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Underwater landscapes of Lake Wielki Staw in the Karkonosze Mountains – the only high-mountain lobelia lake in Poland

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Abstract: The implementation of the sustainable development objectives, requires additional knowledge about underwater landscapes of inland reservoirs. In this article, we assumed that (1) underwater landscapes of lakes are shaped mainly by the type of substrate and the assemblages of flora and fauna inhabiting a given reservoir; (2) vegetation is one of the most important elements of underwater landscapes, which dynamically reacts to environmental changes. This article presents the results of a study on the underwater landscapes of Lake Wielki Staw in the Karkonosze Mountains. Thirteen types of underwater landscapes were distinguished in the lake based on underwater inventory and spatial analysis using ArcGIS 10.7 software. The level of changes that occurred in the underwater landscape studied was determined using the underwater landscape structure maps for 2005, 2011, 2017, and 2021. In addition, the landscape change index (*LCI*) for Lake Wielki Staw was determined for 2005–2011, 2011–2017, and 2017–2021. The results obtained indicate that underwater landscapes in lakes, similarly to terrestrial landscapes, are dynamic and subject to changes. In the case of Lake Wielki Staw, the changes in the range of *Isoëtes lacustris* communities in individual parts of the lake limited the differences in the area of all types of underwater landscapes distinguished. This allows us to use underwater vegetation inhabiting a given reservoir as an indicator of changes in underwater landscapes.

Keywords: GIS, landscape change indicator, mapping, scuba diving, underwater landscape, underwater scientific research

INTRODUCTION

For many years now, governments around the world have been taking actions related to the implementation of objectives of the sustainable development policy. These include the protection of ecosystem resources and services, and the conservation of the natural and cultural heritage of water reservoirs. Comprehensive surveys using a landscape approach are one of the primary sources of data used in spatial planning and development. They are used for the analysis of directions, dynamics, and possibilities for the transformation of space as a result of natural forces and human activity, e.g. Ganzei *et al.* (2020) and Senetra *et al.* (2023). The concept of landscape has been defined in many different ways (Hutchinson, 2016; Antrop, 2018; Atha *et al.*, 2018). The most commonly used definition of an aquatic ecosystems is that a landscape is an integrally homogeneous part of a water body with a solid geological foundation, the same type of relief, common climate, and similar biocenoses (Isachenko, 1982). Relief, geology, erosion patterns, vegetation cover, habitats and human activity are all taken into account, as is the case on the land ecosystem.

In the scientific literature, studies on the landscapes of seas and oceans are the most common, e.g. Torre-Castro de la *et al.* (2014), Alvarez-Berastegui *et al.* (2016), Tambutti and Gómez (2020). This does not mean, however, that underwater landscapes in freshwaters do not need to be studied. Unfortunately, there is little data in the literature on the underwater landscapes of inland freshwaters, e.g. Julian *et al.* (2013) and Delaere, Guédron (2022). However, we should remember that lakes are an important element influencing the economy of lake districts. Inland freshwaters are also essential for the functioning of local and regional ecosystems. In terms of habitats and organisms they contain, freshwaters are also highly valuable. Examples of this are habitats and species listed in the Natura 2000 documents, which include aquatic and underwater environments. For this reason, there is a need to expand scientific knowledge in the field of underwater lake landscapes.

The study assumes that lakes have a landscape that can be defined primarily by their bedrock (static and inanimate part of landscape) and by their animal and plant communities (dynamic and animate part of landscape). Vegetation is one of the most important elements of underwater landscapes, which dynamically responds to environmental changes. This means that it is possible to use plants as an indicator of changes in the underwater landscape. For the purpose of testing the validity of the research hypothesis, one of the lobelia lakes located in Poland, Lake Wielki Staw in the Karkonosze Mountains, was chosen.

MATERIALS AND METHODS

Description of the study area. Lake Wielki Staw is located in the Karkonosze National Park (Fig. 1), the Karkonosze Mountains in the Western Sudetes, south-western Poland. The lake is situated at an altitude of 1225 m a.s.l. on the north-eastern slope of Smogornia, in the post-glacial Kocioł Wielkiego Stawu. Lake Wielki Staw has an area of 8.321 ha, a shoreline length of 1540 m and the maximum depth of 24.4 m. The water temperature reaches a maximum of 14°C.

Lake Wielki Staw is the only lobelia lake located in the mountainous region of southern Poland. Due to its unique vegetation and fauna, the area around the lake is strictly protected and access to it is forbidden. A relic of the post-glacial period, *Isoëtes lacustris* grows in the waters of the lake. The fauna includes *Turbellaria*, *Triturus alpestris* and *Salmo trutta* m. *fario*, as well as a melanistic variety of *Bufo bufo* (Knapik, Migoń and Raj, 2017; Spallek (ed.) 2021). Lobelia lakes are soft-water oligotrophic, mesotrophic and early stages of dystrophic lakes. Wherever they occur, they are treated as valuable ecosystems requiring special care due to their high sensitivity to environmental changes. In the European Union, lobelia lakes are recognised as endangered ecosystems of pan-European importance (Natura 2000 network, natural habitat 3110) (Council Directive, 1992). Lobelia lakes are also covered by the Convention on the Conservation of European Wildlife and Natural Habitats – Bern Convention (Convention, 1982).

Underwater surveys. Having obtained all the permits required by Polish legislation, two teams of qualified scuba divers conducted underwater surveys of the whole lake bottom in 2011, 2017, and 2021. During each diving session, the divers' position was monitored by two researchers in a boat, and divers described the appearance of the bottom on special plates with tables containing fields, such as depth, bottom cover with vegetation or lack of it, type of bottom (slope, ground structure), presence of stones and boulders, and presence of wood fragments. At the same time, the location of the site of was determined with the use of a Garmin GPS receiver (waypoints, to specify geographic

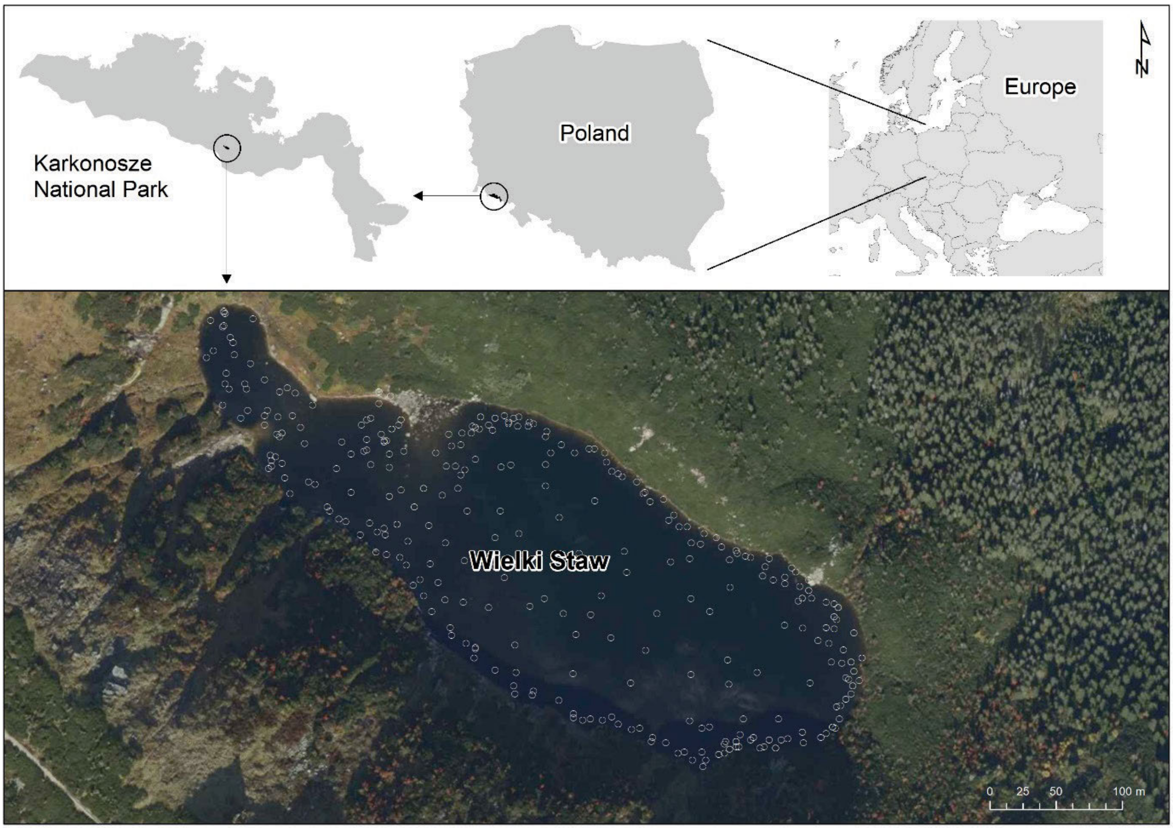

Fig. 1. Location of the studied lake; centroids of research plots were marked on the surface of the lake; source: own study

coordinates), and relevant information was communicated to team members on the surface.

Compact patches of *I. lacustris* (places where it formed its own communities) were considered to be areas where the bottom coverage by plants per 1 m^2 was greater than or equal to 25%. The remaining places of findings were described as occurrence sites.

Underwater notes were taken each time the nature of the landscape changed. The variability of landscapes was documented in photographs in parallel with the underwater recordings.

Classification and mapping. Field data formed the basis for the classification of underwater landscapes. The first stage of work consisted in exporting a point cloud with numbers corresponding to underwater notes from a GPS receiver to ArcGIS 10.7 software. The points marked the centroids of study plots, which were assigned a specific underwater inventory plot (sometimes different depending on visibility). Then, the type of landscape appropriate for each plot was determined and boundaries set between them. The results of the 2005 study (Bociąg *et al.*, 2007) were also used for spatial analyses. The occurrence of aquatic mosses was not included in the analyses, as no communities were found during the authors' own research. This may be due to the ephemeral nature of this group of plants. Spatial analyses allowed to map the distribution of each landscape type, as well as changes in the extent of *I. lacustris* occurrence and landscape change dynamics over the period of 14 years.

The landscape change index (*LCI*) was determined according to the method provided by Krajewski (2018). The essence of this method is to compare values obtained by means of a quantitative analysis of each landscape type in a selected period of time with the value obtained for the previous period, called the reference criterion. Variation of the surface relative to the reference criterion by 1% is equal to a deviation of +1 or −1. Deviation from the reference criterion gives information about changes in the area of individual landscape types. The sum of absolute values obtained for all the analysed landscape types makes it possible to determine the *LCI*.

This analysis is performed in the stages described below.

$$P_{ij} = \frac{A_{ij}}{A} 100 \tag{1}$$

where: P_{ij} = percentage of the total lake area occupied by landscape type i in the year of research j, A_{ij} = area of landscape type i in the research year j, A = total area of the of the studied lake.

$$V_{ik} = P_{ik_1} - P_{ik_0} \tag{2}$$

where: V_{ik} = change in the percentage of the area of the landscape type i in the total area of the lake in relation to the reference criterion in the selected period k (in this case: 2005–2011; 2011–2017 and 2017–2021); P_{ik_1} takes the value of P_{ij} for the landscape type i from the year being the final year of the analysed period; P_{ik_0} = reference criterion, takes the value of P_{ij} for the landscape type i from the year which is the beginning of the analysed period.

$$D_{ik} = \frac{V_{ik}}{1\%} \tag{3}$$

where: D_{ik} = deviation of the area of landscape type i from the reference criterion in the selected period k (in this case: 2005–2011; 2011–2017 and 2017–2021).

$$LCI = \sum_{i=1}^{n} |D_{ik}| \tag{4}$$

where: LCI = landscape change index in the selected period, n = number of landscape types i in in the selected period k, $|D_{ik}|$ = absolute values of D_{ik}.

The results of spatial analyses were used to verify the research hypotheses.

RESULTS AND DISCUSSION

On the basis of the research results, two groups and 13 landscape types were distinguished in Lake Wielki Staw. Landscapes with inanimate elements were the first group to be identified. In these group, 8 types of landscapes were distinguished. Landscapes with animate elements formed the second group. There were 5 types of landscape in the group. The details of particular groups and landscape types are summarised in Table 1. In Lake Wielki Staw, landscapes with inanimate elements were clearly dominant in all years of the study (Tab. 1, Fig. 2).

As already mentioned, research on underwater landscapes to date has mainly applied to large water reservoirs (primarily seas and oceans) that are of great human importance. For instance, based on the shape of the bottom and the presence of vegetation, Beurier (2002) identified eight main types of "natural" underwater landscapes in the sea. A classification of coastal landscapes of the Shkota Island (Sea of Japan) was presented by Ganzei *et al.* (2020). This was also based on the shape of the bottom and the presence of macrophytes, calcareous coralline algae, benthic microalgae or seagrass meadows. It was pointed out that the types of natural landscapes that occurred in the underwater part of the Baltic Sea were mainly determined by the type of substrate and communities of flora and fauna that present (Zaucha, 2018). In the case of lakes, the research focused on large water reservoirs (of very diverse geological structure, very large depths, and heterogeneous distribution of vegetation and animals), such as Baikal, for which a landscape zoning scheme was developed (Karabanov *et al.*, 1990; Timoshkin *et al.*, 2005). It covered 61 bottom landscapes and 11 physical and geographical regions of the basin. Additionally, studies of the coastal zones of the lake allowed to determine the specificity of its development and allowed to define its unique biodiversity (Potemkina and Suturin, 2008).

Therefore, it can be assumed that the scheme proposed in this article for subdividing the underwater landscapes of Lake Wielki Staw is correct. On the basis of the geospatial information gathered, the distribution of the different types of underwater landscapes in Lake Wielki Staw was mapped for each year of the survey (Fig. S1).

When analysing the data presented in Tables 1 and S1 and Figure S1, it can be seen that the underwater landscapes of Lake Wielki Staw are characterised by a certain degree of variability.

In 2005 (Tabs. 1 and S1, Fig. S1a), *I. lacustris* communities occupied the largest area in the north-western part of the lake and formed a landscape that was mainly of the BL1 type. On the south-eastern shore of Lake Wielki Staw, there was the second (smaller) patch of *I. lacustris* which formed a landscape of the BL2 type. A small area of the BL4 landscape and two small patches of the BL3 landscape were also identified in that year.

Table 1. Areas occupied by specific types of landscapes in particular years of research

Landscape group	Landscape type	Total area (ha) of a particular landscape type in a given year			
		2005	2011	2017	2021
Landscapes with inanimate elements (AL)	steeply sloping bottom with the presence of boulders and stones (AL1)	1.66	1.66	1.66	1.66
	sloping bottom with the presence of boulders, stones, branches and twigs of *P. mugo* growing on the banks of the lake (AL2)	1.12	1.12	1.12	1.12
	flat, sandy bottom, with the presence of boulders, stones, branches and twigs of *P. mugo* growing on the banks of the lake (AL3)	1.00	1.38	1.61	1.51
	gently sloping bottom with the presence of boulders, stones, branches and twigs of *P. mugo* growing on the banks of the lake (AL4)	0.93	0.68	1.12	1.07
	flat, sandy bottom with the presence of stones and boulders (AL5)	0.87	0.87	0.87	0.87
	flat, sandy bottom with the presence of stones (AL6)	0.35	0.38	0.41	0.41
	steeply sloping bottom with the presence of walls, boulders and stones (AL7)	0.33	0.32	0.33	0.33
	flat, sandy bottom (AL8)	0.08	0.09	0.09	0.09
Total area of landscapes with inanimate elements		**6.34**	**6.5**	**7.21**	**7.06**
Landscapes with animate elements (BL)	flat, sandy bottom, with the presence of boulders, stones, branches and twigs of *P. mugo* growing on the banks of the lake and *I. lacustris* communities (BL1)	0.66	0.28	0.05	0.15
	gently sloping bottom with the presence of boulders, stones, branches and twigs of *P. mugo* growing on the banks of the lake and *I. lacustris* communities (BL2)	0.57	0.82	0.38	0.43
	flat, sandy bottom with the presence of stones and *I. lacustris* communities (BL3)	0.06	0.03	0.00	0.00
	flat, sandy bottom and *I. lacustris* communities (BL4)	0.01	0.00	0.00	0.00
	steeply sloping bottom with the presence of walls, boulders, stones and *I. lacustris* communities (BL5)	0.00	0.01	0.00	0.00
Total area of landscapes with animate elements		**1.30**	**1.14**	**0.43**	**0.58**

Source: own study.

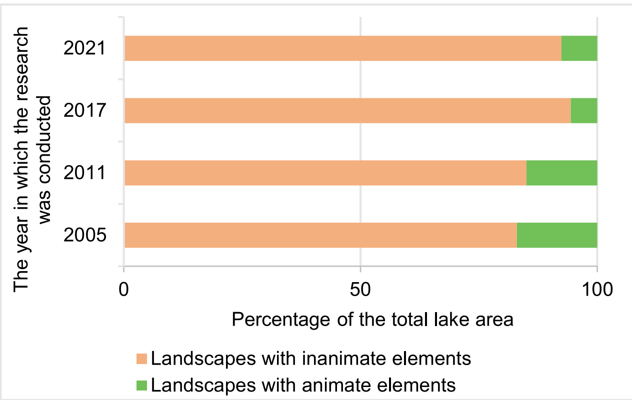

Fig. 2. Contribution of each landscape group to the total area of the lake in successive survey years; source: own study

During the 2011 survey (Tabs. 1 and S1, Fig. S1b), it was noted that *I. lacustris* had receded from practically half of the area in the north-western part of the lake within four years. This changed the character of the landscapes in this part of the lake to one dominated by landscapes with inanimate elements. Moreover, the area of the BL2 landscape has almost doubled (in comparison to 2005) and was it found in two large and dense patches. A small area of the BL5 landscape was also recorded in that year.

In 2017 (Tabs. 1 and S1, Fig. S1c), a significant regression of *I. lacustris* was observed. This resulted in the lowest proportion of all landscape types with animate elements among all of the survey years. Out of the 5 landscape types with animate elements that were identified, only 2 were found. The area of the BL1 landscape was 12 times smaller than in 2005 and 6 times smaller than in 2011, while the area of the BL2 landscape was 1.5 times smaller than in 2005 and twice smaller than in 2011.

An increase in the area of landscapes with animate elements was observed in 2021 (Tabs. 1 and S1, Fig. S1d). This was due to an increase (compared to 2017 observations) in the number of *I. lacustris* communities in Lake Wielki Staw. In the north-western part of the reservoir, three new small patches of *I. lacustris* were recorded, resulting in a threefold increase (compared to 2017) in the area of the BL1 landscape. It should be noted that this landscape did not form a compact area but had an island character. Meanwhile, the area of the BL2 landscape has increased due to an increase in a dense patch of *I. lacustris* in the south-eastern part of the lake.

The landscape change index (*LCI*) was calculated for three research periods (Tab. S1). In the first study period (2005–2011), the *LCI* was 17.80, in the second period (2011–2017), it was 18.59, and in the third period (2017–2021), the *LCI* was 3.93. Therefore, more intensive changes in the underwater landscape of Lake Wielki Staw took place in 2005–2011 and 2011–2017. In these periods, the main reasons for the transformation should be sought. A decrease in the area occupied by *I. lacustris* communities, and thus a decrease in the area of landscapes with animate elements, with a concomitant increase in the area of landscapes with inanimate elements, was the main factor influencing the higher *LCI* level.

Landscapes are known to be constantly undergoing natural processes and alteration by human activity (Jaszczak, 2019; García-Martín *et al.*, 2021; Stephens *et al.*, 2021; Trykacz and Bernat, 2022). The consequence of this is the variability of the landscape. This means that potentially serious consequences for the landscape configuration can result from a small change in the land cover over time. In the case of underwater landscapes, as confirmed by the research carried out in Lake Wielki Staw, the dynamics of changes taking place can be observed by monitoring vegetation growing under water (e.g. Léonard *et al.* (2008), Pankeeva and Mironova (2019), Ganzei *et al.* (2020), and Pankeeva and Mironova (2022)).

It should also be noted that there is a growing pressure to use non-expert assessment of underwater landscape variability for the initial monitoring of habitats of natural value worldwide, and that the use of such information for the monitoring of the habitats should also be encouraged (Pert *et al.*, 2020).

CONCLUSIONS

The research hypothesis set out in the article was confirmed by the results of the survey and analysis. As a result of mapping the underwater landscapes of Wielki Staw in the Karkonosze Mountains, 13 types of landscapes were identified. These were primarily determined by the type of bottom (inanimate and static element of landscape) and the type of vegetation (animate and dynamic element of landscape) that inhabited the lake. The differences in the area of all the landscape types distinguished were limited by the variation in the extent of *Isoëtes lacustris* communities in different parts of the lake. Landscapes with inanimate elements formed dense areas, whereas landscapes with *I. lacustris* often had an island character. In the same way as terrestrial landscapes, the underwater landscapes of lakes are dynamic and variable. For the initial monitoring of underwater ecosystems, it is appropriate to assess the variability of underwater landscapes in reservoirs with a small number of plant communities composed of characteristic (easily identifiable) species. Even untrained hydrobotanists can provide basic information for expert monitoring of habitats and species by recording changes in the area and structure of landscapes.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at https://www.jwld.pl/files/Supplementary_material_Dynowski.pdf

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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