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Digitization as one of the methods of assessing the number and distribution of small water bodies

by

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Abstract

Small water bodies (ponds) are a widespread component of the landscape; however, their exact number is often estimated by their small size, temporal variability, or being invisible due to dense vegetation cover. Their distribution is typically assessed through the analysis of aerial and satellite imagery. Nevertheless, a more traditional but labor-intensive approach—manual digitization from topographic maps—has been considered highly precise. In an area of 12 400 km^2 in northern Poland, nearly 32 000 ponds were digitized, with their occurrence strongly linked to geomorphological units. While they are most abundant in moraine plateaus, ponds are present across all post-glacial landscapes. Additionally, the authors observed that although pond distribution appears largely random, some exhibit distinct spatial patterns, forming linear chains or clustered groups.

Key words: kettle holes, lake abundance, ponds, post-glacial landscape

1. Introduction

Determining the number and size of small water bodies is crucial for assessing their role in regional and global water systems, as well as in biogeochemical processes (Downing, 2010; Hanson et al., 2007; Pi et al., 2022; Seekel et al., 2013). However, global knowledge regarding the number of lakes remains limited and highly heterogeneous. Over the past decades, numerous attempts have been made to estimate their number, with the first efforts dating back to the 1930s. Early studies focused primarily on large lakes exceeding 10 km^2 in area (Halbfass, 1933, as cited in Bartout et al., 2015). With advancements in technology, these estimates have increased significantly—from tens of thousands of lakes over 10 km^2 (Lehner & Döll, 2004; Meybeck, 1995) to over 8.44 million lakes exceeding 1 ha (Meybeck, 1995), and up to 117 million lakes larger than 0.0002 km^2 (Verpoorter et al., 2014). The total global lake area is estimated to range from approximately 2 million km^2 (Shiklomanov, 1993) to over 5 million km^2 (Verpoorter et al., 2014).

Most estimates of lake numbers rely on mathematical models rather than fieldwork (Downing, 2010; Downing & Duarte, 2009; Downing et al., 2006; Minns et al., 2008). Small water bodies are often excluded from such calculations (Lehner & Döll, 2004; Meybeck, 1995) or are only roughly estimated (Downing et al., 2006). However, recent studies suggest that small water bodies occur in high densities across various spatial scales—global, continental, and local (Chumchal et al., 2016; Mai & Bill, 2011). Their total number is now estimated at over 277 million, accounting for approximately 90% of all hydrographic features worldwide (Downing et al., 2006). This vast number highlights their significant role in water and nutrient cycles (Golus & Bajkiewicz-Grabowska, 2017; Marcé et al., 2019) and their contribution to biodiversity conservation (Céréghino et al., 2008; Cuenca-Cambronero et al., 2023; Hassall, 2014; Hill et al., 2017; Oertli et al., 2002; Sebastián-González et al., 2010).

Due to their small size, knowledge about these water bodies remains limited (Boix et al., 2012; Downing, 2010). Historically, research has focused on larger lakes, which were considered more ecologically significant. However, as freshwater resource concerns gain attention, small water bodies are increasingly recognized for their importance, leading to a growing body of research (Catalán et al., 2014; Hill et al., 2021; Jeffries, 2016; Obrador et al., 2018; Premke et al., 2016). Despite this, understanding their ecological role remains challenging due to insufficient data (Downing et al., 2006). Many ponds are ephemeral, periodically drying out, and their hydrological functions vary depending on biotic and abiotic factors (Altenfelder et al., 2014; Batzer & Wissinger, 1996; Bilton et al., 2009; Coccia et al., 2024; Collinson et al., 1995). A fundamental step toward understanding their role in the landscape is determining their number and distribution.

Ponds are a widespread landscape feature across nearly all countries. However, their distribution is irregular, with concentrations often found in post-glacial regions (e.g., Kalettka et al., 2001) in Europe and North America. Despite their abundance, precise data on their numbers are lacking. Many remote sensing-based estimations overestimate their presence, while those based on manual mapping tend to underestimate it (Verpoorter et al., 2014). Ponds are often difficult to detect in aerial and satellite imagery, particularly in areas densely covered with vegetation (Calhoun et al., 2003) or where ponds are highly dynamic, appearing only seasonally or ephemerally (Jeffries, 2016). Remote sensing studies (Huang et al., 2018) highlight several limitations, including resolution constraints, cloud and vegetation cover, shadowing, and the need for visual verification, which slow down data processing. Consequently, field verification remains essential (Jeffries, 2016), yet it poses a challenge for comprehensive and large-scale pond inventories. The absence of direct field validation often leads to errors in publicly available datasets, as evidenced by the presence of "artifacts," such as erroneously identified ponds just a few cm^2 in size, which require filtering.

Topographic maps provide a standardized and reliable data source, ensuring consistency in pond inventories. Although vectorization from such maps is labor-intensive, it remains a preferred method due to the frequent lack of high-quality automated classification tools. Despite these challenges, this study undertook a detailed inventory of small water bodies using topographic maps, making its findings unique.

The study area lies within the juvenile post-glacial landscape of northern Poland, characterized by numerous lakes interconnected by a relatively sparse river network. Endorheic areas are also a common feature. While large lakes in the region are well documented, the origins and characteristics of smaller water bodies remain unclear. Some ponds formed naturally through dead-ice melting, whereas others are anthropogenic, particularly in agricultural regions (Mętrak et al., 2014).

In Poland, pond research has been growing, though studies primarily focus on distribution and disappearance trends (Marszelewski & Podgórski, 2004; Pieńkowski, 2003, 2004), often examining individual ponds at a local scale. These studies are predominantly conducted by biologists and ecologists (e.g., Basińska et al., 2010; Brysiewicz et al., 2017; Nagengast & Kuczyńska-Kippen, 2014), while hydrological investigations remain limited. Moreover, many studies rely on short-term observations, providing fragmented insights. Estimates of pond numbers in Poland vary widely, ranging from tens of thousands to several hundred thousand, depending on the cartographic material used (Choiński, 1999).

Due to their post-glacial origin, ponds are abundant in northern Poland, often forming "pondscapes" where nearly every depression holds a permanent or temporary pond. The region's extensive hydrological modifications, such as drainage systems, have historically influenced pond numbers. Although many ponds have disappeared (Marszelewski & Podgórski, 2004; Pieńkowski, 2004), they remain a significant landscape feature.

Limited hydrological research on ponds means that their role in lake-district water cycles is still not fully understood. Recent studies suggest that ponds significantly influence river outflow, as they periodically or permanently connect to river networks, discharging excess water (Golus & Bajkiewicz-Grabowska, 2017). These hydrological interactions depend on various factors, including catchment characteristics, land use, soil permeability, and climatic trends (Golus & Bajkiewicz-Grabowska, 2017; Kalettka & Rudat, 2006). Understanding pond connectivity is essential for evaluating their role in hydrological systems, especially in the context of climate change, to which small water bodies are particularly vulnerable (Ewald et al., 2014; Boix et al., 2011; Pätzig & Düker, 2021). Although some studies indicate that pond communities exhibit resilience to changing climate conditions, extreme events pose significant threats. In this region of Europe, both flood and drought frequencies have increased (Ziernicka-Wojtaszek & Kopcińska, 2020), impacting local flora and fauna (Pätzig & Düker, 2021).

Ponds also play a crucial role in biodiversity conservation, acting as refuges in otherwise monotonous agricultural or forested landscapes and facilitating ecological connectivity (Thornhill et al., 2017). As key components of water storage, they influence river outflows (Golus & Bajkiewicz-Grabowska, 2017) and biogeochemical cycles (Robotham et al., 2021), particularly carbon and nutrient fluxes (Catalán et al., 2014; Downing, 2010; Obrador et al., 2018; Premke et al., 2016). Their spatial distribution affects ecosystem dynamics (Cardoso et al., 2017; Cottenie et al., 2003), with biodiversity generally increasing alongside pond density (Bosiacka & Pieńkowski, 2012; Thiere et al., 2009).

Given their ecological significance, accurately determining pond distribution and abundance is fundamental. This study aimed to address this gap by inventorying ponds within a typical post-glacial landscape, focusing on (1) detailed mapping, (2) distribution within geomorphological units, (3) size analysis, and (4) spatial arrangement, including patterns of linear and clustered formations.

2. Methods

To determine the number, hydrological type, and distribution of ponds in the Gdańsk Pomerania region, the authors selected a 12 400 km^2 area of irregular shape (Fig. 1). This area was chosen for several reasons:

1. Cartographic materials of similar dates are available.
2. It represents a post-glacial landscape formed after the last glaciation (Bajkiewicz-Grabowska et al., 2020).
3. It lies within the boundaries of a single administrative unit (Pomorskie Voivodeship).

Thus, an irregular polygon was defined, with the eastern boundary marked by the valley of Poland's largest river, the Vistula; the northern boundary by the Baltic Sea; and the southern and western boundaries by the border of the Pomeranian Voivodeship, which roughly coincides with the poorly defined historical and geographical boundaries between Gdańsk Pomerania and Western Pomerania. The identification and digitization of ponds were based on topographic maps in the 1965 coordinate system (PPWK, 1965–1980). The north-western part of Gdańsk Pomerania was excluded from the analysis due to the absence of color topographic maps. Gdańsk Pomerania is part of the Central European Lowland, culminating at 329 m in the center. It features a typical post-glacial landscape, with a mosaic of moraine plateaus, outwash plains, and subglacial channels, as well as melt-out hollows (Fig. 2). Additional terrain forms include erosion terraces and coastal dunes, which together comprise only 2% of the area. A key feature of the region is the presence of numerous ponds. The analysis of pond occurrence and distribution was conducted in two main stages. The first stage involved an inventory of the ponds, while the second stage focused on spatial analyses based on the data collected in the first stage. Both stages were carried out using GIS tools: ArcGIS by ESRI (Redlands, California, USA). The starting material for the inventory was a raster topographic map at a

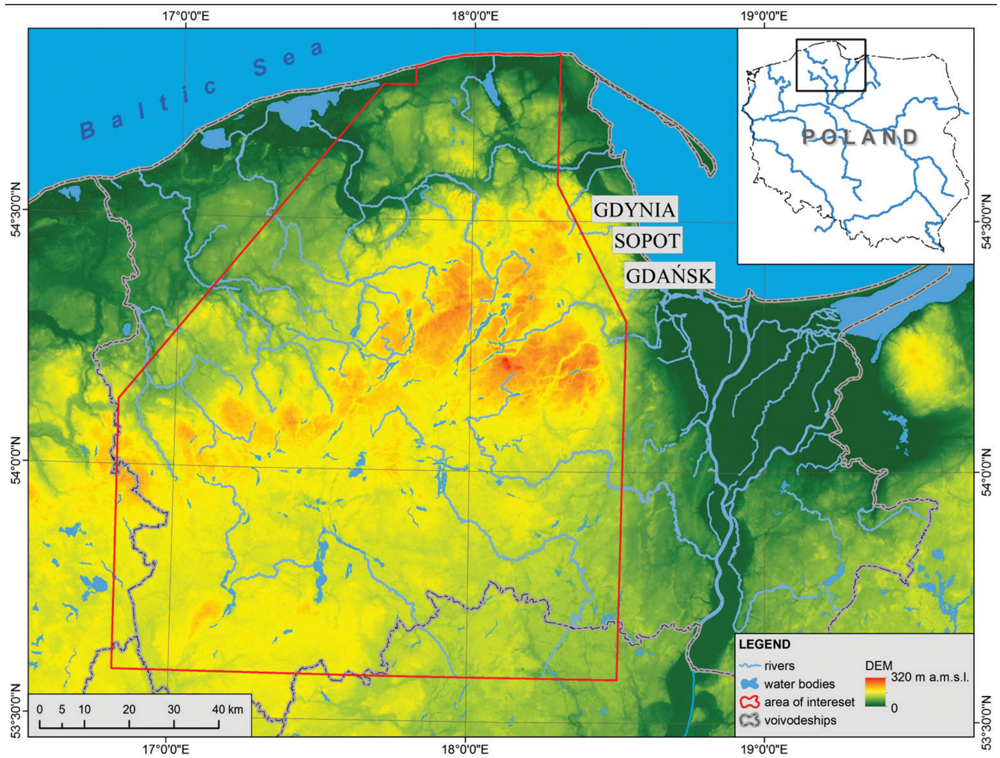

Figure 1

Study area (key: 1—watercourses, 2—lakes, 3—study area boundary, 4—administrative borders, and 5—elevation [m]).

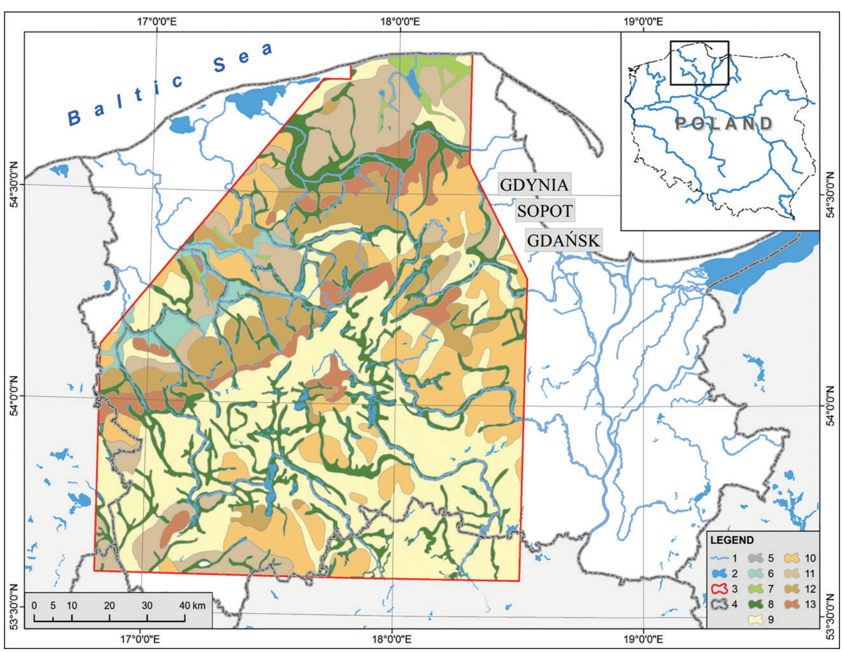

Figure 2

Geomorphological units within the study area (key: 1—watercourses, 2—lakes, 3—study area boundary, 4—administrative border, 5—coastal dunes, 6—erosion terraces, 7—valley forms, 8—subglacial channels, 9—OutP, 10—FMPs, 11—UndMPs, 12—HummMPs, and 13—hilly moraine plateaus). FMPs, flat moraine plateaus; HummMPs, hummocky moraine plateaus; OutP, outwash plains; UndMP, undulating moraine plateau.

1:25 000 scale. Using this map, all ponds (both natural and man-made) up to 5 ha in size were digitized (vectorized). Reference materials included a 1:10 000 scale raster topographic map, historical German topographic maps (Messtischblätter) from the early 20th century at a 1:25 000 scale, orthophoto maps, and satellite images. During the digitization process, the authors observed that the hydrological function of the ponds, in addition to their pattern, was a significant factor. As a result, pond groups occurring in clusters were identified. A pond group was defined as a cluster containing at least three ponds within a single terrain depression (bounded by a given contour). The classification of ponds into their hydrological functions was based on their connection to the river system, leading to the identification of lentic, outflow, and flow-through ponds. The hydrological function is also linked to string patterns, although no pond strings were designated due to the need for field verification. The collected cartographic data were cataloged in a Feature Geodatabase and subsequently analyzed spatially. After assigning a unique identifier to each pond, their area was calculated, and their spatial distribution was analyzed using cartographic methods (pond-density analysis). This analysis was conducted for two reference levels: 1 km^2 and 10 km^2 grids. Further geospatial analyses, due to the large number of features, were performed using the extract transform load (ETL) tool, specifically the feature manipulation engine (FME) by the SAFE software. These analyses assessed the distribution of ponds within various geomorphological units (Solon, 2018), considering both the size structure of the ponds and their hydrological function. All collected data underwent verification and both quantitative and qualitative validation, also utilizing the FME tool.

3. Results

In the 12 268 km^2 area of Gdańsk Pomerania selected for the study, 30 778 water bodies with an area of <5.0 ha were recorded based on 1:25 000 scale topographic maps. The average density of these hydrographic features is 2.5 ponds · km^{-2}. Despite such a high number of water bodies, nearly 48% of the area lacks ponds (Fig. 3). The highest concentration of ponds is found in the eastern, plateau region, where their average density exceeds 50 ponds · km^{-2} (Fig. 3). The lowest pond density (below 5 ponds · km^{-2}) is found in the south-western part and

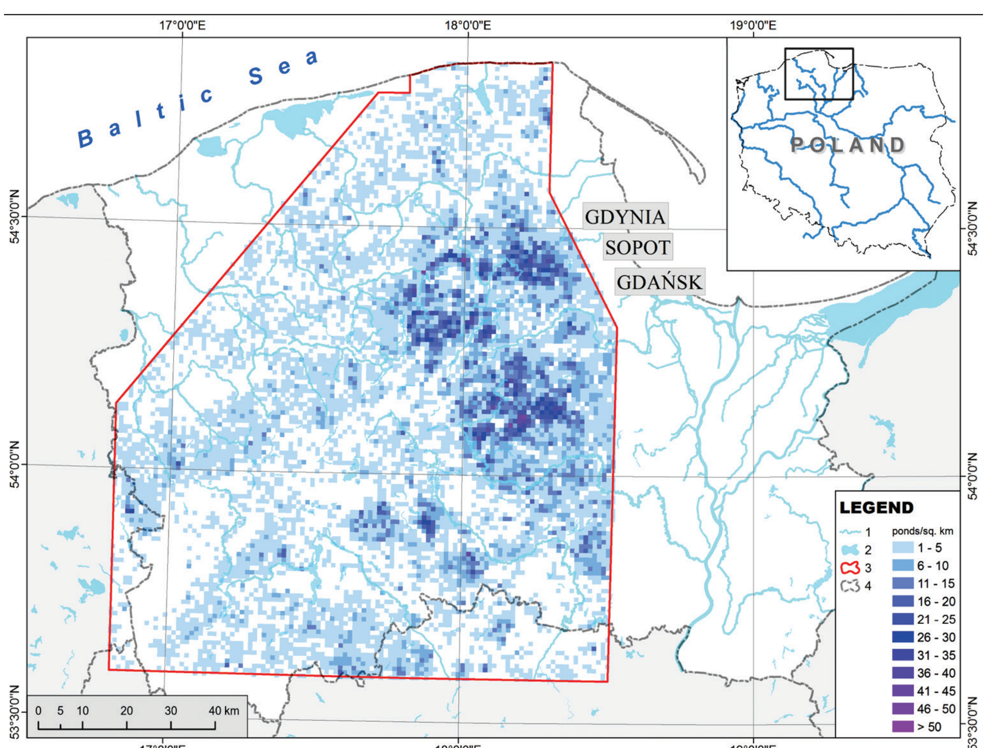

Figure 3

The density of ponds in the selected section of Gdańsk Pomerania (key: 1—watercourses, 2—water bodies, 3—study area boundary, and 4—administrative border).

the highest outwash plain levels, at the border with the Pomeranian watershed. A small number of ponds also occur in the valleys of larger Pomeranian rivers (Słupia, Łeba, and Brda).

Post-glacial pond studies indicate that the number and distribution of ponds correlate with geomorphological units (Drwal & Lange, 1985). This pattern was also observed in Gdańsk Pomerania, where nearly 67% of the ponds (20 558) occur on moraine plateaus (Fig. 4A), over 22% (6848) on outwash plains, and 10% (3187) in subglacial channels.

On moraine plateaus, the greatest number of ponds (11 241) occurs in undulating areas, where pond density is highest, averaging 5.7 ponds · km^{-2} (Fig. 4B) and reaching a maximum of 50 ponds · km^{-2} (Fig. 4C). On hummocky plateaus, there are fewer ponds (4611), with an average density of 4 ponds · km^{-2}, though a maximum of 84 ponds · km^{-2} is found. Ponds are less frequent on hilly and flat plateaus, with approximately 2300 ponds in total. The average density on hilly plateaus is 3.4 ponds · km^{-2}, while on flat plateaus, it drops to 1.7 ponds · km^{-2}.

On the expansive outwash plains, the average pond density is 1.6 ponds · km^{-2}, compared to moraine plateaus, with a maximum of 29 ponds · km^{-2}.

Ponds were categorized by size as follows:

- Very small: <0.1 ha
- Small: 0.1–0.5 ha
- Medium: 0.5–1.0 ha
- Large: 1.0–2.5 ha
- Very large: 2.5–5.0 ha

This classification partly follows the size division proposed by Drwal and Lange (1985).

The majority of ponds in the studied part of Gdańsk Pomerania are small and very small (Fig. 4D), totaling 29 243 (94%), with 21 832 (70%) being very small, and it is these smallest ponds that dominate across all geomorphological units (Fig. 4D). Only 6% of the ponds have an area between 1 ha and 5 ha.

The total area of all ponds in the study region is approximately 5014 ha. Although very small and small ponds dominate in number, they represent only half of the total pond area. Very small ponds account for 21%, small ponds for 31%, and large and very large ponds for 37% of the total area. This distribution reflects the average size of each category: very large ponds have an average size of 3.57 ha, large ponds of 1.57 ha, medium ponds of 0.71 ha, small ponds of 0.20 ha, and very small ponds of just 0.05 ha.

Pond size is primarily influenced by the terrain. Very small ponds are most common on undulating moraine plateaus, comprising nearly 80% of ponds in this geomorphological unit, with an average size of 0.10 ha. On other types of moraine plateaus (hilly, hummocky, and flat), very small ponds still predominate (60%–65%), but there is a higher proportion of small

Figure 4

(A) The number of ponds in geomorphological units, (B) pond density (ponds per 1 km^2) in geomorphological units, (C) maximum pond density (ponds per 1 km^2) in geomorphological units, and (D) share of ponds in size classes in geomorphological units (1—very small, 2—small, 3—medium, 4—large, and 5—very large). Designations: VD, ETerr, SubCh, HillMP, HummMP, UndMP, FMP, OutP, and Dun. Dun, coastal dunes; ETerr, erosive terraces; FMP, flat moraine plateau; HillMP, hill moraine plateaus; HummMP, hummocky moraine plateau; OutP, outwash plains; SubCh, subglacial channels; UndMP, undulating moraine plateau; VD, valley depressions.

ponds (about 30%). This results in a slightly larger average pond size ranging from 0.17 ha to 0.18 ha. Small and very small ponds are also prevalent on outwash plains and in subglacial channels. On outwash plains, they make up about 93% of all ponds in the study area, while in subglacial channels, they account for 91%. The average pond size on outwash plains is approximately 0.20 ha, and in subglacial channels, it is 0.23 ha. In valley depressions (VDs) and on erosive terraces, small ponds (51%–53%) and very small ponds (55%) predominate. Among the relatively few ponds in these geomorphological units, those found on erosive terraces are the largest, with an average area of 0.82 ha. The ponds in VDs and coastal dunes do not differ in size from those in other geomorphological units of Gdańsk Pomerania.

The spatial pattern of ponds

The manner of the layout of ponds gives their spatial pattern. Kalniet (1952) indicated that “the ponds appear both in clusters and individually, usually they are scattered randomly, sometimes they form strings.” The studies by Golus (2007) show some regularities in the pattern of these small water body forms in Lake District catchments. Some of these hydrographic features are chaotically distributed in the catchment area, while some show spatial regularity.

Chaotic pattern

Most ponds in the Lake District landscape are distributed irregularly or chaotically. Of the nearly 31 000 ponds recorded in the selected part of Gdańsk Pomerania, 70% have a chaotic pattern. They occur individually, occupying terrain depressions with favorable water conditions, and do not form part of a specific pattern. They are usually associated with the highest parts of the undulating or flat moraine plateaus (FMPs) whose relief prevents the organization of surface runoff, and the size of the depressions does not allow the formation of larger pond systems. Therefore, these are lentic and usually very small ponds. They are a relatively permanent element of the landscape.

Pond strings

Quite often, ponds are arranged in a linear manner creating a “cascade system,” the so-called pond strings (Fig. 5). These are the ponds lying at the bottom of elongated depressions that can be combined into one string connected by streams of a permanent or periodic nature or separated by a wetland or dry areas (Fig. 5). A string of ponds consists of at least three, and its course is determined by the river outflow direction. Strings of ponds can connect with each other to form

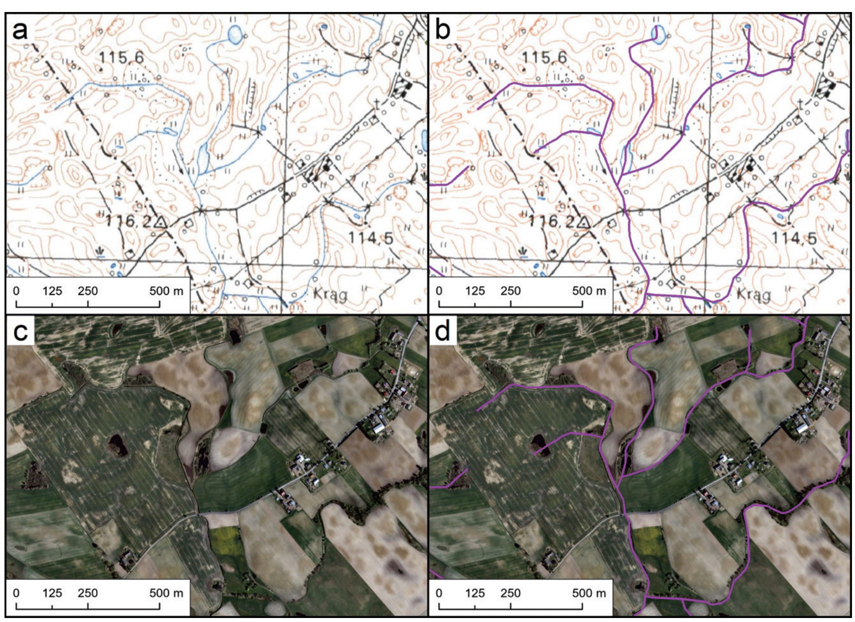

Figure 5

Probable course of pond strings: (A) topographic map 1:25 000, (B) the same topographic map with the marked pond strings (solid line—certain course, dashed line—uncertain course), (C) satellite image (source: maps.google.pl), and (D) satellite image with the probable course of pond strings.

"cascade systems" several hundred meters to several kilometers long, consisting of several dozen water bodies, including small lakes, similar to a river and lake system on a microscale. The end of a pond string can be a single water body, a pond or lake (lotic or lentic), or a permanent or periodic watercourse.

Strings of ponds occur mainly in plateau areas and in small and poorly developed subglacial channels incising moraine plateaus and outwash plains. Long strings of ponds are particularly abundant on flat and undulating moraine plateaus. There were no occurrences of pond strings in the hilly plateau landscape, i.e., in areas with significant relative height differences and large slopes. It can, therefore, be assumed that the factors favoring the formation of strings of ponds are relief (flat and undulating) and surface sediments (glacial till) limiting infiltration and promoting the formation of periodic and episodic watercourses.

Strings of ponds usually have a similar structure. Most often, they consist of a sequence of dry, longitudinal depressions. These depressions cut the upper parts of the moraine plateaus or dry subglacial channels. As the number of ponds and depressions connecting them increases, a periodic or permanent watercourse develops. The formation of a permanent watercourse usually results in the termination of the string of ponds. The string of ponds is, therefore, a specific periodically developing stream and water body system, in which the last link is a well-organized permanent watercourse (Golus, 2007).

Figure 5 shows how to determine the strings of ponds. Among those visible on the topographic map on a scale of 1:25 000, the following can be distinguished: flow-through, outflow, and lentic ponds (Fig. 5A). The ponds are connected by watercourses into a series (Fig. 5B, a continuous pink line). The beginning of the string is the outflow pond from which surplus water drains through the watercourse marked on the map, although it may also be a watercourse flowing into a flow-through pond. Figures 5C and 5D show a fragment of an orthophoto map of the same area. The determination of the strings of ponds on an orthophoto map or satellite image is more subjective. Determining them is hindered by the lack of contour lines and the small size of the examined features that disappear into the vegetation. It is possible, however, to notice differences in the shapes of the ponds and their size. Some ponds marked on the topographic map are not visible on the satellite image. However, the river network and elongated depressions of the terrain, which provide river runoff, are visible in the photo.

The given example shows that the correct determination of the strings of ponds based on a topographic map or aerial photo, especially in the area of moraine plateaus, is complicated and requires verification in the field. As demonstrated by the author's research (Golus & Bajkiewicz-Grabowska, 2017), strings of ponds are a dynamically changing system of the water network depending on excess water which occurs during spring thaws and intense summer rainfall. Therefore, in the selected area of Gdańsk Pomerania, the number of strings of ponds and their lengths was not determined.

Groups of ponds

In the Lake District landscape, ponds often appear in groups, occupying the bottom of a depression (Golus, 2007). A depression with a flat bottom must be occupied by at least three ponds, which are accompanied by swamps. Small permanent or periodic watercourses usually connect the ponds in the group. The border of the pond group is determined by the first contour above the bottom of the depression (Fig. 6). Groups of ponds may have no outflow or inflow, but there are also groups with surface drainage of surplus water, both outflow and flow-through. The size of the groups ranges from several hundred square meters to several hectares (Golus, 2007). Many ponds, both forming strings (Fig. 7) and groups (Fig. 8), are most likely of anthropogenic origin. An analysis of the content of the Messtischblatt 1:25 000 maps from 1902 shows that these are often recent excavations (peat pits) (Fig. 8).

Groups of ponds are common throughout the entire area of Gdańsk Pomerania. Of them, 441 are delimited here comprising 2522 ponds, i.e., 8.2% of the ponds in this part of Pomerania, and occupy a total area of 31.52 km^2. The number of ponds in a group ranges from 3 to 65 (Fig. 9), and the area of a single group of ponds ranges from 0.286 ha to 89.7 ha. The average group contains six ponds and covers an area of 7.15 ha. Groups of ponds occur in all types of post-glacial landscapes. Most of them are on the undulating moraine plateaus (159) and outwash plains (133). Individual groups of ponds are also found on erosive terraces and between coastal dunes. They are only absent in VDs (Figs. 10A–10C).

On the moraine plateaus, the average group has seven ponds in the hummocky and hilly landscape, six in the undulating landscape, and five in the flat plain landscape. The largest average area of a group of ponds is found in the flat plain landscape (9.86 ha), while the lowest is found in the

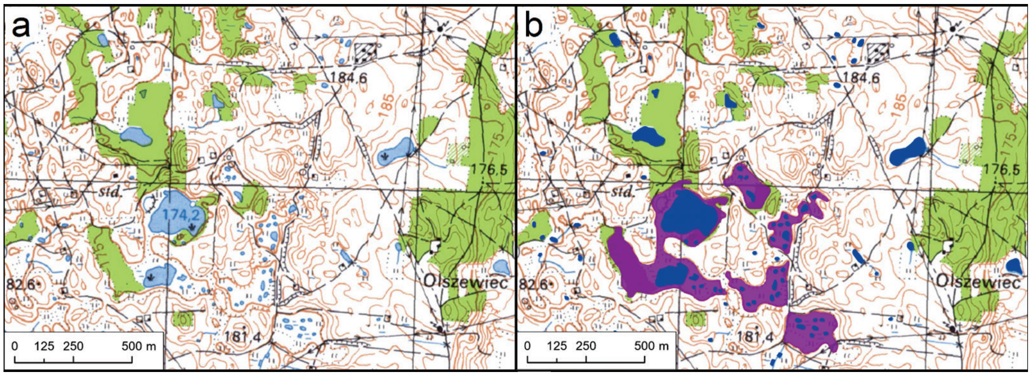

Figure 6

Delimitation of groups of ponds on topographic maps: (A) topographic map 1:25 000 and (B) the same map showing grouped ponds.

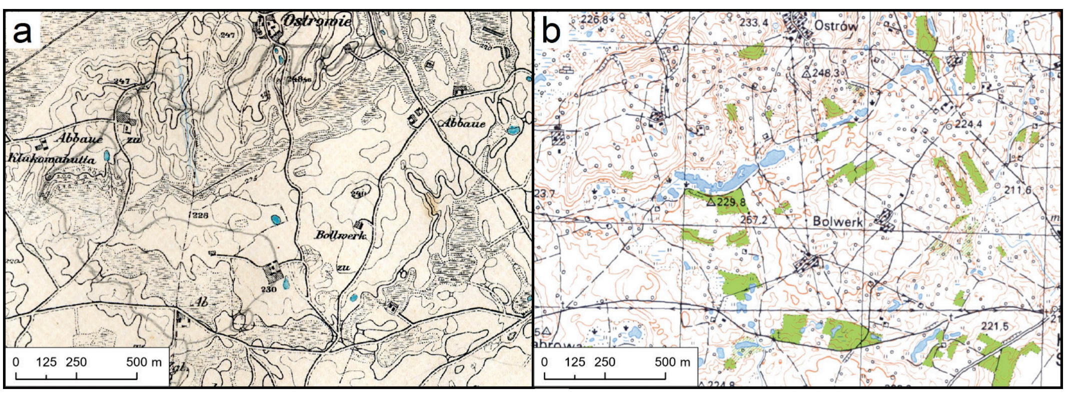

Figure 7

Strings of ponds on topographic maps: (A) Messtichblatt map at 1:25 000 (the year 1902) and (B) modern map at 1:25 000.

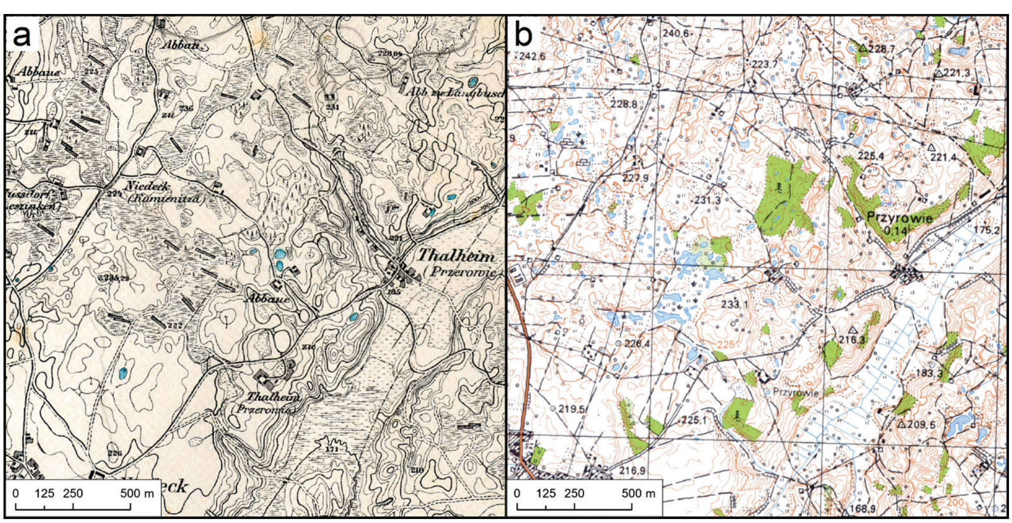

Figure 8

Groups of ponds on topographic maps: (A) Messtichblatt map at 1:25 000 (the year 1902) and (B) modern topographic map at 1:25 000 (1980).

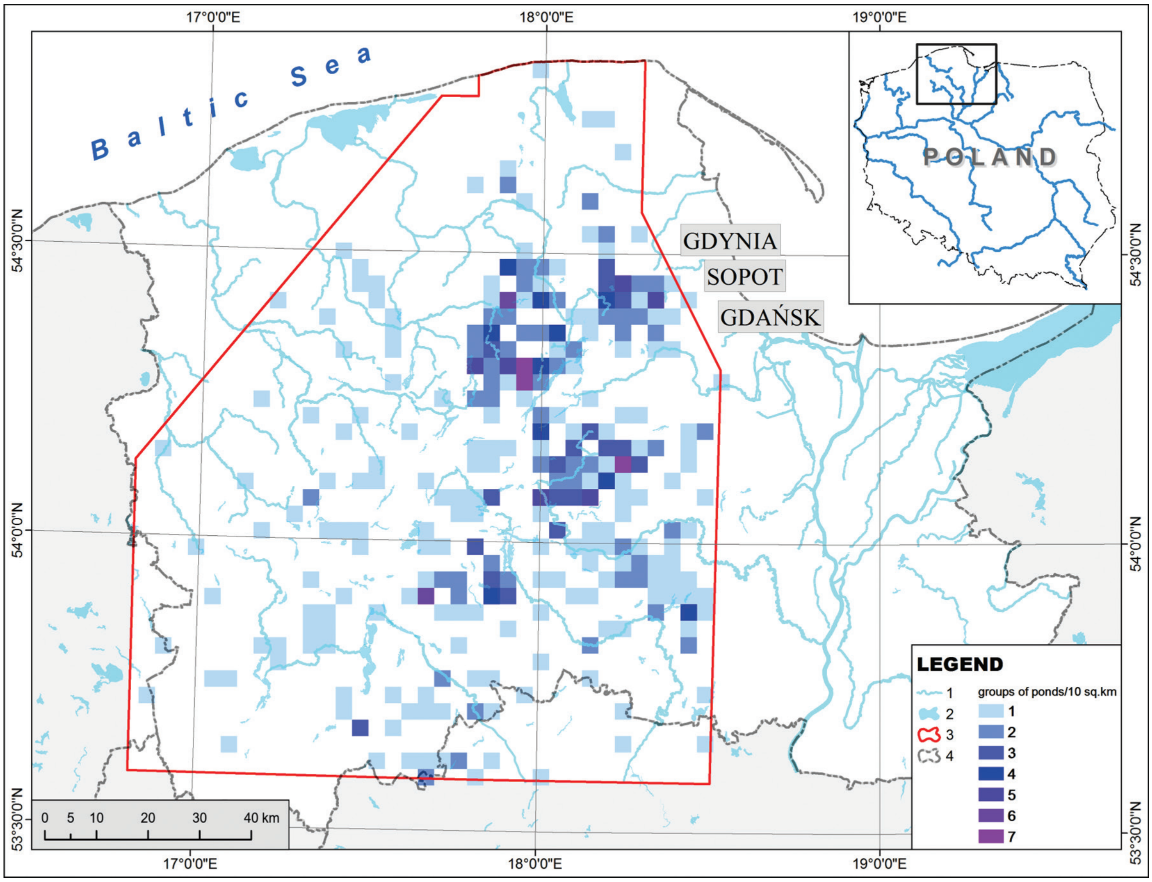

Figure 9

The density of groups of ponds in Gdańsk Pomerania (key: 1—watercourses, 2—lakes, 3—study area boundary, and 4—administrative border).

hilly landscape (5.01 ha). On outwash plains, the average group has five ponds and covers an area of 8.05 ha, while in subglacial channels, the average group is five, which occupies 8.08 ha. The total number of ponds concentrated in groups varies from 947 in the undulating landscape to 0 in valley depressions (Fig. 10D).

4. Discussion and limitations

Although ponds are small and seemingly insignificant elements of the post-glacial landscape, numerous attempts to quantify and analyze their historical presence are often imprecise or even contradictory. As a result, the number of ponds on regional, continental, or global scales is often estimated using formulas (Seekel et al., 2013), extrapolation from well-surveyed areas (Verpooter 2015), or readily available official spatial data (the so-called census) (Cael & Seekell, 2016). Homogeneous topographic maps and manual vectorization of these objects are rarely used. Even with state-of-the-art detection tools, researchers face various obstacles that make the exact number of ponds impossible to determine. Topographic maps based on field geodetic surveys are one of the most accurate methods for assessing pond numbers and distribution, and such maps are available for many regions. Based on these maps, the disappearance of ponds in the landscape is analyzed (Jeffries, 2016). Due to climate change, global warming, and the intensification of extreme weather events, small hydrographic features are particularly vulnerable, causing their numbers to fluctuate. This is confirmed by Polish research, where Pieńkowski (2004) stated that ponds in Poland are disappearing, and their numbers have decreased by several percentage points in various parts of north-western Poland over the past 100 years. Conversely, other researchers (Marszelewski & Podgórski, 2004) have found that the number of ponds in the Dobrzyń Lake District has increased.

It is also extremely difficult to base analyses of pond distribution on currently available aerial and satellite

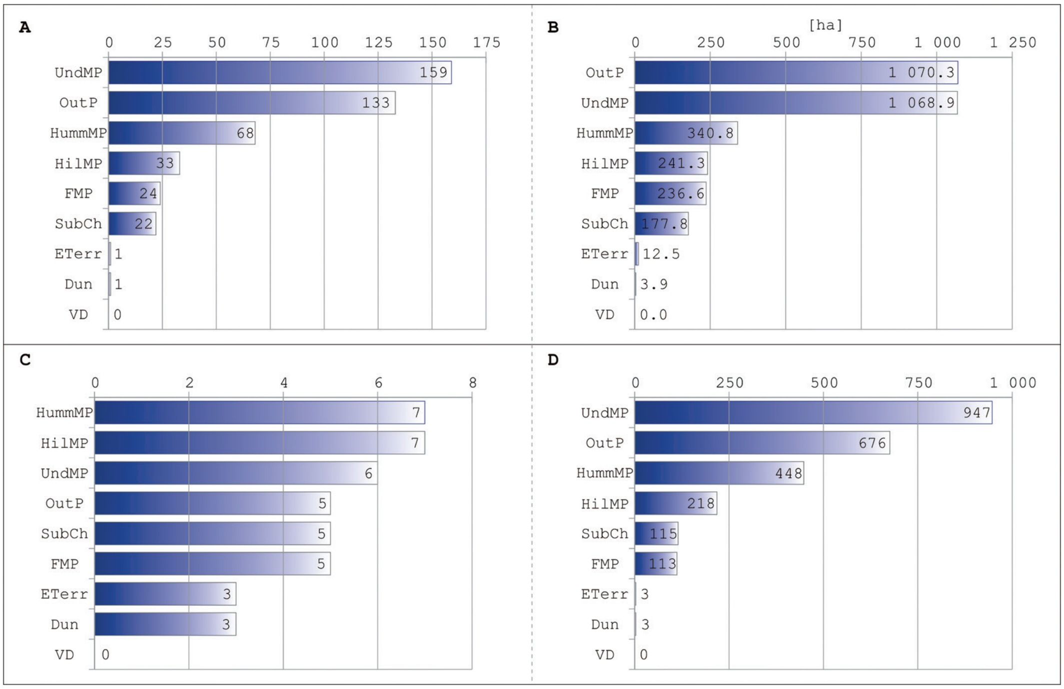

Figure 10

(A) The number of groups of ponds in geomorphological units, (B) the total area of groups of ponds, (C) the average number of ponds in a group, and (D) the total number of ponds in groups. Dun, coastal dunes; ETerr, erosive terraces; FMP, flat moraine plateau; HillMP, hill moraine plateaus; HummMP, hummocky moraine plateau; OutP, outwash plains; SubCh, subglacial channels; UndMP, undulating moraine plateau; VD, valley depressions.

images. While their quality and timeliness improve each year, like topographic maps, their accuracy varies by region. The biggest challenge in using these materials is the poor visibility of small hydrographic features. Ponds that are highly overgrown, located in forests, or hidden among dense vegetation are practically invisible and easily overlooked during surveys. This leads to underestimation in the results obtained, which is why older but more reliable cartographic materials were chosen.

Another issue hindering the pond inventory is the seasonal nature of some water bodies and the presence of ghost ponds that only appear during the wet season, typically in early spring in Poland. After a few months, these ponds dry up or transform into small swamps. Their presence is often revealed by moisture-loving vegetation or land use around these ephemeral ponds, excluding them from agricultural use. Another difficulty in estimating pond numbers is the presence of peat pits. These are easily identifiable due to their rectangular and clearly anthropogenic shape. Peat pits are common in some areas and often accompany natural water bodies. From a hydrological perspective, they are considered water bodies and are included in the total pond count.

When analyzing topographic maps, artificial water bodies can also be identified. In Gdańsk Pomerania, these were primarily created by damming a watercourse, flooding a previously dry depression, or digging a small basin and flooding it. It is often debatable whether such water bodies replaced former natural ponds or dry basins. These artificial water bodies are included in the total count, as they are part of the landscape, though they constitute only a small fraction of the total.

An essential element in this analysis is the selection of cartographic material. The authors chose to use maps at a scale of 1:25 000. Although the most accurate cartographic materials are not available, the available ones offer advantages that outweigh their limitations. First, the topographic maps were created around the same time, in the 1980s, and are colored, which significantly facilitates the identification of water bodies. More detailed and colored maps are available at a 1:10 000 scale, but they do not cover the entire area of Gdańsk Pomerania and were produced over a much longer period than 3 years, which would significantly increase the workload for a similar pond count. Therefore, older but more reliable material was chosen, with the understanding that the result obtained represents the historical distribution of ponds, and future verification will be necessary when more reliable and easier-to-interpret cartographic materials become available. A significant limitation of topographic maps is that due to generalization and limited printing capabilities, the smallest ponds are not marked on the maps (Jeffries, 2016). However, research by the authors indicates that the number of missing ponds in the overall count is negligibly small.

There is a strong need to expand knowledge about ponds. In Poland, there is a widespread lack of awareness about these small hydrographic features, even among authorities. Ponds are often classified as wastelands, and their owners can use them in any way they see fit. During field surveys, the authors observed significant human pressure on ponds, manifested primarily by deepening, drainage, reshaping, vegetation clearing, fish farming, and sewage disposal. There is a common belief that ponds do not interact with groundwater or the river network, and as a result, the law ignores them. This belief is incorrect, as demonstrated by numerous studies in Poland and around the world (Golus & Bajkiewicz-Grabowska, 2017; Onandia et al., 2018; Pätzig & Düker, 2021).

The vast number of ponds means they are considered a permanent element of the lake landscape, but their small size makes them highly sensitive and easily destroyed. Northern Poland, especially some areas of moraine plateaus, is a "pondscape", where ponds are a characteristic and common element of the landscape. This landscape is unique and should be protected. The role of ponds in the hydrological cycle is as important as their ecological function (e.g., Altenfelder et al., 2014; Davies et al., 2008; Lewis-Phillips et al., 2020; Riley et al., 2018).

Pond identification, their numbers, distribution, pattern, hydrological function, and size are the first steps toward their protection. It is essential to know what is being protected in order to do so wisely and thoughtfully. It is particularly noteworthy that some ponds are connected to the river system, making them part of the main drainage network.

Summary

A detailed analysis of topographic maps and the vectorization of mapped features allowed for the identification of nearly 31 000 ponds in the Gdańsk Pomerania region—an area that has not previously been subject to such a comprehensive survey. In some locations, their density reaches up to 50 ponds per km$^{2.}$ These ponds are typically very small, with an area of less than 1000 m^2, yet they play a crucial role both as landscape features and within the hydrological cycle. Until now, their exact number and spatial distribution were unknown. It had been previously assumed that they primarily occurred on moraine plateaus, forming part of the hydrological network of endorheic areas. However, the analysis of topographic maps, which are considered the most effective method for estimating their distribution, revealed that small water bodies are not only present within moraine plateaus but also, in significant numbers, across all geomorphological units of post-glacial landscapes.

Moreover, precise map analysis enabled the identification of spatial patterns among these ponds, revealing their tendency to form linear sequences (strings) and clustered arrangements (groups). Many ponds are located in depressions associated with poorly developed subglacial hollows and kettle holes. Pond strings are interconnected by intermittent watercourses, while grouped ponds are situated in close proximity within larger depressions. Although these spatial formations account for only a small proportion of all ponds (up to 20%), they may significantly influence ecological connectivity, hydrological processes, water storage, and future conservation efforts.

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