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The concept of the terrestrial–subaqueous topographical and lithological continuum: a case study of the Lake Gopło region (north-central Poland)

Abstract

The research objective is to produce thematic maps of the continuum of terrestrial and subaqueous terrain and surface lithology of the Lake Gopło region. The maps were based on the results of geomorphological and geological mapping in the vicinity of Lake Gopło and a reconnaissance of the shape and sediments of the lake basin and the morphology of the basins of other large lakes in its vicinity. A geomorphological classification of subaqueous landforms was carried out and, in the case of Lake Gopło, a lithological classification of its bottom sediments was also conducted. According to the authors, the features of the subaqueous relief and lithology of lake sediments should, depending on the degree to which they have been identified, be included in studies and legends of large- and medium-scale geomorphological and geological/lithological maps. This would significantly enrich their content and could be used to draw detailed conclusions as to the genesis and evolution of the landscape and its geodiversity.

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1 Introduction

Waters cover about 71% of the Earth's surface, of which only about 0.82 p.p. are inland waters. Recent studies estimate that there are over 304 million lakes on Earth totalling approximately 4,200,000 km^2 (2.8% of the planet's land area). The vast majority are of less than 1 km^2 (Downing et al. 2006). The share of inland waters in a given area is measured by lake percentage (the area occupied by lakes expressed as a percentage of the total reference area) and by lake density (the number of lakes per unit of area, e.g., 1 km^2) (Bajkiewicz-Grabowska 2021). There are regions of land with very high lake percentages and lake densities, e.g. in the Finnish Lakeland, where numerous small lakes often lie very close together. In areas of high lake percentages, e.g. the Great Lakes of North America or the Masurian Lake District in Poland, lakes are fewer but large. As a consequence, thematic maps (e.g., geomorphological and geological maps) of these areas are relatively poor in content, as most of the area is covered by lakes (Figure 1).

In many countries, medium-scale geomorphological and geological maps (scales from 1:20,000 to 1:300,000) are drawn up, including map series issued in individual sheets. They are prepared at various scales and by various methodologies (e.g., Klimaszewski 1956; 1982; Galon 1962; Tricart 1965; Gilewska 1968; Barsch and Liedtke 1980; Embleton and Verstappen 1988; Evans 1990; GNGFG 1994; Otto and Dikau 2004; Smith and Clark 2005; Krygowski et al. 2007; Dykes 2008; Gustavsson et al. 2008; Knight et al. 2011; Seijmonsbergen et al. 2011; Rączkowska and Zwoliński 2015). The vast majority of publications presenting maps of the results of geomorphological or geological surveys conducted in areas with a high share of lakes in their surface area and on geomorphological and geological maps of such areas do not present the topography or lithology of lake basins (e.g., Lisicki 1994; Molewski 1999; 2012a; Poppe et al. 2013; Rožič et al. 2019; Öhrling et al. 2020). Regardless of whether the lakes domi-

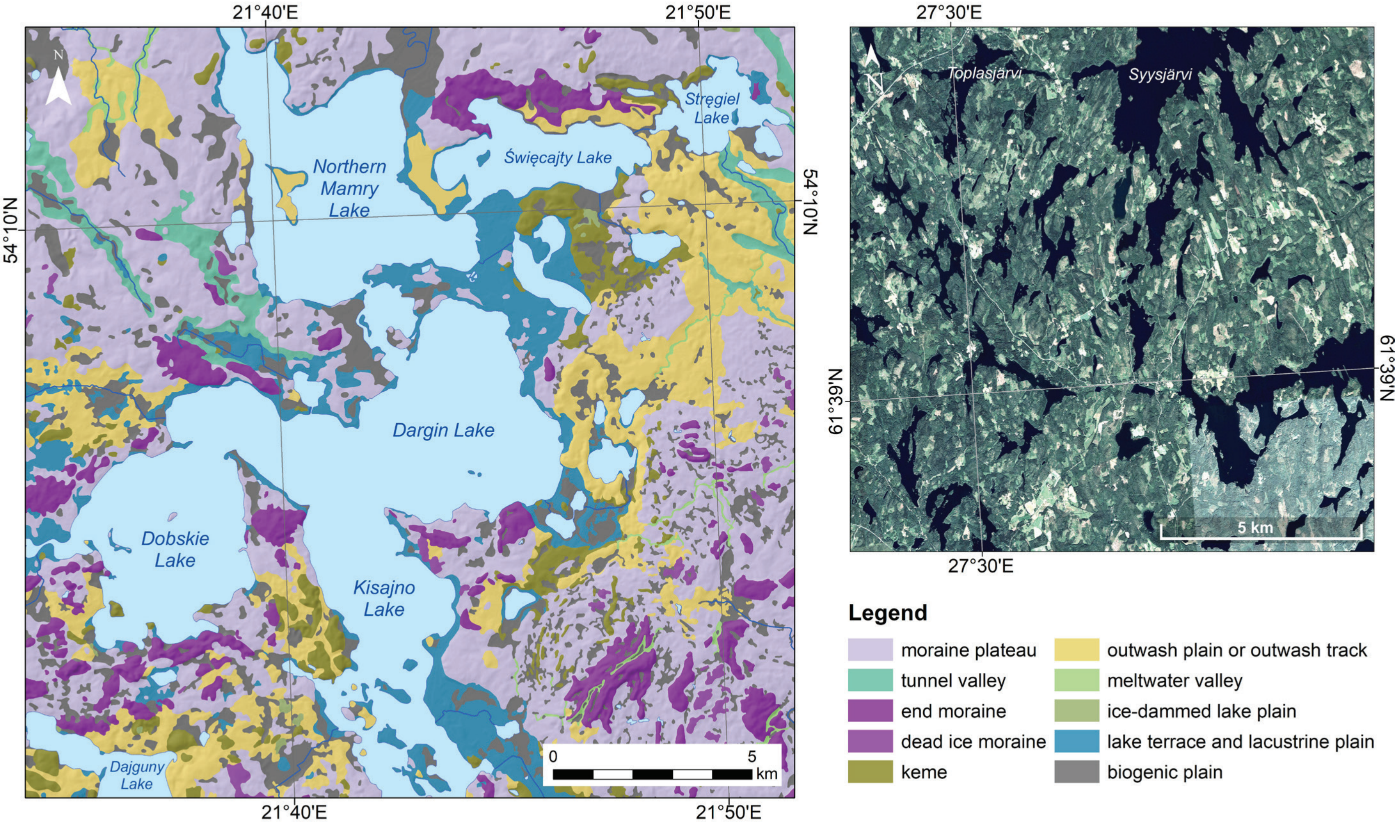


Figure 1. Excerpt from a geomorphological map of the north of the Great Masurian Lakes Region (NE Poland, Kot et al., 2020) with a high lake percentage, and a satellite image of part of the Finnish Lake District with a high lake percentage and high lake density (source: Google Earth Pro).

nate the maps or occupy only a small part of them, they are marked with standard surface marks that do not reflect the diversity of their beds.

Modern technologies and research tools allow the shape of the beds of water bodies and their sediments to be reconnoitred at various scales. This is confirmed by works elaborated at overview map scales (i.e., smaller than 1:200,000) in large ocean and marine areas (e.g., Sacchetti et al. 2011; Rydningen et al. 2013; Dowdeswell et al. 2014; Bradwell and Stoker 2015; Dowdeswell et al. 2016; Dorokhov et al. 2017; Kaskela and Kotilainen 2017; Federici et al. 2019; Batchelor et al. 2020). In Poland, the shape and sediments of the southern part of the Baltic Sea have been identified in detail (Kramarska 2020). Many years of research have produced the 1:200,000 *Geological Map of the Baltic Sea* (Mojski ed. 1989–95; MGDB) and the 1:500,000 *Geological Atlas of the Southern Baltic* (Mojski ed. 1995). In recent years, the concept for a 1:100,000 geological map of Polish marine areas has also been developed (Kramarska et al. 2019).

Works on mapping the shape and geological structure of lake basins are sparse. Bozzano et al. (2009) used multibeam sonar to investigate the dynamics of an underwater slope of Lake Albano (Italy) and relationships between subaqueous and subaerial slope processes. Within the underwater slopes, the authors identified several gravity-induced landforms: landslide scarp areas, landslide accumulations, erosional chutes and channels, block fields, isolated blocks, scarps and slope breaks. Fabbri et al. (2021) used a combination of high-resolution bathymetric mapping and seismic reflection data to quantify the sediment budget in the alpine Lake Brienz. New bathymetric data were used to distinguish three geomorphological areas: slopes with intercalated terraces, a flat basin plain, and delta areas with subaquatic channel systems. Most studies on the characteristics of lake bottoms consider only parts of a lakebed. In Switzerland, for a part of Lake Lucerne, new bathymetric studies led to the development of a detailed Digital Terrain Model (DTM) of the lake floor, and the lake's history was reconstructed on the basis of the subaqueous sediments (Hilbe et al. 2011). Part of the British glacial lake Windermere, which lies in overdeepened basins in glacial valleys, was studied by Miller et al. (2013). The authors used high-resolution datasets obtained from multibeam bathymetry systems and developed a geomorphological map of the lakebed and sedimentological processes taking place there. Silva et al. (2019) used two bathymetric datasets to map the sediment transfer system and a sediment budget for the Rhone River in the eastern part of Lake Geneva (Switzerland/France).

Lake sediments are usually analysed using point-sampled cores. Detailed, interdisciplinary studies of these cores (including sedimentological and palaeobotanical studies) to investigate the evolution of a lake basin and its immediate surroundings. In Poland, one such comprehensive study of lake sediments is the study of Lake Gościąż in the Vistula valley (Ralska-Jasiewiczowa et al. 1998). The morphology and sediments of the bed of Lake Wigry in north-eastern Poland have been investigated in detail (Rutkowski and Krzysztofiak 2009; Aleksander-Kwaterczak and Król 2021). That research produced maps of the lakebed topography and sediment diversity at a scale of approximately 1:200,000.

The research objective is to produce thematic maps of the continuum of terrestrial and subaqueous terrain and surface lithology of the Lake Gopło region and to develop a methodology for mapping "blanks spots" (i.e., inland water areas) on geomorphological and lithological (geological) maps. The maps were based on the results of geomorphological and geological mapping in the vicinity of Lake Gopło and a reconnaissance of its bed topography and sediments and of the morphology of the basins of other large lakes in the vicinity. A geomorphological classification of subaqueous landforms was performed, and, for Lake Gopło, a lithological classification of sediments was also conducted.

An innovative synthetic approach to capturing the continuum of supra- and subaqueous topography and surface lithology was built on modern technical possibilities and on the accessibility of data, the ease with which they can be sourced and collected, and the speed with which they can be processed and analysed in Geographic Information Systems (GIS).

2 Study area

The research area lies within three physico-geographic mesoregions of the Wielkopolskie Lakeland macroregion in north-central Poland, and constitutes part of the Polish Lowlands, themselves within the Central European Lowlands (Figure 2). The three mesoregions are: the Żnin-Mogilno Lakeland, the Inowrocław Plain and the Kujawy Lakeland (Kot 2016; Solon et al. 2018).

The entire study area is located within the range of the last Pleistocene glaciation – the Weichselian – when glacial and fluvioglacial processes were the main relief-forming factors. The Scandinavian ice sheet then covered about 30% of the territory of modern Poland and is estimated to have reached its maximum about 20,000 years ago (Kozarski 1991; 1995). It retreated from there about 14,700 years ago, and, with its gradual disappearance, the relief began to be shaped by fluvial, aeolian, denudational and biogenic processes. Beginning 11,700 years ago, the Holocene climate warming and vegetation development inhibited the dynamics of natural geomorphological processes and, with the advent of agriculture in the Neolithic, the transformation of the topography also became associated with human activity. Glacial lakes are a major feature of the Polish landscape within the range of the last glaciation (Figure 2). There are seven large lakes in the area in question, with areas of 35.5 to 2,154.5 ha and maximum depths of 4.3 to 25.7 m (Choiński 2006) (Table 1, Figure 3). The largest is Lake Gopło, which is one of the largest (2,154.5 ha) and longest (25 km) lakes in Poland (Choiński 2006). The relief and surface geological structure in the vicinity of this lake have been the subject of detailed studies (Molewski 1999; 2012b; 2012c; Kozydra 2013). The morphology and sediments of this lake have also been identified in more detail as part of a study of the composition and spread of pollutants in its waters (Juśkiewicz 2014; Juśkiewicz et al. 2015).

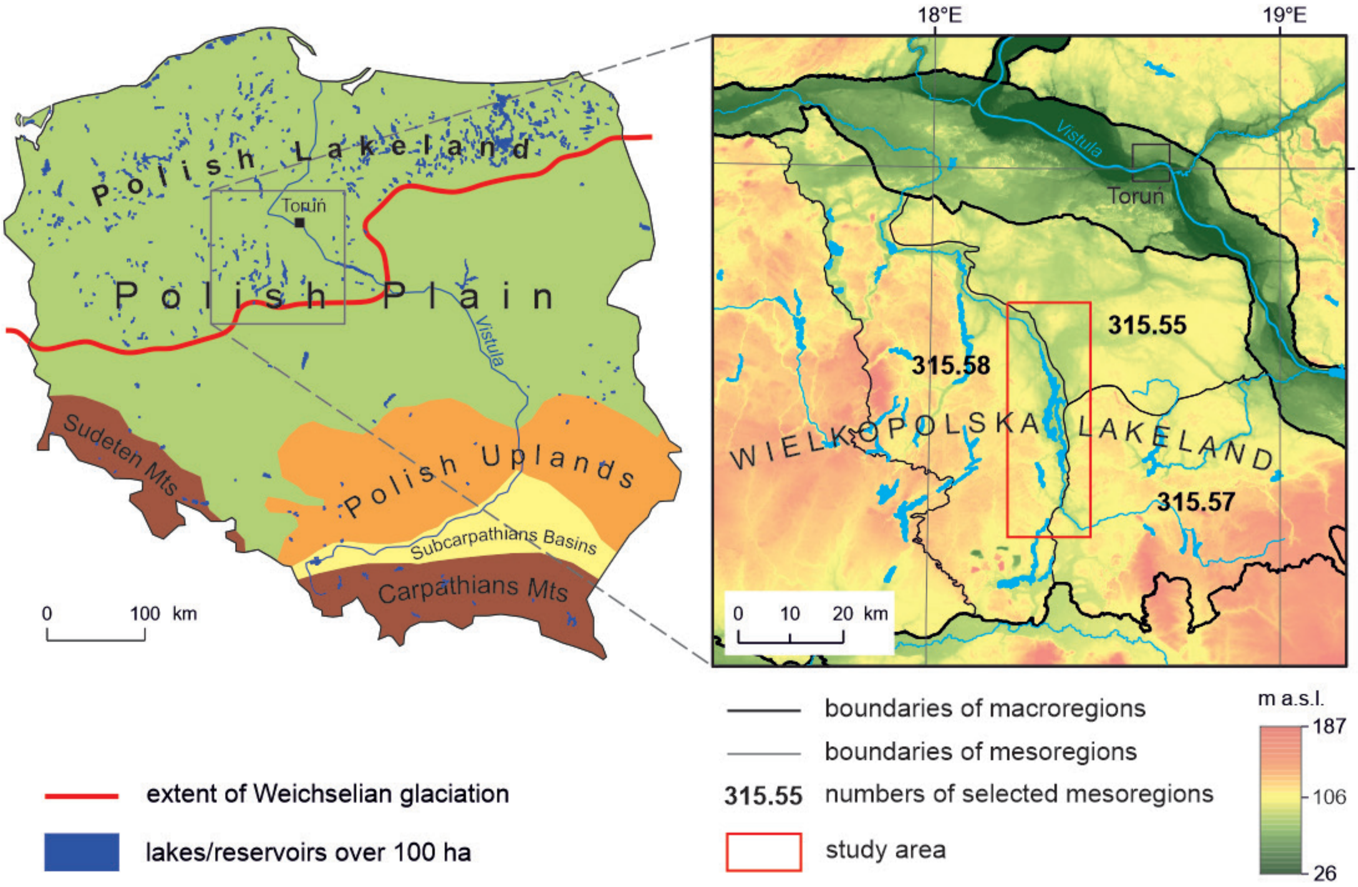


Figure 2. The distribution of lakes in Poland and location of research area against the background of the Żnin-Mogilno Lakeland, Inowrocław Plain and Kujawy Lakeland mesoregions (315.58, 315.55 and 315.57, respectively) (Kot 2016; Solon et al., 2018).

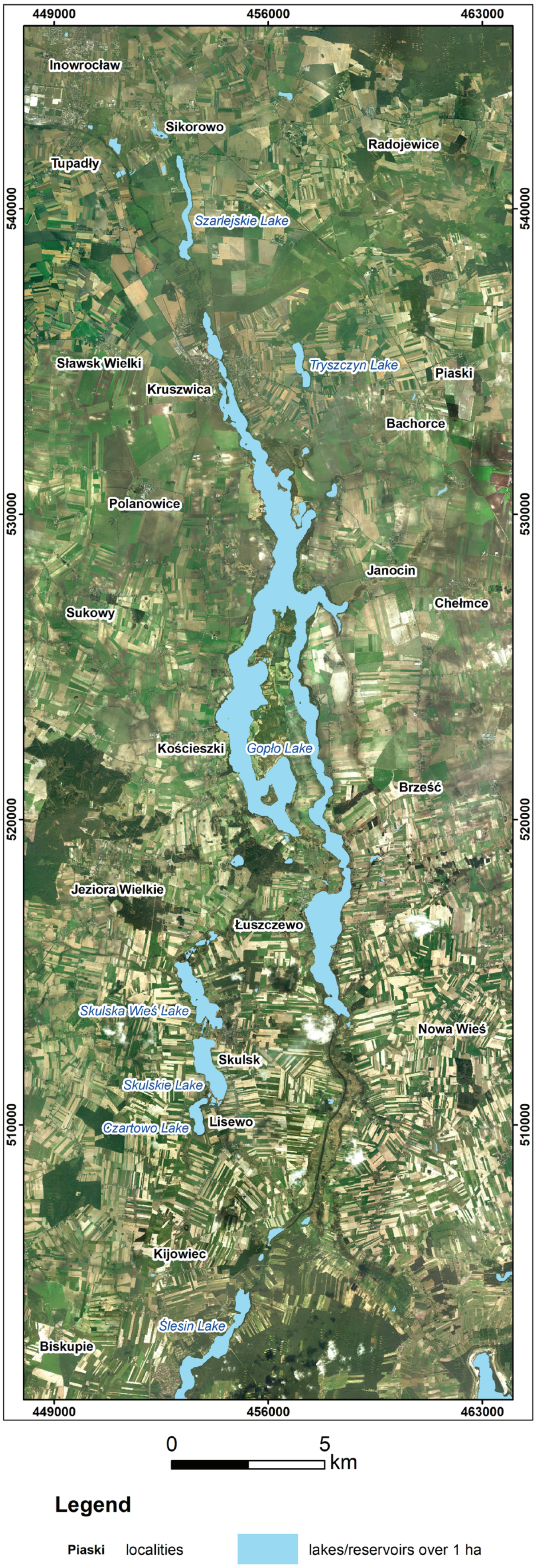


Figure 3. Location of the largest lakes in the research area and against the background of an orthophotomap.

3 Materials and methods

A DTM was developed using LiDAR (Light Detection And Ranging) data from ALS (Airborne Laser Scanning) and orthophotomaps obtained from the Head Office of Geodesy and Cartography in Warsaw (GUGiK 2020), though it excluded the basins of the lakes. A DTM with an original resolution of 1 m × 1 m was generalised to a 5 m × 5 m model. The shores of the lakes were digitised based on an orthophotomap of 5 m × 5 m resolution (source: Google Maps). Within the borders of the lakes, data on the water table were removed from the model.

The DTM for the bottom of Lake Gopło and the largest water bodies in its vicinity was constructed using bathymetric plans based on a grid of point soundings of the depth of lakes taken by the Inland Fisheries Institute (IRŚ) in Olsztyn (IRŚ 1958–62) from the surface of the lakes when frozen. The bathymetric plans, with isobaths of 1-m intervals, were scanned, calibrated, digitised and processed into a DTM for the lake beds. In order to verify and update the DTM of the Lake Gopło bed, it was probed with a dual-beam echosounder with a GPS receiver mounted on the boat. The effectiveness and accuracy of the measuring device were verified against manual measurements (Issa et al. 2013). Measurements were made around the lake shore, then along transects at variable distances perpendicular to its main axis, and as a measurement grid in specific locations. In areas where the bottom was flat, the transects were spaced several tens of metres apart, while in zones with underwater slopes and deeps they were narrowed to just a few metres apart. The data from the soundings were compared against an existing bathymetric plan and, where discrepancies occurred, the measurement grid was densified in selected zones (Hollister and Milstead 2010). The depth data obtained from the sounding were compiled with the DTM based on the IRŚ data and the model of the topography of the lake basin was generated by converting the depths from the soundings to absolute terrain elevations. The resultant DTM of the beds of Lake Gopło and the other largest lakes of the research area were integrated with the DTM of the land area.

Table 1. Summary of basic morphometric parameters of lakes.

Lake name	Height above sea level [m]	Area [ha]	Volume [thous. m^3]	Maximum depth [m]	Average depth [m]
Szarlejskie	76.8	66.9	1377.2	4.3	2.1
Gopło	76.9	2154.5	78497.0	16.6	3.6
Tryszczyn	78.0	35.5	1571.9	8.8	4.4
Skulska Wieś	86.2	120.1	8098.3	17.6	6.7
Skulskie	86.3	116.3	4872.8	8.2	4.2
Czartowo	86.2	42.0	2546.3	13.0	6.1
Ślesińskie	83.5	148.1	11072.7	25.7	7.5

ArcGIS ESRI and Global Mapper were used for the manipulation and mapping of all spatial data sets. The Poland CS92 (EPSG:2180) coordinate system was used.

The lithology of the bed of Lake Gopło was reconnoitred using several tens of sediment cores of about 1 m length collected from places of distinct relief, as determined from the DTM. The cores were collected using a proprietary, patented probe that provides undisturbed cores of plastic or semi-liquid sediments of up to 2 m long and 8.5 cm in diameter (Figure 4). Some of the collected cores were tested in the laboratory; a total of 477 sediment samples were analysed (Juśkiewicz 2015). Their physico-chemical characteristics, such as granulometry, carbonate and organic matter contents, and mineral parts were determined (Heiri et al. 2001). The volumetric weight and moisture of the sediments in fresh state were also measured, and photographic documentation was prepared. Due to the muddy nature of the sediments, for the particle-size analysis, laser diffraction was performed using two grain-size analysers – a Fritsch Analysette 22 and a Malvern Mastersizer 2000 (Krawczykowski et al. 2012). Statistical parameters of the grain-size distribution were calculated according to Folk and Ward (1957). The results of the laboratory analyses allowed us to determine the type of sediments according to the Markowski classification (1980).

Digital geomorphological and lithological maps of the land area were developed using the results of Molewski's (1999) geomorphological and geological surveys, as well as geological maps and geomorphological sketches of the study made during the field mapping for the 1:50,000 *Detailed Geological Map of Poland* sheets for Inowrocław (Molewski 2012b; 2013), Piotrków Kujawski (Molewski, 2012a, 2012c) and Ślesin (Kozydra 2013; 2014).


clay-carbonate gyttja

detritus-carbonate gyttja

Figure 4. Collection of Gopło bottom sediments by sampler, and sample sediment cores.

4 Results

The performed works resulted in a DTM, geomorphological and lithological maps, all of which were continuous, i.e. they included the area both of land and of lakebeds. The thematic maps show a rich set of relief and sediment forms – mainly glacial and hydro-glacial, but also aeolian, fluvial, denudational, lacustrine, biogenic and anthropogenic forms. Based on the shape of the lake basins (bathymetry), eleven subaqueous types of relief were distinguished and classified. In Lake Gopło, the type and spatial distribution of bottom sediments were also classified. The digital geomorphological map includes classifications from the onshore and underwater parts of the studied area, and the lithological map also shows the Gopło subaqueous sediments.

4.1 Hypsometry

The leading feature of the study area is the longitudinal tunnel valley of Lake Gopło between Sikorów in the north and Kijowiec in the south (the tunnel valley ends to the east of the latter town). In its middle part, the tunnel valley divides into two parts that today are separated by a biogenic plain. The tunnel valley is about 40 km long, 1.2 km wide at its widest, and with a maximum depth of about 30 m. Nowadays, the main part of the tunnel valley is occupied by Lake Gopło and Lake Szarlejskie, and the rest comprises biogenic plains (former lakes). The other large lakes of the area also lie in the bottoms of tunnel valleys (Figure 5).

Outside the depression of the Gopło tunnel valley, the surrounding area rises generally southwards from about 75–80 m a.s.l. within the wide bottoms of the Bachorze and Noteć valleys to about 100–105 m a.s.l. on the moraine plateau around the southern part of the tunnel valley. In accordance with the adopted concept of a topographic continuum that includes lake depressions, the lowest points in the research area are at the bottom of Lake Gopło, near Łuszczewo (60.4 m a.s.l.), and in a flooded former open-pit mine (57.7 m a.s.l.) to the very south-east. The highest points are the peak of a dune (124.1 m a.s.l.) to the west of the village of Jeziora Wielkie and a moraine hill in Chełmce (117.9 m a.s.l.). The maximum difference in absolute heights, taking into account the depth of water bodies, is about 66.4 m, but 48.1 m accounting for subaerial land only. The average elevation of the research area is about 90 m a.s.l.

The largest differences in relief altitudes (including underwater parts) occur within the post-glacial tunnel valleys of: Lake Ślesińskie and Lakes Skulskie and Gopło (about 30 m) and the flooded former open-pit mine (about 35 m). The moraine hill in Chełmce, the dunes to the west of the village of Jeziora Wielkie and settling tanks in the region of Inowrocław reach differences in elevation of almost 20 m (Figure 5).

4.2 Geomorphology

The relief of the research area, despite relatively little hypsometric differentiation, has a typologically rich set of forms (Figure 6). The Lake Gopło tunnel valley connects in the south-east with the post-glacial Nykielska valley used by the River Noteć, and in the south-west (via an artificial ditch) with the tunnel valley of Lake Ślesińskie. To the north-west it joins the Noteć valley. Numerous meltwater valleys flow into the Gopło tunnel valley, mainly from the east, the largest being the Parchańska, Bachorzy and Głuszyńska valleys. In the Janocin region, small post-glacial tunnel valleys of various courses, together with the Gopło tunnel valley, form a local system of subglacial meltwater outflow. To the north-west of the southern, lakeless section of the Gopło tunnel valley, there is the Skulskie Lakes tunnel valley.

The topography of the moraine plateau surrounding the Gopło tunnel valley is diversified. It is very monotonous in its northern part. What dominates here is the flat surface of a ground moraine, from which there project isolated overridden moraines in the Chełmce region and to the west of Polanowice. In the vicinity of the tunnel valley, within the moraine plateau, the terrain features include steps separated by gentle slopes, such as near the village of Bachorce. The southern part of the research area is dominated by a wavy bottom moraine, and the relief is much more diversified. There is a rich complex of marginal forms: end moraines, ice-contact sedimentary scarps and ice-contact fans created during the standstill phases of the last ice sheet, and stagnant- and dead-ice landforms: eskers, dead-ice moraines,

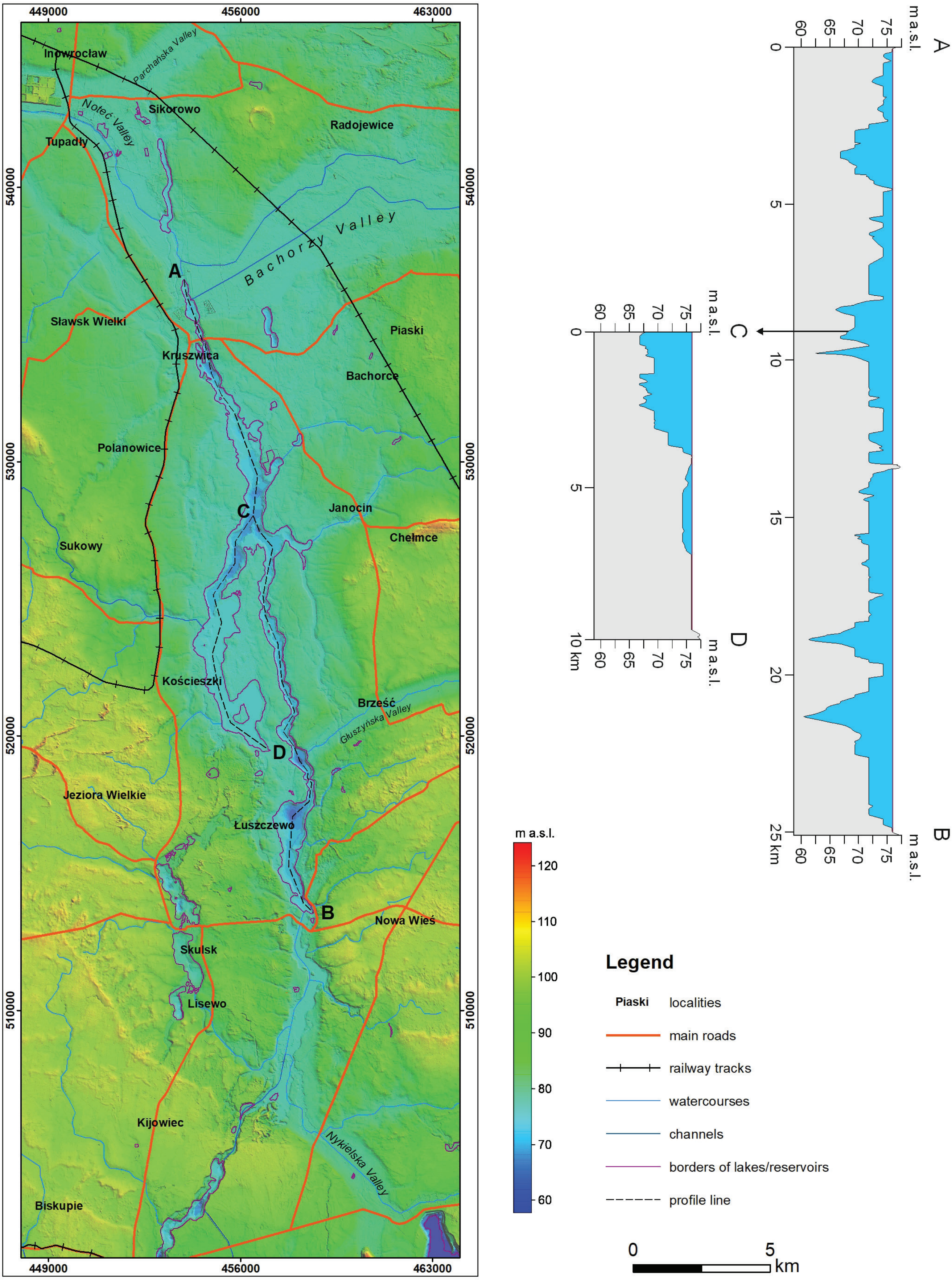


Figure 5. DTM of the research area and longitudinal profile of Lake Gopło.

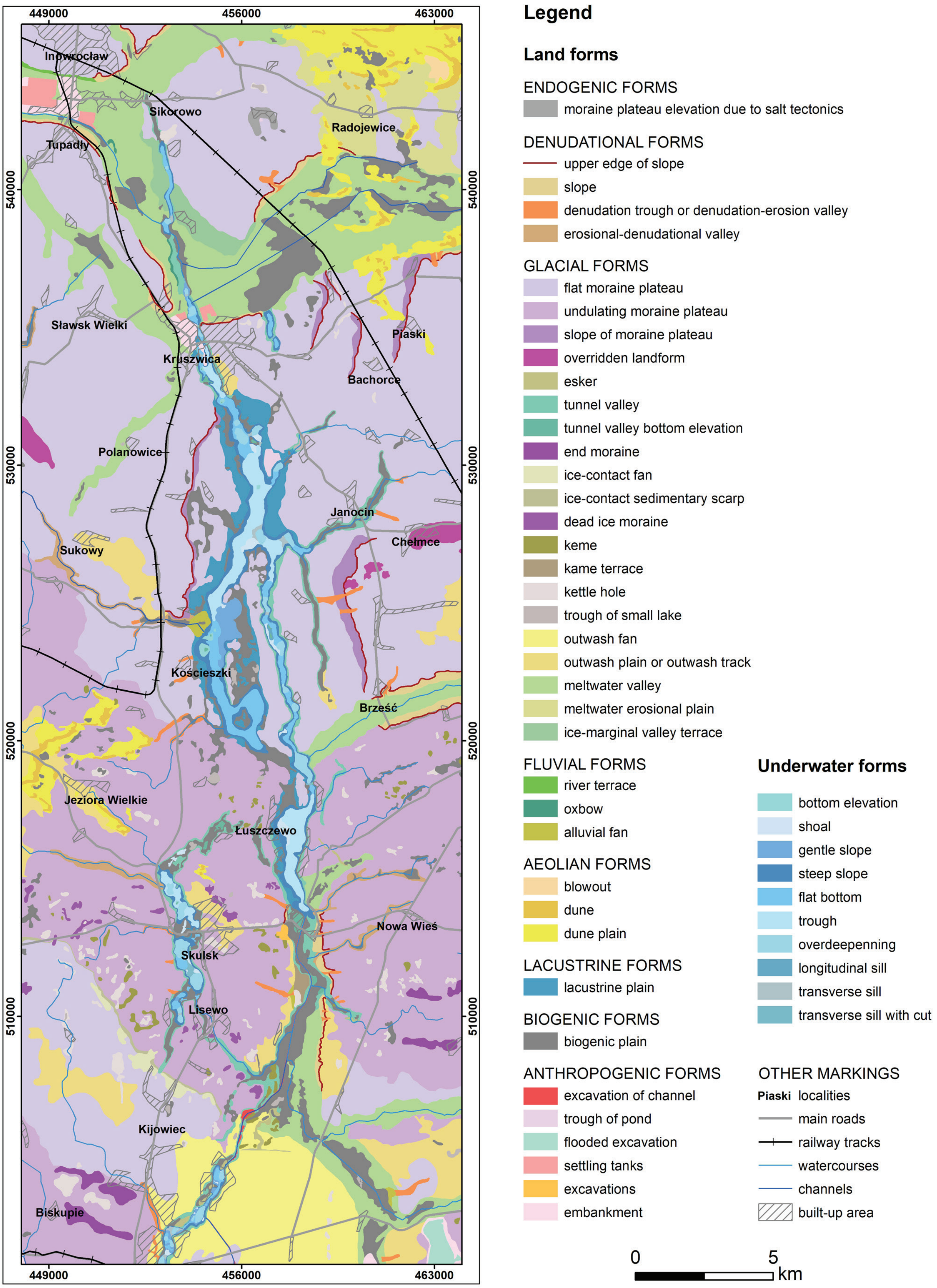


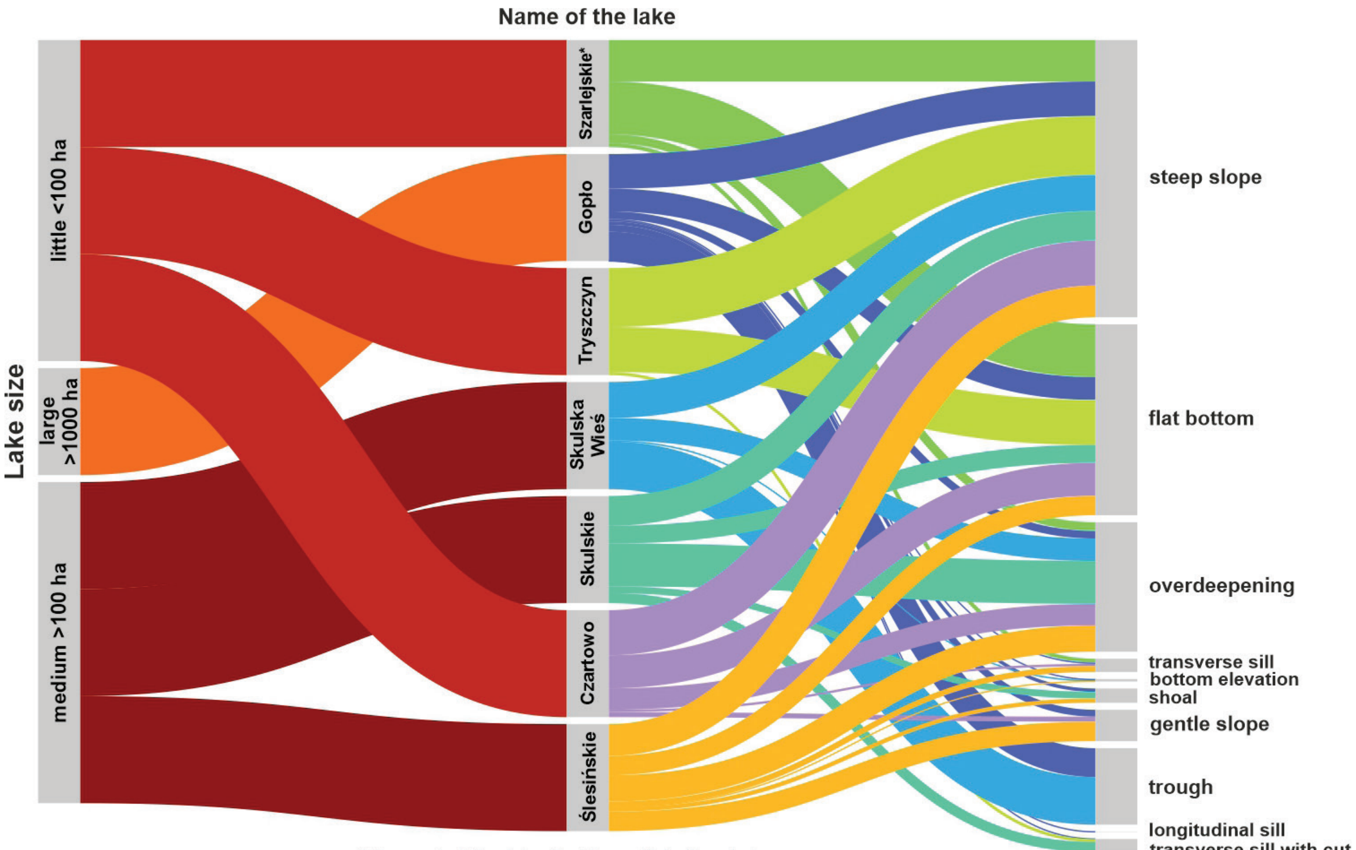
Figure 6. Geomorphological map of the research area.

kemes, kettle holes. In the south, at the mouth of the Gopło tunnel valley, the largest sandur in this area was created (Molewski 1999).

The end of the Pleistocene is the main period in which dune plains and dunes on sandy surfaces were formed of: sandurs, meltwater erosional plains and meltwater valleys around the villages of Radojewice, Piaski and Jeziora Wielkie; and denudation landforms, mainly comprising slopes and denudation-erosion valleys. Typical riverine landforms constitute a small share of the study area's topography because the river network inherited forms from the glacial drainage system, i.e. tunnel valleys, outwash tracks and meltwater valleys. In the Holocene, lake terraces developed and the lakes began to be overgrown and biogenic plains to form, which continues to this day. There were similar processes of the deposition of mineral-organic sediments in the numerous kettle holes. Locally, the landscape of the study was dominated by anthropogenic forms, e.g. around the towns of Inowrocław and Kruszwica (e.g. settling tanks, embankments) and in the area of the flooded former open-pit mine (Molewski 1999).

In line with the adopted concept, subaqueous topographical forms were distinguished in the bottoms of the largest lakes: bottom elevations, shoals, gentle and steep slopes, flat bottoms; two types of depressions, i.e. troughs and overdeepenings; and three types of sills separating depressions, i.e. longitudinal sills, transverse sills and transverse sills with cut (Table 2, Figure 6). Together with the subaerial landforms, these relief forms constitute the topographical continuum of the study.

The bottom shape is most varied in Lake Gopło, where all the distinguished subaqueous types of relief were found (Table 2, Figures 6 and 7). The fewest types are found in the smallest of the analysed lakes – Lake Tryszczyn. Steep slopes occupy the highest percentage of the lakes' surface areas, confirming their origins as tunnel valleys. In some places the underwater slopes continue above the water level in the onshore part of the subglacial tunnel valleys. Usually, however, these slopes are separated by lake terraces and near-shore shoals. The tunnel valley genesis of the lake basins is also attested by the numerous overdeepenings and sills, which cre-



* the part of the lake that lies within the study area

Figure 7. Division of the examined lakes by size and percentage share of individual subaqueous relief types.

Table 2. Area of subaqueous relief types as a proportion of lake surface area, for the largest lakes in the research area.

Name of lake	**Szarlejskie**	**Gopło**	**Tryszczyn**	**Skulska Wieś**	**Skulskie**	**Czartowo**	**Ślesińskie***
Subaqueous landform	Share of landform in lake area [%]						
bottom elevation		1.2		0.9			0.1
shoal		3.2			6.2		4.0
gentle slope		6.4				4.7	18.2
steep slope	38.8	32.3	55.1	33.5	27.7	42.1	29.6
flat bottom	49.4	21.3	42.1		16.6	30.9	18.1
trough		27.0		44.6			
overdeepening	8.1	7.1		21.0	40.1	20.1	24.6
longitudinal sill		0.3					
transverse sill	3.7	1.1				2.2	5.4
transverse sill with cut		0.1	2.8		9.4		
number of form types	4	10	3	4	5	5	7
lake area [ha]	66.9	2154.5	35.5	120.1	116.3	42.0	144.4

* the part of the lake that lies within the study area

ate the uneven longitudinal profiles characteristic of post-glacial tunnel valleys formed by the subglacial erosion of ice sheet meltwaters under hydrostatic pressure.

The overdeepenings are usually small with steep slopes and resemble inverted cones. Large lakes usually contain several, while in small lakes contain one or none at all. Their depths vary from several to tens of metres; they constitute the deepest parts of the lake basins.

The saddle-shaped transverse sills occur in narrowings in the lake basins and separate their deeper parts. There were probably formed during subglacial discharge in the tunnel valley. Some of the sills show erosive cuts, which are interpreted as traces of the flow of ice-sheet meltwaters during the deglaciation of the study area. In the central, flow-through part of Lake Gopło, a longitudinal sill of more than 600 m long about 150 m at its widest was also distinguished, which can be interpreted as a preserved fragment of an esker that formed in a dead-ice crevice. Some of the sills rise above the water to form islands.

Between the sills, which cover a relatively small area, there are troughs and flat bottoms. After steep slopes, flat bottoms occupy the second-highest total percentage of the area of the lakes. They occupy large areas mainly in smaller and shallower lakes. Vast, gently sloping troughs usually occur in large lakes and, after the overdeepenings, constitute the next deepest parts of the lake basins.

The bottom elevations, which, like some of the sills, often continue above the surface of the lakes as islands, have a small share. The elevations are usually oval and reach relative heights of up to a few metres. These elevations may be the result of the accumulation of sedimentation from meltwaters flowing in the fissures or depressions of dead-ice filling the tunnel valley after the retreat of the ice sheet.

4.3 Lithology

The surface geological structure of the area in question, including the Gopło subaqueous sediments, is dominated by glacial and fluvioglacial sediments. Aeolian, lacustrine, and biogenic sediments have a smaller share. Alluvial sediments, and above all fluvial sediments, have a small share due to their aforementioned inheritance of sub-glacial drainage forms and the fact that the glacifluvial outflow landforms have been little transformed by rivers. The smallest areas are occupied by deluvial, eluvial and anthropogenic sediments (Molewski 2012a; 2013; Kozydra 2014).

On the moraine plateau, there are glacial tills, as well as glacial (ablation and runoff) sands, gravels and, occasionally, boulders. Moreover, these types of sediments make up end moraines and dead-ice moraines (Figure 8). Glaciofluvial sands and gravels build sandur surfaces and fill the bottom of the meltwater valley. Sand-gravel sediments, and in some places silts and clays, also build smaller postglacial forms such as kemes, keme terraces and eskers. The

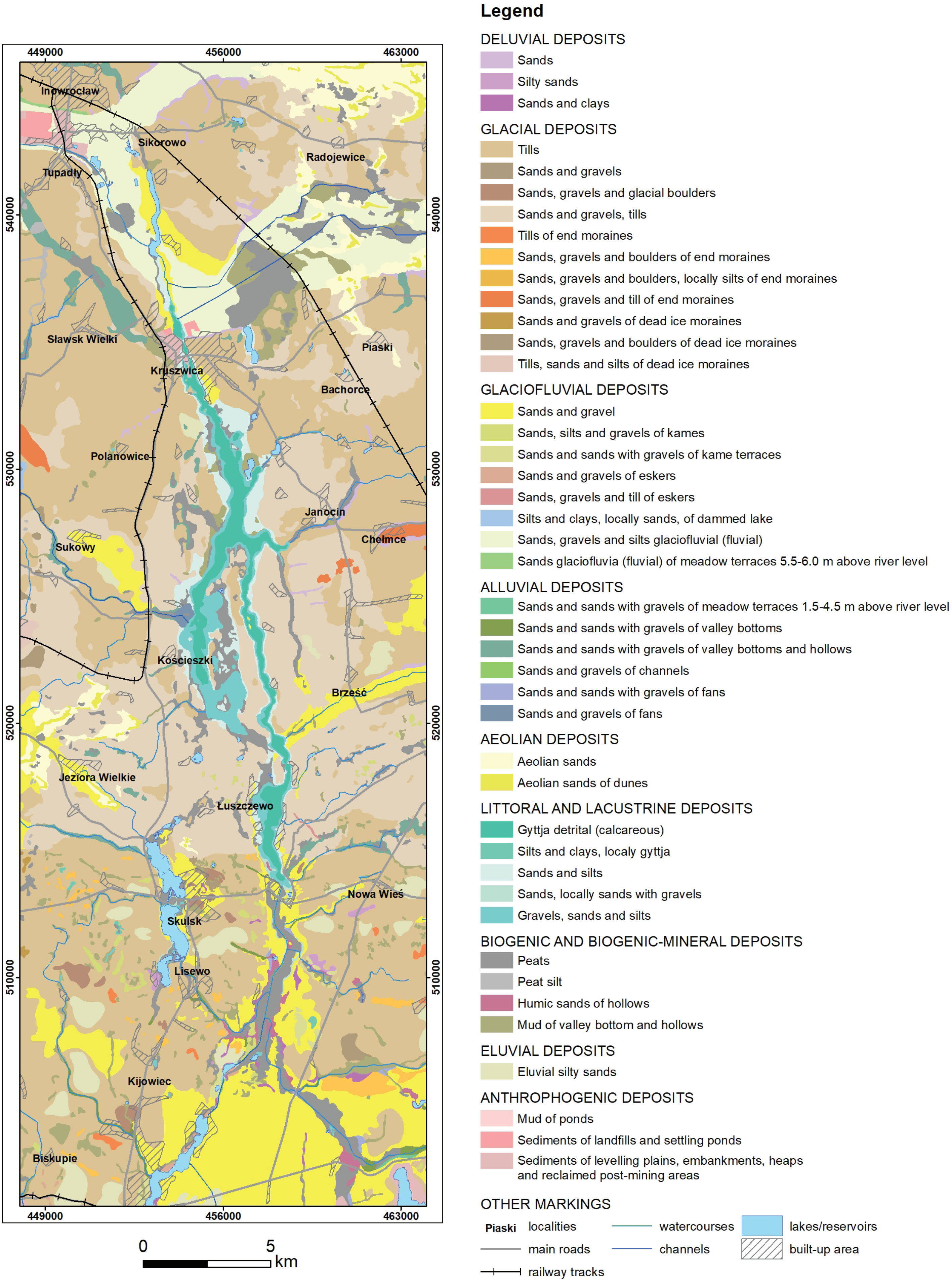


Figure 8. Lithological map of the research area.

sands of aeolian plains and dunes were formed on the surfaces of rewashed glacial and fluvioglacial sands. The deluvial sands were created mainly by deforestation and agricultural activities. These sediments are thickest at the foots of slopes of topographic depressions and of the largest elevations within the moraine plateaus. Peat is quite common in the bottoms of tunnel valleys, meltwater valleys, and larger kettle holes. The bottoms of valleys and topographic depressions of various origins contain muds, humic sands, and silts. Within larger towns, the sediments of embankments and landfills were distinguished, while in industrial and mining areas sediments of settling tanks, waste heaps, and reclaimed areas were distinguished (Molewski 2012b; 2012c; Kozydra 2013).

In the littoral zones and shallower parts of the lake bottoms, sand and silt sediments dominate, while mainly detritus gyttjas (less often calcareous gyttjas) dominate in the deeper parts. The dominant Gopło sediments are: carbonate gyttja, including clay-carbonate and detritic-carbonate gyttja, and mainly coarse- and medium-grained mineral gyttja (Figure 8). These are deep-water sediments. The shallow-water sediments are mainly consist of fine and very fine-grained sands. Gyttja accounts for about 50.9% of the entire surface of the lake bottom, and mineral sediments about 49.1%. The identification of these sediments within the lake completed the continuum of surface lithology within Lake Gopło and its surroundings.

5 Discussion

Most of the lakes on Earth were formed not earlier than in the Neogene, i.e. their age can reach up to about twenty-something million years, and those that formed in the Quaternary predominate. The most numerous are lakes found at temperate latitudes of the northern hemisphere, whose formation is associated with the Pleistocene glaciations. Their age is dated to 12–11 thousand years. Only a few lakes are older; these are mainly tectonic lakes that, thanks to their size and depth, have survived to this day (e.g. Caspian Sea, Lakes: Baikal, Superior, Victoria, Alberta, Geneva) or subglacial lakes (Lake Vostok in Antarctica). Lakes, even relatively young ones, are gradually disappearing under the influence of natural and anthropogenic processes. Climax communities or anthropogenic ecosystems are currently observed in the place of former lakes.

Contemporary lakes in the lake districts of the Polish Lowland (including those considered in this article) were formed as a result of changes in hydrological conditions after the withdrawal of the last ice sheet, from the late Pleistocene to the early Holocene. During this period, the melting of blocks of dead ice in depressions of various origins played a key role in the formation of lakes. These depressions in the field were created as a result of earlier erosion (tunnel valleys, evorsion, and exaration depressions) or accumulation (moraine lakes) of the ice sheet and its meltwaters. In addition, the mechanisms of their formation and morphology were affected by features of the older substrate, as exemplified by the Gopło tunnel valley, whose course and morphology refer to fossil structures (Molewski 1999). The genetic classification of lake basins is not determined on geomorphological maps, and the factors forming them are generally inferred on the basis of their size, shape, and depth.

Since the glacial lakes were created, the process of their disappearance has begun. The thickness of the sediments within them has increased, the shape of the lake basins and the shoreline has changed, and the water surface has decreased. It is estimated that since the beginning of the Holocene in Poland, about one third of the area of glacial lakes has disappeared (Kalinowska 1961). In the conditions of ever-increasing anthropogenic pressure and climate change (climate warming), this process can be expected to accelerate.

The presented concept of the continuum of terrestrial and underwater relief and lithology can be considered not only in the geomorphological or geological aspect but also in the landscape aspect. According to the definition given in the *European Landscape Convention*: “landscape is an area perceived by people, the character of which is the result of the action and interaction of natural and/or human factors” (ELC 2000). In the case of an underwater landscape, this perception is limited for obvious reasons, and its model can be a map containing its elements.

The suggested cartographic representation of the two basic abiotic components of the underwater landscape, i.e. relief and lithology, can be the basis for research on its evolution and threats, including changes related to the disappearance of lakes and the causes thereof.

Landscape variability (palimpsest) resulting from the impact of natural and anthropogenic factors in space and time (Bailey 2007; Barett 2014; Ingold 2014) can be analyzed in terms of ecology (Pirnat, Hladnik 2018; Fischer, Lindenmayer 2006), culture (Traba 2009; Affek 2015), planning (Levin et al. 2007) or geography (Doretto et al. 2020; Vannote et al. 1980). Lakes, as already mentioned, are ephemeral phenomena. They are very sensitive ecosystems, subject to anthropogenic pressure, the effect of which may be eutrophication, toxic algae bloom and drastic reductions in ecosystem services. In this context, the presented continuous cartographic representation of the relief and lithology of the terrain, i.e. including lake basins, together with a detailed recognition of their catchments, may be an important support for landscape studies, including in monitoring and assessing the dynamics of adverse changes in terrestrial and aquatic ecosystems (Sayer 2014).

Studies of underwater lake landscapes are complex, primarily due to the difficulties in obtaining comprehensive data. Characterisations of the shape and lithology of the bottom of lakes are insufficient, despite their potential as a basis for research on the biotic components of underwater landscapes. Publications on research into lakes, usually carried out on a spot basis (discretely) take into account the impact of geomorphological and geological processes, including sedimentological, stratigraphic, chemical, and biological processes, on the landscape structure, as well as on the ecological functions of lakes (Smol et al. 2001; Mäckel et al. 2009; Brauer 2004; Brauer et al. 1999). On thematic maps, lakes are presented as homogeneous components of the landscape, although they may differ significantly in the lithology and physicochemical properties of bottom sediments and other features, including biotic ones. This makes it difficult to view them holistically. In addition, the clear borders of lakes on thematic maps introduce an erroneous idea of the lack of continuity and penetration of specific landscape components. The concept of a continuum of terrestrial and underwater relief and lithology is the first step towards a comprehensive classification of lakes and can be a starting point for interdisciplinary research.

As already mentioned, previous geomorphological/geological studies of lake beds of various origins have had a limited scope or concerned lake fragments, and their results have been presented on maps at small scales (e.g., Bozzano et al. 2009; Fabbri et al. 2021; Hilbe et al. 2011; Miller et al. 2013; Silva et al. 2019). In the presented studies of the relief of the Gopło region, the inclusion of underwater areas significantly increased the number of distinguished types of relief and the observed height differences. Studies of the lithology of the bottom of Lake Gopło significantly expanded the content of the lithological map, mainly with the distribution of deep and shallow water sediments. In addition, extending the scope of the developed maps with underwater elements is important for assessing the geodiversity of the analyzed area (Gray 2013; Kot 2015; Zwoliński 2004).

Field research and development of thematic maps, in particular geomorphological and geological ones, is a complex and time-consuming undertaking. On the other hand, expanding their content to include underwater areas is relatively easy, as long as data of appropriate quality and detail are available. The authors are aware that the presented solutions are not universal and may be modified depending on the specificity of the researched area and water body as well as the availability and possibility of obtaining data.

6 Conclusion

According to the authors, the features of the subaqueous relief and lithology of lakes should, depending on the degree to which they have been identified, be included in studies and legends of large- and medium-scale geomorphological and geological/lithological maps. This would significantly enrich their content and could be the basis for in-depth conclusions about the development of the landscape, in particular about the genesis and evolution of lake basins. The proposed classification of subaqueous types of relief forms can be applied to lake basins of similar origin.

The presented continuous presentation of content (continuum) on thematic maps undoubtedly represents an improvement over their current form. The omission of this content, in particular the relatively easily obtained bathymetric data and the classification of subaqueous relief types based thereon, also significantly impoverishes the analysis and assessment of geodiversity (e.g., Hjort and Luoto 2010; Melelli et al. 2017). This issue is of particular importance in the context of climate change and the progressive disappearance of lakes.

Furthermore, the presented concept of the continuum of terrestrial and subaqueous relief and lithology is in line with contemporary geographic research on cause–effect relationships between all abiotic and biotic landscape features, both natural and anthropogenic (e.g., Prince et al. 2009; Weng and Lu 2009). It can therefore be a point of reference for the development of interdisciplinary research, including into abiotic and biotic processes. This concept may fill the research gaps in identifying landscape continuity, e.g. in landscape continuum models (LCM), enabling biochemical transport processes in terrestrial ecosystems to be explained (Seastedt et al. 2004).

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