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Role of riparian buffer zones in shaping water quality and vegetation diversity of small mid-field reservoirs in an agricultural landscape (SE Poland)

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ABSTRACT

Small mid-field water reservoirs are multifunctional ecosystems occurring as isolated elements within agricultural landscapes and highly susceptible to external pressures. Although they are often treated as uniform systems, evidence for fine-scale spatial heterogeneity remains limited. This study examined two adjacent mid-field reservoirs in south-eastern Poland, embedded in an intensively used agricultural area. The aim of the study was to assess the ecological value of the reservoirs and to determine how shoreline land use and riparian buffer-zone structure affect floristic diversity and selected physical and chemical parameters of surface water and shallow groundwater. Investigations were conducted at four sites representing contrasting shoreline management types. Water quality, nutrient concentrations, vegetation composition and land-cover characteristics were analysed using standard methods. Despite their small size and close proximity, the reservoirs showed pronounced spatial variability in water quality and vegetation structure. Shoreline sections exposed to intensive agriculture and steeper slopes were associated with higher nitrate and phosphate concentrations and lower plant diversity, whereas sites bordered by dense shrub and tree buffer zones exhibited lower nutrient levels and higher floristic diversity. These results demonstrate that small mid-field reservoirs cannot be regarded as homogeneous systems and confirm the key role of buffer zones in shaping their ecological condition, providing practical guidance for the design and management of vegetated buffers in small agricultural catchments.

Keywords: small agricultural reservoirs, buffer zones, water quality, macrophyte diversity, agricultural landscape.

INTRODUCTION

Small mid-field water reservoirs are common elements of agricultural landscapes, yet their total abundance and cumulative contribution to freshwater resources remain difficult to quantify at regional scales. In Poland, such reservoirs are widespread, particularly in Lakeland regions, although a long-term decline in their number has been documented (Bielecka, 2006; Brysiewicz et al., 2013; Dudzińska et al., 2016). Typically small and shallow, these water bodies function as isolated landscape elements and are therefore highly exposed to local land-use practices, hydrological alterations and shoreline management. Due to their limited volume and high shoreline-to-area ratio, even minor differences in their immediate surroundings may result in pronounced spatial heterogeneity of physicochemical conditions and biological communities within a single reservoir.

Despite their limited size, mid-field reservoirs perform multiple ecological and socio-environmental functions. They contribute to local water retention and groundwater stabilization, influence microclimatic conditions, and provide habitats for aquatic and semi-aquatic organisms associated with shallow littoral zones. In agricultural landscapes, they also function as biogeochemical barriers, intercepting nutrients and sediments transported from arable land and thereby reducing their transfer within catchments (Kuczyńska-Kippen and Joniak, 2010; Mielczarek and Szydłowski, 2017). However, their shallow depth and close proximity to intensively cultivated farmland make them particularly vulnerable to degradation driven by both natural and anthropogenic pressures (Bielecka, 2006).

In recent years, small standing waters have gained increasing recognition as key components of freshwater biodiversity. Comparative studies across diverse landscape types have shown that ponds and small reservoirs may support a disproportionately high number of species relative to their area, often exceeding that of larger lakes and rivers, and thus function as important refugia in highly transformed environments (Biggs et al., 2017; Hill et al., 2021). Despite their ecological importance, these ecosystems remain underrepresented in routine monitoring and management frameworks, including those implemented under the Water Framework Directive (Kelly-Quinn et al., 2017). As a consequence, degradation processes in small water bodies may proceed unnoticed until advanced stages.

Nutrient enrichment constitutes one of the most significant threats to mid-field reservoirs in agricultural landscapes. Excessive inputs of nitrogen and phosphorus from fertilizer application, soil erosion and surface or subsurface runoff accelerate eutrophication and alter ecosystem functioning (Domagała-Świątkiewicz, 2005; Lutnicka, 2011; Sender and Jaruga, 2017). In shallow systems, eutrophication typically leads to reduced water transparency, oxygen deficits and shifts in primary producer communities. Such changes may trigger feedback mechanisms that stabilize turbid states and suppress submerged vegetation, as described in conceptual and empirical studies on shallow lake dynamics (Scheffer et al., 2001; Jeppesen et al., 2017). Previous research has shown that nutrient concentrations in both surface water and associated groundwater are closely linked to the intensity and type of land use in the immediate surroundings of agricultural reservoirs (Gałczyńska et al., 2009; Grochowska et al., 2011), particularly where water exchange is limited and residence time is short.

The ecological condition of littoral and shoreline zones is particularly important for the functioning of small reservoirs. Aquatic macrophytes and structurally diverse shorelines enhance habitat complexity, support aquatic food webs and increase ecosystem resilience to external pressures (Kuczyńska-Kippen and Joniak, 2010; Sender and Kułak, 2014; Jeppesen et al., 2017). Conversely, simplification or degradation of these zones, often associated with intensive agricultural land use, may reduce habitat quality and biodiversity, even in water bodies not directly used for fisheries.

Among the measures proposed to mitigate agricultural pressures on small reservoirs, the establishment and maintenance of vegetated shoreline and riparian buffer zones is considered particularly effective. Buffer zones composed of grasses, shrubs and trees intercept surface runoff, reduce flow velocity, trap sediments and particle-bound phosphorus, and enhance nitrogen removal through plant uptake and microbial processes (Mander et al., 2005; Zhang et al., 2010). From an ecological engineering perspective, buffer zones represent a manageable landscape element capable of reducing diffuse pollution and improving ecosystem stability. However, their effectiveness depends strongly on local factors such as vegetation density, buffer width and terrain slope, which determine hydrological connectivity and nutrient delivery to shoreline areas (Klarzyńska et al., 2018). Consequently, buffer performance may vary substantially even within a single small reservoir.

Although the impact of agricultural land use on mid-field reservoirs has been widely investigated, important aspects remain insufficiently resolved. In particular, fine-scale spatial variability within individual reservoirs has received limited attention, especially with regard to the integrated response of water chemistry, groundwater nutrient inputs and shoreline vegetation structure to buffer-zone characteristics. Most studies focus on differences between water bodies rather than on internal spatial gradients within small reservoirs. This gap is particularly relevant for shallow systems, where even minor variations in shoreline management may generate pronounced physicochemical and biological contrasts.

In this context, the present study examined two adjacent mid-field reservoirs located in south-eastern Poland within an intensively used agricultural landscape. The objectives were to assess the ecological value of the reservoirs and to determine how differences in shoreline land use and buffer-zone structure influence floristic diversity as well as selected physical and chemical parameters of surface water and shallow groundwater. It was hypothesised that shoreline sections bordered by trees or shrubs would exhibit higher vegetation diversity and lower nutrient concentrations than sections directly exposed to agricultural use. Additionally, it was hypothesised that the small size of the reservoirs might limit internal spatial differentiation of physicochemical conditions and vegetation structure. This assumption was tested against the observed fine-scale variability within individual water bodies. By addressing these issues, the study contributes to a better understanding of how buffer-zone structure and local geomorphological factors shape the ecological condition of small agricultural reservoirs.

MATERIALS AND METHODS

Study area

The study was conducted in the western part of the Lublin Province (south-eastern Poland), within the Lublin Upland. The investigated reservoirs are situated in the catchment of the Chodelka River, a right-bank tributary of the Vistula River. According to the physical–geographical regionalisation of Poland, the area belongs to the Chodel Basin mesoregion (Kondracki, 2001; Franczak and Franczak, 2012).

The region is characterised by a moderately continental climate, with relatively hot summers and cold winters. Mean annual precipitation ranges from approximately 550 to 650 mm, and the growing season lasts about 205–210 days (Woś, 1999). The geological substratum of the basin consists mainly of chalk marls, which influence groundwater chemistry and hydrological conditions in small surface water bodies.

The studied reservoirs are located near the village of Nowe Komaszyce, within an intensively used agricultural landscape (Figure 1). Both reservoirs are of natural origin and are embedded in arable land dominated by perennial and seasonal crops. Two adjacent mid-field reservoirs, separated by a distance of approximately 3 m, were selected for detailed investigation. According to information obtained from local inhabitants, the reservoirs did not form a single water body in the past and were historically separated by an embankment, which may have contributed to differences in their present morphometric and ecological characteristics.

The reservoirs differ in size and shoreline characteristics. The smaller reservoir is largely surrounded by a vegetated buffer zone, covering approximately 80% of its shoreline, whereas the larger reservoir is bordered by shoreline sections with contrasting land-use types, including woody vegetation, shrub belts and areas directly exposed to agricultural activity. This spatial configuration allowed the assessment of how local variation in shoreline buffer structure and land use affects water quality and vegetation diversity within and between small, closely situated reservoirs.

Analysis of physical and chemical parameters

Field investigations were conducted in 2022 and 2023 at four sampling sites. Three sites (S1–S3) were located along the shoreline of the larger reservoir, whereas site S4 was situated within the smaller adjacent reservoir. Measurements and sampling were performed seasonally, three times per year, in spring, summer and autumn, in order

Figure 1. Arrangement of study sites (Source of orthophotomap: Geoportal www.geoportal.gov.pl)

to capture intra-annual variability of water conditions. At each site, measurements were repeated during each sampling campaign and seasonal values were used for further analyses.

Sampling sites were selected to represent contrasting types of shoreline use and buffer-zone structure in the immediate vicinity of the reservoirs. Site S1 was located along a shoreline section bordered by shrubs and trees adjacent to a planted forest, with an estimated vegetation cover of approximately 70%. Site S2 represented a shoreline adjacent to seasonal cereal crops, partially separated from the reservoir by a shrub belt of about 50% cover. Site S3 was situated next to perennial raspberry cultivation, with sparse shrub vegetation covering approximately 10% of the shoreline. Site S4 represented the smaller reservoir, where about 80% of the shoreline was surrounded by shrubs and trees with an average vegetation density of approximately 60% (Figure 1).

In surface waters of both reservoirs, the following physical and chemical parameters were measured: water transparency using a Secchi disk, electrolytic conductivity ($\mu S \cdot cm^{-1}$) using a portable electronic conductometer (Hanna Instruments), water hardness (°dH) and pH using a multiparameter meter (WTW Multi 340i), and concentrations of nitrates (NO_3^-) and phosphates (PO_4^{3-}) determined photometrically (Slandi LF 300 photometer). All measurements were conducted in situ or immediately after sample collection, following the manufacturer's instructions for each device. Concentrations of nutrients are expressed as nitrate (NO_3^-) and phosphate (PO_4^{3-}) ions in $mg \cdot L^{-1}$.

In addition to surface water sampling, groundwater was collected from piezometric wells installed in the coastal zone at each study site. Piezometers were located in front of the shoreline vegetation belt, at a distance of approximately 5–10 m from the waterline, to assess nutrient concentrations in shallow groundwater entering the reservoirs. Piezometric wells were constructed from PVC pipes with a diameter of 110 mm and a length of 2000 mm. The pipes were perforated with holes of 2.5 mm diameter, and installed to a depth of approximately 0.5 m below the first aquifer. Depending on local conditions, the depth of the first aquifer ranged from about 0.6 to 2.0 m below ground level. Groundwater samples collected from the piezometers were analysed for nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations using the same photometric method as applied for surface water samples (Slandi LF 300 photometer).

Land-use and shoreline mapping (revised version)

Land-use patterns in the surroundings of the studied reservoirs were analysed to characterise spatial heterogeneity of the coastal and ecotone zones and to support subsequent ecological valorisation. The analysis was based on orthophotomaps, topographic maps at a scale of 1:2000, and field verification conducted during the study period.

Spatial analyses were performed using ArcGIS software, supported by graphic processing in CorelDRAW. A buffer zone extending approximately 100 m from the shoreline of each reservoir was delineated and analysed, as this distance is commonly considered sufficient to reflect the most direct land-use pressures on small standing waters.

Within the delineated buffer zone, land use was classified into the following categories: arable fields, forests, meadows, shrub vegetation, other water bodies, and dispersed buildings. The resulting land-use maps were used to describe differences in shoreline surroundings between study sites and to relate land-use structure to observed patterns in water quality and vegetation diversity.

Floristic analysis

Floristic surveys were conducted in the littoral and shoreline (coastal) zones of both reservoirs, including the adjacent buffer zones. A total of 24 phytosociological relevés were recorded using the Braun–Blanquet method (Chytrý et al., 2011). Sampling was carried out along transects perpendicular to the shoreline to capture vegetation gradients from the waterline towards the terrestrial buffer zone. Individual relevés were established on plots of 5 m², following standard phytosociological practice for small aquatic and semi-aquatic plant communities (Dzwonko, 2007).

Plant species were identified according to the taxonomic system proposed by Rutkowski (2004). The floristic composition of each site was characterised using basic diversity metrics, including species richness (S, number of species) and the Shannon–Wiener diversity index (H′), calculated as:

$$H' = -\sum_i p_i \, ln(p_i) \tag{1}$$

where: p_i represents the relative abundance of species i within a given relevé.

These indices were used to quantify differences in vegetation diversity between sites with contrasting shoreline buffer structures and land-use characteristics.

Ecological valorization

Terrain slope was considered an important geomorphological factor influencing surface runoff and nutrient transport from the surrounding land into the reservoirs. Slope inclination (S, %) was calculated according to the formula:

$$S = (\Delta h / L) \times 100 \tag{2}$$

where: Δh is the difference in elevation between the endpoints of the slope line (m), and L is the horizontal length of the slope segment (m), measured from cartographic materials.

Ecological valorisation of the studied reservoirs was performed using the method proposed by Skwierawski (2005), subsequently applied and modified in studies on small water bodies in agricultural landscapes (Sender and Kolejko, 2013). The method is based on the assessment of three functional zones of a reservoir: the surroundings (buffer zone), the shoreline (coastal) zone, and the water zone. The assessment integrated cartographic, physicochemical and biological data collected during the study.

Within each zone, selected environmental and biological attributes were evaluated and scored on a five-point scale (0–5), where higher scores indicate better ecological condition. Based on the total score, reservoirs were classified into one of four ecological status classes, ranging from very good ecological condition (recommended for legal protection), through valuable but threatened reservoirs, to moderately valuable and low-value reservoirs requiring remedial or restoration measures.

Statistical analysis

Multivariate statistical analyses were applied to explore relationships between environmental variables and floristic diversity characteristics of the studied sites. Principal component analysis (PCA) was used as a dimension-reduction and ordination technique to identify the main gradients structuring variability across biotic and abiotic data. Prior to analysis, all variables were standardised (z-scores) to eliminate the influence of differing measurement units. Only variables with complete data sets were included in the ordination analyses.

PCA allowed the joint interpretation of water quality parameters, groundwater nutrient concentrations, shoreline characteristics and vegetation diversity indices along the main ordination axes. Environmental variables were displayed as vectors, with their length and orientation indicating the strength and direction of correlations with the ordination axes (Czerepko, 2006). The significance of correlations between selected environmental variables and PCA axes was assessed using Pearson correlation coefficients.

To complement ordination results and assess similarity in floristic composition among study sites, hierarchical cluster analysis was performed using the Bray–Curtis similarity index and the unweighted pair-group method with arithmetic mean (UPGMA), based on Braun–Blanquet cover–abundance data (Chytrý et al., 2011). Statistical analyses were carried out using the XLSTAT-Ecology software package (Addinsoft).

RESULTS

Land-cover characteristics of the reservoir surroundings

The land-cover analysis encompassed approximately 20 ha surrounding the studied reservoirs. The larger reservoir covered 18.63 a, with a maximum depth of 1.0 m and a mean depth of 0.6 m, whereas the smaller reservoir occupied 1.02 a and reached a maximum depth of 0.7 m (mean depth 0.4 m). Both reservoirs were shallow systems potentially sensitive to external nutrient inputs and shoreline influences.

Arable land clearly dominated the buffer zone, covering 12.8 ha (approximately 66% of the analysed area). Other land-cover categories, including forests, meadows, shrub vegetation, dispersed buildings and additional small water bodies, occupied markedly smaller proportions. Built-up areas and other water bodies accounted for only 0.02% and 0.87%, respectively (Figure 2).

Despite the dominance of arable fields at the buffer scale, the immediate shoreline displayed strong spatial heterogeneity. Sections bordered by dense shrub and tree vegetation contrasted sharply with sections directly exposed to agricultural use or separated from fields by narrow, sparsely vegetated belts. This structural differentiation of shoreline zones provided the basis for distinguishing study sites with contrasting buffer characteristics.

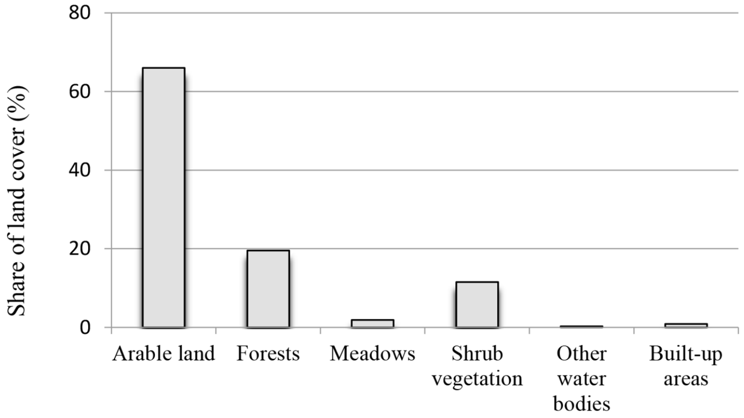

Figure 2. Land-cover structure within a 100 m buffer zone surrounding the studied reservoirs Cover-abundance values follow the Braun–Blanquet scale (+, 1–5)

Characteristics of physical and chemical parameters of water

Despite the limited surface area and close spatial proximity of the reservoirs, both surface water and groundwater exhibited pronounced spatial differentiation. Clear internal gradients were observed within the larger reservoir, as well as between the two reservoirs (Table 1).

Seasonal variability was evident across most parameters. Water temperature peaked in summer, whereas nutrient concentrations, particularly nitrates in groundwater, were highest in spring. Conductivity and hardness also showed site-dependent seasonal patterns.

Waters in both reservoirs were slightly alkaline, with mean pH values ranging from 7.2 to 7.6. Water transparency was generally low, with mean Secchi depth ranging from 0.25 m at site S4 to 0.60 m at site S1 (Table 1). The small reservoir (S4) exhibited the highest mean conductivity (421 µS·cm⁻¹) and water hardness (7.3 °dH), indicating more mineralised water conditions.

Within the larger reservoir, site S3 consistently showed the highest mean values of most analysed parameters, forming the upper end of the nutrient gradient. Elevated phosphate concentrations were also recorded at site S2, characterised by a narrow and discontinuous shrub belt. In contrast, site S1, adjacent to forest and a well-developed buffer zone, showed consistently lower values of the analysed physicochemical parameters (Figure 3).

Table 1. Content of the analysed parameters in the water of the studied reservoirs

Season	Study sites	parameter																	
		Surface water														Ground water			
		Temperature (°C)	SD	Visibility (m)	SD	Conductivity (µS·cm⁻¹)	SD	pH	SD	Total hardness (°dH)	SD	PO_4^{3-} (mg·L⁻¹)	SD	NO_3^- (mg·L⁻¹)	SD	PO_4^{3-} (mg·L⁻¹)	SD	NO_3^- (mg·L⁻¹)	SD
Summer	SS1	21	2.7	0.45	0.01	243	24	7.34	0.4	4.75	1.4	0.087	0.01	0.76	0.01	0.129	0.05	0.23	0.004
	SS2	23	3.4	0.3	0.1	248	26	7.22	0.6	4.49	1.2	0.9	0.02	1.17	0.02	0.432	0.02	0.14	0.03
	SS3	24	5.2	0.4	0.2	248	23	7.77	1.3	5.8	1.4	0.12	0.01	0.68	0.03	0.136	0.04	6.87	2.1
	SS4	20	4.3	0.25	0.01	465	67	7.2	1.1	7.55	1.6	0.51	0.21	0.41	0.01	0.156	0.06	1.12	0.3
Autumn	SS1	10	0.5	0.5	0.07	348.6	37	6.99	0.1	3.04	1.2	0.31	0.01	0.09	0.01	0.135	0.05	0.12	0.02
	SS2	12	1.0	0.4	0.04	361.2	33	6.67	0.6	2.25	0.01	0.012	0.1	0.07	0.01	0.153	0.05	0.09	0.001
	SS3	13.5	2.5	0.4	0.03	385	64	7.33	0.8	5.64	0.8	0.66	0.01	0.16	0.1	0.142	0.02	0.42	0.07
	SS4	10	2.8	0.3	0.02	374.5	57	6.87	1.4	5.79	1.3	0.074	0.02	0.40	0.02	0.212	0.08	0.62	0.01
Spring	SS1	9.5	2.1	0.6	0.08	365.4	29	7.85	1.2	7.52	2.1	0.222	0.04	0.07	0.03	0.054	0.04	0.78	0.1
	SS2	11	1.4	0.45	0.1	371.7	34	7.81	1.4	6.77	1.04	0.02	0.01	0.5	0.1	0.318	0.1	1.15	0.4
	SS3	10	1.2	0.5	0.1	363.5	38	7.8	0.4	5.7	0.2	0.48	0.01	1.39	0.2	0.46	0.01	32.71	3.5
	SS4	9.0	0.5	0.35	0.03	423	55	7.69	0.9	8.56	1.8	0.369	0.03	0.53	0.02	0.07	0.002	1.45	0.02

Groundwater results followed a similar spatial pattern. The highest phosphate concentrations were recorded at sites S2 (0.301 mg $PO_4^{3-}\cdot L^{-1}$) and S3 (0.246 mg $PO_4^{3-}\cdot L^{-1}$), whereas the lowest occurred at site S1 (0.106 mg $PO_4^{3-}\cdot L^{-1}$). Nitrate concentrations in groundwater were highest at site S3 (13.33 mg $NO_3^-\cdot L^{-1}$), exceeding values observed at sites with denser shoreline vegetation (Table 1).

Floristic characteristics and vegetation diversity

A total of 23 vascular plant species were recorded across the study sites (Table 2). Seven species occurred in the littoral zone, with emergent macrophytes forming the dominant functional group.

Clear differences in species richness were observed among sites. Site S1 supported the highest number of species (18), whereas site S3 exhibited the lowest richness (11 species). These differences were reflected in Shannon–Wiener diversity values, which were higher at sites characterised by more continuous and structurally complex buffer vegetation.

The relative contribution of functional groups also varied. Rush species were most diverse and abundant at site S1, whereas segetal species represented a greater proportion at sites S2 and S3, which were more directly influenced by adjacent agricultural land use (Table 2).

Cluster analysis based on the Bray–Curtis index confirmed distinct floristic differentiation.

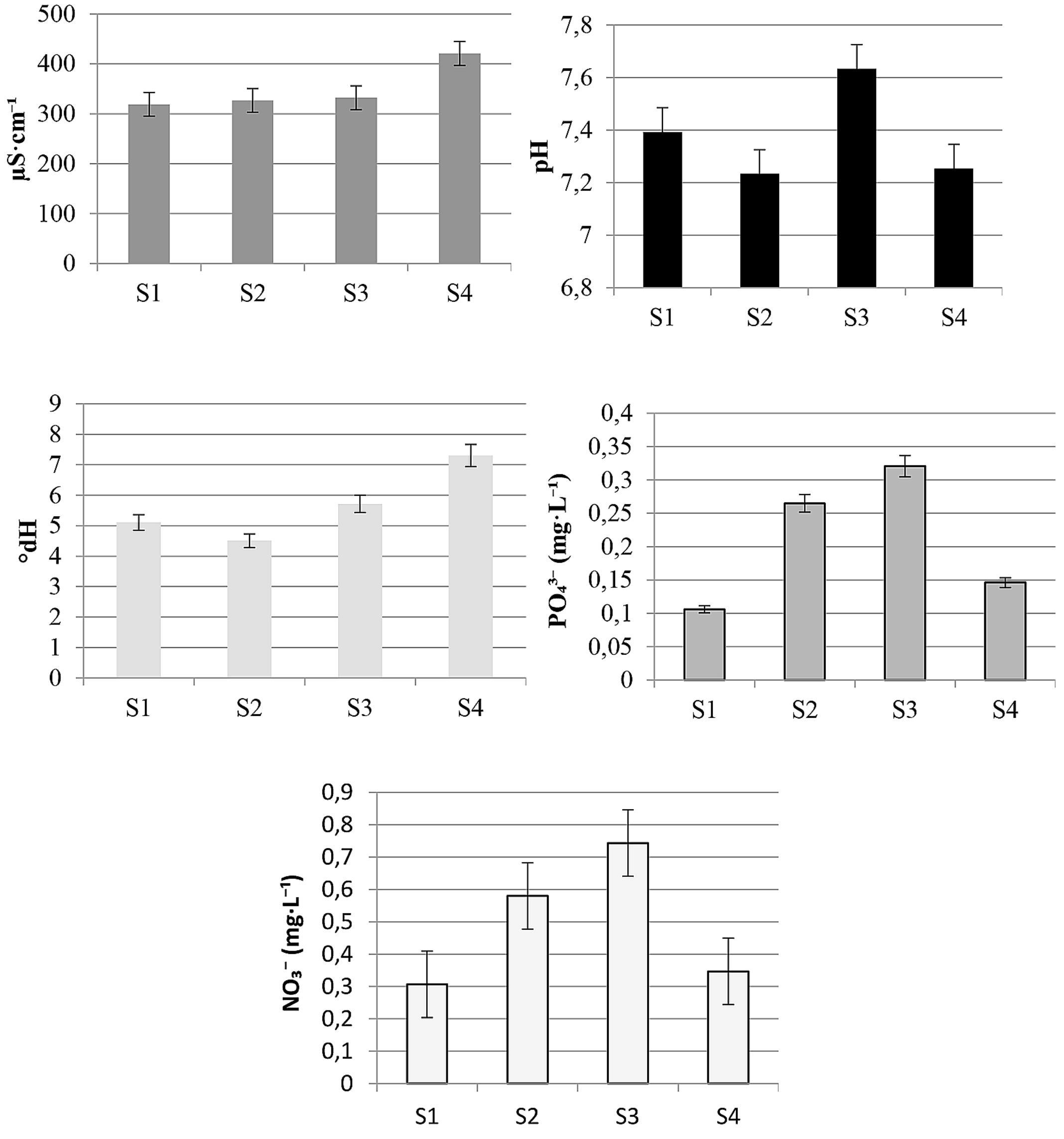

Figure 3. Mean values (± SD) of selected physicochemical parameters of surface water at study sites (S1–S4): (a) electrical conductivity, (b) pH, (c) total hardness, (d) phosphate concentration (PO_4^{3-}), and (e) nitrate concentration (NO_3^-)

Sites S1 and S2 formed one similarity group, while site S3 was clearly separated, indicating a divergent vegetation structure associated with more intensive shoreline exposure (Figure 4).

Ecological valorization and multivariate analysis

Terrain slope differed substantially among sites. The steepest slopes were recorded at site S3 (7.0%) and site S2 (6.7%), followed by site S4 (4.5%). The lowest slope occurred at site S1 (1.7%), where a dense and continuous buffer zone was present.

Ecological valorisation classified the larger reservoir as class III and the smaller reservoir as class IV (Table 3). These classes indicate significantly transformed systems with moderate to unfavourable habitat conditions.

Principal Component Analysis revealed clear separation of sites along gradients defined by nutrient concentrations, shoreline structure and surrounding land use. Sites S2 and S3 were associated with higher nitrate and phosphate concentrations and with dominance of arable land and built-up surroundings. In contrast, sites S1 and S4 were associated with higher water transparency, greater buffer continuity and more natural land-cover types, including forests and meadows (Figure 5). These sites were additionally linked to gentler terrain slopes and higher vegetation density in the shoreline zone.

DISCUSSION

Small water reservoirs are typically shallow and exhibit substantial variability in size, origin

Table 2. Species composition and diversity of plant communities at the study sites (S1–S4). Cover–abundance values follow the Braun–Blanquet scale; S – species richness, H′ – Shannon–Wiener index

Species	S1	S2	S3	S4
Littoral zone				
Phragmites australis (Cav.) Trin. ex Steud	3	2	1	1
Glyceria maxima (Hartm.) Holmb.	2	1	3	1
Typha angustifolia L.	1	1	+	+
Iris pseudacorus L.	+			
Lemna trisulca L.				+
Potamogeton natans L.	+			
Lysimachia vulgaris L.	+			
Ceratophyllum demersum L.	+			
Shoreline (coastal) zone				
Alnus glutinosa Gaertn.	3	+		1
Phalaris arundinacea L.	1	+	+	+
Eupatorium cannabinum L.	+	+	+	+
Galium mollugo L.	+	+		
Lythrum salicaria L.	+	+		+
Scirpus silvaticus L.	+	1	+	+
Utrica dioica L.	+	2	3	1
Echinochloa crus-galli (L.) P.Beauv.	+	1	2	+
Calystegia sepium (L.) R.Br.	+	+	+	+
Salix fragilis L.	1	+		
Salix cinerea L.	+	+		
Artemisia vulgaris L.		+	1	
Sambucus nigra L.				+
Corylus avellana L.			+	
Crataegus monogyna Jacq.		+		
S	18	16	11	13
H′	1.032	1.088	0.82	1.04

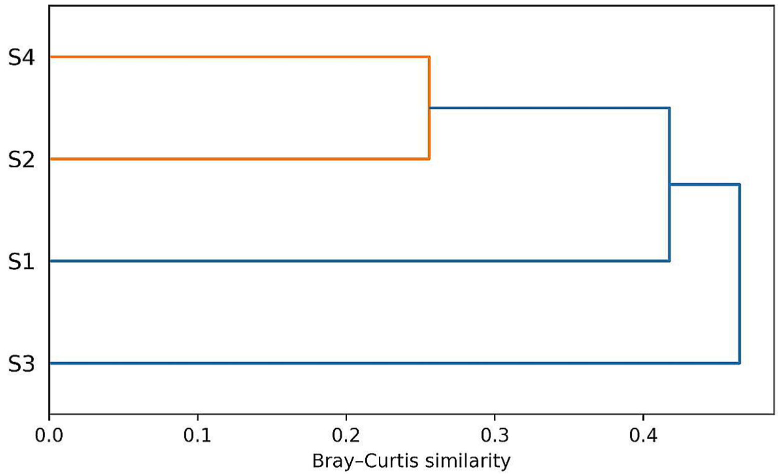

Figure 4. Hierarchical cluster analysis (Bray–Curtis similarity, UPGMA linkage) of floristic composition at the studied sites (S1–S4), based on Braun–Blanquet cover–abundance data

Table 3. Results of ecological valorisation of the studied reservoirs. Ecological classes were assigned according to the method of Skwierawski (2005), where class I represents very good ecological condition and class IV indicates low ecological value

Sites zone	S1	S2	S3	S4
A – water zone	15	5	4	6
B – shoreline (coastal) zone	17	12	9	11
C – surroundings (buffer) zone	8	4	3	8
Total valorisation score	40	21	16	25
Ecological class	III	IV	IV	IV

and hydrological permanence. They include both natural and anthropogenic water bodies, such as ponds, which together constitute an important but increasingly threatened component of agricultural landscapes. Across Europe, the rate of disappearance of small reservoirs has exceeded their rate of formation, with losses estimated at 40–90% over the last century, depending on the region. A similar downward trend has been observed in Poland, reflecting both land-use intensification and climate-related pressures (Ożgo, 2010).

The small surface area of mid-field reservoirs makes them particularly vulnerable to anthropogenic pressure, as even minor changes in land use or shoreline management may rapidly affect their ecological condition (Wojtasik, 2013). The present study confirms that, despite their limited size, pronounced spatial heterogeneity in both physicochemical water properties and vegetation structure can occur within and between small reservoirs. These findings contradict the common assumption that small water bodies are internally homogeneous and demonstrate that pronounced spatial heterogeneity may occur even within very small reservoirs. Similar patterns of fine-scale variability have been reported for ponds and other small standing waters in agricultural and semi-natural landscapes, where local shoreline conditions and habitat structure strongly influence physicochemical properties and biological communities (Scheffer et al., 2001; Biggs et al., 2017). Recent syntheses further emphasize that small water bodies often function as spatially complex ecosystems rather than uniform units, despite their limited size (Hill et al., 2021).

The persistence and functioning of small reservoirs are also strongly influenced by climatic conditions, especially precipitation patterns. In the study region, rainfall regimes have undergone considerable changes in recent decades, potentially altering hydrological connectivity, water residence time and nutrient transport to small standing waters (Bielecka, 2006; Kaszewski, 2020). Such changes may further exacerbate the susceptibility of shallow reservoirs to degradation processes.

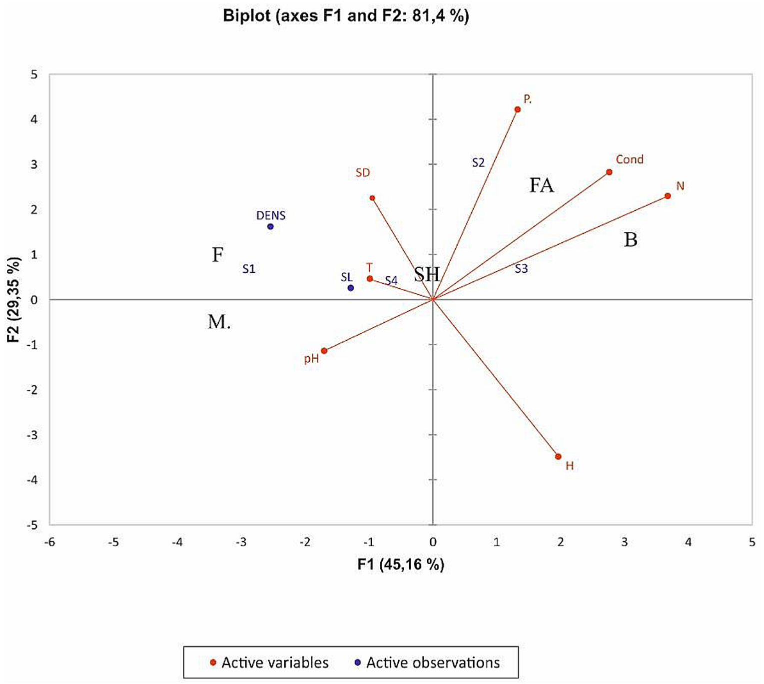

Figure 5. Principal component analysis (PCA) biplot showing relationships between environmental variables and study sites (S1–S4)
Note: The first two principal components (PC1 and PC2) explain 81.4% of the total variance. Environmental variables include water chemistry parameters, buffer-zone characteristics and terrain slope. Abbreviations: Cond – electrical conductivity; H – total hardness; N – nitrate concentration; P – phosphate concentration; DENS – buffer-zone vegetation density; SL – terrain slope; FA – arable land; F – forest; M – meadow; SH – shrub vegetation; B – built-up areas.; active variables – environmental variables, active observations – study sites

Seasonal variability in water chemistry is a well-documented feature of small reservoirs (Moniewski, 2014) and was clearly reflected in the present study. Elevated nutrient concentrations, particularly nitrates in groundwater, were observed in spring, which likely reflects fertilizer application combined with enhanced subsurface flow during early-season recharge. Vegetation developing both within the reservoir and along its margins plays a key role in moderating these processes. Aquatic and shoreline plants are known to contribute to nitrate reduction through uptake and associated microbial processes, as demonstrated in previous studies (Małek and Gawęda, 2006). In the analysed reservoirs, shoreline sections bordered by trees and shrubs forming compact buffer zones exhibited lower concentrations of nutrients, which is consistent with the protective role attributed to vegetated buffer zones in previous studies (Klarzyńska et al., 2018).

The results further indicate that the effectiveness of buffer zones is closely linked to their structural characteristics and to local geomorphological conditions. Numerous studies have shown that buffer width, vegetation density and species composition strongly influence the retention of nutrients transported from agricultural land, while terrain slope controls the intensity of surface runoff and subsurface flow pathways (Mander et al., 2005; Zhang et al., 2010). In the present study, higher concentrations of nitrates and phosphates were recorded at sites where the slope of the surrounding terrain reached approximately 7% and buffer-zone vegetation density did not exceed 50%. Under such conditions, enhanced surface runoff and subsurface transport may occur, potentially reducing the nutrient interception capacity of the buffer zone. These conditions coincided with lower vegetation diversity in both the buffer and littoral zones. In contrast, gentler slopes and denser buffer vegetation were associated with lower nutrient concentrations and higher floristic diversity. Vegetation composition in the shoreline zone also appeared to influence nutrient dynamics within the reservoirs. Where *Phragmites australis* dominated the shoreline vegetation, lower nitrogen and relatively higher phosphorus concentrations were observed, suggesting possible species-related differences in nutrient dynamics (Klarzyńska et al., 2018). Similarly, the presence of submerged macrophytes in the littoral zone was associated with reduced nutrient concentrations, supporting their role in nutrient uptake and stabilization of water quality in small agricultural reservoirs (Sender and Kułak, 2014).

Nitrates and phosphates are key drivers of eutrophication and algal blooms in small standing waters. Nitrogen inputs are particularly difficult to control when drainage water from agricultural fields enters reservoirs directly (Fiedler, 2011). Numerous studies have shown that shallow water bodies respond rapidly to external nutrient loading, often shifting towards turbid, phytoplankton-dominated states that restrict light availability and limit the development of submerged macrophytes (Scheffer et al., 2001; Jeppesen et al., 2017).

Terrain slope strongly modulates erosion and nutrient transport, with slopes in the range of 5–10% potentially leading to the annual loss of approximately 1 mm of topsoil. Assuming an average phosphorus content of 0.1% in arable soils, such erosion may result in phosphorus losses of about 10 kg ha^{-1} $year^{-1}$. Even low phosphorus concentrations (as little as 0.01 $mg \cdot L^{-1}$) can pose a serious threat to aquatic ecosystems (Domagała-Świątkiewicz, 2005), highlighting the potential importance of buffer effectiveness in agricultural landscapes.

Small water reservoirs play a disproportionally important role in maintaining freshwater biodiversity, often harbouring rare or regionally valuable demonstrating species (Davies et al., 2007; Ożgo, 2010; Klarzyńska et al., 2018). In the studied reservoirs, species richness was highest in the shoreline zone, whereas the littoral zone was dominated by a limited number of emergent macrophytes. No rare or protected species were recorded, which is typical for intensively used agricultural landscapes. Nevertheless, sites with denser buffer zones supported higher numbers of rush and aquatic species, likely due to improved water quality and shading effects that reduce extreme temperature fluctuations in shallow reservoirs (Mander et al., 2005; Sender, 2016).

Successional processes were evident in the vegetation surrounding the reservoirs, with the encroachment of woody species such as common hazel, elderberry and hawthorn. While these processes are natural, their pace is strongly influenced by land-use practices in the catchment and may lead to the displacement of typical wetland species if unmanaged. In mid-field reservoirs, agricultural surroundings remain a key driver of floristic change and should therefore be carefully considered in management strategies.

Fish are typically absent or occur sporadically in small isolated reservoirs (Ożgo, 2010). In the studied reservoirs, reduced development of submerged vegetation was observed, possibly linked to limited light availability under eutrophic conditions. Such habitat simplification may influence the broader ecological functioning of these systems. Given their multifunctional role in agricultural landscapes, small reservoirs may benefit from targeted protection and restoration measures. Reservoirs of high ecological value may be designated for legal protection, whereas those with lower ecological status, such as the studied reservoirs classified as class III and IV, require targeted remedial actions. These may include restoration measures such as shoreline reshaping, selective deepening and, most importantly, the establishment of structurally diverse buffer zones composed of trees, shrubs and herbaceous vegetation (Bielecka, 2006).

Buffer zones have been shown to reduce nitrate concentrations in percolating water by up to thirtyfold compared to adjacent arable land, with multi-species plantings being more effective than monocultures (Symonides, 2010). In the studied reservoirs, sites characterised by denser and more continuous buffer zones were associated with substantially lower nutrient concentrations in surface water compared to sites directly exposed to agricultural land use. In some cases, nutrient levels differed by up to 80% between contrasting shoreline sections. The strongest contrasts were observed at sites adjacent to seasonal crops, where nitrate concentrations before the buffer were several times higher than those measured in the reservoir. These findings highlight the need for further research on optimal buffer width, species composition and spatial configuration to enhance the protective function of buffer zones in small agricultural reservoirs.

Ecological valorisation of small mid-field reservoirs in Poland most commonly assigns them to class III, indicating moderate ecological status (Sender and Kolejko, 2013; Skwierawski, 2005). Reservoirs of higher status (class II) are typically located in river valleys or forested areas (Sender et al., 2014), although even these systems remain influenced by surrounding land use (Maślanko et al., 2010). The classification of the studied reservoirs as class III and IV emphasises the urgency of comprehensive management actions. Importantly, the present study demonstrates that such actions should not be limited to the creation of buffer zones alone but should encompass integrated land-use management in the immediate surroundings of small reservoirs.

Recent syntheses and reviews emphasise that buffer-zone performance is controlled by interacting structural and geomorphological drivers rather than by vegetation presence alone. In particular, buffer width, vegetation density and functional stratification (herbaceous–shrub–tree layers) jointly determine hydraulic roughness, infiltration opportunity time and nutrient retention pathways, while slope governs whether flow remains diffuse or concentrates into preferential runoff routes that can bypass the buffer and deliver nutrients directly to the shoreline (Wang et al., 2024; Wu et al., 2023; Ramler et al., 2022). Our results are consistent with this framework: the highest NO_3^- and PO_4^{3-} concentrations and the lowest macrophyte diversity occurred at shoreline sections combining steeper slopes (~7%) with low buffer density (≤50%), which may indicate reduced nutrient interception efficiency under steeper slope conditions. Similar slope–vegetation interactions have been reported in experimental and field studies, where vegetation type and structural continuity influenced runoff attenuation and sediment or nutrient delivery from agricultural land (Dunn et al., 2022). Moreover, recent European pond studies demonstrate that even relatively narrow buffers (e.g., ~5 m) can measurably reduce TN/TP and suspended solids, but effectiveness increases with buffer width and is context-dependent across regions, highlighting the need for site-specific design rather than uniform prescriptions (von Plueskow et al., 2025). This variability is also supported by a recent global meta-analysis showing that retention efficiency is highly sensitive to climatic and landscape settings, reinforcing the view that buffer design may need to account for slope, hydrological connectivity and vegetation structure when targeting nutrient mitigation in small agricultural catchments (Pan et al., 2025).

CONCLUSIONS

The studied mid-field reservoirs were classified as water bodies of average to low natural value, with the larger reservoir assigned to ecological class III and the smaller one to class IV, indicating unfavourable habitat conditions. Vegetation diversity was generally low, reflecting both the limited size of the reservoirs and the strong influence of surrounding agricultural land use. Nevertheless, clear internal spatial heterogeneity in water quality and vegetation structure was observed, demonstrating that small mid-field reservoirs should not be treated as environmentally homogeneous systems.

Pronounced spatial variability in physicochemical parameters was primarily associated with differences in shoreline land use, buffer-zone structure and terrain slope. Shoreline sections directly exposed to agricultural activity, especially under steeper slope conditions, were characterised by elevated nitrate and phosphate concentrations and reduced floristic diversity. In contrast, forested and densely vegetated buffer zones were linked to lower nutrient concentrations and higher plant diversity.

The eutrophic character of both reservoirs highlights their vulnerability to external nutrient inputs. The results indicate that vegetated buffer zones, particularly those characterised by sufficient density and structural continuity, significantly enhance the ecological resilience of small agricultural reservoirs. Terrain slope should be considered a key design factor influencing buffer effectiveness.

From a management perspective, the establishment and maintenance of structurally diverse riparian buffer zones, adapted to local geomorphological conditions, should be prioritised as a practical and cost-effective measure for mitigating nutrient inflow and improving the ecological status of small mid-field water bodies in agricultural landscapes.

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