square variance of kriging. This method, similarly to IDW, assigns higher weights to points located closer to the tested point. The weights are determined based on the semivariogram [Anselin 2004]. One kind of kriging used in environmental studies is cokriging, which assumes that apart from the main regionalized variable, the interpolated value is also influenced by other variables (also regionalized) [Fiedukowicz et al. 2015].

The differences in interpolation with the methods described above are shown in Figure 4. The two first methods, spline and IDW, are usually considered relatively simple compared to kriging, as they are based mainly on the spatial relationships of each pair of points. Therefore, these methods could be considered less informative than kriging, which can reflect the overall characteristics of the interpolated data. The most important limitation of IDW is the assumption that minimum and maximum values in the interpolated area are equal to the range of observations (Figure 4a). Another limitation is its limited capability for estimating the values outside the area delimited by sampling points – there is no 'distance' between points that can be used. Similar limitations can be attributed to the spline method. In this case, however, the interpolation is not limited to the range between minimum and maximum observations. This characteristic can be advantageous or disadvantageous. When the relatively large or small values are near the border of interpolated area, the spline method can show the extreme values out of the area delimited by monitoring points (Figure 4c). Moreover, using the spline method a less accurate result of interpolation can be obtained when the interpolated parameter varies in distances shorter than the distance between measurement points [Ikechukwu et al. 2017]. It is difficult to explain the difference in results obtained using the kriging method in Figure 4b compared to other methods, because the kriging itself can produce different results depending on which parameters have been chosen. The application of this interpolation method requires informed decisions based on a high level of experience. This method requires knowledge about the type of variogram model that fits the observations and estimation of the variogram parameters. Kriging method allows for the possibility to reflect the spatial correlation between observations in addition to the relations between each pair of points (like in IDW). It may also be more suitable than other methods when

the space of sampling is irregular [Curtarelli et al. 2015]. One of the limitations of the method may result from the assumption that the variogram must be stationary over the analyzed area, and, therefore, the interpolation of parameters, which are explained by a variety of factors in lakes, may be difficult. For example, when analyzing how representative the sampling of sediment in a lake were, the IDW and spline methods performed much better than kriging [Simpson, Wu 2014].

5.2. Modeling of the Processes in the Catchment Area and in the Lake

According to the "first law of geography" [Tobler 1970] "Everything is related to everything else, but near things are more related than distant things." This law forms the basis of spatial modeling that can be performed in GIS environments. Modeling in limnology mainly concerns issues related to the runoff of diffuse pollutants from the catchment area and the processes inside the lake (water mixing, sediment resuspension, contamination spreading, etc.) [Urbański 2012]. Modeling the status of lakes can be particularly reasonable for those waterbodies for which reporting status is required, but no data from SEM are available.

In the GIS environment, it is possible to create algorithms with conditional and iterative instructions (Model Builder in ArcGIS, graphical modeler in QGIS), which allows the user to build simple simulations. In addition, several standalone GIS-integrated spatial modeling programs are available. The most important models used in limnological research include the following:

- **AGNPS** (Agricultural Nonpoint Source Model) was developed by the United States Department of Agriculture [http://go.usa.gov/KFO]. This model describes the flow of agricultural pollutants from the catchment into a lake. The input data for the model include the DTM and information about soils and climate. The inflow of organic and inorganic pollutants as well as their suspension in water are modeled, taking into account runoff and erosion [Young, Shepherd 1995]. In addition to pollutants from crops, the model also takes into account the inflow of pollutants from animal husbandry.
- **SWAT** (Soil and Water Assessment Tool) is a model available in the public domain [https://swat.tamu.edu]. It is used to assess the quantitative and qualitative status of surface and groundwater. It takes into account the impact of land use, land management, climate change, catchment area erosion, and area pollution sources. The program is coupled with the GIS software. This model is widely recognized and used [Gassman et al. 2007].
- **BASINS** (Better Assessment Science Integrating Point and Non-point Sources) is a program based on the SWAT model, developed by the United States Environmental Protection Agency [https://www.epa.gov]. It models water quality by integrating point and area pollution sources. The model has a user-friendly interface similar to that of the GIS and allows for precise short-term predictions. It is a good tool for beginners in environmental modeling [Whittemore, Beebe 2000].
- **WAM** (Watershed Assessment Model) was developed by the Soil and Water Engineering Technology Incorporation [www.swet.com]. It is a model integrated with the GIS environment that is used to simulate the processes in the lake that are related to changes in land use and in the catchment area. In addition to land use, WAM takes into account a number of factors, such as hydrological network, flows, canals, groundwater, and hydrological modifications [Bottcher et al. 2012].

Modeling systems based on GIS enable the processing of many factors in a way that was impossible without digitalization. The use of environmental modeling programs improved the scientific research as well as works of public administration in water management, environmental protection, and spatial planning [e.g. Brzozowski et al. 2011; Ulańczyk et al. 2018].

5.3. Spatial Data Visualization

The introduction of GIS tools has enabled hydrological studies to go beyond the limitations of traditional cartography. In the GIS environment, the map is dynamic, that is, a user can freely enlarge or reduce its scale to view the areas and objects of interest. Additionally, in the GIS, the number of feature classes (layers) can be much greater than the maximum legible number of feature classes on a paper map. This is because in a GIS-compiled map, layer visibility can be quickly turned on and off, which allows the user to generate several different maps on the fly, within a single project. The GIS environment also offers numerous tools to visually make the map more attractive and improve the efficiency of information transfer, such as various options for designing a geographic grid, legend, signatures, adding charts and statistics, and many others. This enables creating not only maps but also the entire infographics.

Furthermore, it is possible to assign numerical, logical, or text information to each spatial object in the vector layer using the attribute table in the GIS environment. GIS, therefore, integrates the map and the database. The data contained in the attribute table can be used for automated data visualization, for example, by assigning different appearances for the objects depending on their attributes. All vector objects can be visualized by selected color, transparency, contours, graph, and labeling. The size and shape of the point, as well as the line, pattern, thickness, and mark of the direction are adjustable in the case of rivers, for example, which is important when visualizing the hydrological characteristics of flow-through lakes. Raster data can be depicted using contrasting colors for individual classes or continuous color scales, which can be useful when visualizing a bathymetric map,

for instance. GIS tools also offer possibilities in terms of 3D data visualization, which allows, for example, better visualization of the terrain of the catchment area and tracing of the routes of pollutants entering the lake.

There are many possibilities with respect to visualization in GIS. Symbolization can be adapted as per general good practices in map design [Peterson 2009], as well as an individual's aesthetic preferences. At the same time, the dynamic change of visualization makes it possible to highlight the aspects of a user's interest, for example, the concentration of pollutants in surface waters [Bielczyńska, Ochocka 2016]. It is also possible to present the concentration range of the selected substance. In addition, once the data is updated, it can be replaced within a single project in the attribute table, and the visualization will change accordingly. Often such data visualization is an initial analysis of spatial data and their attributes. This can be a good introduction to the selection of further data analyses in the GIS environment.

Multi-channel satellite images can display each channel of multi- and hyperspectral images, and raster composites can also be displayed. Moreover, in addition to the connection of the red (R), green (G), and blue (B) channels, which results in the creation of a composite in natural colors, other channels can also be lined up in a different order to create the so-called false color composite. The appropriate selection of channels in the false color composite can emphasize the land/water boundary or help to distinguish clouds from ice, which can be very useful in hydrological analyses [Riebeek 2014; Sharma et al. 1989].

The GIS is, thus, an efficient tool for data visualization and sharing. The ease of creating maps and the possibility of placing statistical analyses on the map, for example, in the form of a graph, supports an attractive presentation of data. Additionally, GIS offers tools for presenting data online [Huang et al. 2001].

In Poland, public data on lakes is easily accessed for stakeholders through geoportals run by government institutions, such as the Chief Inspectorate of Environmental Protection, the General Directorate for Environmental Protection, and the State Water Holding Polish Waters. The State Water Holding, as a part of the website https://mapy.geoportal.gov.pl/, provides, among other information, layers of lakes and their catchments. The Chief Inspectorate of Environmental Protection publishes reports on the monitoring results of the ecological status of lakes with maps and layers in the shapefile format, allowing for independent visualization and analysis. In turn, on its own geoportal [https://inspire.gios.gov.pl/] this institution provides also the results of the monitoring of Natura 2000 habitats, including aquatic habitats. The General Directorate for Environmental Protection provides information about various forms of nature protection in the form of a geoportal [http://geoserwis.gdos.gov.pl/], including lakes protected under the RAMSAR Convention. Therefore, GIS tools and related visualization possibilities play an important role in informing and educating the public about national water resources and their protection.

6. ADVANTAGES AND TRAPS FOR USING GIS IN LAKE MONITORING AND MANAGEMENT

In the 1980s, the use of the GIS tools was limited to a small group of specialists. The intensive development of these techniques in the 1980s was related to the dynamic development of information science and the growing demand for spatial information processing. With the development of computerization in the 1990s, this system became a common tool for the processing and presentation of spatial data [Malczewski 2004], accessible to a larger number of users.

The intensive progress in the development of GIS techniques and their dissemination has brought significant benefits to effective environmental protection and water management. These benefits primarily include increased accuracy and precision of analysis, reduced processing time, process automation, the ability to create algorithms, and facilitation of the sharing and acquisition of spatial data. Preparation of planning documents for Water Plans is largely based on spatial data processed with the use of GIS tools.

Delimitation of the water bodies in a way that they meet the criteria of WBs set in the WFD can be an iterative process. Such an update is justified, for example, when WBs change their morphometry due to climate change [Prange et al. 2020] or activities disrupting water management [Ilnicki, Orłowski 2006; Ilnicki et al. 2017]. Recently, the rapid decrease in lake area is observed in Poland (up to 27% of area in 50 years [Ławniczak, Kutyła 2015]) and world (up to 20% of area in 60 years [Yang, Lu 2014]). There are also cases where, as a result of the regulation of the water level, the water resources of lakes increase. For example, in Lake Niesłysz located in Greater Poland region in Poland the water volume increased from 34.457×10^6 m^3 in the 1970s up to 34.807×10^6 m^3 in 2005 as a result of damming activities. This contributed to a slight increase in the lake area [Nowak, Grześkowiak 2010]. In all these situations, the delineation of water bodies and their typology should be verified and updated.

For monitoring and management of lakes in Poland the correct determination of the WB boundaries is particularly important [Hobot et al. 2015]. In the SEM, only lakes with an area of at least 50 ha are included (significant water resources, WBs). Therefore, a correct determination of the geometry of lakes with an area close to 50 ha may result in their inclusion or exclusion from monitoring for a 6-year period (planning water cycle).

One of the major problems in lake monitoring and assessment in Poland is the lack of consistency in the morphometric data, which is necessary for the delimitation of lake WBs and determination of their abiotic types [Kolada et al. 2005; 2017]. Currently, the list of lake WBs is elaborated based on the updated HMP10 database and includes 1068 lakes' WBs. Correct determination of the abiotic type of the lake depends on its morphometric parameters (mean depth, area of the active bottom, proportion of water

volume stratified during the summer stagnation period) as well as catchment area. The first determine whether a lake is classified as stratified or polymictic, which influences phytoplankton assessment. The latter determines the Schindler's ratio [Schindler 1971] – whether it is below or above 2 – which influences the classification of biological and physicochemical elements [Kolada et al. 2017].

The morphometric data affects also the design of monitoring biological elements, that is, phytoplankton, macrophytes, and macrozoobenthos. The sampling site for phytoplankton should be designed at the deepest point of a lake [Hutorowicz, Pasztaleniec 2014; 2020]. In the macrophyte survey, the lake area and perimeter determine the number of transects designated for research [Ciecierska, Kolada 2014; Kolada et al. 2020]. For macrozoobenthos, the number of sampling sites depends on the lake area [Bielczyńska et al. 2020]. Moreover, to perform a lake assessment based on macrophytes, data on area and water volume between subsequent isobaths are required, and these data until recently have been derived from the morphometric plans developed in the 1960s by the Inland Fisheries Institute in Olsztyn. To provide a more reliable and current assessment results, these data should be updated using currently available GIS techniques. All the above indicates the importance of the reliable morphometric data for effective monitoring and management of lakes in Poland.

Precise delimitation of river and lake catchments influences the reliability of the pressure analysis. Quantification of the potential nutrient load from catchment is necessary to recognize the needs for protection measures as designed in the RBMPs and for prediction of lake ecological status in Poland [Soszka et al. 2016].

As mentioned before, the area of catchment may change over time due to anthropogenic activities, and the need for verification of the catchment borders arises repeatedly, particularly in suburban areas. Although GIS tools offer automatic catchment delimitation based on DTM, this method also has limitations. Correct delimitation of the catchment in anthropogenic areas at the DTM pre-processing stage requires information on the anthropogenic drainage network, that is, drainage ditches, open channels, and, in particular, the rainwater and combined sewage system Wałek [2017] and Mrozik et al. [2020]. This information can be obtained from the Database of Topographic Objects at a scale of 1:10,000 [Regulation… 2011] and Geodetic Records of Land Utilities [Regulation… 1989]. The use of the latter source requires care, because it contains typological errors that may affect the quality of the pre-processing [Wałek 2017].

Additionally, automatic methods using the GIS for catchment delimitation determine the catchment boundary along the highest ridge of the terrain, often along flood embankments [Mrozik et al. 2020]. Such inaccuracies should be manually corrected, for example, based on the field inspection. Attention should be also paid to the rapidly occurring changes in land cover in suburban areas (e.g., roads, railway tracks, and infrastructure), which may influence the shape of the catchment borders and modify their course.

In the case of the prediction of lake classification into five ecological status classes, the agreement of the theoretical and actual assessment was, on average, slightly over 45%, and for individual status classes considered separately from 11% to over 60%, which is relatively low [Soszka et al. 2016]. There is a need for upgrading methods for lake classification prediction. Potential tools for this upgrade are numerical models for lake and catchment management (see Section 5.2.).

Sampling of physicochemical and phytoplankton data within SEM is performed at one representative point per lake, although this approach does not always result in reliable information [Blukacz et al. 2009]. Based on Water Plans protective measures such as lake restoration could be planned. Additionally, according to Polish law [Regulation… 2017] there is an instrument for protective areas of inland waters reservoir [Soszka et al. 2015; Pasztaleniec et al. 2021]. In the case of these water management instruments being introduced, as regulated by European or Polish law, there is a substantial need for detailed analysis of lakes state, before introducing specific actions. In order to perform such analysis, after collecting field data, GIS tools for interpolation and modelling are necessary.

In addition to fulfilling the provisions of the Water Framework Directive, GIS tools can be helpful in fulfilling the recommendations of other legal acts related to environmental protection and water management. The Aarhus Convention [Convention... 1998] regulates the issues of public access to public information, including information on the environment. Tools such as online GIS or geoportals serve this purpose by supporting stakeholders in obtaining information about the environment, thereby increasing environmental awareness and supporting citizens' participation in decision-making. For instance, Geoportal was used in public consultation of RBMPs, making it easier for the public to access knowledge about future plans for improving the ecological status of inland water. Public information consists of, among other things, the results of the SEM and monitoring of species and habitats in Natura 2000 network [Directive... 1992]. GIS tools, therefore, provide significant support to public administrative bodies and researchers involved in the implementation of environmental legislation and water resource management.

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