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Original paper

Using UAV approach in monitoring of macrophytes and their habitats within small water bodies of pristine riparian wetlands: a case study of the Middle Danube Area (Serbia)

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Summary. Conservation of fragile riverine wetlands with pristine or near pristine hydro-morphological regimes has become imperative in this late Anthropocene era of severe biodiversity and habitat loss. Monitoring of wetland habitats provides necessary scientific information for adequate management of these ecosystems. The remote sensing capabilities of drones offer less invasive, non-hazardous, cost- and time-effective tools for nature monitoring and assessment. Opportunities offered by drones within the scope of macrophyte monitoring and habitat conservation assessment in riverine wetlands were tested and discussed in this paper. In order to explore the potential benefits of an unmanned aerial vehicle (UAV) approach against traditional fieldwork, data were collected using both approaches and compared using several data parameters: resolution of obtained information, applicability in conservational purposes and relevance. UAV imagery collected during drone flights was used for the production of orthomosaics, which were segmented and classified into digital orthomaps using an OBIA approach. Macrophyte plot data and digital orthomaps of the lake were assessed using various conservation frameworks (The Habitats Directive, The Bern Convention, The European Red List of Habitats and Serbian national conservation framework). UAV – GIS tools enabled successful delineation of aquatic habitat types following EUNIS habitat classification scheme and have also managed to distinguish all protected and conservationally important species for the area of the Republic of Serbia. High classification accuracy of digital orthomaps (average overall accuracy = 85%, average Kappa hat = 0.8) enabled precise mapping and calculation of the research area covered by each species or habitat type. These results indicated that UAV – GIS tools offer new insights into the domain of macrophyte research and aquatic habitat conservation assessment, and should be included into existing assessment frameworks.

Keywords: aquatic habitats, conservation, macrophytes, monitoring, riparian wetlands, UAV, water body.

INTRODUCTION

Macrophytes are an essential part of aquatic ecosystems (Bornette et al. 2011), which create physical habitat structures and have key functions in biochemical cycles within the riverine ecosystems (Bornette et al. 2011; Cvijanović 2022). Natural riverine floodplains with high spatio-temporal heterogeneity are among the most biodiverse and productive ecosystems, providing a mosaic of freshwater habitats (Gyosheva et al. 2020). Aquatic ecosystems of the riverine wetlands represent biodiversity hubs for the main river channel and downstream part of the basin (Cellot et al. 1998). Due to their integral and essential role in aquatic ecosystems, macrophytes are one of the mandatory elements for river and lake ecological assessment (European Commission 2000; Moreno et al. 2022). Moreover, macrophytes are considered to be indicator species in several habitat classification systems, including the Habitats Directive (European Commission 1992) and

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the European Nature Information System (EUNIS) system relevant in the Bern Convention (Council of the European Communities 1979), and the EU Biodiversity Strategy for 2030 (European Commission 2021) which is core part of European Green Deal (European Commission 2019; European Environment Agency 2019).

Standard conservation assessment methods, which are based on extensive fieldwork and sampling (Dronova et al. 2021; European Commission 1992, 2000), can be effectively supplemented, boosted, or even replaced by remote sensing tools (Venturi et al. 2016; Bellia et al. 2020; Moreno et al. 2022). Successful use of unmanned aerial vehicles (UAVs) in surveillance, research, mapping and monitoring actions in diverse ecosystems and habitat types, including wetlands and freshwaters, has been reported in recent years (Dronova et al. 2021). This is especially important for developing regions where funding for nature conservation and management are quite limited (Murray-Hudson et al. 2015), such is the case in Serbia and the Western Balkan region. Small fixed- or rotary-wing drones / unmanned aerial vehicles (UAVs) with lightweight cameras and sensors, having high flight precision and autonomy, offer time- and cost-effective, non-invasive, and non-hazardous solutions for the evaluation of wetland habitat and ecological status indicators (Dronova et al. 2021). Easy to manage, low-altitude drone flights may deliver higher resolution habitat imagery compared to the satellite or traditional plane imagery (Marcaccio et al. 2015), and more accurately estimate site-scale changes than the ground-based surveys (Dronova et al. 2021). Also, most of the aquatic habitats within the wetlands are hard or non-approachable and therefore represent a challenge for safe and regular monitoring activities (Dronova et al. 2021).

The aim of this study was to compare macrophyte monitoring and conservation assessment in the Middle Danube wetland mosaic in Serbia using traditional field-based methods and the UAV-based approach. Near pristine floodplains of the Danube River in Serbia are recognized as rare and fragile habitats important at the national and international level (PZZP 2010). Appropriate monitoring, management and conservation activities should be carried out regularly in this area (European Commission 1992, 2000; JP “Vojvodinašume” 2012, 2021). However, monitoring programs of freshwater habitats within these wetlands are not yet developed or implemented mostly due to complex labour-intensive, time and cost consuming fieldwork.

MATERIALS AND METHODS

Study area

“Koviljsko-Petrovaradinski rit” is a near pristine and well-preserved floodplain of the Danube River, located in its middle course through Serbia, downstream from Novi Sad (Fig. 1) (PZZP 2010; JP “Vojvodinašume” 2021). It represents a mosaic of alluvial willow-poplar forest, wet meadow, wetland, swamp (type of wetland ecosystem characterized by mineral soils with poor drainage, saturated in water, often dominated by trees) and open water habitats supporting high biodiversity (PZZP 2010). Due to its undisturbed nature, it is part of several national (Special Nature Reserve (SNR), ecologically significant area within Ecological Network of the Republic of Serbia) and international (IUCN – Category IV; IBA; IPA; ICPDR - Protected Areas for Water-Dependent Species and Water-Related Habitats; Danube Network Protected areas; RAMSAR area; EMERALD candidate area) nature protection networks (PZZP 2010). Fluvial lake Arkanj is a 2 km long and 100 m wide old Danube meander (Fig. 1) (JP “Vojvodinašume” 2021). Arkanj represents a eutrophic fluvial lake (Laketić 2013), supporting characteristic rooted floating, free-floating and rooted submerged aquatic vegetation of eutrophic waterbodies (Radulović 2000; Laketić 2013).

Protection and preservation of aquatic ecosystems, vegetation, and flora through spatial inventorying and mapping of sites with aquatic vegetation represents one of the priority tasks of scientific work according to the first and second special nature reserve “Koviljsko-petrovaradinski rit” management plans (JP “Vojvodinašume” 2012, 2021). While mapping of indicator and protected species represents one of the planned activities for the sustainable use of natural values (JP “Vojvodinašume” 2021), continuous monitoring of *Nuphar lutea, Nymphaea alba* and *Hottonia palustris* is one of priority measures and activities for the protection, maintenance, and monitoring of the state of the reserve according to the management plan 2022–2031 (JP “Vojvodinašume” 2021). Apart from these named species, aquatic vegetation *per se* should be continuously monitored as one of the fundamental values of the reserve (JP “Vojvodinašume” 2021).

Data collection and processing

Aquatic vegetation data was extracted from available literature resources (Radulović 2000; Laketić 2013; JP “Vojvodinašume” 2021). For the purposes of this study, aquatic vegetation of the Arkanj lake was surveyed during the summer or early autumn months of 2017, 2018, 2019, 2020, 2022 and 2023. Macrophytes were assessed twofold, using traditional field assessment methods and UAV vehicles. Field assessment method included macrophyte plot approach applying five-point DAFOR scale (Kolada et al. 2009) on 10, 20 and 30 m^2 plots, while in the 2018 and 2023 only qualitative assessment of the macrophytes was performed. Plant identification was carried out according to Fassett (1940), Josifović (1970-1977), Jávorka and Csapody (1975), Cook

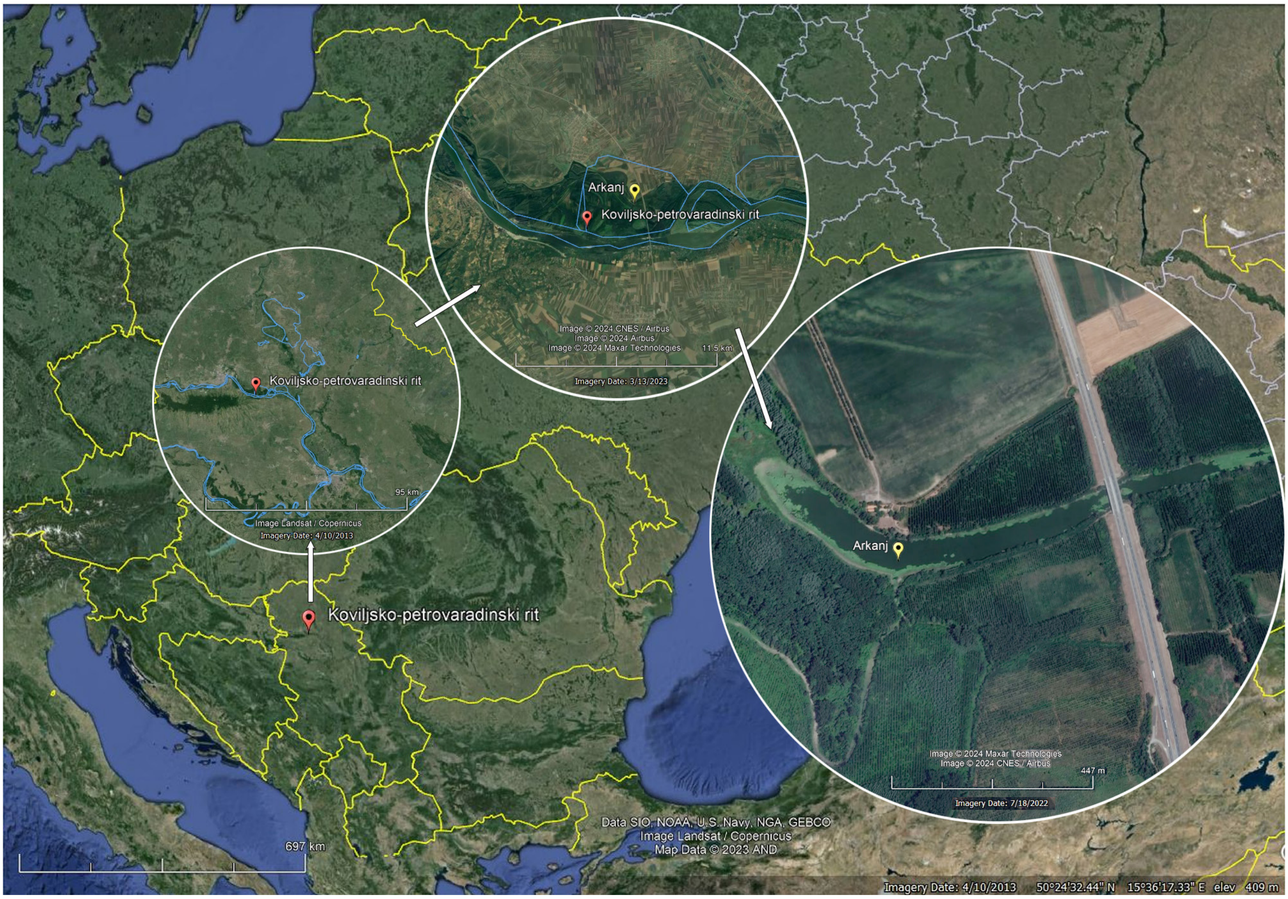

Fig. 1. Position of the „Koviljsko-petrovaradinski rit" wetland in the Middle Danube area in Serbia and the position of the Arkanj fluvial lake within the wetland.

(1990), Felföldy (1990), Bowmer et al. (1995), Preston (1995). UAV data set was collected with rotary-wing drones using different RGB cameras. Close to nadir imagery was collected at different flight altitudes set according to the orthomosaic target resolution (Venturi et al. 2016; Husson et al. 2017). Target resolution of photogrammetry products was set according to the size of the smallest individual object which needed to be determined from the orthomosaics (Sibaruddin et al. 2018; Novković et al. 2023). In the case of aquatic vegetation, the goal was recognition of individual water caltrop rosettes or waterlily leaves (leaf radius ~15-35 cm).

Images were adjusted and stitched into orthomosaics using ArcGIS Pro 2.6.0 software. In order to perform object-based image classification (OBIA) orthomosaics were segmented using Orfeo Toolbox (OTB) 7.2.0 and 8.0.1 within the QGIS 3.22.8 software. *LargeScaleMeanShift* segmentation algorithm groups neighbouring pixels and creates polygons – objects which will be subsequently classified. A series of spectral and texture indices were calculated for each orthomosaic (Tables 1 and 2). Mean value of each index was calculated for each segment using *Zonal statistic* tool. These values were used as classification attributes during OBIA as several studies showed that they increase classification accuracy (Pande-Chhetri et al. 2017). To avoid the noise caused by terrestrial vegetation and artificial bank objects during the classification process, polygons encompassing only the water area and aquatic vegetation were clipped from each orthomosaic (Area of Interest – AOI) (Fig. 2).

Supervised object-based classification was performed using *Random Forest* classifier as it was recognized as one of the most successful, redundancy, and noise resilient machine learning algorithms for classification of remote sensing data (Chabot et al. 2018; Villoslada et al. 2020) and adequate for OBIA classification (Ma et al. 2017). Training datasets were manually created by a selection of 50 reference polygons for each object class (Chabot et al. 2018; Ventura et al. 2018), while validation datasets were created by the random extraction of up to 400 polygons (Pande-Chhetri et al. 2017; Ventura et al. 2018) and their manual classification. Object classes were image object categories used for the classification process, while image feature classes were defined in order to represent macrophyte species and aggregations in

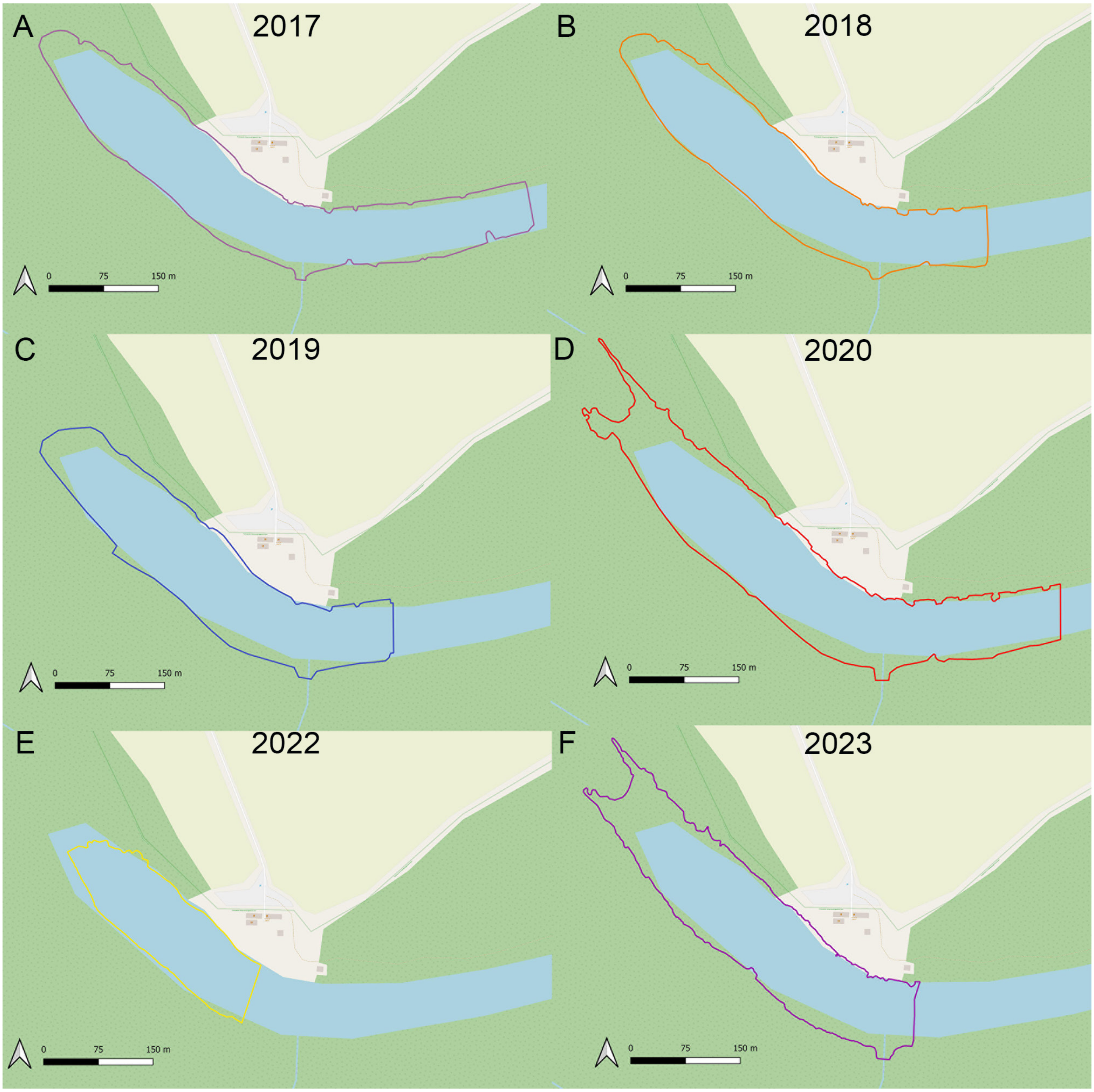

Fig. 2. Area of Interest (AOI) polygons for every research year 2017 (A), 2018 (B), 2019 (C), 2020 (D), 2022 (E), 2023 (F).

the final digital maps of the lake. After the initial classification, created maps were visually inspected, and poorly classified regions were selected. To mitigate errors, additional reference segments were added to the misclassified object classes, algorithms were retrained and orthomosaics were reclassified (Novković et al. 2023). Finally, some object classes were merged into feature classes to produce ecologically meaningful digital maps of macrophytes along the fluvial lake (e.g. three object classes of *Nuphar/Nymphaea* feature classes).

Digital maps were further processed to determine their accuracy. Per-polygon and per-pixel classification accuracy analyses were performed for the classification and reclassification phase, while per-pixel approach was used to test the accuracy of the final maps (Husson et al. 2017). Per-polygon approach included Kappa index (KI) and the overall accuracy (OA) calculation. Per-pixel analysis calculated Kapa hat index (KHI) and overall accuracy (OA) for each map, but also User's (UA), Producer's accuracy (PA), and Kappa Hat index for each feature class (Ventura et al. 2018; Kaplan et al. 2022) and aquatic vegetation *per se*. Kappa index was interpreted according to Landis and Koch (1977). For each digital map the relative percentage of the AOI, as well as the absolute area covered by each object class, was calculated.

Conservation value and protection status

National and international conservation status was determined for the Arkanj fluvial lake according to available data sources. Nationally protected and strictly protected species were determined according to the National Assembly of the Republic of Serbia (2016). International conservation status of the species was assessed using the IUCN Red List for Europe (Lansdown 2011). Lake conservation index was calculated according to Damnjanović et al. (2019) following Oertli et al. (2002) and Linton and Goulder (2000), based on macrophyte designation status and rarity (National Assembly of the Republic of Serbia 2016). Sum of the species conservation values were added up resulting in a C score (Supplement 1). C scores were divided by the species number to derive the relative conservation index – Csp score (Damnjanović et al. 2019). Conservation value of the lake was also presented according to the national rulebook for distinguishing, classification and protection of habitats (National Assembly of the Republic of Serbia 2010), The Habitat Directive (European Commission 1992), The Bern Convention (European Commission 2019a) and The European Red List of Habitats (European Environment Agency 2022). Lake conservation values based on traditional fieldwork and UAV data were analysed and compared.

RESULTS

Literature data

Studying the aquatic vegetation of the Koviljski rit, Radulović (2000) found 16 aquatic plant species (Supplement 2) in four phytosociological relevés forming four macrophyte associations (*Ceratophyllo-Trapetum natantis* Müller & Gors (1962) ex Pass. 1992, *Salvinio-Spirodeletum polyrrhizae* Slavnić 1956, *Potamogetono - Ceratophylletum demersi* Soó (1928) Hild. 1956, *Nympaeo-Nupharetum luteae* Nowinski 28) at the Arkanj lake, confirmed by Laketić (2013) (Supplement 2). SNR "Koviljsko-petrovaradinski rit" management plan for the 2022-2031 period (JP "Vojvodinašume" 2021) provided a list of 22 aquatic macrophyte species found along the Arkanj lake (Supplement 2). Only data provided by Laketić (2013) included spatial information about the plot position, while the rest of the available data did not have spatial references.

New data

During the field research conducted within this study, a total of 26 macrophyte species were recorded (Supplement 2, Supplement 3). The lowest number of species (5) was recorded in the late summer of 2022 (due to low water level and the fact that the boat was not available, Fig. 5B), while maximum number of species (19) was recorded in 2017. UAV data collection was performed through low height singular flights each year (Table 3). Depending on the flight height and camera characteristics, spatial resolution of the products varied from year to year, with the tendency of increase from first to the last research year (Fig. 3, Table 3). Orthomosaics were segmented and classified. For each classification phase accuracy metrics were calculated (Table 4). There is a noticeable improvement of classification accuracy after the reclassification phase leading to substantial or almost perfect classification accuracy (Landis and Koch 1977) of produced digital maps.

In total, 23 object classes were determined from the orthomosaics, while they constituted 16 image feature classes in the final digital maps. Ten feature classes corresponded to the specific aquatic macrophyte taxa, out of which eight classes had some specific species reference (Table 5). Aquatic vegetation was very successfully distinguished from the surrounding water, mud and terrestrial vegetation with average PA and UA over 90%, and OA over 0.85. Floating vegetation was determined to the single species level (Table 5). Best classification accuracy was achieved for *Nuphar/Nymphaea* feature class, while poorest accuracy was noted for the *Trapa natans* feature class. Submerged vegetation could only be defined *per se,* without the identification of individual species. Emergent vegetation stands of *Phragmites australis* and *Schoenoplectus lacustris* were determined to the species level. Orthomosaics and digital maps of the area are presented in figures 4 and 5. For every digital map, the spatial extent of every feature class was expressed in m^2 and percentage area of the digital map (Figs 4 and 5; Table 6). *Nuphar lutea / Nymphaea alba* group was the most abundant macrophyte group in every research year, followed by the submerged vegetation group and free-floating macrophytes stands.

Conservation value and protection status

Conservation status of the lake was determined based on traditional and UAV data. Three nationally strictly protected (*Callitriche palustris* L., *Nymphaea alba* L., *Salvinia natans* (L.) All and *Nuphar lutea* (L.) Sm) and one protected species (*Trapa natans* L.) were found in the Arkanj lake. According to the European list of endangered flora, *Salvinia natans* (L.) (Christenhusz et al. 2017) and *Trapa natans* L. (Lansdown et al. 2011) belong to the group of near threat-

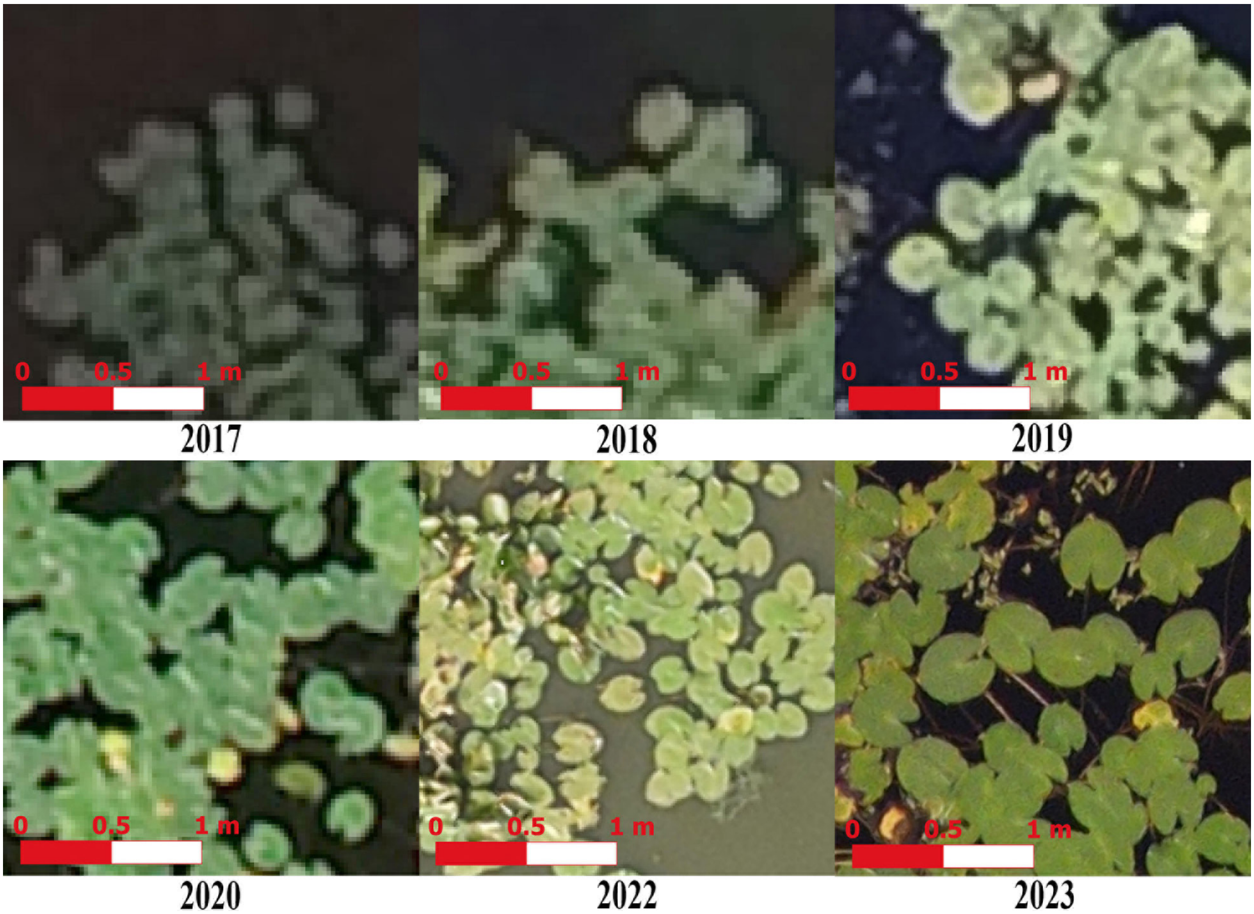

Fig. 3. Fragments of orthomosaics depicting *Nuphar/Nymphaea* stands.

ened (NT) species. The lake conservation index calculated following Damnjanović et al. (2019) ranged from 1.9 to 2.5 for the traditional survey methods, while the values were almost doubled using UAV data as the calculation source (Table 7). According to the national legislation, all determined habitat types (F1.31 Plankton communities of eutrophic stagnant waters, F1.33 Rooted submerged communities of eutrophic stagnant waters, F1.34 Rooted floating communities of eutrophic stagnant waters, F1.35 Free-floating communities of eutrophic stagnant waters) are marked as Frag(A) – fragile habitat due to functional instability and sensitivity to degradation and are recognized as priority habitat types for conservation (National Assembly of the Republic of Serbia 2010) (Table 7).

DISCUSSION

UAV workflow

UAV data collection and GIS classification approach used in this study were shown to be effective and accurate in recognition and delineation of aquatic vegetation properties. Dronova et al. (2021) found that a combination of quadcopter drone and native RGB camera is the most common approach in the 122 reviewed studies using UAV technology in wetlands assessment. They have also stated that OBIA analysis, coupled with Random Forest classification algorithm, was the most common and reliable approach for the analysis of orthomosaics, which were also the most used photogrammetry product (Dronova et al. 2021). So, even though UAV standardized vegetation monitoring methodology still does not exist, some approaches are obviously emerging as the best available practice.

Orthomosaic resolution used in this study is in accordance with the GSDs used in similar studies mapping aquatic vegetation (Brinkhoff et al. 2018; Chabot et al. 2018; Ventura et al. 2018; Kislik et al. 2020; Taddia et al. 2020; Moreno et al. 2022). The ground sampling distance (GSD) of the orthomosaic in this study was adequate, although a pixel size of 0.02 m^2 appears to be the best resolution as a compromise between the level of orthomosaic details and processing computational load. Appropriate GSD enabled the segmentation

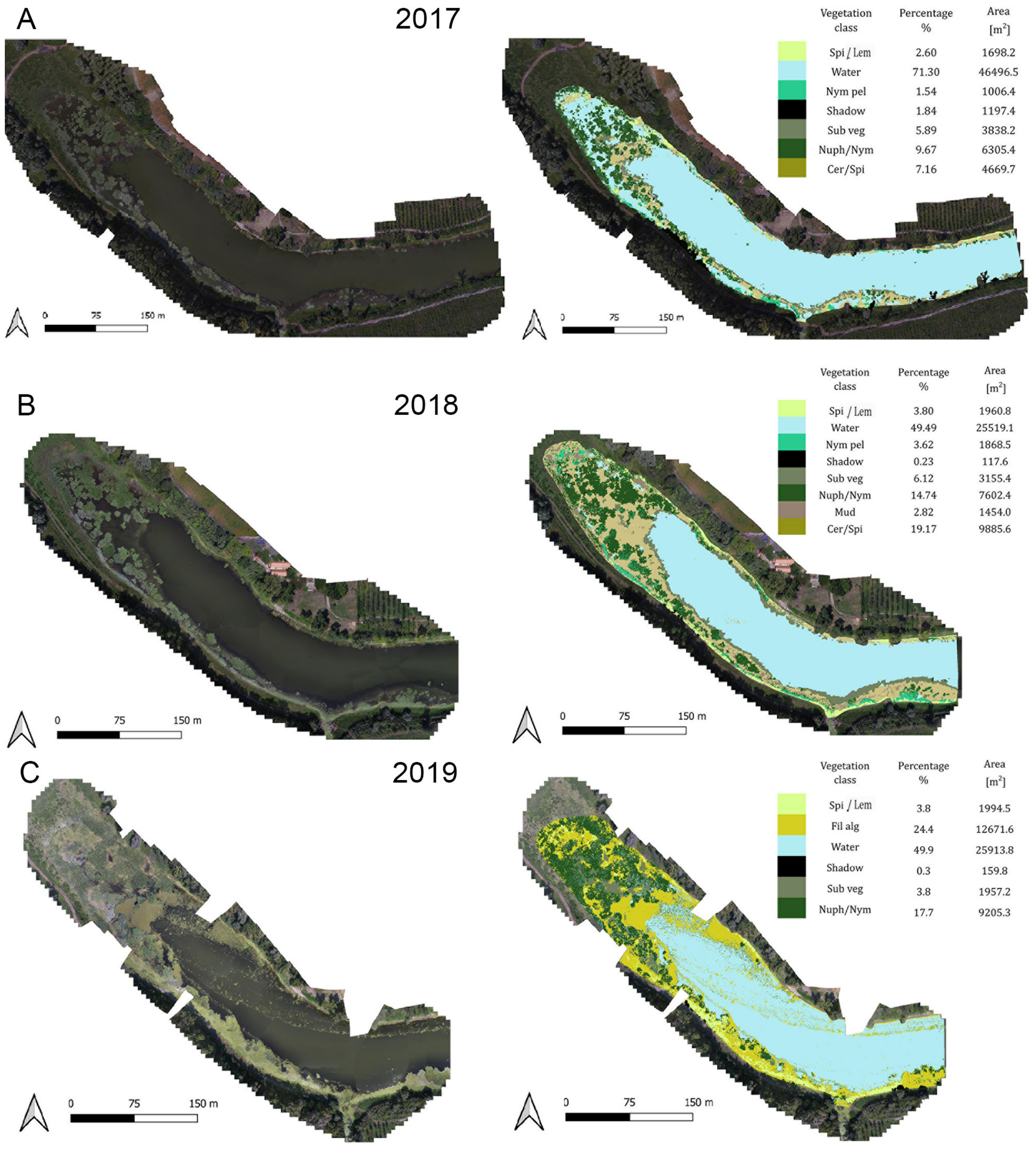

Fig. 4. Orthomosaic and digital map of Arkanj lake for 2017 (A), 2018 (B) and 2019 (C).

algorithm to successfully distinguish different image objects. Image feature classes were a combination of species-based and trait-based approaches similar to many other studies mapping macrophytes (Chabot et al. 2016, 2018; Husson et al. 2016, 2017; Pande-Chhetri et al. 2017; Villoslada et al. 2020; Agioutanti 2022). Same as in this study, Chabot et al. (2016, 2018), Pande-Chhetri et al. (2017), Taddia et al. (2020) have also clustered all submerged macrophytes in the submerged vegetation feature class. While there are studies exploring the delineation of submerged macrophyte species

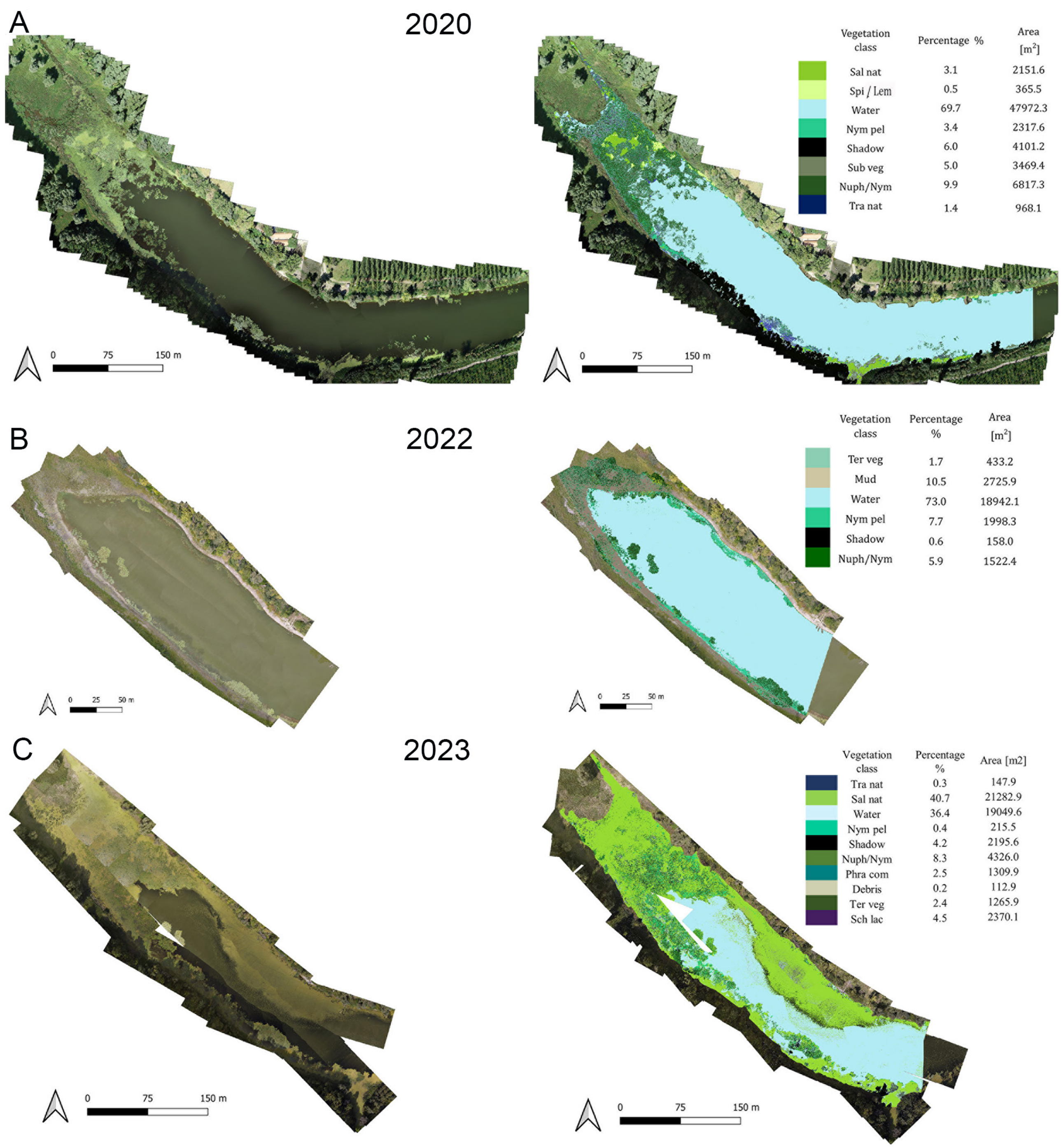

Fig. 5. Orthomosaic and digital map of Arkanj lake for 2020 (A), 2022 (B) and 2023 (C).

typical for clear, shallow waterbodies with simple or monotypic submerged strata (Flynn and Chapra 2014; Chabot et al. 2016, 2018; Ventura et al. 2018), it was not possible to do due to water turbidity, vegetation complexity and spectral similarity of submerged macrophyte stands in this study. Floating vegetation was quite successfully determined to the species level. Stands dominated by *Salvinia natans* were distinguished from Lemnoid species dominated stands, while *Nymphoides peltata* and *Trapa natans* stands were delineated among each other and waterlily stands. On the other hand, *Nymphaea alba* and *Nuphar lutea* could not be automatically delineated due to spectral similarity of leaves, and consequently were clustered in *Nuphar/Nymphaea* group as in Husson et al. (2016, 2017). Moreover, the *Nuphar/Nymphaea* feature class needed to be separated into three object classes due to the spectral differences of viable and withered leaves, and those affected by the sun glint. Pande-Chhetri et al. (2017) and Ventura et al. (2018) have also formed separate object classes for viable and dry or dead plants. *Phragmites australis* was also classified using two classes in this study, one for adults and one for young light green plants.

Orthomosaic classification accuracy with reclassification workflow phase was overall satisfactory. Digital map accuracy varied from 0.56 to 0.93 KI and from 65.1 to 96.0 OA. However, classification accuracy of aquatic vegetation *per se* against surrounding image objects is in the better result range than in the similar studies (Husson et al. 2016; Brinkhoff et al. 2018; Kislik et al. 2020; Agioutanti 2022). Per class accuracy was in accordance with the results available in other studies. Among the emergent vegetation, the species *Phragmites australis* had moderate classification accuracy due to highly complex stand structure, as expected. While *Schoenoplectus lacustris* was poorly classified, it achieved good PA, but very poor UA, which was expected due to a small single (30 m^2) stand. Floating vegetation was almost perfectly classified (KI > 0.8, PA/UA > 80), likewise to Husson et al. (2016, 2017), Pande-Chhetri et al. (2017), Chabot et al. (2018), Fustinoni (2022). The exception was the *Trapa natans* group which was determined in two years in very poor classification conditions, i.e. partly covered with shadow and in the area of the orthomosaic affected by sun glint. Submerged vegetation group had good classification accuracy (average KI = 0.79; average PA = 69% / UA = 80%) in this study. Submerged vegetation represents a challenge within the UAV approach in aquatic vegetation monitoring (Ventura et al. 2018; Kislik et al. 2020; Agioutanti 2022). Visser et al. (2018) have classified submerged vegetation to the species level and obtained a moderate classification accuracy using OBIA on multispectral imagery, but recognized the potential of UAV approach.

Conservation value and protection status

According to the The European Red List of Habitats, Arkanj belongs to the Mesotrophic to eutrophic waterbodies with vascular plants (RLC1.2b) and therefore has a Near Threatened status (C/D1). As mentioned before, aquatic vegetation *per se* was almost perfectly distinguished in the orthomosaics, which implies that habitats could easily be determined using both approaches, traditional fieldwork and UAV approach.

Going further and recognizing *Lemna* sp. and *Spirodela* sp. stands (*Hydrocharition* group) it was possible to determine Natural eutrophic lake with *Magnopotamion* or *Hydrocharition* -type vegetation (Habitats directive code 3150) according to Annex I of the Habitats Directive and therefore recognize the lake as a potential candidate for the ecological network of special areas of conservation Natura 2000. In addition to *Hydrocharition* group, it was possible to delineate *Salvinia natans* stands and map free-floating vegetation of eutrophic waterbodies (EUNIS code C1.32). As the submerged vegetation stratum was constituted from *Ceratophyllum* sp. and *Myriophyllum* sp. species, rooted submerged vegetation of eutrophic waterbodies (EUNIS code C1.33) could also be determined. Both habitat types are listed in the Resolution 4 (1994) of the Bern Convention as habitat types to be protected by the Emerald network of Areas of Special Conservation Interest (ASCI's) within the EMERALD network. Finally, by delineating *Nuphar/Nyphaea*, *Nymphoides peltata* and *Trapa natans* groups it was also possible to distinguish floating rooted vegetation of eutrophic waterbodies (EUNIS code C1.34). The exact spatial distribution for each mentioned habitat type was determined and, if needed, could be represented on separate thematic maps using the UAV/GIS approach. Compared to the traditional survey methods UAV methodology could not map Arrowhead communities (EUNIS habitat C3.241) due to the small area covered by the stand and low plant abundance. According to the national habitat legislation (National Assembly of the Republic of Serbia 2010), plankton communities (habitat code F1.31), rooted submerged communities (habitat code F1.331), rooted floating communities (habitat code F1.34) and free-floating communities (habitat code F1.35) of eutrophic standing waters belong to the group of priority habitat types for conservation. Obtaining this type of information using traditional survey methods would be immensely time consuming, costly and logistically difficult as it requires delineation of every stand using handheld GNSS mapping device. This also implies unnecessary intense disturbance of these fragile habitats and the communities they support. Therefore, UAV monitoring approach could be used in NATURA and EMERALD network habitat assessments and facilitate the designation and monitoring of these areas.

All nationally protected species were successfully determined using the UAV approach. Both Near Threatened European Union Red List species were successfully determined using both approaches. The lake conservation scores (Damnjanović et al. 2019) were shown to be only a rough proxy of the conservation value. Namely, *Nuphar/Nupmhaea* group was assigned conservation score for both species and in the species number value it was counted twice. On the other hand, all submerged species were counted as one 'common species that does not have protection status and is not invasive'. Although none of the present submerged species are endangered, there is more than one submerged species in the lake, some of which are invasive. Also, three more *Lemna* species are present within the stands of *Spirodela polyrhiza*, and they could not be determined based on the UAV data, not only due to extremely small size and spectral similarity, but also their surface submerged life form. Therefore, use of solely UAV data is not applicable to assess ecological indices which demand full taxa list.

The possibility to distinguish, map and to some extent quantify macrophytes and habitats in this study gives a certain encouragement towards the development of UAV-based ecological and conservation indices. Moreno et al. (2022) evaluated the ecological status of the lake based on UAV acquired data. They have managed to derive macrophyte metrics (hydrophyte and helophyte percentage cover) proposed by Spanish national legislation from the RGB orthomosaic. Ecological status of lakes based on macrophytes in Serbia is determined according to the number of taxa and Shannon-Weaver species diversity index (National Assembly of the Republic of Serbia 2011) and therefore relies on the ability to determine all present taxa. Therefore, at this stage of development, a UAV approach cannot solitarily answer the need, but can substantially upgrade the traditional field methods. The UAV monitoring approach, evaluated in this study, can be also applied in other wetland management measures, such as possibility of determination of riparian forests and forest health (Michez et al. 2016; Gallo et al. 2019) and mapping of anthropogenic pressures surrounding the lake (Medvedev et al. 2020). Several very interesting studies tackled the possibility of incorporating UAV tools into ornithology-related activities (Barnas et al. 2019; Jones et al. 2019; Lyons et al. 2019; Corredigor-Castro et al. 2022; de Leija et al. 2023). There are also studies concerning invasive species inventory (Mallmann et al. 2020; Sladonja et al. 2022; Bergamo et al. 2023). Moreover, there is a plethora of studies using UAV tools in hydrological regime investigations. In summary, UAVs are recognized as great supporting tools in hydrological research as well, but there is still room for improvement in technology and processing workflows (Vélez-Nicolás et al. 2021). All these efforts support the fact that drone technology is seen as a new, potentially valuable tool in various domains of wetland research, but also confirm the effectiveness of the tool in terms of assessing an array of conservation and ecologic parameters and information based on only one source of information.

CONCLUSIONS

Even though UAV / GIS approach faces certain challenges and needs to be further improved and standardized, the results of this study indicate that the obtained results were adequate for monitoring on the large habitat scale. On the other hand, traditional survey is needed to provide full taxa list and accurate species abundance. These high-resolution data, combined with time and cost-efficient assessment, their replicability, and exactness of obtained information, could perfectly supply existing national and international frameworks. It would improve the process of determining and mapping the habitats of special importance for protection and establishment of national ecological network (National Assembly of the Republic of Serbia 2010). Also, it could upgrade mapping of indicator and protected species as provided by the Water law (National Assembly of the Republic of Serbia 2018) and Rulebook on protected species (National Assembly of the Republic of Serbia 2016), respectively. It could help in determining and monitoring the state of nature (National Assembly of the Republic of Serbia 2021) and establishment of regular monitoring of rare and vulnerable habitats.

Even though UAVs have been present in wetlands research for more than a decade, the majority of performed studies can be recognized as pioneering work, testing the possibilities and limits of the available technology. When it comes to macrophyte and habitat research and monitoring, UAV / GIS approach has the potential to become the most important upgrade of traditional methods in recent history.

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Table 1. List of spectral indices that were calculated for each orthomosaic, and whose mean values per segment represented attributes for orthomosaic classification.

Abbreviation	Index	Formula	Reference
MGRVI	*Modified Green Red Vegetation Index*	(G)2−(R)2 (G)2+(R)2	Bendig et al. 2015
RGBVI	*Red Green Blue Vegetation Index*	(G)2−(B∗R) (G)2+(B∗R)	Bendig et al. 2015
GRVI or MPRI	*Green Red Vegetation Index* *Modified Photochemical reflectance Index*	G−R G+R	Tucker 1979 Yang et al. 2008
NDRGI	*Normalized difference red green index*	(R −G)/(R + G)	Yang et al. 2008
GLI	*Green Leaf Index*	2G - R - B 2G + R + B	Louhaichi et al. 2001
ExG	*Excess of green*	2G – R – B	Woebbecke et al. 1995
G-B	Green-Blue difference	G-B	
G-R	Green-Red difference	G-R	
R-B	Red-Blue difference	R-B	

Table 2. List of textural indices that were calculated for each orthomosaic, and whose mean values per segment represented attributes for orthomosaic classification.

Abbreviation	Index	Measure	Reference
r.tex	*r.texture*	*Sum Average (SA)*	
		Inverse Difference Moment (IDM)	
SFS	*Structural Feature Set*	*SFS'PSI*	Huang et al. 2007
		SFS'SD	
HAR or GLCM	*Haralic Texture* or *Gray Level Co-Occurrence Matrix*	*Entropy*	Kupidura 2019
		Inverse Difference Moment	
		Innertia	

Table 3. Characteristics of aircraft, cameras, images and flights of unmanned aerial vehicles used to assess the Arkanj lake.

Year	UAV	Camera	Image size (px)	Flight start	Flight end	Flight height (m)	Number of images	Total area(~ha)	Orthomosaic resolu-tion	Date
2017	Inspire 1	FC350	4000 × 2250	14:19	14:23	116	84	6.5	0.04	18.08.
2018	Inspire 1	FC350	4000 × 2250	12:52	12:55	95	100	5.2	0.04	28.08.
2019	Phantom 4	FC330	4000 × 2250	12:10	12:17	47	68	5.3	0.02	27.08.
2020	Phantom 4 PRO	FC6310S	5472 × 3078	14:07	14:15	59	210	6.9	0.02	30.06.
2022	Mavic Air 2	FC3170	4000 × 3000	15:35	15:51	40	284	3.8	0.01	14.09.
2023	Mavic Air 2	FC170	8000 × 6000	13:39	13:57	40	226	5.2	0.01 (0.006)	29.09.

Table 4. Arkanj lake orthomosaic classification precision measures in each of the phases.

	Cassification					Reclassification					Digital maps		
		Per polygon		Per pixel			Per polygon		Per pixel			Per pixel	
Year	No of classes	Kappa index	Overall accuracy [%]	Kappa hat index	Overall accuracy [%]	No of classes	Kappa index	Overall accuracy [%]	Kappa hat index	Overall accuracy [%]	No of classes	Kappa hat index	Overall accuracy [%]
2017	7	0.72	77.5	0.87	90.0	7	0.74	79.2	**0.93**	**96.6**			
2018	8	0.58	66.8	0.41	51.5	8	0.63	71.6	**0.56**	**65.1**			
2019	7	0.69	75.9	0.71	79.8	7	0.76	82.4	0.87	91.3	6	**0.88**	**92.0**
2020	14	0.51	55.0	0.63	66.2	14	0.59	63.2	0.70	73.9	10	**0.78**	**82.2**
2022	9	0.48	56.4	0.69	73.4	9	0.51	60.1	0.77	81.3	8	**0.79**	**83.5**
2023	12	0.43	52.4	0.68	77.4	15	0.59	63.6	0.84	88.5	10	**0.86**	**90.8**

Table 5. Per class accuracy of Arkanj lake orthomosaics classification.

EUNIS habitat code		C1.33		C1.34				!C1.32		C3.21	C3.22						
NATIONAL habitat code		F1.33		F1.34				F1.35		F3. 121	F3. 125						
Image feature classes →		Submerged vegetatio	Subm. veg./ *S. polyrhiza*	*Nuphar* / *Nymphaea*	*Nymphoides peltata*	*Nymphoides peltata* subm.	*Trapa natans*	*Salvinia natans*	*Spirodela* / *Lemna*	*Phragmites australis*	*Schoenoplectus lacustris*	Filamentous algae	Mud	Water	Shadow	Terrestrial vegetation	Wood debris
2017	PA (%)	85.3	86.3	98.4	85.0				91.1					98.8	98.1		
	UA (%)	88.3	85.3	96.7	92.8				74.0					99.3	99.9		
	Kappa hat	0.88	0.84	0.96	0.93				0.73					0.97	1.00		
2018	PA (%)	22.3	64.1	98.1	66.2				73.9				95.4	92.2	0.0		
	UA (%)	96.6	83.6	77.2	67.0				99.2				72.0	47.5	nan		
	Kappa hat	0.95	0.78	0.74	0.66				0.99				0.71	0.30	nan		
2019	PA (%)	69.9		99.2					85.1			87.5		97.5	21.5		
	UA (%)	89.0		64.1					98.2			95.5		100	100		
	Kappa hat	0.88		0.59					0.98			0.94		1.00	1.00		
2020	PA (%)	99.1		91.1	82.0		52.0	85.0	49.2					71.5	97.4	72.1	100
	UA (%)	48.8		88.6	87.3		25.7	94.3	57.4					100	75.3	76.9	100
	Kappa hat	0.45		0.85	0.86		0.24	0.94	0.57					1.00	0.72	0.76	1.00
2022	PA (%)			76.0	87.6	78.1						0	98.6	75.2	93.8	60.5	
	UA (%)			95.9	57.1	74.1						0	93.8	98.2	100	74.8	
	Kappa hat			0.95	0.52	0.72						-0.01	0.90	0.98	1	0.73	
2023	PA (%)			66.3	35.5		0.00	94.0		75.0	84.3			98.3	90.9	59.74	60.9
	UA (%)			92.7	56.7		0.00	99.6		53.5	18.4			99.6	75.4	21.65	84.6
	Kappa hat			0.92	0.56		0.002	0.99		0.53	0.18			0.99	0.75	0.21	0.53

*EUNIS habitat codes: C1.32 Free-floating vegetation of eutrophic waterbodies, C1.33 Rooted submerged vegetation of eutrophic waterbodies, C1.34 Rooted floating vegetation of eutrophic waterbodies, C1.35 Plankton communities of eutrophic standing waters, C3.21 *Phragmites australis* beds, C3.22 *Scirpus lacustris* beds; NATIONAL habitat codes: F1.31 Plankton communities of eutrophic stagnant waters, F1.33 Rooted submerged communities of eutrophic stagnant waters, F1.34 Rooted floating communities of eutrophic stagnant waters, F1.35 Free-floating communities of eutrophic stagnant waters F3.121 *Phragmites australis* beds, F3.125 *Scirpus lacustris* beds.

Table 6. Percentage cover and absolute area of AOI of Arkanj lake covered by image feature classes.

EUNIS habitat code		C1.33	C1.32 C1.33	C1.34	C1.34	C1.34	C1.32	C1.32	C3.21	C3.22						
NATIONAL Habitat code		F1.33	F1.33 F1.35	F1.34	F1.34	F1.34	F1.35	F1.35	F 3.121	F 3.125						
Image feature classes →		Submerged vegetatio	Subm. veg./ *S. polyrhiza*	*Nuphar / Nymphaea*	*Nymphoides peltata*	*Trapa natans*	*Salvinia natans*	*Spirodela / Lemna*	*Phragmites australis*	*Schoenoplectus lacustris*	Filamentous algae	Mud	Water	Shadow	Terrestrial vegetation	Wood debris
2017	%	5.9	7.2	9.7	1.5			2.6					71.3	1.8		
	[m²]	3838	4670	6305	1006			1698					46497	1197		
2018	%	6.1	19.2	14.7	3.6			3.8				2.8	49.5	0.2		
	[m²]	3155	9886	7602	1869			1961				1454	25519	118		
2019	%	3.8		17.7				3.8			24.4		49.9	0.3		
	[m²]	1957		9205				1994			12672		25914	160		
2020	%	5.0		9.9	3.4	1.4	3.1	1.4					69.7	6.0	0.9	0.1
	[m²]	3469		6817	2318	968	2152	968					47972	4101	608	56
2022	%			5.9	7.7							10.5	73.1	0.6	1.7	
	[m²]			1522	1998							2726	18942	158	433	
2023	%			8.3	0.4	0.3	40.7		2.5	4.5			36.4	4.2	2.4	0.2
	[m²]			4326	216	148	21283		1310	2370			19050	2196	1266	113

*EUNIS habitat codes: C1.32 Free-floating vegetation of eutrophic waterbodies, C1.33 Rooted submerged vegetation of eutrophic waterbodies, C1.34 Rooted floating vegetation of eutrophic waterbodies, C1.35 Plankton communities of eutrophic standing waters, C3.21 *Phragmites australis* beds, C3.22 *Scirpus lacustris* beds; NATIONAL habitat codes: F1.31 Plankton communities of eutrophic stagnant waters, F1.33 Rooted submerged communities of eutrophic stagnant waters, F1.34 Rooted floating communities of eutrophic stagnant waters, F1.35 Free-floating communities of eutrophic stagnant waters, F3.121 *Phragmites australis* beds, F3.125 *Scirpus lacustris* beds.

Table 7. Habitat types found on the Arkanj lake using traditional and UAV survey approaches according to the national and international classification systems and conservations frameworks.

	Traditional methods					UAV methods				
	NATION-AL	EUNIS	NATURA	EU RED	Csp	NATION-AL	EUNIS	NATU-RA	EU RED LIST	Csp
Radulović 2000	F1.351! F1.331! F1.34!	C1.32! C1.33! C1.34	3150	RLC1.2b [NT] C/D1	2.3	-				
Cvijanović 2010	F1.351! F1.331! F1.34!	C1.32! C1.33! C1.34	3150	RLC1.2b [NT] C/D1	2.0					
Novković 2017	F1.35! F1.331! F1.34! F1.31!	C1.32!* C1.33! C1.34 **C1.35** **C3.241**	3150	RLC1.2b [NT] C/D1	2.3	F1.35! F1.33! F1.34!	C1.32! C1.33! C1.34	3150	RLC1.2b [NT] C/D1	3.8
Novković 2018	F1.35! F1.331! F1.34! F1.31!	C1.32! C1.33! C1.34	3150	RLC1.2b [NT] C/D1	-	F1.35! F1.33! F1.34!	C1.32! C1.33! C1.34	3150	RLC1.2b [NT] C/D1	3.8
Novković 2019	F1.35! F1.331! F1.34! F1.31!	C1.32! C1.33! C1.34 C1.35	3150	RLC1.2b [NT] C/D1	1.9	F1.35! F1.33! F1.34! F1.31!	C1.32! C1.33! C1.34 C1.35	3150	RLC1.2b [NT] C/D1	4.5
Novković 2020	F1.351! F1.331! F1.34!	C1.32! C1.33! C1.34	3150	RLC1.2b [NT] C/D1	2.2	F1.35! F1.33! F1.34!	C1.32! C1.33! C1.34	3150	RLC1.2b [NT] C/D1	5.0
PZZP 2021	-	-	3150	RLC1.2b [NT] C/D1	2.0	-	-	-	-	-
Novković 2022	F1.34! F1.31!	C1.34 **C1.35**	3150	RLC1.2b [NT] C/D1	2.5	F1.34!	C1.34	3150	RLC1.2b [NT] C/D1	5.7
Novković 2023	F1.35! F1.331! F1.34! F3.121	C1.32! C1.33! C1.34 C3.21	3150	RLC1.2b [NT] C/D1	2.3	F1.35! F1.331! F1.34! F3.121 F3.125	C1.32! C1.34 C3.21 C3.22	3150	RLC1.2b [NT] C/D1	5.0

*NATIONAL – National habitat conservation assessment (Official Gazette of RS, No. 35/2010); EUNIS - EUNIS habitat types classification (! - Bern Convention Resolution 4 habitat types (Emerald network)); NATURA - Habitats Directive Annex I habitat types (Natura 2000 network); EU RED LIST OF HABITATS; Csp - Lake conservation index (Damnjanović et al. 2019).

*EUNIS habitat codes: C1.32 Free-floating vegetation of eutrophic waterbodies, C1.33 Rooted submerged vegetation of eutrophic waterbodies, C1.34 Rooted floating vegetation of eutrophic waterbodies, C1.35 Plankton communities of eutrophic standing waters, C3.21 *Phragmites australis* beds, C3.22 *Scirpus lacustris* beds; NATIONAL habitat codes: F1.31 Plankton communities of eutrophic stagnant waters, F1.33 Rooted submerged communities of eutrophic stagnant waters, F1.34 Rooted floating communities of eutrophic stagnant waters, F1.35 Free-floating communities of eutrophic stagnant waters, F3.121 *Phragmites australis* beds, F3.125 *Scirpus lacustris* beds.

Supplement 1. Species conservation score according Damnjanović et al. (2019).

Species conservation score	Conservation status/ National protection	Description of conservation status and national protection level
1	LR (Low risk)	Common, a species that does not have protection status and is not invasive.
2	P (Protected)	A species that is nationally protected for the territory of the Republic of Serbia.
4	SP (Strictly protected)	A species that is nationally strictly protected for the territory of the Republic of Serbia.
8	NT (Near threatened)	A species IUCN status for the territory of the Republic of Serbia.
16	EN (Endangered) / VU (Vulnerable)	A species IUCN status for the territory of the Republic of Serbia.
32	CR (Critically endangered)	A species IUCN status for the territory of the Republic of Serbia.

Supplement 2. List of macrophyte species found during the field research.

	Radulović 2000	Cvijanović 2010	Novković 2017	Novković 2018	Novković 2019	Novković 2020	PZZP 2021	Novković 2022	Novković 2023
Myriophyllum spicatum L.	*	*	*	*	-	*	-	*	*
Lemna trisulca L.	*	*	*	*	*	*	*	-	*
Callitriche palustris L.**	-	*	-	-	-	-	-	-	-
Elodea nuttallii (Planch.) H. St. John	-	*	*	*	-	-	-	-	*
Sium latifolium L.	-	*	-	-	-	-	-	-	-
Paspalum distichum L.	-	*	-	-	-	-	-	-	-
Spirodela polyrhiza (L.) Schleid.	*	*	-	*	*	*	*	-	*
Lemna minor L.	*	*	*	*	*	*	*	-	*
Nymphaea alba L.**	*	*	*	*	*	*	*	*	*
Ceratophyllum demersum L.	*	*	*	*	*	*	*	-	*
Nymphoides peltata (S. G. Gmel.) Kuntze	*	*	*	*	*	*	*	*	*
Lemna gibba L.	*	*	*	*	*	*	-	-	*
Hydrocharis morsus-ranae L.	*	*	*	*	*	*	*	-	-
Wolffia arrhiza (L.) Wimm.	-	*	-		-	-	-	-	-
Salvinia natans (L.) All.***	*	*	*	*	*	*	*	-	*
Persicaria amphibia (L.) Delarbre	*	*	*	-	-	*	*	-	-
Nuphar lutea (L.) Sm**	*	*	*	*	*	*	*	*	*
Cyperus flavescens L.	-	*	-	-	-	-	-	-	-
Azolla filiculoides Lam.	-	*	*	-	*	*	*	-	-
Vallisneria spiralis L.	*	-	-	-	-	-	*	-	-
Trapa natans L.*/***	*	-	*	-	-	*	*	-	-
Potamogeton crispus L.	*	-	-	-	-	-	-	-	-
Ranunculus circinatus Sibth.	*	-	-	-	-	-	-	-	-
Najas marina L.	-	-	*	-	-	*	-	-	-
Sagittaria sagittifolia L.	-	-	*	-	-	-	*	-	-
Filamentous algae	-	-	*	-	*	-	-	*	*
Sparganium erectum L.	-	-	*	-	-	-	-	-	-
Rorippa amphibia (L.) Besser	-	-	-	-	*	*	-	-	-
Oenanthe aquatica (L.) Poir.	-	-	-	-	*	-	*	-	-
Mentha aquatica L.	-	-	-	-	*	-	-	-	-
Veronica beccabunga L.	-	-	-	-	*	-	-	-	-
Veronica anagallis-aquatica L.	-	-	-	-	-	*	-	-	-
Lythrum salicaria L.	-	-	-	-	-	*	-	-	-
Alisma lanceolatum With.	-	-	-	-	-	-	*	-	-
Glyceria maxima (Hartm.) Holmb.	-	-	-	-	-	-	*	-	-
Iris pseudacorus L.	-	-	-	-	-	-	*	-	-
Leersia oryzoides (L.) Sw.	-	-	-	-	-	-	*	-	-
Potamogeton natans L.	-	-	-	-	-	-	*	-	-
Urtica kioviensis Rogow.	-	-	-	-	-	-	*	-	-
Phragmites australis (Cav.) Steud.	-	-	-	-	-	-	-	-	*
Schoenoplectus lacustris (L.) Palla	-	-	-	-	-	-	*	-	*

*Nationally protected species; **Nationally strictly protected species; ***IUCN Near threatened species.
'Species names are given according to the Euro+Med PlantBase 2006+ (https://europlusmed.org/).

Supporting information

Additional supporting information may be found in the online version of this article at the publisher's web-site:
Supplement 3. Macrpohyte plot assessment data.xlsx