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*Article*

# A Century of Changes in the Surface Area of Lakes in West Poland

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**Abstract:** Lakes are an important element of the hydrosphere that contribute to the stabilisation of water circulation by providing biodiversity conditions or supporting the development of different branches of the economy. All these properties depend on the longevity of lakes in the environment and the processes related to their evolution. Based on archival morphometric data from historical maps and modern cartographic studies, this paper presents an analysis of changes in their surface area over a period of 100 years. Among 169 lakes, a decrease in surface area was recorded in 156 cases (including the complete disappearance of two lakes); no change was observed in four lakes; and seven lakes increased their surface area. The total surface area of all the lakes has decreased by 11.4% in comparison with the initial state in the early 20th century. The highest rate of decline concerned the shallowest lakes with a maximum depth of up to 5.0 m and lakes with the smallest surface area of up to 20 ha, averaging 24.1% and 22.2%, respectively. The spatial distribution of changes in the surface area of lakes is variable, and at a larger scale it presents no similarities. This suggests that factors determining the rate and direction of changes in the surface area of lakes depend on their individual features and local conditions, which is in accordance with similar studies from the territory of Poland. The obtained results reveal the scale of the changes in the surface area of the lakes, potentially providing important information for authorities in charge of water management in the context of activities aimed at slowing down the disappearance of these valuable ecosystems.

**Keywords:** water resources; lake disappearance; historical maps

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## 1. Introduction

Lakes play an important role in the course of environmental processes and phenomena at various spatial and temporal scales. Due to their high water retention capacity, they retain its excess and stabilise flow in deficit periods. According to Kimijima; Nagai [1], the rapid shrinking of lakes considerably increases the risk of floods. Lakes are places for the deposition of matter circulating in the catchment, retaining harmful substances in sediments—including heavy metals [2]. Although they constitute a small share of the surface of the globe, they are characterised by a high level of biodiversity [3]. Moreover, lakes play a key role in the development of a number of areas of the economy [4–6] and constitute a place of rest and recreation [7]. Due to these features, in regions devoid of natural lakes dam reservoirs are constructed to fill the gap [8]. The functioning of lakes depends on hydrometeorological factors [9,10] as well as human activity [11,12].

As open environmental systems that receive and produce both energy [13] and matter, lakes are subject to continuous evolution [14]. As concave landforms, they will successively evolve towards their final disappearance. One of the important aspects of modern environmental research is the monitoring and analysis of changes in lakes and the determination of their temporal and spatial evolution [15]. This statement finds confirmation in the analyses of changes in the surface area of lakes and applies to both single cases [16–18] and more extensive studies [19–21].

A large portion of the studies analysing changes in the surface area of lakes is based on satellite images [22–24], and due to the availability of the data, it mainly concerns the last several decades. Another approach applies the cartographic method based on archival cartographic materials. Historical maps provide rich information in many areas [25], offering the possibility to interpret the processes and phenomena on a broader temporal scale. Ostafin et al. [26] used such materials to determine the location of water mills in south Poland in the period 1880–1930. Detailed historical maps facilitated the analysis of changes in the shape of the Tammaro River in Italy [27].

Such an approach therefore allows the consideration of a period with substantially lower human pressure in comparison to that of the modern times [28]. Historical maps are a helpful source of information in research on the scope of limnology, among other areas [29]. In the case of Poland, lakes play an important role, particularly in the northern part of the country where they are the most abundant due to the range of the last Scandinavian glaciation.

According to the general state of knowledge, of the original lakes at the moment of their genesis only 40% currently exist [30]. More detailed research evidence points to the disappearance of lakes at various rates [31–35], and human activity has played a substantial role in this. According to Kaniecki [36], the construction of the navigation canal Warta-Gopło caused decreases in the areas of numerous lakes. Changes in the hydrographic network in the Obra River catchment led to a decrease in the number of lakes [37]. The need to obtain new meadows and pastures resulted in the complete disappearance of Lake Jelenino with a surface area of 495.2 ha [38]. In the context of increasing water deficits in Poland, it is important to enrich knowledge regarding the rate of evolution of lakes that ensure easy and fast access to water resources.

The paper presents the analysis of changes in the surface area of lakes in west Poland, commonly considered as one of the most deficit-prone areas in the country. The objective of the study is to determine the direction and scale of the transformation of lakes in the 20th century. It is of importance in the context of the management of water resources, which are particularly substantial due to the high retention capacity of lakes. References to earlier studies of this type in the region consider the relationships with the morphometric parameters of lakes.

## 2. Materials and Methods

### *2.1. Materials*

The analysis of the changes in lake surface area over the 20th century was divided into five stages (Figure 1).

The first stage involved the acquisition of research materials for analysis. In the early 20th century, the surface areas of lakes were determined based on the archival morphometric data of lakes developed by Schütze [39]; these data were included in the publication Die Posener Seen. Moreover, archival German topographic maps, Messtischblatt, at a scale of 1:25,000, developed and updated at the turn of the 20th century, were acquired (the article adopts one date, namely 1900) (Figure 2a).

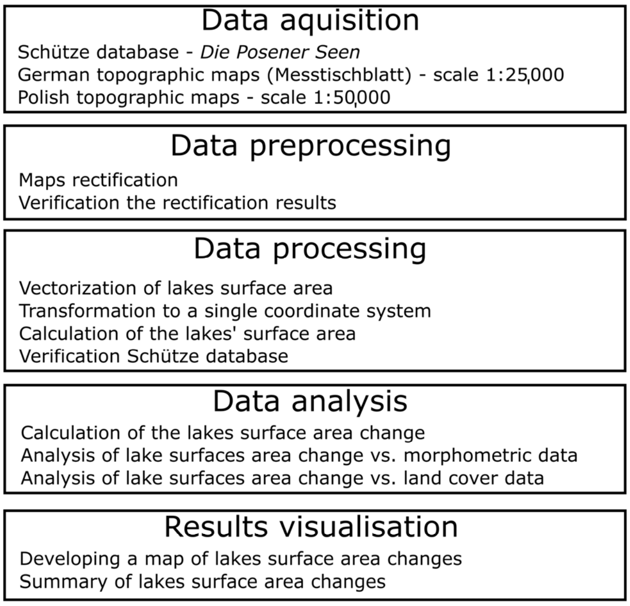


**Figure 1.** Data processing methodology.

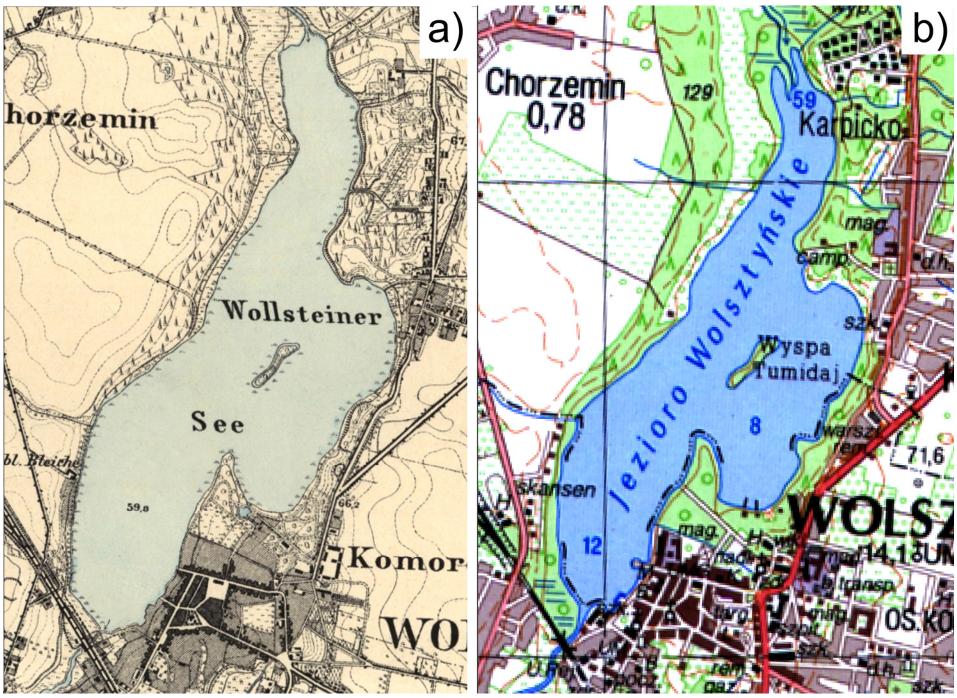


**Figure 2.** German (**a**) and Polish (**b**) topographic maps presenting the studied lakes at the beginning and end of the 20th century.

Importantly, in addition to the surface areas of lakes, the study from the early 20th century also includes data on their depths; depth is one of the elementary parameters affecting the evolution of lakes [40]. In order to show the spatial extent and the areas of the lakes from the end of the 20th century, actual topographic maps of Poland developed at a scale of 1:50,000 (PUWG-92 coordinate system, GRS-80 ellipsoid) were acquired (Figure 2b).

## 2.2. Methods

As mentioned previously, due to the period of the map edition lasting several years, a single date was adopted, namely 2000. Messtischblatt maps and topographic maps of Poland were obtained in raster form in *.jpg and *.tif formats, respectively. The analysis covered a total of 169 lakes (Figure 3, Table S1). The second stage involved the preprocessing of maps for further analysis. During this stage, the maps were rectified. The Messtischblatts used the Mercator transverse projection, and Bessel's ellipsoid was applied as the Earth model. The territory of the German Third Reich until 1945 was divided into 6 mapping zones with a width of 3 degrees; the territory of today's Poland is in zones 5 and 6 (DHDN/3-degree Gauss–Kruger zones 5 and 6). The German main triangulation network (DHDN—Das Deutsche Hauptdreiecksnetz) was the superior triangulation network of the Federal Republic of Germany. The map rectification procedure employed the coordinates presented in the original topographic grid. Polish topographic maps were prepared in the local coordinate system for Poland PL-1992. PL-1992 is a coordinate system with the geodetic reference surface ETRF89, with a GRS80 ellipsoid and Gauss–Krüger projection in one ten-degree zone. The system code according to the European Petroleum Survey Group (EPSG) is 2180. During georeferencing, the first-order polynomial transformation (Affine transformation) was applied. Finally, each rectified map sheet was validated against the root mean square error (RMSE) values in ArcMAP 10.7.1. In the third stage, the data were processed from the raster to the vector form. For this purpose, the shoreline contours of lakes contained in the historical and contemporary maps were manually vectorised. Vectorisation of the surface area of the lakes was conducted with the application of the ArcMap software. In order to ensure the highest quality of the obtained results, vectorisation was carried out at a zoom of 1:2500, resulting in the obtaining of vector *.shp files. During this stage, the data contained in the database developed by Schütze [39] and included in the publication Die Posener Seen were validated. For this purpose, 5 lakes were selected from the database developed by Schütze [39]; the lake surface areas were calculated from the Messtischblatt maps. Due to the high consistency of these results, the Schütze base [39] was considered a reliable source of information on lake surface areas from the early 20th century. Subsequently, *.shp files containing information on the spatial extent of the lakes determined based on the Messtischblatt maps were transformed to the coordinate system for Poland PL-1992. Finally, using the Calculate geometry function, the areas of the analysed lakes were determined for the two periods of 1900 and 2000. In the fourth stage, the rate of change in lake surface area $A_{ch}$ was determined as the ratio of the difference between the surface area on the actual map $A_{act}$ and the historical map $A_{his}$ and the surface area of the lake on the historical map $A_{his}$, according to the formula:

$$A_{ch} = \frac{A_{act} - A_{his}}{A_{his}} \times 100\%$$

where

$A_{act}$—actual lake surface area ($m^2$)

$A_{his}$—historical lake surface area ($m^2$)

The analysis of changes in the surface area of the lakes was conducted with regard to the morphometric parameters (surface area, maximum depth, length of shoreline, and aspect ratio) in the context of their location, as determined by the geographic coordinates (longitude, latitude, and altitude) and the land cover in the zone directly adjacent to the lake. The land cover was determined based on data included in the Corine land cover database from 2018. The percent share of artificial areas, agricultural areas, forest and seminatural land, wetlands, and water areas was determined for the zone at a distance of up to 100 m from the shoreline of the lake. The analysis of changes in the lake surface area in relation to actual land cover was intended to show the overall impact of human pressure. In the sixth stage, the spatial presentation of changes in the surface area of the lakes involved the preparation of maps of the point signatures. For the purpose of associating the changes in the surface area of the lakes with the aforementioned parameters, a Pearson correlation analysis was conducted. The analysis was conducted at a significance level of 0.05.

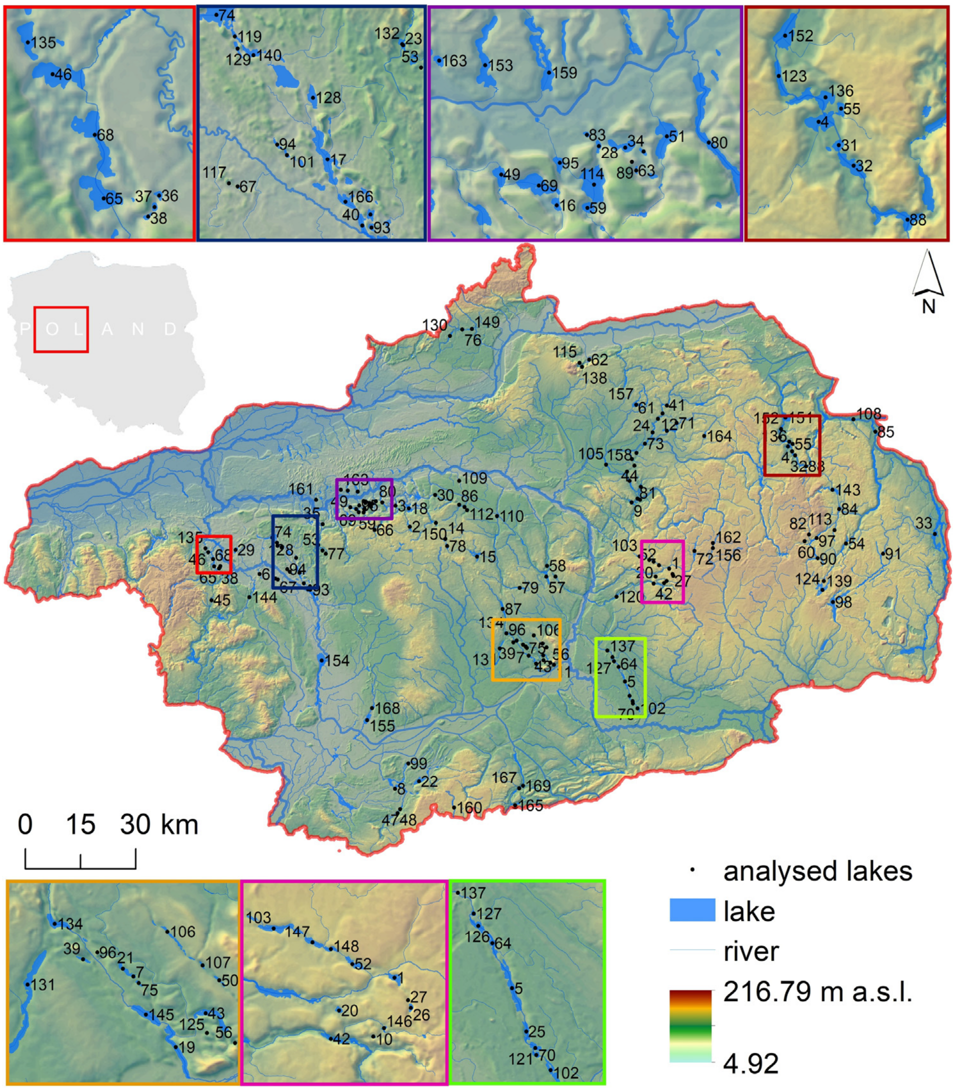


**Figure 3.** Location of research objects.

## 3. Results

### *3.1. Changes in Lake Surface Area*

The analysis of changes in the surface area of the lakes presented in this paper points directly to their reduction as the dominant trend (Figure 4a). The total surface area of all the analysed lakes throughout the 20th century reduced by 11.4%, i.e., 2432.8 ha less than the initial state. For 130 lakes, the decrease in surface area did not exceed 25%; for 26 lakes, the decrease in the surface area was less than 40%. In three cases, the decrease in the scope varied from 55 to 69.5%, and two lakes completely disappeared. Moreover, situations were observed in which the surface area of a lake was subject to no changes (4), along with seven cases of an increase in the surface area. The spatial distribution of the changes in the surface area of the lakes was variable, and at a larger scale it showed no similarities (Figure 4b). However, certain smaller clusters of lakes exist that were characterised by a similar rate of changes in surface area. This suggests that the basic factors determining the rate and direction of changes in the surface area of lakes depend on their individual properties and local conditions.

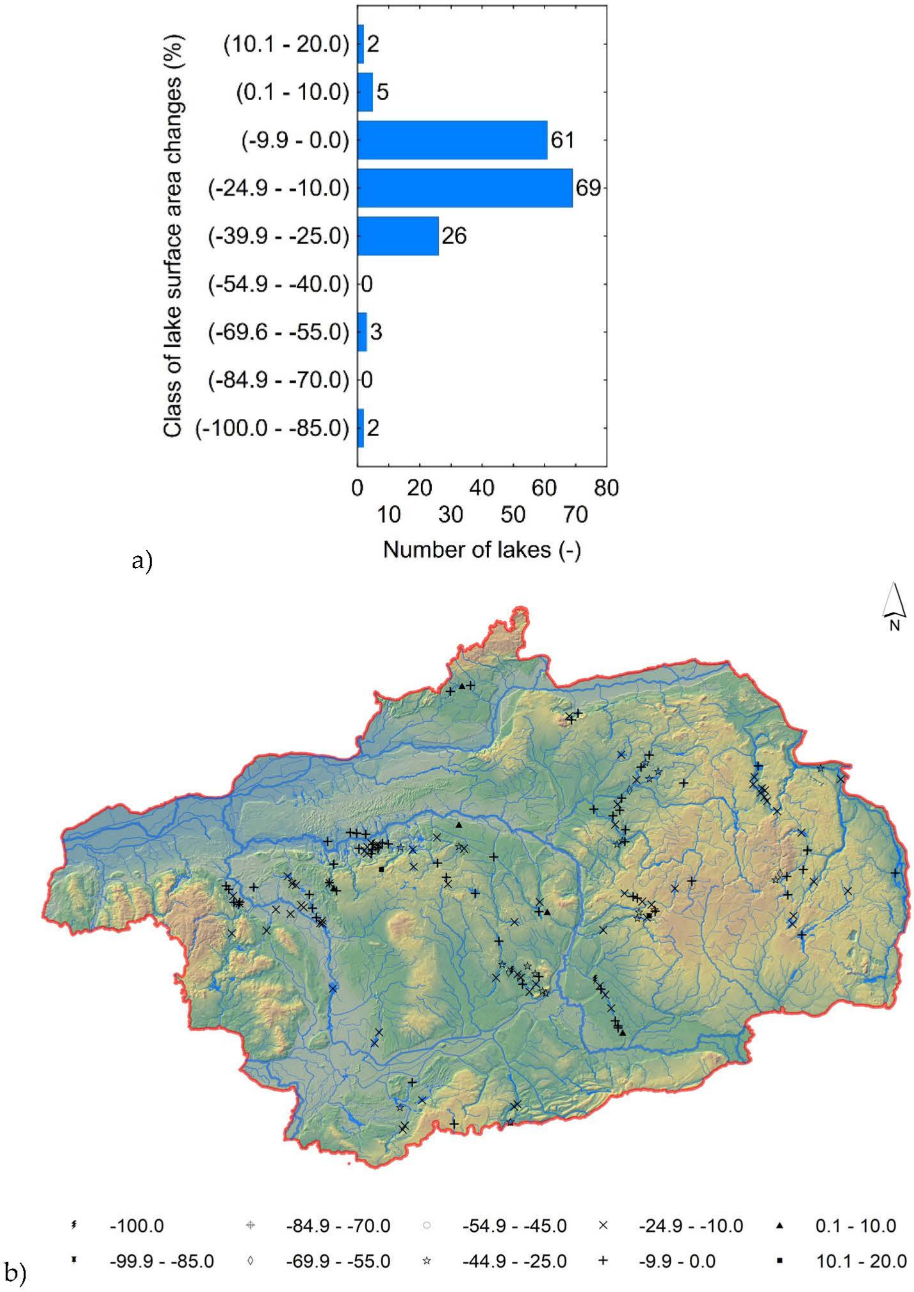


**Figure 4.** Changes in the surface of lakes (**a**) and their spatial distribution (**b**) (%).

### 3.2. Correlations of Changes in Surface Area with Lake Morphometry

In this context, the correlation analysis was conducted between a change in the surface area of a lake and the parameters describing the lake's location and morphometry and the land use in the immediate area of the lake. The obtained results showed that a change in the surface area is statistically significantly correlated with maximum depth (r = 0.30), the surface area of the lake (r = 0.20), and the length of the shoreline (r = 0.20). The changes in the surface area of the lakes showed no (statistically not significant) correlation with the other variables.

Because the variable that most effectively determines the disappearance of lakes is depth, further analyses were conducted to consider that parameter, with a division into more detailed classes. The following division of lakes according to maximum depth was adopted: up to 5 m (Class 1), from 5.01 to 10 m (Class 2), from 10.01 to 20.0 m (Class 3), and above 20 m (Class 4). The classes included 26, 61, 48, and 20 lakes, respectively. The means and median values of the changes in surface area in these groups are presented in Table 1. The obtained results show that in the case of the mean values, the differences were not significant only between the lakes included in Classes 2 and 3. Regarding the median values, no significant differences occurred between Classes 1 and 2 or between Classes 3 and 4. It can generally be stated that maximum depth is a variable that explains the disappearance of lakes to the greatest degree, whereas the shallowest lakes disappear the fastest. Considering the postglacial origin of a large majority of lakes in Poland, a small surface area usually corresponds with low depth (except for rare cases in this genetic type, i.e., kettle lakes).

**Table 1.** Decrease in the surface area of lakes in groups defined by maximum depth.

| Class | Depth (m) | Number (-) | Mean Change in Surface Area (%) | Median of Change in Surface Area (%) |
|---|---|---|---|---|
| 1 | 0–5.0 | 26 | −24.1 | −21.0 A |
| 2 | 5.01–10.0 | 61 | −16.7 A* | −12.2 AB |
| 3 | 10.01–20.0 | 48 | −13.8 A | −13.2 B |
| 4 | 20.01–50.5 | 20 | −9.5 | −7.1 |

* the same letters in a column mean lack of a significant difference at a significance level of 0.05 between mean or median values.

The lakes were divided into three groups based on their surface area (Table 2). The smallest lakes, with a surface area of up to 20 ha, disappear the fastest, at a rate of 22.2% (mean) and 18.3% (median). The differences between lake classes 1 and 2, as well as between 1 and 3, are statistically significant in terms of both the value of the mean change and the median value.

**Table 2.** Decrease in the surface area of lakes in groups defined by the surface area of the lake.

| Class | Surface Area (ha) | Number (-) | Mean Change in Surface Area (%) | Median Change in Surface Area (%) |
|---|---|---|---|---|
| 1 | 0–20 | 43 | −22.2 | −18.3 |
| 2 | 20.1–100 | 65 | −14.9 A | −12.7 A |
| 3 | >100 | 47 | −12.2 A | −11.5 A |

In addition to the morphometric parameters, the surroundings of the lakes were also considered in the analysis of the effect of land cover in their immediate vicinity on their surface area decline. For this purpose, the dominant type of land cover was determined as follows: when a given type of land cover exceeded 70%, it was assigned a category (single type). In other cases, two types of land cover with the greatest share were considered—two categories were assigned if their share exceeded 70%. A similar procedure was adopted for three categories.

As a result, it was determined that the areas directly adjacent to the lakes were dominated by four types of land cover: agricultural–forest, urbanised–agricultural, forest, and agricultural. The obtained results suggest that the type of land cover is not related to a change in the surface area of lakes when considering the mean values. For median values, significant differences only occurred between lakes within the range of the agricultural–forest and urbanised–agricultural areas. A greater disappearance of lakes occurred when the adjacent land was dominated by urbanised areas together with agricultural land. In other cases, the differences were not statistically significant.

## 4. Discussion

The processes shaping Earth's surface lead to its flattening, i.e., the nivelation of convex and concave landforms. The latter include lakes that have been subject to evolution practically from the moment of their origin. The rate of their changes is a complex result of the properties of the lakes themselves and their surroundings. The results presented in the paper correspond with the trend of earlier research regarding this issue. Research conducted in southeast Poland on numerous lakes revealed that over a period of more than 100 years their surface area decreased by 10.26% [41]. A similar analysis conducted in the Iławskie Lakeland (north-east Poland) showed that over a period of more than a century the surface area of lakes decreased by 8% [42]. The results show a similar scale of disappearance to that of the lakes in west Poland analysed in this paper.

The factors contributing to a change in the surface area of the lakes are largely variable and, depending on the region, they can take a different course. An analysis of ten lakes with considerable importance in Turkey showed a decrease in the surface area of nine of them, reaching 81% in the years 1985–2022 [20]. Research on changes in the surface area of Lake Ugii Nuur (Mongolia) showed that in the period of 1986–2018 it decreased by 13.5%, and the primary hydrometeorological factors determining the situation included evaporation and river outflow [43]. Wine et al. [44] determined that agriculture and changes in the direction of water flow were the main factors causing the substantial shrinking of Lake Kinneret. Lakes in the middle course of the Jangcy River in the 20th century considerably declined (at a level of 58%), largely due to rapid land reclamation [45].

Based on the analysis of sediment from Lake Nanyi, Wang et al. [46] recorded a decrease in its surface area, whereas excessive reclamation around the lake was the dominant factor contributing to the situation. According to the determinations for Lake Urmia, anthropogenic factors (use of water in agriculture and surface and groundwater uptake in the catchment) contributed considerably to a decrease in its surface area [47]. The intensification of human activity, such as the fast development of breeding and coal extraction, is the main driver of the transformations of the lakes in Inner Mongolia [48]. The rapid shrinking of Lake Limboto (Indonesia) is caused by the deposition of the fine-grained sediments constituting the remains from the fast upheaval by the Eurasian and Australian plate [49].

The transformations of the surface area of lakes basically depend on two factors: a change in water level and the filling of the lake basin with material supplied both from the catchment area and the lake itself [50]. More specifically, they are determined by natural factors and human activity, deposition of sediments by rivers, an increase in eutrophication, and the consequent acceleration of overgrowth.

In Poland, water level fluctuations show no spatial variability (suggesting the dominant role of climatic factors) [51]. The individual parameters of lakes and local water circulation conditions are of key importance. The greatest and most dynamic water level fluctuations are generated by human activity, including the building of hydrotechnical infrastructure or melioration works [52]. In the latter case, they may lead to the complete disappearance of lakes, even those with large surface areas. This situation is exemplified by Lake Sitkowiec (186 ha), where the need to obtain new green areas led to its complete disappearance [53]. A similar situation occurred in the group of the analysed cases and concerned Lake Podgaje (with a surface area of 27 ha). The expansion of a system of ditches and melioration canals (Figure 3) resulted in a decrease in the water level in the lake itself and in the adjacent areas, consequently leading to its complete disappearance.

The dominant human role in water circulation resulting in changes in the surface area of lakes is also confirmed by earlier research. A substantial decrease in the surface area of Lake Kamińsko (by 52%) could have been caused by two basic factors, i.e., the connection of ditches with another lake and the construction of a water uptake in a nearby municipality [54]. According to Gradtke [55], the primary cause of a decrease in the surface area of Lakes Breńskie and Białe-Miałkie (Sławskie Lakeland, Poland) were hydrotechnical works involving drying large fragments of land in catchments of the lakes. It is worth emphasising the morphometric parameters of the lakes themselves. As determined based on the obtained results, the fastest rate of decline was observed in the shallowest lakes and those with the smallest surface area. According to Scheffer [56], shallow lakes are largely unstable ecosystems. They are therefore objects that are more prone to water level fluctuations, where the deposition of sediments that results in their shallowing also occurs the fastest. It is evident in the case of a river flowing through a lake. At the inflow of the Dojca River to Lake Wolsztyńskie (146 ha, depth 4.5 m), a delta developed (Figure 5). Simultaneously, Lake Borówiec (17 ha, depth 0.8 m) became a place of deposition of sediment for the Głuszynka River flowing through its axis, resulting in its complete overgrowth (Figure 5). Lakes do not always respond uniformly to processes occurring in their catchments. A decrease in the surface area of Lake Huri Chagannao'er primarily occurred in its western part, whereas its eastern part remained stable [57]. Its depth variability substantially contributed to a considerable shrinking (by more than 1/3, Figure 3) of Lake Łoniewskie. The shallower northeastern part was subject to shallowing, followed by the occupation of the area by vegetation. A similar situation occurred among others in the case of Lake Litworowy Staw (with a decrease in the surface area by 46.4%) [58], where the accumulation of fine sediments and dead vegetal remains provided conditions suitable for overgrowth. Transformations primarily caused by anthropogenic factors resulted in the rapid overgrowth of the surface of former Lake Rakutowskie (central Poland) with reed beds and clusters of willows [59]. Macrophyte succession is favoured by narrow bays sheltered from wind and wave action [60]. Such a situation, among others, was observed in Lake Łeknińskie. Its northern bay, with a width of approximately 300 m, was completely occupied by vegetation that also expanded from the island already observed in the early 20th century (Figure 5). The last of the important statistical parameters related to changes in the surface area of lakes is the length of the shoreline; this should be considered in the context of land use structure. The longer the shoreline, the longer the route of the supply of substances affecting water quality. The buffer designated for analysis showed the greatest decrease in the surface area of lakes in the case of the dominance of an urbanised–agricultural land structure, i.e., with the highest inflow of substances (nitrogen and phosphorus compounds) responsible for accelerated overgrowth. The successive intensification of human activity is related to changes in the quality of the lake waters [61], including an increase in their trophic status [62]. According to Lossow [63], the primary causes of the acceleration of lake evolution in the Mazurskie Lakeland (east Poland) include changes in the land use in agricultural catchments, excessive tourist pressure, urbanisation, and the resulting sewage supply. An increase in the eutrophication and improperly conducted melioration are among the main causes of drastic changes in the surface area of Lake Udzierz and Lake Mątasek, which shrank by 53.3% and 97.9%, respectively, over the century [64]. Clear regulations regarding the supply of nutrients to surface waters were introduced at the moment of Poland's accession to the European Union, but in addition to the external supply, the issue of the accumulation of such compounds in lake sediments remains unsolved [65]. Moreover, the disappearance of elements of the hydrographic network can be determined by the expansion of the settlement network [66]. Conducting agrarian activity favours the supply of matter to rivers and lakes and therefore results in changes in their morphometry. According to Bakoariniaina et al. [67], the consequence of the deforestation of the catchment of Lake Alaotra was an increase in soil erosion and the consequent filling of most of the lake.

The decrease in the surface area of the lakes recorded in the paper, which consequently leads to their successive disappearance, will have a number of negative consequences; these consequences are both environmentally significant and important from an economic point of view. In the case of Poland, where periods with water deficits are recorded increasingly frequently, the disappearance of the natural places of its retention will negatively affect all the economic sectors that are strongly dependent on water. In addition to agriculture, fishing, or industry, this also concerns the dynamically developing tourist sector, where lakes are one of the key components of the natural environment determining investments in the area [68]. Therefore, the obtained results reflecting the scale of changes in the surface area of lakes can constitute important information for the authorities responsible for water management in the context of inhibiting their disappearance. Due to the multitude of factors affecting the process, it is a complex task, but the faster that suitable activities aimed at lake protection are undertaken, the greater the chance of their longer survival in the environment.

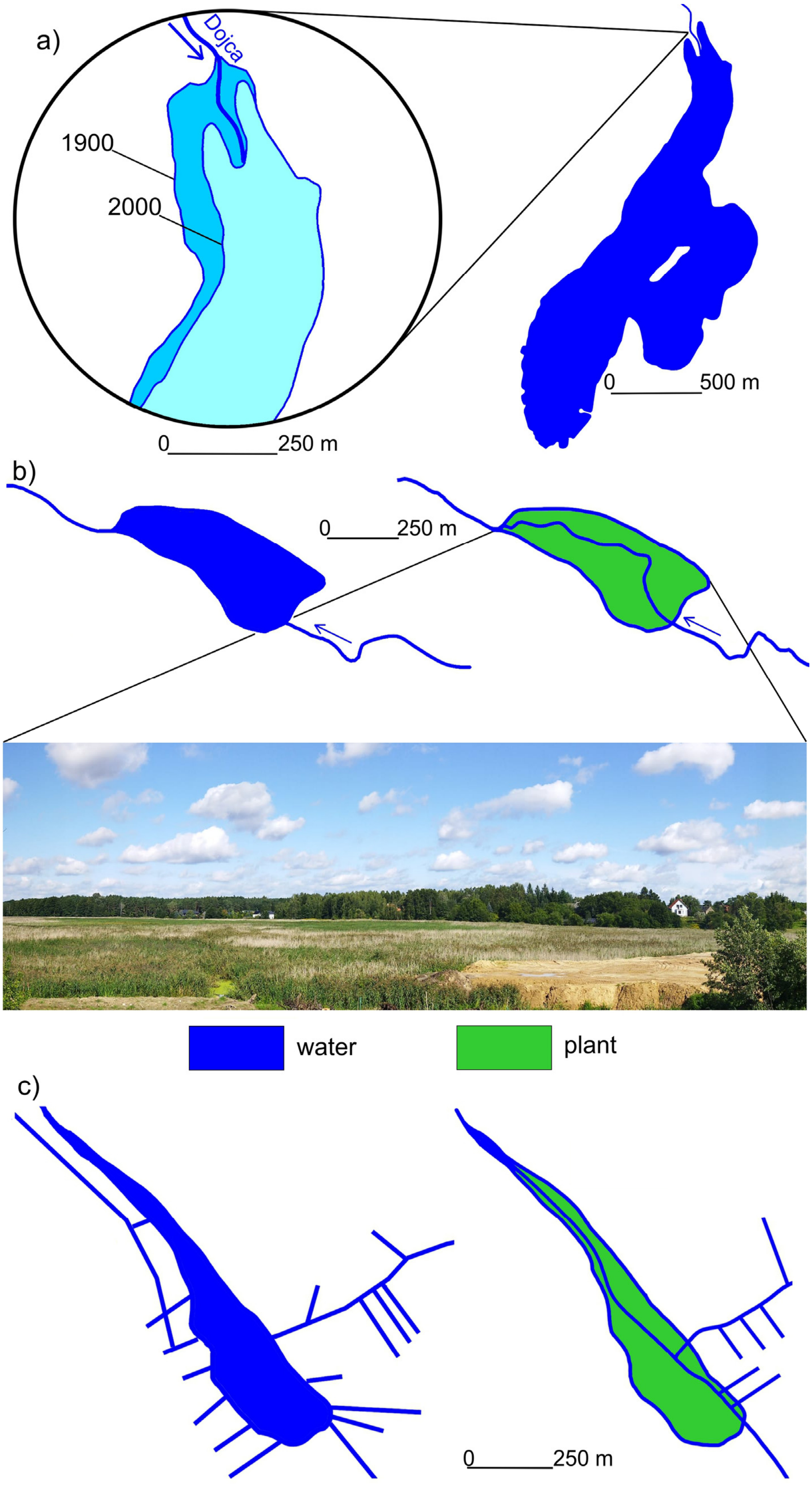


**Figure 5.** *Cont*.

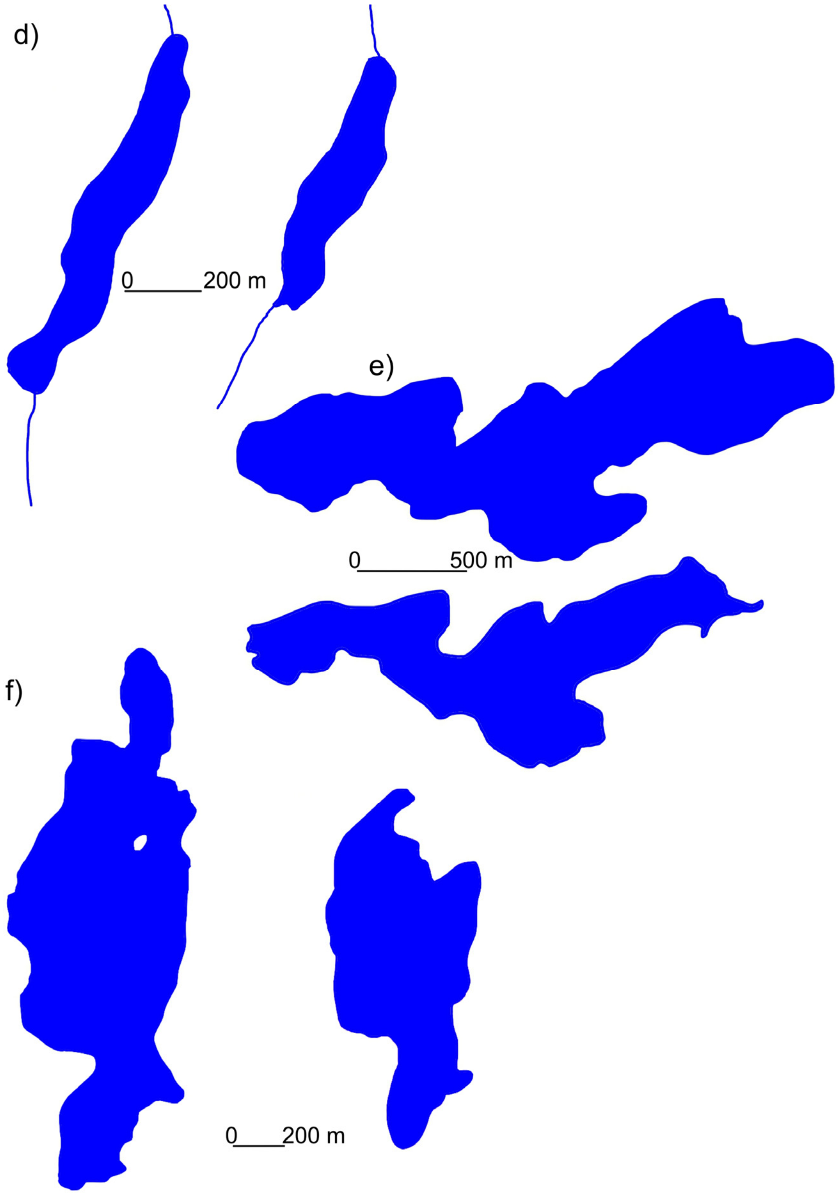


**Figure 5.** Examples of changes in the surface of lakes: (**a**) Wolsztyńskie, (**b**), Borówiec, (**c**) Podgaje, (**d**) Żydówko, (**e**) Łoniewskie, (**f**) Łeknińskie.

## 5. Conclusions

Due to their morphometric parameters and high ability to accumulate matter, lakes are among the least permanent elements of the environment. They also constitute an important element of water circulation, which is essential to environmental and economic processes. The analysis conducted in the paper showed that over the period covering the 20th century, the total surface area of the analysed lakes decreased by 11.4%. It should also be emphasised that all the situations concerning lake evolution were recorded, i.e., growth, lack of transformations, and their complete disappearance. The magnitude of changes does not show regions with a similar distribution, suggesting the dominant role of the individual parameters of lakes and their relationships with the surroundings and confirming earlier studies of this type in the territory of Poland. Among the morphometric parameters, the depth, surface area, and the length of the shoreline of the lakes were key for the scale of their evolution and in the context of the land use dominance of urbanised areas with agricultural land. Changes in the surface area of lakes are a result of the many processes occurring in the lakes themselves as well as in their surroundings. The knowledge of the scale and rate of changes in the surface area of lakes is important in the context of the preservation of biodiversity and water management aimed at the maintenance and stabilisation of water resources in a given area.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources12090110/s1. Table S1: Change in the area of the analyzed lakes (1900–2000).

**Author Contributions:** Conceptualisation, M.P.; methodology, M.P. and M.S.; software, M.S.; validation, M.P. and M.S.; formal analysis, M.P. and M.S.; investigation, M.P. and M.S.; resources, M.P.; data curation, M.P. and M.S.; writing—original draft preparation, M.P., M.S., K.S.-P., S.H. and S.Z.; writing—review and editing, M.P., M.S., K.S.-P., S.H. and S.Z.; visualisation, M.P. and M.S.; supervision, M.P.; project administration, M.P.; funding acquisition, M.P., M.S., K.S.-P., S.H. and S.Z. All authors have read and agreed to the published version of the manuscript.

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