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Research Article

Conservation and ecological screening of small water bodies in temperate riverine wetlands using UAV Photogrammetry (Middle Danube)

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Abstract

Aquatic ecosystems in riverine wetlands are important refuges and nurseries for freshwater biota. Given the significant global loss and degradation of wetlands, regular conservation assessments of these habitats, even in not easily accessible regions, are crucial for implementing effective management. Thus, developing cost-effective approaches for rapid ecological and conservation screening of water bodies in floodplains, such as the Danube, is a priority. One potential solution is the use of UAV-based (Unmanned Aerial Vehicle) ecological indicators to complement existing monitoring frameworks. This paper aims to explore whether UAV-based macrophyte data can provide a more precise indication of the trophic state and conservation indices (assessed through fish and macroinvertebrate communities) of temperate wetland lentic ecosystems, compared to traditional field surveys. The fieldwork was conducted during the summer months of 2019 at 23 sampling sites within eight lentic water bodies located in three wetland areas along the Middle Danube in Serbia. Data on aquatic vegetation, fish, and macroinvertebrate communities, and samples for water quality analysis were collected simultaneously. UAV images were acquired using an RGB camera. Orthomosaics were processed using supervised object-based image (OBIA) classification to obtain a single vector layer with macrophyte functional groups and taxa. Macrophyte cover metrics obtained during the fieldwork and UAV data processing were correlated against water quality parameters and conservation indices calculated for fish and macroinvertebrate assemblages. The study demonstrated that UAV photogrammetry can provide relatively precise measurements of macrophyte cover characteristics compared to traditional plot-based monitoring methods, making it effective for assessing aquatic ecosystems. The analysis revealed that sites with high values of fish and macroinvertebrate conservation indices, optimal oxygen conditions, and mesotrophic states were associated with UAV orthomosaic polygons showing relatively high macrophyte functional diversity and a presence of floating-rooted species. Conversely, sites experiencing eutrophication and a poor oxygen regime with species-poor fish assemblages correlated positively with a higher cover of amphibian and free-floating vegetation, as well as filamentous algae. In conclusion, UAV photogrammetry offers a cost-effective method to monitor aquatic habitats along large river floodplains, including those that are not easily accessible.

Key words: Aquatic vegetation, fish, macroinvertebrates, ponds, riverine wetlands, UAV indicators

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Introduction

Aquatic ecosystems in riverine wetlands represent important refuges and nurseries for freshwater biota (Biggs et al. 2017; Damnjanović et al. 2019; Bolpagni et al. 2019; EEA 2019a). In order to tackle the high global loss and degradation of wetlands (IPBES 2019), precise monitoring is needed to identify hotspots for conservation and deficits for management and improvement. Thus, the development of cost-effective approaches for rapid ecological and conservation screening of these habitats along large river floodplains, such as the Danube, also in not easily accessible regions is a priority (Roni et al. 2019; Hill et al. 2021). According to Jiménez López and Mulero-Pázmány (2019), one potential solution is the use of UAV- based (Unmanned Aerial Vehicle) ecological indicators complementing existing monitoring frameworks. By focusing the detailed monitoring actions on pre-selected freshwater patches (Tu et al. 2020), available conservation/restoration funds could be managed effectively.

Aquatic vegetation is widely used in the conservation assessment of freshwater ecosystems, serving as surrogates for diversity indices of macroinvertebrate and fish communities (Hassall et al. 2011; Thornhill et al. 2017; Law et al. 2019), as well as indicators of the physical and chemical properties of water bodies (Gebler et al. 2014; Gebler et al. 2017; Krtolica et al. 2021). Additionally, the coverage and diversity of macrophyte functional groups are strong predictors of animal communities and the conservation value of lentic water bodies (Law et al. 2019). Water bodies with complex macrophyte stands and rich floating vegetation typically host the richest macroinvertebrate assemblages, which exhibit high conservation indices (Thornhill et al. 2017). Furthermore, in various types of wetlands, macrophyte metrics are often more critical for structuring fish assemblages than environmental and spatial variables (Cvetkovic et al. 2010; Hsu et al. 2011; Granzotti et al. 2019).

The presence and characteristics of aquatic vegetation, which are considered robust ecological or conservation indicators in dynamic wetland landscapes (Aznar et al. 2003; Rosset et al. 2013), can be effectively assessed using UAV-based photogrammetry (Biggs et al. 2018; Kislik et al. 2020). The spectral signature of specific macrophyte functional groups, such as submerged filamentous algae, rooted floating and emergent macrophytes can be clearly distinguished from other vegetation types (Kislik et al. 2020; Higgisson et al. 2021). On the other hand, vegetation attributes, such as species abundance and stand area, can also be successfully determined from orthophotos (Biggs et al. 2018).

Moreover, the identification of single macrophyte taxa, particularly floating ones is also possible using UAV-based photogrammetry (Chabot et al. 2016; Benjamin et al. 2021). Macrophyte functional groups can be successfully identified in the UAV multispectral or RGB images by applying Object-based image analysis (OBIA) (Husson 2016; Husson et al. 2016; Benjamin et al. 2021). The overall accuracy of the OBIA method in the detection of aquatic vegetation, mostly the non-submerged stands and species, is up to 80–95% (Husson 2016; Husson et al. 2016; Chabot et al. 2018; Benjamin et al. 2021). The OBIA is a suitable approach for processing UAV images of aquatic vegetation since it starts with the segmentation of an image into objects (segments), based on the spatially connected pixels having similar spectral properties (Kelly et al. 2011; Husson 2016; Husson et al. 2016). These objects are further classified according to their shape, size, spatial and spectral characteristics. However, only a limited number of previous studies attempted to investigate the potential of using remote sensing-based macrophyte metrics as indicators of aquatic ecosystems (Biggs et al. 2018; Pace et al. 2022). Biggs et al. (2018) demonstrated that macrophyte abundance, assessed using UAV photogrammetry, can clearly indicate a hydraulic pattern of aquatic habitats. To the best of our knowledge, there have been no prior studies that have utilized UAV photogrammetry of aquatic vegetation to assess the conservation indices of aquatic ecosystems.

The aim of this paper is to explore if macrophyte cover data derived from UAV images can provide a more precise indication of the trophic state and conservation index values (assessed through fish and macroinvertebrate communities) of the Danube wetland lentic ecosystems in Serbia, compared to the traditional field survey. In order to achieve the primary objective of the study, the following tasks were established: 1) to determine water quality (dissolved oxygen, orthophosphate, and total organic carbon) and conservation indices of lentic water bodies based on fish and macroinvertebrate assemblages; 2) to compare the sensitivity of macrophyte metrics derived by UAV monitoring (UAVM) and by field monitoring (FM) for the conservation assessment; 3) to identify macrophyte metrics obtained by UAV monitoring, which significantly indicate sites having high conservation index values.

Material and methods

Study sites

The large floodplains along the Middle Danube are recognized as sites of high conservation value and importance at the national and international levels (Radulović et al. 2011; Cvijanović 2022). The fieldwork included three Middle Danube wetland areas in Serbia (Fig. 1): i) Special Nature Reserve (SNR) Koviljsko-Petrovaradinski rit (Ramsar site no. 2028, IPA, IBA); ii) the wetland area located near the Bačko Novo Selo village (the National Ecological Network code BAČ04; a candidate for SNR); iii) Nature Park Begečka jama. These naturally flooded wetlands are located upstream from the Danube section affected by the Djerdap I dam at the Iron Gate (Vukov et al. 2006). Due to the time and cost-consuming fieldwork and difficult accessibility, many freshwater habitats along the Middle Danube wetlands were not included in the routine monitoring programmes, and were consequently overlooked by conservation plans.

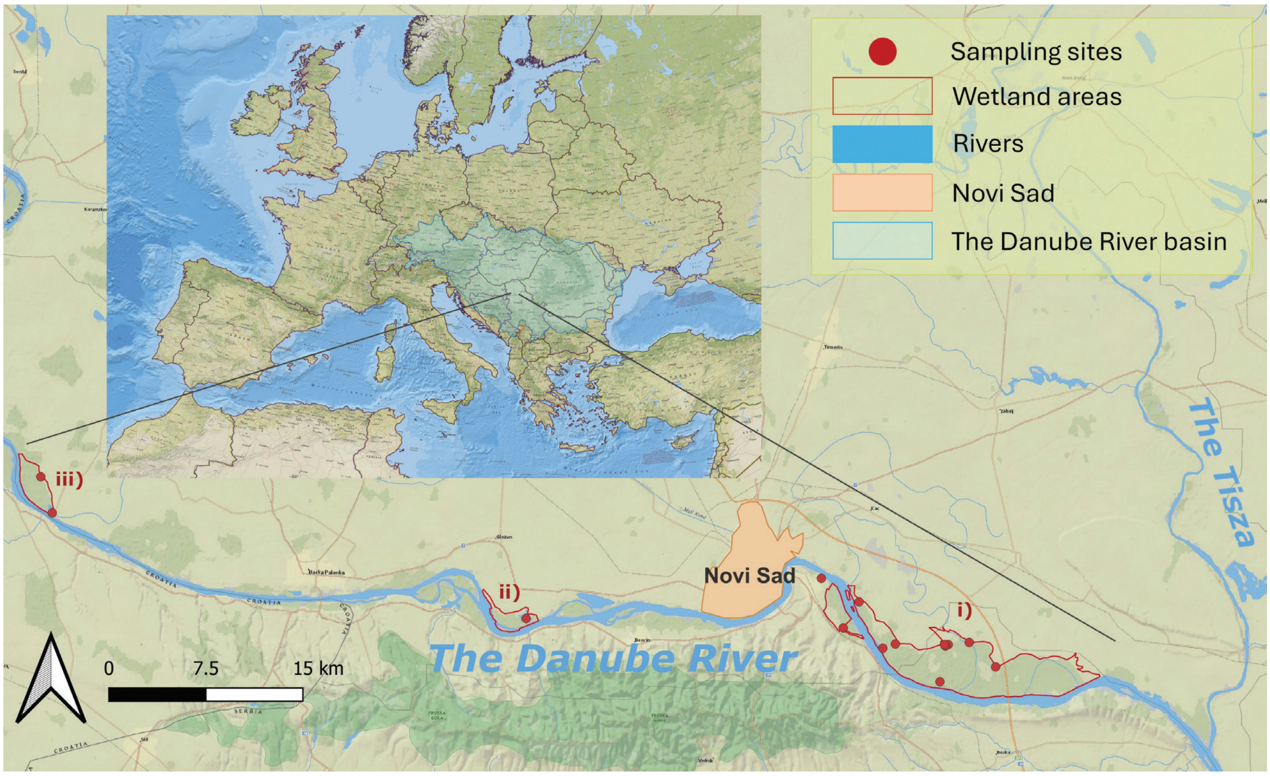

Figure 1. Distribution of studied wetland areas and sampling sites along the Middle Danube in Serbia: i) SNR Koviljsko-Petrovaradinski rit; ii) the wetland area located near the Bačko Novo Selo village; iii) Nature Park Begečka jama.

Data acquisition

Field work

Field work was carried out during the summer months of 2019 on 23 sampling sites within the 8 lentic water bodies (Fig. 1). Water bodies were distributed along the three wetland areas in the Middle Danube Basin in Serbia (Fig. 1). Data for aquatic vegetation, fish and macroinvertebrate communities, and samples for the analysis of water quality attributes (dissolved oxygen, orthophosphates, total organic carbon, water depth, Secchi depth and turbidity) were collected simultaneously at each sampling site. The number and location of sampling sites were chosen to cover all macrophyte-based habitat types *sensu* EUNIS classification (EEA 2013). Fieldwork was undertaken after the Danube flooding, during the peak of the aquatic vegetation season, a period typically used for conservation assessment of water bodies in the Middle Danube wetlands (Radulović et al. 2011; Cvijanović et al. 2018).

Vegetation data were collected within the circle polygons of 2.5 m radius using the species relative abundance DAFOR scale following standard method EN 15460:2007 (European Committee for Standardization 2007). Water samples were collected at a depth of 0.5 meters. For sampling points with water depths of less than 0.5 meters, samples were taken 0.2 meters below the water surface. Dissolved oxygen was measured *in situ* electrochemically with WTW Inco Lab 4. The concentration of orthophosphates was measured in laboratory with the Lovibond Water Testing MD 600 meter (method 320: Phosphate, ortho LR with Tablet); while the portable SECOMAM Pastel UV spectrophotometer was used for measuring total organic carbon, and Eutech TN-100 Turbidimeter for turbidity.

Macroinvertebrate communities were collected in transects - one per each sampling site. At each transect, three benthic samples were collected with a 15 × 15 cm Ekman grab. Transects were distributed to cover all mesohabitats, starting from the shoreline, towards the increasingly deeper water. The benthic samples were preserved in 70% ethyl alcohol and individuals were sorted in the laboratory. All macroinvertebrates were identified to the lowest possible taxonomic level (mostly species or genus) using the relevant taxonomic keys (Elliot et al. 1988; Nilsson 1997; Waringer and Graf 1997; Gerken and Sternberg 1999; Timm 1999; Pfleger 2000; Bauernfeind and Humpesch 2001; Glöer 2002; Eiseler 2005; Elliot and Humpesch 2010).

The fish were sampled along transects from a boat using a DC Aquatech IG 1300 electro-fisher (2.6 kW, 80–470 V). For each selected transect, the constant catch-per-unit-effort (CPUE) of time (10 min) was provided. Each fish was identified at the species level.

UAV data

UAV images were acquired by Phantom 4 FC330 (12.5MP) RGB camera on summer sunny days in August 2019, between 7:10 a.m. and 12:17 p.m. to correspond with an *in-situ* field survey (Kislik et al. 2020). Flights were performed at altitudes ranging from 60 to 125 m above the water surface, depending on the complexity of riparian vegetation and canopy configuration, which may affect further classification accuracy of aquatic features (Rusnák et al. 2018). Depending on the water body surface area, 15 to 250 closes to nadir photos of 4000 × 2250 px/75 dpi resolution were captured per entire water body area with 30% of cross-strip, and 60% in-strip image overlap. For detailed characteristics of the flights and acquired images please see Suppl. material 1: Flight and average OBIA parameters per pond.

Data processing

Conservation indices

Conservation indices, relevant for the conservation management of fluvial lentic ecosystems were obtained for fish and macroinvertebrate assemblages for each sampling site: Shannon diversity index (SD) (Shannon 1948), species richness (SR), conservation value (C) (Linton and Goulder 2000; Oertli et al. 2002), and mean conservation value (Csp) (Linton and Goulder 2000; Oertli et al. 2002).

Conservation scores C and Csp (Linton and Goulder 2000; Oertli et al. 2002; Damnjanović et al. 2019) were calculated for both fish and macroinvertebrates, based on the status and rarity of the species in Serbia and in Europe (IUCN reference, National Assembly of the Republic of Serbia 2011a). For each species, conservation values were assigned according to the following criteria: 0 for non-native species, 1 for common native species, 2 for nationally protected species, 4 for nationally strictly protected species, 8 for IUCN Near Threatened species, and 16 for IUCN Vulnerable species. “Conservation value C” was further calculated as the sum of conservation values of all species present at the sampling site, while the Csp score represents the C value divided by the number of species per sampling site.

Macrophyte metrics obtained during the field survey

For each sampling site, the cover of a single species was summarized to the following macrophyte metrics, considered as explanatory variables in the further analyses: the total macrophyte cover, the total cover of emergent macrophytes, the total cover of rooted floating-leaved macrophytes; total cover of free-floating macrophytes; and the total cover of submerged macrophytes. The floating-leaved (rooted) macrophyte group was also differentiated into the cover value of waterlily species, the cover value of *Nymphoides peltata*, and the cover value of *Trapa natans*.

UAV imagery processing

For each water body, UAV-based geotagged images were block adjusted and stitched into individual georeferenced orthomosaics using default settings of the Adjust and Orthomosaic wizard tools within the ArcGIS Pro 2.6.0 software (Perform Camera Calibration checked, Blunder Point Threshold 5, Image Resolution Factor 8× Source Resolution) (ArcGIS Pro [GIS software] (2021) Version, 2021). Withing the Orthomosaic wizard tool as elevation source - World Elevation Service was selected, colour balancing was performed using the Dodging method, and seamlines computation using the Voronoi diagram method. Orthomosaics were further processed using supervised object-based image classification (Ma et al. 2017) to recognize and distinguish macrophyte functional groups and taxa. Image classification was conducted in Quantum GIS (QGIS) 3.16.3-Hannover software (QGIS 2021) using Orfeo Toolbox (OTB) 7.2.0 provider (OrfeoToolbox [GIS software] Version 7 2021). The orthomosaic classification workflow included three phases: i) orthomosaic segmentation and calculation of classification criteria ii) training and validation data sets creation iii) classification and reclassification (Fig. 2).

Image segmentation was performed using LargeScaleMeanShift algorithm (Spatial Radius: 30; Range Radius: 10; Minimum Segment Size: 50 px and Tile Size: 1024 × 1024 px). During the segmentation process, orthomosaic features were partitioned into discrete entities – segments based on the similarity of their spectral characteristics and spatial distribution. In order to increase classification accuracy, a set of classification attributes (RGB spectral and texture indices, Suppl. material 2: RGB-based and texture indices) was calculated for each orthomosaic segment (Visser and Wallis 2010; Husson et al. 2016; Chabot et al. 2018; De Swaef et al. 2021). RGB indices were calculated using the Raster calculator tool in QGIS 3.16.3-Hannover (QGIS 2021), while the texture indices were calculated using the FeatureExtraction tool of Orfeo Toolbox (OTB) 7.2.0, and the r.texture tool of the GrassGIS 7.8.3 providers within QGIS platform. Since the texture indices are calculated based on the single band raster layers, 3-band RGB orthomosaics were transformed into the single band raster layer using PCA analysis. The first PCA axis was used as input for computation of texture indices. Area of interest (AOI) polygons were created for each orthomosaic encompassing the areas covered by the aquatic vegetation and open water, while areas occupied by terrestrial vegetation, bare bank material and artificial construction were omitted from further analyses as they were beyond the scope of this research. Finally, the characterization of each orthomosaic segment was carried out using Zonal statistics tool, based on mean values of each RGB and texture index.

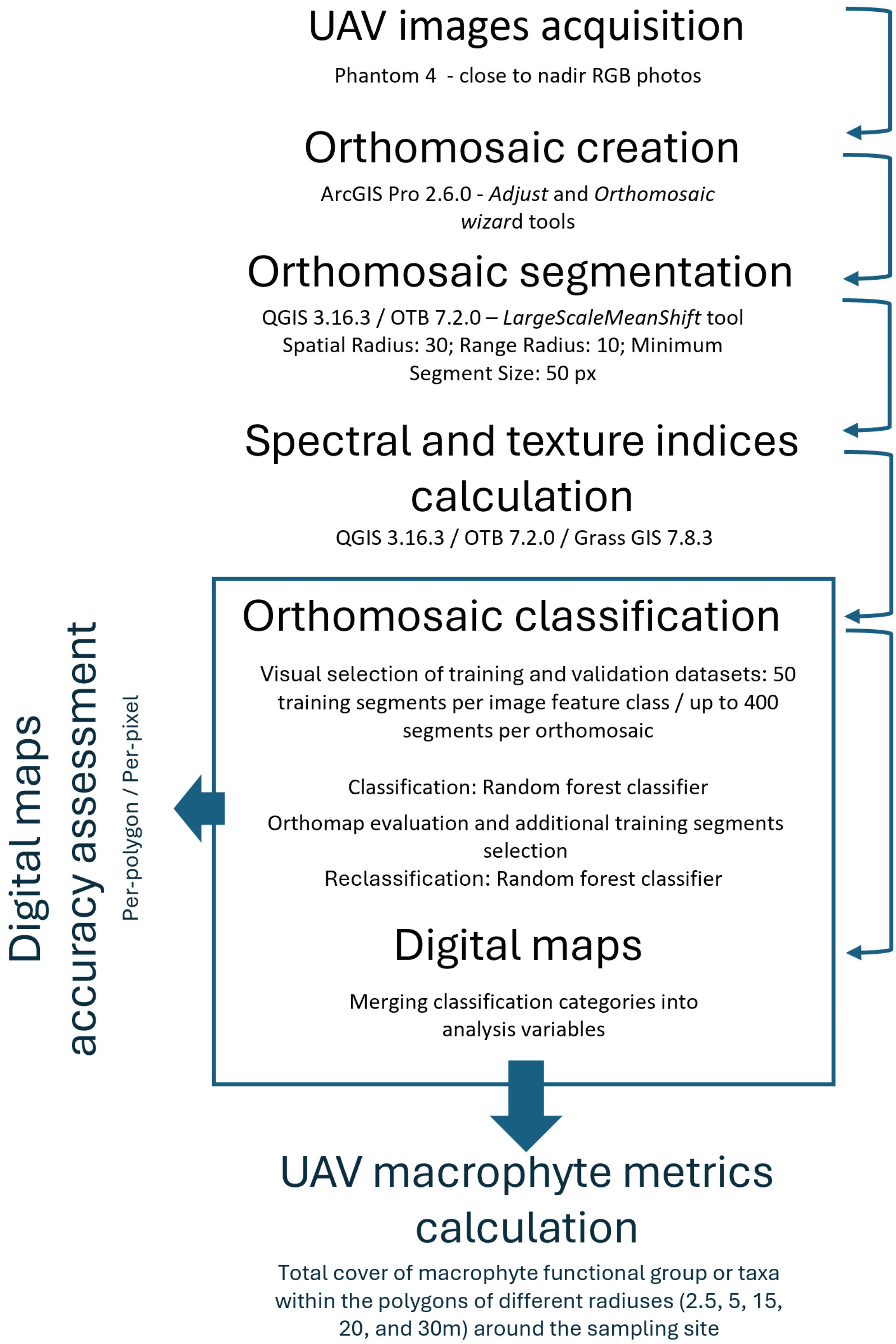

Figure 2. UAV data processing workflow.

For each orthomosaic, a training data set was created by selecting 50 representative reference polygons representing a specific macrophyte image feature class (macrophyte functional groups or stands of particular macrophyte taxa; for further details please see Suppl. material 3: Macrophyte OBIA parameters). An expert-based selection of the reference polygons was conducted based on the ground-truthing data collected during the fieldwork. In the case when single macrophyte taxa included more than one phenophase or different spectral patterns, each phenophase or spectral pattern was assigned to the specific feature class (e.g. stands of water lilies were distinguished as green and yellowish stands). Different feature classes for the single taxa were aggregated for the purpose of accuracy analysis.

A validation data set for each orthomosaic included independent and unbiased polygons selected using the Random points tool in QGIS. A different number of random polygons were selected depending on the waterbody size (<1.5 ha – 100; 1.5–2.5 ha – 200; 2.5–3.5 ha – 300 and > 3.5 h – 400 points) (for further details please see Suppl. material 1: Flight and average OBIA parameters per pond).

Object-based classification of orthomosaic segments was further performed using a Random Forest (RF) classifier (TrainVectorClassifier and VectorClassifier tools of the Orfeo Toolbox (OTB) 7.2.0), and the following parameters: Maximum depth of trees: 10; Minimum number of samples in each node: 7; Maximum number of trees in forest: 225; OBBerror: 0.01. TrainVectorClassifier tool performs training of the RF algorithm using training and validation dataset, while VectorClassifier tool performs classification of the orthomosaic segments using model file obtained in the previous step.

After the initial classification, orthomaps were visually evaluated. In the orthomosaic areas which were poorly classified additional training segments were assigned to the misclassified image feature categories and added to the training data set. The training process was repeated. This allowed the lowest size of the training data set to be considered in the analysis and to target and address challenging areas of the orthomosaics. This allowed the lowest size of the training data set to be considered in the analysis, while targeting the classification challenging areas of the orthomosaics and image feature categories. As a result of classification, each orthomosaic segment was assigned to a specific macrophyte functional group or macrophyte taxa.

Two approaches of accuracy analysis were applied to macrophyte metrics, Per-Pixel and Per-Polygon. Per-Polygon analysis was performed with the TrainVectorClassifier tool based on the Kappa index. Per-Pixel accuracy was estimated using the Accuracy tool from Semi-Automatic classification plugin, which includes Kappa-hat index, Standard error, Standard error area, Users accuracy, Producers accuracy and Kappa-hat index.

Macrophyte metrics obtained from the UAV photogrammetry

Therefore, the result of the OBIA classification was a single vector layer with different macrophyte image feature classes (macrophyte functional groups or taxa) (for further details please see Suppl. material 3: Macrophyte OBIA parameters). The cover value for UAVM macrophyte metrics were further calculated and extracted using QGIS within the various circular polygons (Fig. 3). Each UAVM macrophyte metric (e.g. cover value of free-floating macrophytes) was calculated by adding cover values of all belonging image feature classes (e.g. Stands dominated by *Salvinia natans*; stands dominated by *Spirodela polyrhiza*; mixed stands of *S. natans* and *S. polyrhiza*), (for further details please see Suppl. material 3: Macrophyte OBIA parameters). Due to the different microhabitat and size requirements of fish and macroinvertebrate communities, the polygons for analysis were generated for different radii (2.5, 5, 15, 20, and 30 m)

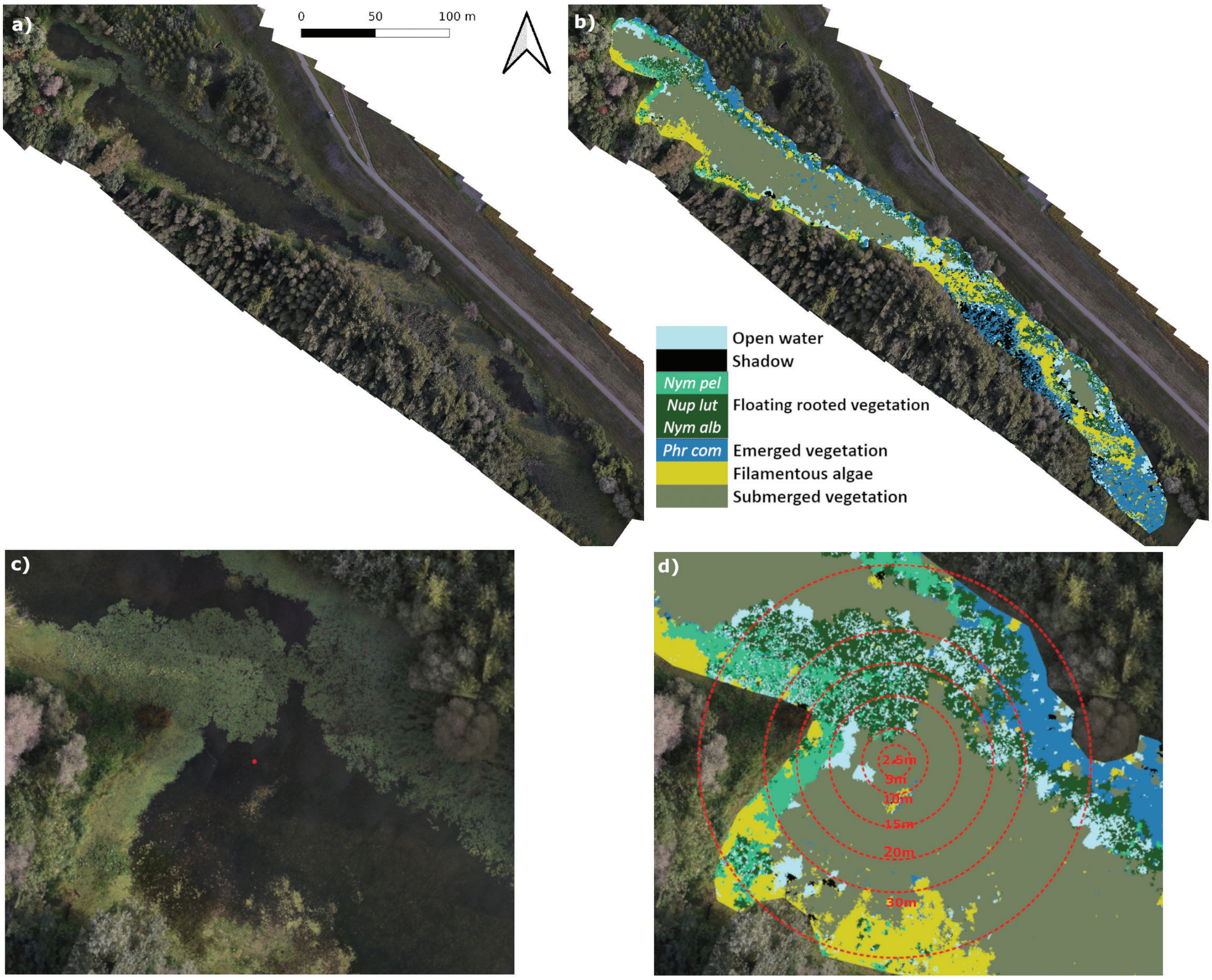

Figure 3. An orthomosaic of the Doktor Pumpa fluvial lake - the wetland area located near Bačko Novo Selo (**a**) with classified main macrophyte metrics; (**b**) enlarged fraction of an RGB orthomosaic (**c**) and image classification showing location of field sampling point and also GIS approach for extraction of macrophyte metric areas within the polygons of different radii (**d**).

around the sampling sites (Fig. 3). While the radius of 2.5 m corresponds to the size of traditional vegetation survey plots, the radius of 30 m represents the maximal area that could be evaluated in the studied water bodies without polygon overlapping. Therefore, for each polygon, the following macrophyte metrics (UAVM) were calculated: the total macrophyte cover, the total cover of free-floating macrophytes, the total cover of floating rooted macrophytes, the total cover of amphibian macrophytes, the total cover of emerged macrophytes, the total cover of submerged macrophytes, the total cover of filamentous algae, the total cover of *Nymphoides peltata* species, the total cover of *Trapa natans* species, the total cover of water lilies, and the number of macrophyte communities (dominant species). For further details please see Suppl. material 3: Macrophyte OBIA parameters.

Macrophyte metrics obtained during fieldwork and UAV data processing were further correlated against the conservation metrics and water quality (dissolved oxygen content, total organic carbon and orthophosphates) using the non-parametric Spearman's rank in STATISTICA 14 software (TIBCO Software Inc 2020).

Results

In total, 43 macrophyte taxa were recorded in the study area, forming vegetation stands of free-floating duckweeds, occasionally submerged anchored ceratophyllids, and rooted aquatic vegetation (for further details please see Suppl. material 3: Macrophyte OBIA parameters) (Cvijanović et al. 2018). The depths of the vegetation sampling polygons varied from very shallow (0.3 m) to shallow (2.5 m).

Dissolved oxygen concentrations varied among water bodies and within individual sampling points in a single water body—from low oxygen levels (1.37 mg/L) to good water quality (>9 mg/L), indicating conditions ranging from eutrophic to oligo-mesotrophic (Leuschner and Ellenberg 2017). A wide range of values was also observed for orthophosphates and total organic carbon, covering all water quality classes defined by the National Assembly of the Republic of Serbia (2011b), from mesotrophic to eutrophic conditions (Carlson 1977; Dunalska 2011). For further details, please see Suppl. material 4: Physical and Chemical Parameters. Turbidity in the water bodies varied from very low (1.11 NTU) to moderately high (26.70 NTU), suggesting a spectrum of water clarity from clear to moderately turbid across most sampling locations.

The relatively lower OBIA classification accuracy was observed for the cover of amphibian vegetation (Producer's acc. 49.35%, Users acc. 30.43%, Kappa-hat index 0.29) and *Trapa natans* species (Producer's acc. 93.45%, Users acc. 44.22%, Kappa-hat index 0.42), compared to other macrophyte metrics (maximal Producer's acc. 87–100%, maximal Users acc. 90–100%, maximal Kappa-hat index 0.89–1) (Suppl. material 3: Macrophyte OBIA parameters). FM metrics showed a significant correlation with seven conservation indices and two water quality parameters (please see Suppl. material 4: Physical and chemical parameters). Meanwhile, the UAVM metrics were found to be a relevant predictor of eight conservation metrics and all three water quality parameters (Tables 1, 2). Variables captured exclusively by UAVM metrics were the total organic carbon and C value calculated for macroinvertebrate assemblages. Additionally, the total cover of aquatic vegetation, amphibian macrophytes, filamentous algae and water lily species, as well as the number of macrophyte communities were relevant ecosystem indicators only in the UAV data set analysis.

Table 1. Non-parametric Spearman's rank values ($P < 0.05$) for significant correlations of macrophyte cover classes obtained during the fieldwork against the conservation indices for fish and macroinvertebrate assemblages and water quality parameters.

	Fish Species richness	Fish Csp value	Fish C value	Fish Shannon-Wiener index	Macroinvertebrate Species richness	Macroinvertebrate Csp	Macroinvertebrate Shannon-Wiener index	Orthophosphates	Dissolved oxygen
Total cover of free-floating macrophytes									-0.50
Total cover of floating rooted macrophytes	0.50			0.52				-0.44	
Total cover of emerged macrophytes	-0.56		-0.54		-0.52		-0.50	0.46	
Total cover of submerged macrophytes	0.45	0.45	0.58			-0.58		-0.50	0.51
Cover of *Trapa natans*								-0.52	
Cover of *Nymphoides peltata*	0.65		0.43	0.50				-0.55	

Table 2. Non-parametric Spearman's rank values for significant correlation (P < 0.05) of macrophyte metrics obtained using the UAV data processing against the conservation indices for fish and macroinvertebrate assemblages.

	Radius (m)	Fish Species richness	Fish Csp	Fish C	Fish Shannon-Wiener index	Macroinvertebrate Species richness	Macroinvertebrate Csp	Macroinvertebrates C	Macroinvertebrate Shannon-Wiener index	Total Organic Carbon	Orthophosphates	Dissolved oxygen
Total cover of aquatic vegetation	2.5		0.43	0.42								
	5		0.43									
	30							0.48			-0.52	
	2.5									0.50		
Total cover of free-floating macrophytes	5					0.53				0.53		-0.44
	10					0.48				0.48		-0.47
	15					0.48				0.48		
	20									0.49		-0.44
	30											-0.44
Total cover of floating rooted vegetation	2.5	0.56	0.42	0.65					0.50			0.42
	5			0.47					0.53			
	10								0.48			
	15								0.48			
	20								0.49			
	30										-0.45	
Total cover of submerged vegetation	5									-0.44		
	15							0.48				
	30								0.64			
Total cover of amphibian vegetation	15	-0.49	-0.49	-0.49		-0.55			-0.48			
	20	-0.49	-0.49	-0.49		-0.55			-0.48			
	30	-0.49	-0.49	-0.49		-0.55			-0.48			
Total cover of emergent vegetation						-0.52					0.46	
Filamentous algae	2.5					0.69					0.45	
	5					0.56					0.51	
	10					0.53					0.51	
	15					0.53					0.51	
	20					0.53					0.51	
	30					0.70			0.49		0.46	
Trapa natans	15									0.47		
	20									0.50		
Nymphoides peltata	2.5										-0.68	0.56
	5										-0.62	0.65
	10		0.49								-0.65	0.69
	15		0.46				-0.49				-0.65	0.68
	20		0.46				-0.49				-0.67	0.69
	30		0.47				-0.51				-0.67	0.70
Nymphaea alba* and *Nuphar luteum	2.5	0.54		0.42								
	5						0.48					
	10										0.60	
Nymphaea alba* and *Nuphar luteum	15						0.49				0.57	
	20						0.51				0.53	
	30								0.49			-0.44
Number of macrophyte communities / dominant macrophyte species	5							0.64				
	10							0.70				
	15							0.72				
	20							0.72				
	30	0.46			0.46			0.56	0.50	0.43		

When compared with FM equivalents, UAVM metrics (i.e. free-floating macrophytes, floating-rooted macrophytes, amphibian vegetation and *Nymphoides peltata*) showed more significant relationships with conservation metrics and water quality (Tables 1, 2). These UAVM metrics also had a Spearman coefficient value that was at least 10% higher compared to their equivalents in FM analysis, indicating that UAVM metrics generally provided a stronger correlation with the studied variables. However, the total cover of submerged and emerged macrophytes was found to perform better in FM dataset than in the UAVM one.

In summary, fish conservation metrics were positively correlated with floating vegetation types and species in both datasets, in polygons of 2.5 m radius (Tables 1, 2). Exclusively in the FM dataset, fish conservation indices were negatively correlated with emergent vegetation. Meanwhile, in the UAVM dataset they were negatively correlated with the cover of amphibian macrophytes (15–30 m radius polygons). Macroinvertebrate conservation metrics showed a positive relationship with the total cover of aquatic vegetation, filamentous algae, free-floating and submerged macrophytes, water lilies, and water nuts, but a negative relationship with emergent and amphibian macrophytes.

The highest correlation coefficients were obtained between water quality parameters and both types of macrophyte metrics, compared to conservation metrics (Table 2). For the UAVM metrics, the cover of free-floating macrophytes, emergent vegetation, amphibian macrophytes, filamentous algae, and water lilies were positive predictors of water body eutrophication. On the other hand, the total cover of aquatic vegetation, the cover of submerged and floating rooted macrophytes, as well as *Nymphoides peltata* species indicated lower trophic levels. The most relevant polygon size for assessing the trophic status and macroinvertebrate conservation indices was 30 m in radius. For assessing fish conservation metrics, polygon sizes of 2.5 and 30 m were the most relevant (Table 2). Most Spearman coefficients belonged to moderate correlation range (0.4–0.6) (Tables 1, 2). However, a strong correlation (>0.6) was found for *Nymphoides peltata* species against dissolved oxygen and orthophosphates in the UAVM dataset, and against fish species richness in the FM data set. Also, a strong relationship was observed between the total cover of floating rooted vegetation and fish “C conservation value”, as well as between the number of macrophyte communities/ dominant species and macroinvertebrate “C conservation value”. In both data sets, orthophosphates showed the highest number of significant correlations, followed by fish species richness and fish conservation indices.

Discussion

Our study has shown that total organic carbon and C value (calculated for macroinvertebrate assemblages) are captured exclusively by UAVM metrics. These results were obtained for 5–30 m radius polygons, which are larger than the traditional vegetation plots (16–20 m2) (Cvijanović et al. 2018). This implies that 5–30 m radius polygons were sufficient to capture all macrophyte functional groups and taxa, which are considered sensitive indicators of total organic carbon and trophic state (Szoszkiewicz et al. 2014). Previous studies have reported that a 20-meter buffer radius around the sampling site is optimal for assessing the local environmental conditions in the macroinvertebrate community (Campbell and McIntosh 2013). Additionally, Cheruvelil et al. (2000) demonstrated that a 10-meter radius polygon around epiphytic macroinvertebrate sampling points was sufficient to capture the influence of macrophyte functional groups and taxa on macroinvertebrate abundance. Therefore, the spatial scale at which UAV-based vegetation surveys are operated can be adjusted and optimized for different study objectives, offering flexibility beyond the constraints of traditional monitoring methods.

Another important finding of this study is that UAVM macrophyte communities serve as effective indicators for fish, macroinvertebrates, and water quality variables. The number of UAVM macrophyte communities was expressed in our study as a number of dominant macrophyte species, aligning with the formal definitions of Level 4 of the European Nature Information System (EUNIS) aquatic habitat classification (Davies et al. 2004; Moss 2014). Therefore, the UAV-based photogrammetry of aquatic vegetation can be considered as an upgrade of traditional aquatic habitat monitoring rather than a new methodological approach.

Overall, in our study UAVM metrics demonstrated stronger relationships with conservation metrics and water quality attributes compared to FM metrics. This was expected as UAV photogrammetry allows for precise measurements of aquatic vegetation stands, especially floating ones (Husson 2016; Husson et al. 2016; Chabot et al. 2018; Benjamin et al. 2021). Birk and Ecke (2014) have previously shown that observing just a fraction of macrophyte species through remote sensing can indicate water trophic conditions as effectively as when considering the entire assemblage.

For floating rooted and submerged macrophytes, UAV-based metrics were found to be reliable indicators of ecosystem conservation indices and moderate trophic states. Meanwhile, for the free-floating macrophytes, UAV metrics were effective predictors of eutrophic conditions. As expected, submerged vegetation was shown to be a better indicator in the FCM data set compared to the UAVM data set. This is likely because traditional field monitoring provides a more comprehensive view and inspection of the entire submerged layer than UAV imaging. Submerged vegetation can be detected with high accuracy up to 1.2 m depth in conditions of relatively high turbidity (Secchi depth > 2 m) using UAV RGB imagery (Kislik et al. 2020). In our study, turbidity was in the range of 0.17–0.8 m, while the water body depth varied from 0.3 to 2.5 m, which suggests that some parts of submerged vegetation stands couldn't be detected. However, the producer's (76.96) and user's accuracies (76.32) for submerged stands in our study (please see Suppl. material 3: Macrophyte OBIA parameters) were in a range of those reported in previous studies which also employed OBS classification on multispectral (Visser et al. 2018; Brooks et al. 2022) or RGB images (Kislik et al. 2020). Some metrics, such as floating rooted species showed good response in both datasets. However, the correlations were stronger with UAVM metrics. This was expected because traditional vegetation surveys use ordinal cover-value scales (Podani 2006), which are less precise than photogrammetric analysis. In contrast, emergent vegetation performed better in the FCM data set compared to the UAVM one. This is likely because emergent species had low cover values (one to a few individuals present) in the vegetation stands, making them difficult to detected using the OBIA protocol (Baier et al. 2022). Baier et al. (2022) speculated that low accuracy and high error in detecting sparse reed stands could be due to the interference of the water surface between individual reed stems during analysis. Although occasional emergent individuals occurred in the sampling polygons, stands dominated by emergent species were not the subject of our study. Also, due to specific hydrological regimes, emergent communities are not a common type of vegetation in the area studied (Radulović et al. 2011; Cvijanović et al. 2018).

Although the scoring of the water body conservation indices is usually performed at the ecosystem level (Rosset et al. 2013), we applied a different approach. In this study, the conservation indices were calculated for each sampling point, representing patches with unique annual hydroperiods (Kissel et al. 2020) and thus vegetation properties. According to Bolpagni et al. (2019), these water body patches fit the definition of a Small Natural Feature (Hunter et al. 2017) and should be considered as separate conservation targets. A spatial scale of up to 30 m radius around the sample was used to explore the performances of UAVM metrics. This scale was shown to be appropriate and maximal given the distance between ecosystem patches. Since some UAVM metrics showed significant correlations only at the highest radius values analysed, it can be assumed that these relationships might be even stronger with larger polygon areas.

While the methodologies deployed in this study have shown significant potential, there are noteworthy limitations associated with the UAV photogrammetry and field sampling protocols employed. To enhance the georeferencing accuracy of orthomosaics, it would be beneficial to use Real-Time Kinematic (RTK) correction or integrate ground control points data, collected during field operations, as a corrective measure in the orthomosaic generation process. Nevertheless, non-RTK UAVs equipped with consumer-grade GPS systems produce orthoimages with horizontal accuracy suitable for our study design (Hugenholtz et al. 2016). Also, additional spectral or texture indices could be added to the orthomosaic RGB band values in order to increase image objects delineation precision. In our study, objects delineation based on RGB band values was found to be adequate as it successfully separated target image feature categories. On the other hand, additional accuracy could be obtained by using a multispectral camera, which would mitigate the influence of shadows (Milas et al. 2017)—an inevitability in fluvial temperate wetlands due to flooded forests and shrubs in the riparian zone (Fig. 4).

Figure 4. Fluvial lake Arkanj, Koviljsko-Petrovaradinski rit wetland area (Photo by Maja Novković).

Furthermore, this study was designed to align with the practical constraints often faced by wetland stakeholders, such as limited resources for monitoring and restricted temporal windows for fieldwork. Consequently, a single field sampling and UAV imaging session was conducted immediately following the Danube flooding event, during the peak of the aquatic vegetation season. This timing aligns with typical periods used for the conservation assessment of water bodies in the Middle Danube wetlands, as noted in previous research (Radulović et al. 2011; Cvijanović et al. 2018; Cvijanović 2022). While this approach offers a representative snapshot of peak biological activity, it inherently limits the capture of full seasonal dynamics, potentially influencing the ecological interpretations and applicability of the results to other times of the year. This strategic choice reflects the ongoing challenge of balancing detailed ecological assessments with the practical realities of limited financial and human resources.

Conclusion

This study demonstrates the importance of relatively precise measuring of macrophyte cover metrics using UAV photogrammetry compared to traditional plot-based monitoring methods in aquatic monitoring. The cost-effective conservation and ecological screening of aquatic habitats along the great river floodplains can be performed using UAV photogrammetry of macrophyte vegetation. A specific combination of macrophyte functional groups and taxa within the complex wetland mosaics showed good surrogates for water trophic state and conservation indices derived for fish and macroinvertebrate assemblages. In summary, sites of a potentially high conservation indices and mesotrophic conditions can be tracked by the presence of floating rooted species and high macrophyte functional diversity. On the other hand, sites subjected to eutrophication and low dissolved oxygen concentration, with species-poor fish assemblages can be detected based on the cover of amphibian and free-floating vegetation and filamentous algae. While this study was conducted on a temperate large river floodplain, the developed methodological approach should be easily upscaled to other catchments and regions. This is especially important for hard-to-reach wetland biodiversity hot spots, including war-affected and mined areas (Schwarz 2006).

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Average parameters per pond

Authors: Dušanka Cvijanović, Maja Novković

Data type: xlsx

Explanation note: Object based classification parameters for macrophyte cover variables.

Link: https://doi.org/10.3897/natureconservation.58.116663.suppl1

Supplementary material 2

RGB-based and texture indices

Authors: Dušanka Cvijanović, Maja Novković
Data type: docx

Link: https://doi.org/10.3897/natureconservation.58.116663.suppl2

Supplementary material 3

Macrophyte OBIA parameters

Authors: Dušanka Cvijanović, Maja Novković
Data type: xlsx
Explanation note: Object based classification parameters for macrophyte cover variables.

Link: https://doi.org/10.3897/natureconservation.58.116663.suppl3

Supplementary material 4

Physical and chemical parameters

Authors: Dušanka Cvijanović, Maja Novković
Data type: xlsx
Explanation note: Physical and chemical parameters and macrophyte metrics.

Link: https://doi.org/10.3897/natureconservation.58.116663.suppl4