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POSSIBILITIES OF DEVELOPING MAPS OF SIGHT-AESTHETIC ATTRACTIVENESS OF UNDERWATER LANDSCAPES OF LAKES USING THE POINT-VALUATION METHOD AND SPATIAL INTERPOLATION METHODS

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ABSTRACT

Motives: The research investigates the feasibility of using interpolation algorithms for assessment using the point-valuation method in different types of lakes. It shows the possibilities of using the proposed methodology for underwater landscapes under various environmental and geographical conditions.
Aim: The aim of the study is to test the point-valuation method for assessing the sight-aesthetic value of lakes in terms of potential for tourist exploration. The results are presented in the form of maps, resulting from spatial interpolation methods based on a random measurement network.
Results: Maps showing the distribution of the phenomenon under study can serve as a tool for protection and planning of development and tourist use of lakes. Dedicated spatial interpolation methods for this type of assessment map were identified. The methodology is universal and can be applied, with appropriate modifications, in various types of water bodies (lakes).
Conclusion: Successful implementation of point-valuation methods and interpolation algorithms for assessing the sight-aesthetic attractiveness of underwater landscapes of lakes has been achieved. These are pioneering studies in the field of underwater landscape perception and cartographic presentation methodology. This contributes to the development of principles for protection, tourist use (qualified tourism – diving), and channelling tourist traffic in places attractive to users.

Keywords: sight-aesthetic value, underwater landscape, point valuation, interpolation, perception, Poland

INTRODUCTION

Assessment of the sight-aesthetic value of underwater lake landscapes is a relatively new issue. Until now, a comprehensive methodology addressing this topic has not been developed. Moreover, the methodology is still in the developmental phase. Often, such research works reference methods used in the assessment of sea and ocean landscapes (Dynowski et al., 2024; Musard, 2014b, 2014a; Pungetti, 2012).

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At the same time, all attempts to study underwater landscapes are based on the methodology of land landscape assessment. The aim, both in land and underwater studies, is to understand the dynamics and directions of the processes shaping landscapes. The factors causing changes and specific values are divided into anthropogenic and natural. The effects of these processes are also reflected in the sight-aesthetic attractiveness (Gosal & Ziv, 2020).

The purpose of this study is to test the possibility of applying the point-valuation method to assess the sight-aesthetic value of lakes. The proposed methodology has been developed based on algorithms used in terrestrial landscape assessment. The set of components of the assessed landscape (in this study) aims to identify landscapes particularly valuable in terms of their potential for tourist exploration. The detailed objectives concern the applicability of geometric (regular) measurement networks randomly distributed over the map base of the studied lakes. Additionally, an attempt was made to answer the question: are the interpolation algorithms available in Geographic Information Systems (GIS) suitable tools for developing and graphically presenting the attractiveness of underwater landscapes? Lakes with diverse environmental and geographical conditions were studied to compare the applicability of the described methodology to different types of underwater environments.

LITERATURE REVIEW

So far, no single definition of an underwater lake landscape has been developed for the purpose of assessing its sight-aesthetic attractiveness. Moreover, such attempts mainly focus on the underwater landscapes of seas and oceans. These definitions are often derived from those used for land landscapes. The number of such definitions is vast and depends on the purpose of the assessment (e.g., tourist exploration, residential construction, recreational development), often taking the form of classifying an area for different functions (Aretano et al., 2013; Fadel, 2016). Visual attractiveness is one of the most important factors in determining the function of a given area (Domon, 2011; Hur et al., 2010). Visual methods using point-valuation are commonly applied to assess the sight-aesthetic attractiveness of landscapes (Badouna & Fadel, 2014). One of the key trends in land landscape research is to consider the landscape as a multisensory concept, perceived through all senses (Wu, 2024). This aligns with the experience of underwater landscapes, which are perceived through all senses during exploration.

One of the first attempts to define the underwater lake landscape was undertaken by researchers in Poland (Senetra et al., 2023). The definition was based on an aesthetic approach to the assessment of land landscapes. “An underwater landscape is a heterogeneous, distinct portion of the underwater surface, composed of various ecosystems interacting with each other. These factors can be natural and/or anthropogenic” (Dynowski et al., 2024). In the case of very large lakes, schematic regionalisations of the lakebed, geological structures, distribution of fauna and flora, or biodiversity are also proposed (Karabanov et al., 1990; Potemkina & Suturin, 2008).

In the light of aesthetic theory, the most accurate assessment is based on field inventory, though it is highly labour-intensive (Barroso et al., 2012). Cartographic or photographic inventory does not yield as effective results as direct observation. Moreover, the development of modern technologies allows for increasingly time-efficient research. Firstly, the use of underwater scooters enables faster movement for diver-observers. Secondly, available underwater navigation systems optimise movement routes and increase diver safety during underwater research. Thirdly, the functionality of electronic consoles facilitates automatic, semi-automatic, and manual measurement recording, as well as taking photographs and videos documenting the underwater inventory.

Apart from the mentioned studies, no more advanced attempts to explain the phenomenon of underwater lake landscapes have been noted. Research based on marine landscape experiences, which focus on physical features as carriers of attractiveness, is thus justified. An undeniable

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aspect of this attractiveness is the development of specialised tourism related to diving (Cavallini et al., 2023), underwater photography and filming, as well as mapping and visualisation using 3D technology (Musard, 2014b, 2014a). The advancement of modern technologies, education, and awareness of the uniqueness of the underwater world ensure easier access to underwater attractions. Diving tourism is currently experiencing the highest growth dynamics (Dimmock & Musa, 2015). However, this tourism also poses a significant threat to ecosystems. Therefore, research on underwater landscapes is crucial for guiding tourist traffic and protecting the most valuable species and geological formations (Betti et al., 2019). In terms of the development of underwater landscape research, experienced divers play a decisive role. They are unquestionable experts, and their insights are invaluable in developing methodologies for assessing the attractiveness of these landscapes, including in terms of sight-aesthetic value (Johansen, 2013).

MATERIALS AND METHODS

Description of the Research Objects

Five lakes were selected for analysis: Turkusowe, Gałęziste, Muliczne, Białe, Staw (Fig. 1). These lakes are located in Poland. Four of them are situated in the northeastern part of the country, with three located in Wigierski National Park (Gałęziste, Muliczne, Białe) (Table 2, Table 3, Table 4), and one within the Natura 2000 Augustów area – Staw (Table 5). The last one, Lake Turkusowe, is located in the northwestern part of Poland, within Wolin National Park (Table 1). These lakes differ in type and origin, as shown in Table 1–Table 5 and in the descriptive characteristics. This diversity allowed for testing the proposed methodology on different objects, enabling necessary adjustments and recommendations to be made.

Lake Turkusowe (area 6.7 ha, maximum depth 21.2 m) is located on the Wolin Island (Wolin Landscape Park). It is an artificial reservoir formed after World War II in a former chalk quarry near Lubin. The lakebed is located below sea level (cryptodepression). As the name suggests, the water colour is turquoise, which arises from the reflection of sunlight off water containing calcium carbonate compounds and a white limestone lakebed. The lakebed is highly varied with numerous pits and mounds left after chalk extraction. Near the shores, the lakebed drops very steeply, in places forming small vertical walls. Visibility varies depending on the amount of precipitation and surface runoff, which brings a lot of mineral and organic suspension into the reservoir. Underwater, one can admire the post-mining landscape with remnants of equipment, fragments of a road, and trees left along the shores, serving as shelters for perch, roach, and tench. Submerged vegetation is dominated by communities of *Myriophyllum*, with some areas of *Potamogeton* and *Ceratophyllum*. Description of the lake is presented in Table 1.

Lake Gałęziste (area 3.83 ha, maximum depth 14.3 m) is located in the Wigry National Park. The visibility of this eutrophic body of water ranges from 1.5 to 3 m. Near the shores, the lakebed is steep up to a depth of about 4 m. Deeper, it is level, muddy, and gently slopes towards the deeper parts. The underwater landscape around the shores is shaped by a large number of overturned trees and fallen branches, providing natural hiding spots for perch. The submerged vegetation is mainly *Ceratophyllum* and *Myriophyllum*, with a significant presence of floating *Potamogeton* forms, as well as *Nuphar* and

Table 1. Description of Lake Turkusowe

Location	Area	Depth	Trophic type	Bottom and vegetation	Form of protection
Wolin National Park; Natura 2000 Wolin and Usedom Area PLH320019	6.7 ha	max. 21.2 m	–	Chalk quarry excavation (glacial erratic). Karst phenomena occur. The substrate is marl-limestone.	–

Source: own elaboration.

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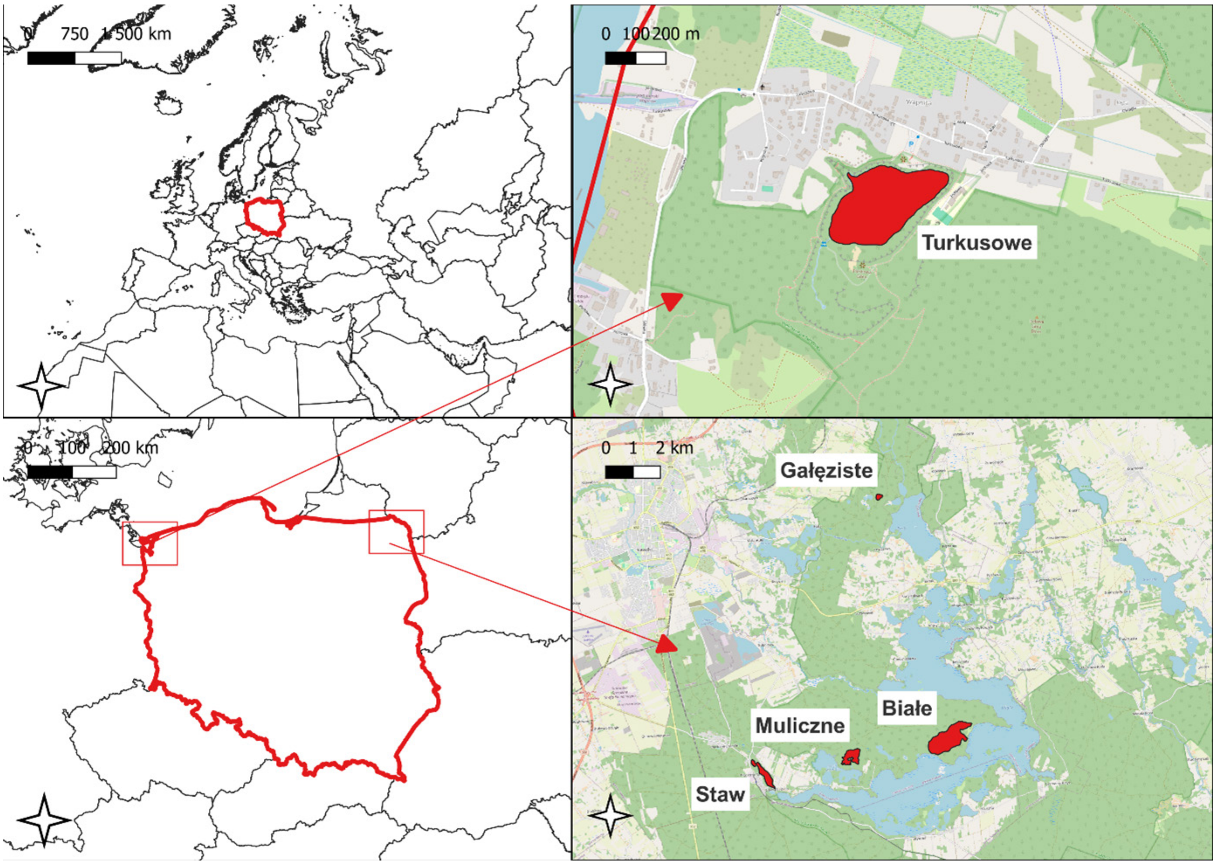

Fig. 1. Location of assessed lakes
Source: own elaboration.

Nymphaea. *Chara* is scarce – virtually not forming its own communities. Description of the lake is presented in Table 2.

Lake Muliczne (area 25.67 ha, maximum depth 11.3 m) is located within the Wigry National Park. It is a eutrophic lake. It is characterised by high biodiversity, both habitat and microhabitat. Visibility is at the level of 1–3 m. Near the shores, the lakebed is occasionally steep, and from a depth of 5 m it becomes level and gently slopes towards the deeper parts. Chara is quite common up to depths of even 5 m. Dominant among the macrophytes are *Ceratophyllum* and *Myriophyllum*, *Nuphar lutea*, and several species of *Potamogeton*. Notable are extensive communities of sea milfoil that cover large areas of the lakebed near the peninsula. The ichthyofauna mainly includes

Table 2. Description of Lake Gałęziste

Location	Area	Depth	Trophic type	Bottom and vegetation	Form of protection
Wigry National Park; Natura 2000 Augustów Site PLH200005 and Augustów Forest PLB200002	3.83 ha	max. 14.3 m	alkalitrophic	A rich phytocoenosis with high species diversity. There are both plants with floating leaves, submerged, and terrestrial-aquatic plants present.	–

Source: own elaboration.

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pike and perch. Detailed description of the lake is presented in Table 3.

Lake Białe Wigierskie (area 101.89 ha, maximum depth 34.0 m) is located in the Wigry National Park. Until recently, it had the characteristics of an oligo-mesotrophic lake. It is now classified as a well-preserved eutrophic lake. It features good visibility, occasionally reaching several meters. It is a stratified lake that mixes down to the lakebed. Vegetation covers the lakebed up to several meters deep. Chara meadows are observed down to depths of even 9 m, ensuring good oxygenation of the water. Submerged vegetation is dominated by various species of *Chara*, *Potamogeton*, and *Alopecurus*. Noteworthy is the poorly developed reed belt composed mainly of common reed and lake bulrush, which encircles the lake in a very narrow and often intermittent strip. Detailed description of the lake is presented in Table 4.

Lake Staw (area 20.75 ha, maximum depth 14.2 m) is located west of Lake Wigry, on the border of the Wigry National Park. It is a shallow eutrophic water body. Its specificity is associated with numerous seeps scattered across the entire lakebed, creating a spectacular landscape of "mineral-filled holes" within extensive *Chara* meadows. It is one of the few lakes in the country where the bottom is covered by 80% dense communities of *Chara*. Their presence ensures high oxygenation of the water and significant water clarity, often to the bottom. The lakebed is sandy and sandy-muddy apart from areas with various species of *Potamogeton*, *Alopecurus*, *Nitella*, *Ceratophyllum*, and *Myriophyllum*. Among the common species of animals other than fish, crayfish, and molluscs, extensive colonies of freshwater sponges can be found. Detailed description of the lake is presented in Table 5.

Table 3. Description of Lake Muliczne

Location	Area	Depth	Trophic type	Bottom and vegetation	Form of protection
Wigry National Park; Natura 2000 Augustów Site PLH200005 and Augustów Forest PLB200002	25.7 ha	max. 11.3 m	mesotrophic	High biodiversity, habitat diversity, and microhabitat diversity. Chara meadows.	Subject to strict protection

Source: own elaboration.

Table 4. Description of Lake Białe

Location	Area	Depth	Trophic type	Bottom and vegetation	Form of protection
Wigry National Park; Natura 2000 Wigry SitePLH200004 and Augustów Forest PLB200002	100.2 ha	max. 34.0 m	mesotrophic	Submerged vegetation is dominated by a community of Chara. Vascular plants are sparse.	Subject to strict protection

Source: own elaboration.

Table 5. Description of Lake Staw

Location	Area	Depth	Trophic type	Bottom and vegetation	Form of protection
Natura 2000 Augustów Site PLH200005 and Augustów Forest PLB200002, Augustów Forest and Lakes Area of Outstanding Natural Beauty; buffer zone of the Wigry National Park	20.75 ha	max. 14.2 m	mesotrophic	Sandy and sandy-muddy bottom densely covered with submerged vegetation. In the water column, Chara vegetation predominates.	–

Source: own elaboration.

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Development of the point valuation method

A point valuation method for the assessment of underwater landscapes of lakes was developed, with a maximum score equal to 39 points and maximum total points in each group of elements distributed according to the percentages obtained (rounded up to 1%). This is a modification of the method used for the study of the underwater landscape of Lake Muliczne, conducted as part of pilot research in 2022 (Senetra et al., 2023).

The developed point-valuation table was used for studying lakes with significant diversity. Based on a field session with a group of 20 experienced divers, minor adjustments to the scale were made. This group consisted of experts involved in the research, holding qualifications as diver ecologists. In the previous version of the method, the results showed little variation, even in areas expected to have different levels of sight-aesthetic attractiveness. The main issue in these types of water bodies is low visibility, up to approximately 6 metres. Under such conditions, the presence of even a few elements within sight significantly increases the sight-aesthetic attractiveness. In contrast to land landscapes, it is highly unlikely to observe multiple elements from each group simultaneously in lakes due to limited visibility. Therefore, the presence of at least one element received the highest score, as it is highly attractive for divers who might visit a specific lake solely to observe one particular species of animal or plant. This reasoning and approach to the research were confirmed by all participants in the field studies. Another issue was the measurement around the central points of the basic assessment grids. By using underwater scooters, which allow for very quick exploration of entire grids, an inventory of all fields was completed. The size of the basic grids was adjusted to the size of each studied water body (Table 6).

Table 6. Size of basic grids and their number for each water body

Lake	Lake surface area	Grid size	Number of grids
Białe	984.825 m^2	10.000 m^2	133
Gałęziste	37.710 m^2	2,500 m^2	27
Muliczne	261.111 m^2	2,500 m^2	136
Staw	225.525 m^2	2,500 m^2	137
Turkusowe	66.496 m^2	2,500 m^2	39

Source: own elaboration.

According to the previously adopted methodology, the results obtained during the assessment of all elements were assigned to the centroids of the basic grids and served as the basis for further calculations. Additionally, the point-valuation scale was proportionally divided into five categories of attractiveness (Table 7).

Table 7. Point valuation and categorisation of the sight-aesthetic value of the underwater landscapes of lakes

Groups of elements	Element	Score	Notes	Scales in groups of elements
1	2	3	4	5
Animals	fish	12	the total score must not exceed 12	scale 0–12
	crayfish	9		
	snails (mussels)	6		
	none	3		
	insects	0		
Submerged anthropogenic objects	wooden boat	9	the total score must not exceed 9	scale 0–9
	metal boat	9		
	obstacle made of wood	9		
	platform	9		
	car	9		

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cont. **Table 7**

1	2	3	4	5
	fixed rope	7		
	deck	7		
	plastic boat	7		
	anchor line	7		
	information board	7		
	obstacle made of plastic	2		
	fishing equipment	2		
	obstacle made of tyres	2		
	none	0		
Natural obstacles	trees	7	the total score must not exceed 7	scale 0–7
	plants	4		
	boulders	3		
	none	0		
Plants	levelled underwater *Charophyte* meadows 0.5 m in height	7	the total score must not exceed 7	scale 0–7
	none	5		
	single plants	5		
	rushes	5		
	plants growing in clumps	5		
	underwater meadows 1.5–2.0 m in height	2		
	plants growing up to the surface	0		
	filamentous algae	0		
Shape and appearance of the bottom	submerged cliffs/walls	4	the total score must not exceed 4	scale 0–4
	boulders	4		
	slope	3		
	hilly	3		
	rocky	3		
	sandy	2		
	flat	2		
	muddy	0		
Scale for the method – 0–39				
Categorisation of the sight-aesthetic value of the underwater landscapes of lakes: category I (very attractive landscapes) – 32–39 category II (attractive landscapes) – 24–31 category III (neutral landscapes) – 16–23 category IV (unattractive landscapes) – 8–15 category V (very unattractive landscapes) – 0–7				

Source: preparation based on (Senetra et al., 2023).

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Cartographic presentation of the landscape's sight-aesthetic attractiveness

The attractiveness of the above-mentioned lakes was visualised using three interpolation methods: inverse distance weighting (IDW), kriging, and nearest neighbour.

The inverse distance weighting method (IDW) method is considered one of the most intuitive and simplest methods for determining the influence of specific phenomena values measured in more or less dispersed points (Kotulak et al., 2017). It is characterised by a decrease in influence with increasing distance between the studied points. The result of interpolating each point is the weighted average of the studied values [Formula (1)]:

$$F(X,Y) = \sum_{i=1}^{n}(w_i f_i) \tag{1}$$

where:

$F(X, Y)$ – the value of the point with coordinates X, Y,
n – number of neighbouring points,
w_i – weight of the i-th neighbouring point,
f_i – value of the i-th neighbouring point,

where weights decrease proportionally to the square of the increasing distance between points (according to Tobler's law) (Bivand et al., 2013; Cichociński, 2011; Longley et al., 2005; Senetra, 2015; Urbański, 2012), according to Formula (2) (Dumitru et al., 2013; Kotulak et al., 2017):

$$w_i = \frac{d_i^{-p}}{\sum_{i=1}^{n} d_i^{-p}} \tag{2}$$

where:

w_i – weight of the i-th neighbouring point,
d_i – distance of the analysed point from the i-th neighbouring point,
p – power parameter, being a positive real number.

The number of points considered depends on the adopted approach: global (treating the entire available set of points as neighbours) or local (using only a limited number of influential nearest points, according to set criteria) (Bivand et al., 2013; Cichociński, 2011; Kotulak et al., 2017; Okabe et al., 2000; Urbański, 2012).

The resulting map resembles the results of using kriging (described below), however, unlike this method, IDW interpolation only considers distances to interpolated points with unknown values, ignoring the spatial configuration of observations, which can lead to incorrect results in the case of numerous clusters in the analysed set (Bivand et al., 2013). Moreover, the weights assigned to individual points during calculations range from 0 to 1, and the results obtained never exceed the size from the studied range (Dumitru et al., 2013; Longley et al., 2005). Despite the relative simplicity of the calculations performed, a significant problem with the IDW method is the time-consuming calculations, excessive data smoothing, and the lack of data extrapolation capabilities (Dumitru et al., 2013; Longley et al., 2005).

The second of the used methods, kriging [also known as the method of optimal prediction of random fields – see Ligas & Kulczycki (2014)], was created by one of the first scientists who began to pay more attention to spatial continuity when estimating the distribution of phenomena – becoming one of the fundamental and most frequently used tools in geostatistics (Dumitru et al., 2013).

According to Stein (1999), "at first glance, kriging is just a special case of optimal linear prediction performed on random processes and fields in space". In practice, this interpolation method involves creating optimal objective estimates of regionalised variables at locations without observed data, based on the hypothesis of stationarity and the structural properties of covariance (Kowalik, 2007). The aim of kriging is local estimation by determining a simple moving average from the studied set of points near the newly interpolated point (Bydłosz et al., 2010). The value of the variable at a point with unknown value is determined in a linear way as the weighted sum of the possessed data set, according to Formula (3) (Kowalik, 2007; Loonis & Bellefon, 2018; Scheuerer et al., 2013):

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$$Z^* = \sum_{i=1}^{n} \omega_i Z_i \tag{3}$$

where:

ω_i – weight determined for the i-th point,
Z_i – value of the variable on the i-th point,
n – number of dispersed points in the analysed set.

The weights of individual points are determined not based on the distance function, but based on the spatial ordering of points (Cichociński, 2011) and using a semivariogram and statistical criteria (Dumitru et al., 2013; Longley et al., 2005; Loonis & Bellefon, 2018), in such a way as to minimise the mean square error of estimation (kriging variance) (Bydłosz et al., 2010). Thanks to taking into account autocorrelation, it is possible to eliminate disturbances caused in the model by extreme values. Moreover, in the case of this method, the direction between the newly interpolated points and the input points is also significant, which manifests itself, for example, by assigning smaller weights to points "obscured" by others (Longley et al., 2005).

Despite the fact that this method allows data extrapolation and exceptionally flexibly adapts to the analysed set of points (especially with uneven data distribution – see Cellmer (2014)), its disadvantage is the long processing time, associated with the large number of generated equations (one for each point) and the size of the studied area (Dumitru et al., 2013). Another – and quite significant drawback – is the excessive smoothing of results compared to reality (Urbański, 2012), because, according to Cichociński (2011), "the processing algorithm respects individual data to a lesser extent, more relating to the surface trend".

A response to most problems encountered with IDW or kriging may be natural neighbour interpolation. Thanks to the use of structures in the form of Voronoi diagrams and Delaunay triangulation, describing the topology in terms of natural neighbours around each of the studied points (Kim et al., 2010; Kotulak et al., 2017), it performs very well in the case of irregularly spaced point sets (Dumitru et al., 2013). By natural neighbours, we mean points located in Voronoi cells directly adjacent to the cell containing the studied point (criterion of common boundary).

RESULTS

Application of the Method at the Assessed Site

The valuation table presented above was used to assess the individual points evenly distributed across each of the studied lakes during the underwater inventory. The fieldwork was conducted by experienced divers using high-tech underwater survey equipment. Direct measurements were made at 472 measurement points covering basic fields – squares (133 in Białe, 27 in Gałęziste, 136 in Muliczne, 137 in Staw, 39 in Turkusowe) (Fig. 2).

Each interpolation was combined with the cartogram method (colour gradation), presenting the attractiveness of the lake by means of the colour green, divided into 5 categories (Senetra et al., 2023), based on previous solutions for terrestrial landscapes: (I) very attractive (32–39 pts.), (II) attractive (24–31 pts.), (III) neutral (16–23), (IV) unattractive (8–15 pts.), (V) very unattractive (0–7 pts.). A darker shade of green on the map indicates greater attractiveness of the area.

Validation

For each lake, interpolation was performed on a selected set of measurement points, among which a group of points was chosen only for later validation of the obtained results. Each point, with a given attractiveness value obtained from direct measurement, was assigned an attractiveness obtained from the 3 interpolation methods used. The differences between the actual value and the interpolated value (Table 8) are shown on the maps (Fig. 3, Fig. 4, Fig. 5, Fig. 6, Fig. 7) using green and red points. The size of the point corresponds to the size of the difference obtained.

The average difference between the actual and interpolated values was -1.49 points for the natural neighbour method (-3.82%), -1.70 for the IDW method

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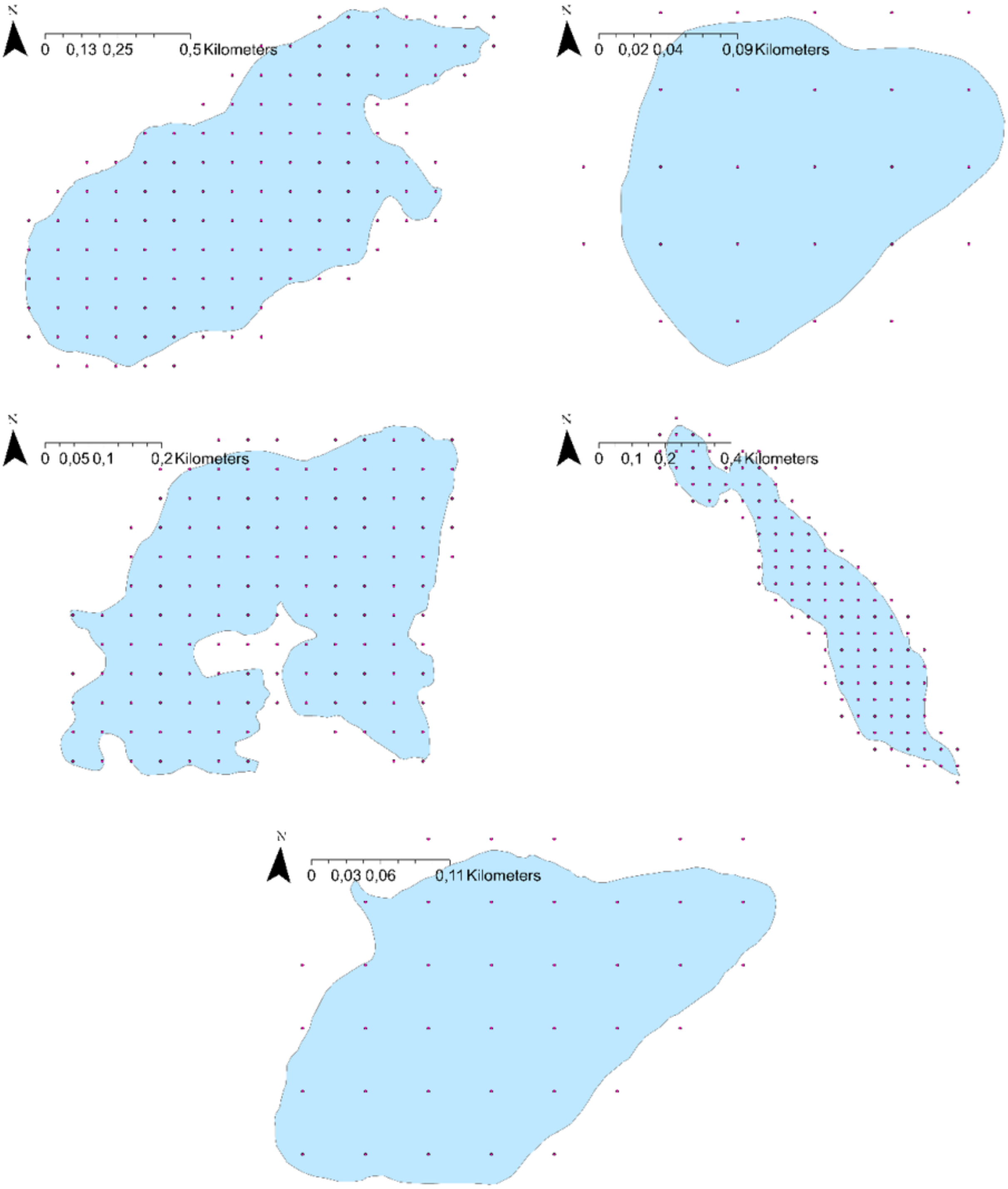

Fig. 2. Measurment points at lakes: Białe (top left), Gałęziste (top right), Muliczne (middle left), Staw (middle right), Turkusowe (bottom)
Source: own elaboration.

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Table 8. Differences between actual and interpolated values

Lake	Mean			Standard deviation			Root Mean Square Deviation (RMS)		
	Natural	IDW	Kriging	Natural	IDW	Kriging	Natural	IDW	Kriging
Turkusowe	-4.83	-4.67	-4.83	2.40	2.88	3.19	5.31	5.35	5.64
Gałęziste	-1.50	-2.25	-1.25	1.73	0.96	2.22	2.12	2.40	2.29
Muliczne	1.10	0.43	0.14	6.34	0.51	7.52	6.28	0.65	7.34
Białe	-0.76	-0.82	-0.94	2.25	2.04	1.85	2.31	2.14	2.03
Staw	-1.45	-1.21	-0.97	4.76	4.97	5.31	4.89	5.03	1.64
mean	-1.49	-1.70	-1.57	3.50	2.27	4.02	4.18	3.12	3.79
mean [%]	-3.82%	-4.37%	-4.02%	8.96%	5.82%	10.30%	10.73%	7.99%	9.72%

Source: own elaboration.

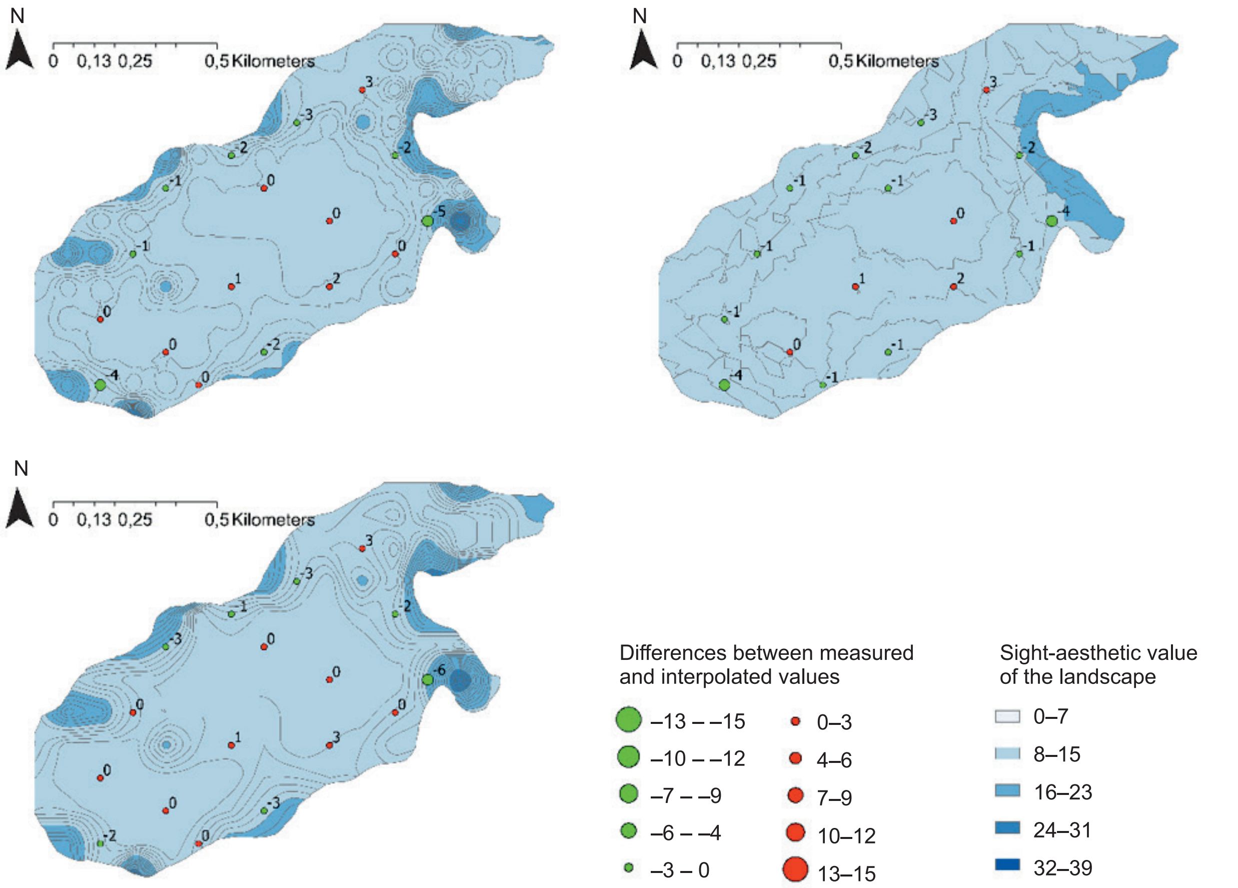

Fig. 3. Lake Białe, IDW (top left), kriging (top right) and natural neighbour (bottom) interpolation
Source: own elaboration.

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(-4.37%), and -1.57 for kriging (-4.02%). The values ranged as follows: from -4.83 to +1.10 for natural neighbour, from -4.67 to +0.43 for IDW, and from -4.83 to +0.14 for kriging. The largest differences for each method were obtained for Lake Turkusowe, and the smallest for Lake Muliczne. On average, the difference for each method was around -1.6 points (about -4%), with the best results achieved using the natural neighbour interpolation method.

In terms of standard deviation, the smallest results were obtained for the IDW method (an average of around 5.82%). In the context of individual lakes, the smallest standard deviation was observed for Lake Gałęziste using the natural neighbour method, Lake Muliczne for the IDW method, and Lake Białe for kriging. The average standard deviation was around 3 points (8%).

The lowest values of Root Mean Square Deviation (RMS) were achieved with the IDW method (an average of 3.12 points – around 8%). The lake with the best RMS score was Lake Muliczne (0.65 points). Relatively small RMS values indicate that the differences between the interpolated and actual values for the lakes studied were minor, meaning the data was modelled correctly. No significant errors in the generated data were detected for any of the interpolation methods across all water bodies.

The most results with the lowest values were obtained for Lake Muliczne, both in terms of the average difference, standard deviation, and RMS, with the IDW method being predominant.

In the case of Lake Białe, for each method, a significant portion of the interpolated values in the central part of the lake matched the actual values.

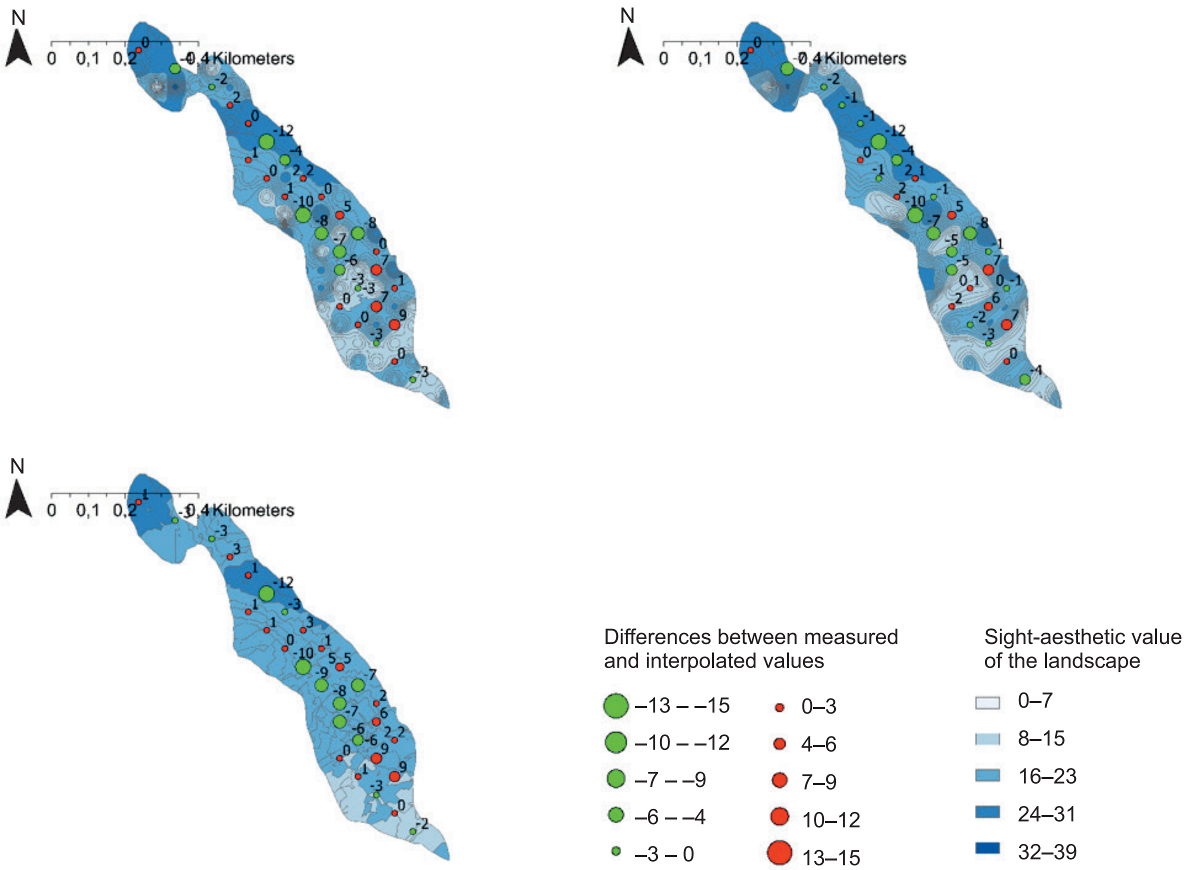

Fig. 4. Lake Staw, IDW (top left), kriging (top right) and natural neighbour (bottom) interpolation
Source: own elaboration.

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However, the majority of overestimated values were also obtained in the central areas, while on the edges, the interpolations generated values lower than the actual ones.

For Lake Staw, the interpolated values were higher than the actual ones, particularly in the central and north-western parts of the lake. Very few control points had interpolated values equal to the actual measured values.

The interpolation results for Lake Turkusowe were lower than the actual values at almost every interpolated point. Only in the northern part, using the IDW method and kriging, was there a single point where the interpolated value was higher than the actual measured value at that location.

For Lake Muliczne, the vast majority of interpolated values exceeded the actual values obtained at the measurement points. Using the IDW method, none of the points had values lower than the actual ones. In the case of kriging, there were the most underestimated values by the model, while for the natural neighbour method, the underestimated values were unevenly distributed.

For Lake Gałęziste, the IDW method resulted in all interpolated values being underestimated. The other two methods produced results where half of the points had values above and half had values below the actual ones.

The overall attractiveness of the entire reservoir in each case was determined as a weighted average

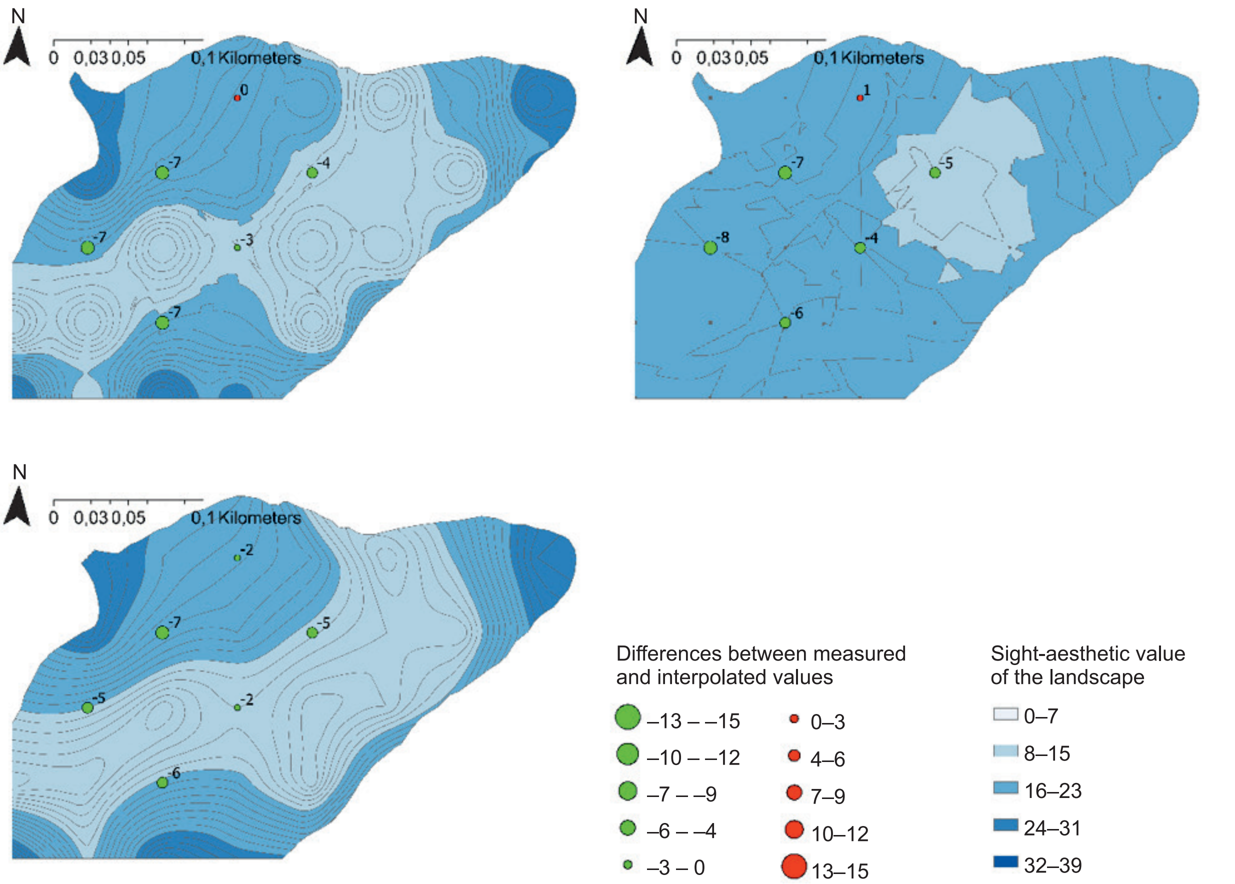

Fig. 5. Lake Turkusowe, IDW (top left), kriging (top right) and natural neighbour (bottom) interpolation
Source: own elaboration.

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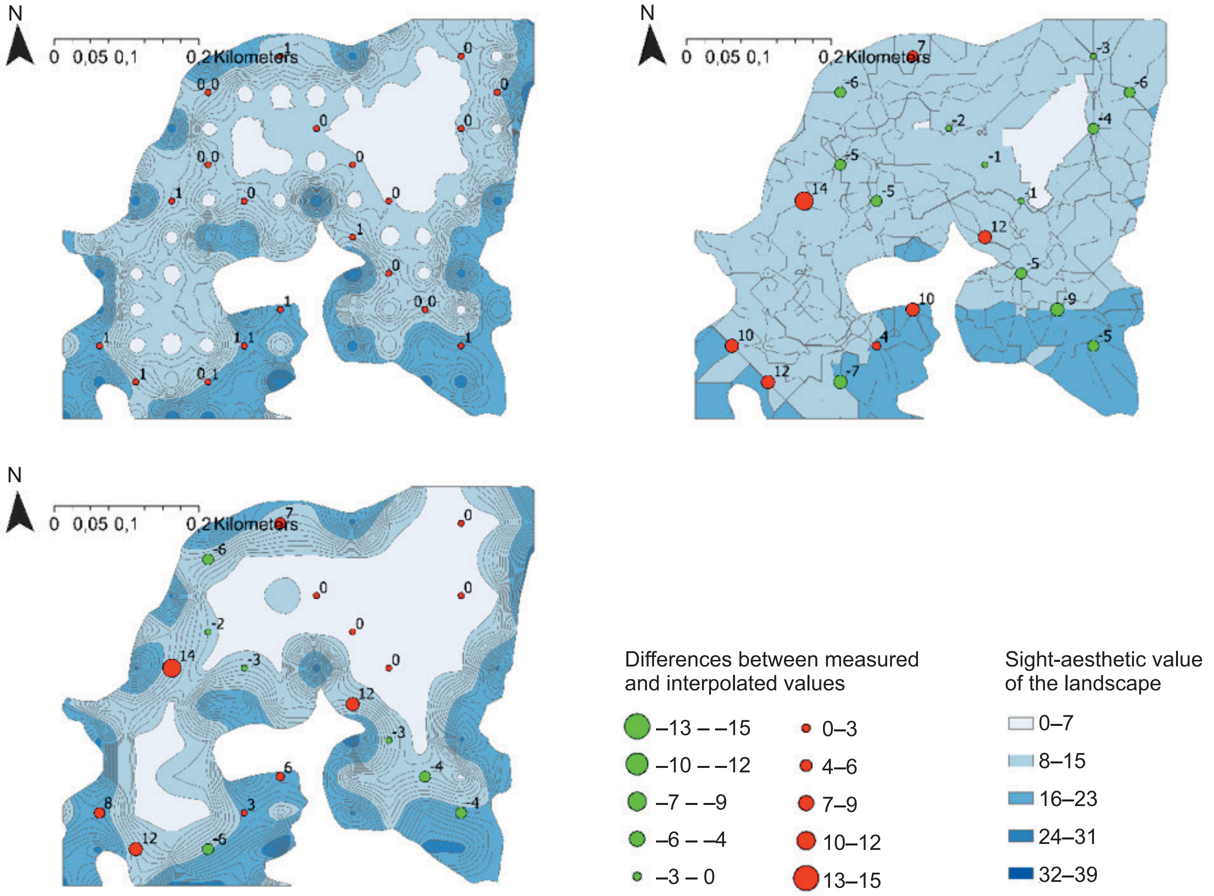

Fig. 6. Lake Muliczne, IDW (top left), kriging (top right) and natural neighbour (bottom) interpolation
Source: own elaboration.

of the areas of contour polygons for each interpolation method separately. This approach is consistent with the Thiessen method, which used this to determine average values over the studied area, typically scattered with irregular objects (Okabe et al., 2000). The results are presented in Table 9.

For each of the assessed water bodies, approximately the same results were obtained, regardless of the interpolation method used. Three of the studied lakes, according to the adopted method of attractiveness assessment, were attractive at around 35% (Lake Gałęziste, Muliczne, and Białe). Comparing the assessed lakes, the most attractive in terms of the sight-aesthetic value of underwater landscapes is Lake Staw, with 53%.

Table 9. Overall attractiveness of assessed water reservoirs

Lake	Method	Attractiveness*	Attractiveness [%]
Turkusowe	IDW	17.74	45%
Turkusowe	Kriging	18.35	47%
Turkusowe	NN	17.56	45%
Gałęziste	IDW	13.55	35%
Gałęziste	Kriging	13.05	33%
Gałęziste	NN	13.23	34%
Muliczne	IDW	13.49	35%
Muliczne	Kriging	13.55	35%
Muliczne	NN	13.27	34%
Białe	IDW	13.29	34%
Białe	Kriging	13.50	35%
Białe	NN	13.29	34%
Staw	IDW	20.56	53%
Staw	Kriging	20.56	53%
Staw	NN	20.64	53%

* out of a possible 39 points
Source: own elaboration.

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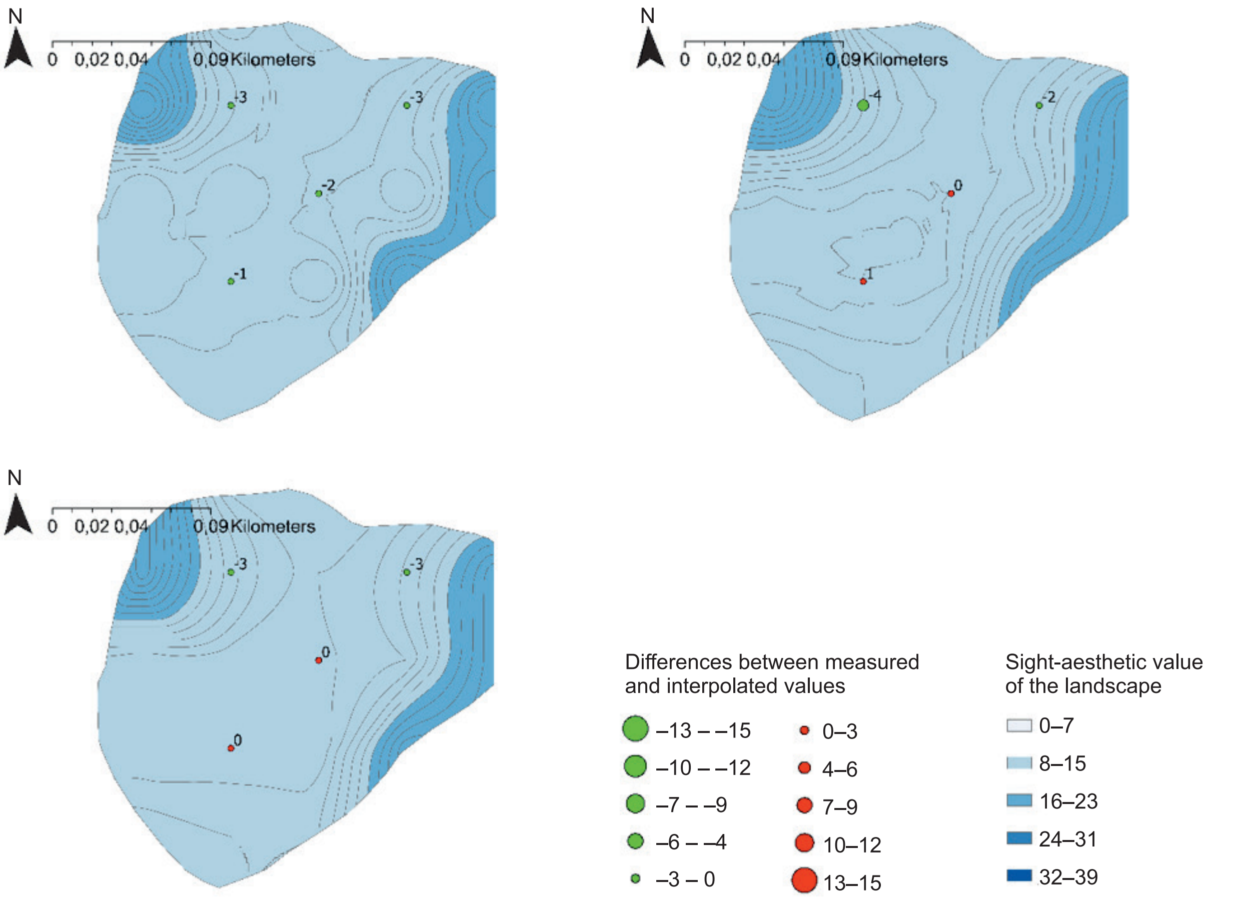

Fig. 7. Lake Gałęziste, IDW (top left), kriging (top right) and natural neighbour (bottom) interpolation
Source: own elaboration.

DISCUSSION

On average, the largest differences were obtained for Lake Turkusowe (using each interpolation method), while the largest standard deviations and mean square deviations – for Lake Muliczne. The average values of the differences were mainly negative numbers, indicating that the interpolated models underestimated the attractiveness values of the studied lakes at the selected points. Taking into account all 3 methods, the results were characterised by minor differences, with a predominance of the IDW method. Although it achieved the largest average differences (-4.37%), it gave the lowest values in the case of standard deviations (5.82% difference between actual and interpolated values), as well as in the case of mean square deviations RMS (7.99% difference).

The presented research has introduced a new quality in the assessment of the sight-aesthetic attractiveness of underwater lake landscapes by implementing the developed point-valuation method. Its usefulness in various environmental and geographical conditions was demonstrated, filling an existing research gap. The analyses conducted showed that the proposed point-valuation method allows for a precise assessment of the attractiveness of underwater lake landscapes. Moreover, the developed maps illustrate the distribution of this attractiveness, which can be used both for environmental protection and planning underwater tourism development.

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Previous research (mainly on seas and oceans) indicated the usefulness of interpolation in analysing underwater landscapes; however, similar studies for lakes were lacking. This article expands the knowledge in this field by introducing a new methodology, based on the solutions previously applied to land landscapes. It can be stated that reliable and satisfactory results were achieved. The tested methodology is related to field methods of assessing the sight-aesthetic value of landscapes and is based on groups of elements distinguished during the development of strict landscape assessment criteria. Additionally, these methods aimed at cartographic visualisation or the development of indicators for landscape attractiveness or suitability for various purposes. These methods include:

1. The LANDEP method (landscape ecological planning) (Ruzicka & Miklos, 1990).
2. The ABC method (Abiotic, Biotic, Cultural) (Bastedo, 1986; Koreleski, 2007).
3. The GEM method (General Ecological Model) (Naveh & Lieberman, 1984).
4. The MENTS method (Man-Economy-Nature-Territorial System) (Kostrowicki, 1990, 1992; Richling & Solon, 2011).
5. The Bogdanowski method (Bogdanowski, 1999).
6. The Söhngen method (Cymerman & Hopfer, 1988; Söhngen, 1975).
7. The Wejchert Impression Curve method (Koreleski, 2007).
8. The method for assessing aesthetic values of landscapes within visually perceived areas (Skarżyński, 1992).
9. The SBE method (Scenic Beauty Estimation) (Janeczko, 2011).

The examples of these methods originate from the second half of the 20th century, indicating the advancement of land landscape research. Currently, further versions are being developed to meet present needs, along with new methods largely based on existing methodological assumptions (Szefler, 2021). These facts demonstrate the significant methodological, technical, and organisational challenges in relation to the research of underwater landscapes, including underwater lake landscapes.

The results obtained were consistent with previous studies on the assessment of sight-aesthetic attractiveness. However, visibility in water (compared to air) was a significant differentiating factor, which proved to be a key influence on the assessment results. Moreover, the interpolation results varied slightly depending on the method used (IDW, kriging, natural neighbour), but the IDW method showed the highest accuracy compared to actual field measurements. In the assumptions of land landscape assessment methods, in addition to aesthetic categories, aspects of environmental function identification and its synthetic description were also perceived. All authors emphasise the need to analyse the interaction between anthropogenic elements and the environmental predispositions of the area. Quantitative evaluation elements, which are included in the sets of elements forming the landscape in a physical sense, were also applied. These methods also partially recommend the use of photographic materials in the assessment process. This approach is ensured by the point-valuation method applied to the assessment of the sight-aesthetic value of underwater lake landscapes, presented in this study.

The proposed methodology can be used as a tool for managing tourist traffic, particularly in the context of protecting water bodies of special value as part of environmental conservation. This will significantly limit tourist traffic in less visually attractive areas, which, however, possess valuable natural assets (Spyrou et al., 2022).

The results indicate the need for further refinement of the presented point-valuation method and its adaptation to the specific characteristics of lakes and underwater conditions. A significant improvement would be the expansion of research to other types of water bodies and the comparison of results obtained at different times of the year to assess the impact of seasonal changes on the sight-aesthetic attractiveness of underwater landscapes. Furthermore, the integration of modern technologies,

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such as underwater drones, seems crucial, as they can enhance the efficiency of measurements.

Another issue is the possibility of expanding the scope of research based on the tests conducted. An underwater landscape can be perceived through multiple senses, just like a landscape on land. The multisensory nature of landscapes has been a topic of research for many years (Bartkowski, 1985; Bernat, 2015; McLean, 2017). In addition to studying visual impressions, attempts should be made to determine the influence of other senses: hearing, smell, taste, and touch. Underwater, these senses play a similar role and are used in the perception of this environment.

The research results confirmed the initial hypothesis. A properly developed point-valuation method, supported by appropriate interpolation methods, can be effectively used to assess the sight-aesthetic value of underwater lake landscapes. The attractiveness maps obtained allowed for the presentation of the distribution of aesthetic values in the studied lakes, confirming that the tools used in land landscape research can also be adapted to aquatic environments. The results obtained using different interpolation methods, despite some differences, support the validity of the adopted methodology and its usefulness in planning and protecting these areas.

CONCLUSIONS

The results obtained indicate that the developed method is similar to those used for terrestrial landscapes. It relates to the field methods of landscape assessment, including the Söhngen method, Wejchert Impression Curve, and criteria for evaluating the visual amenity value of landscapes.

The presented method could in the future be used to assess the sight-aesthetic value of the underwater landscapes of lakes in order to protect the most valuable aquatic ecosystems. However, it has certain limitations, among which the most significant is the difficult perception of the underwater landscape due to visibility underwater. This depends on the type of lake, the clarity of its waters, or the kind of environment producing various pollutants. Nonetheless, it represents an innovative approach to the subject, utilising modern technologies to maximise the efficiency and automation of measurements.

Lakes, from the perspective of the sight-aesthetic value of underwater landscapes, are generally less attractive. The limited visibility in different types of water bodies, during various seasons and at different latitudes, plays a significant role in this matter. When seeking this attractiveness, it is necessary to direct tourist traffic accordingly by designating appropriate paths or underwater trails.

Author contributions: The authors have approved the final version of the article. The authors have contributed to this work as follows: Author1, Author2, Author3, Author4 developed the concept and designed the study, Author3, Author4 collected the data, Author1, Author2, Author3, Author4 analysed and interpreted the data, Author1, Author2, Author3, Author4 drafted the article, Author1, Author2 revised the article critically for important intellectual content.

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