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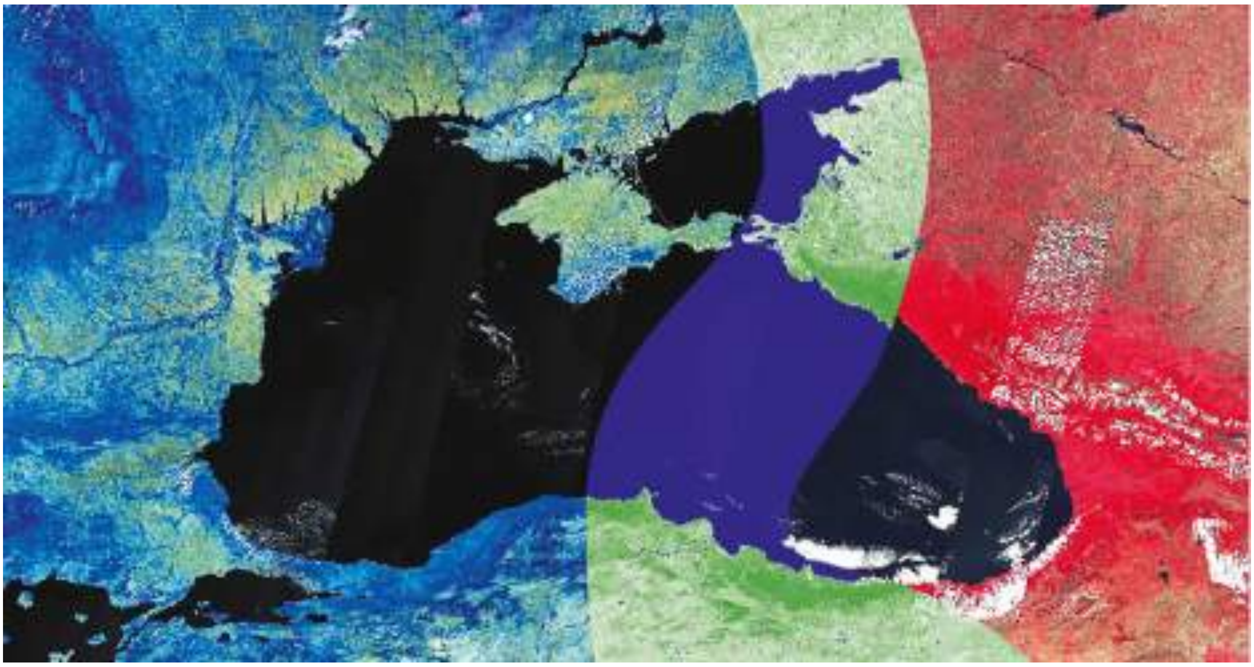

ASSESSMENT ON CHANGES IN WETLAND AND FLOATING VEGETATION COVER

[Deliverable D.T1.2.4]

Pilot site: PONTOS-UA

Country: UKRAINE

Lead Authors: Sergiy Medinets, Yevgen Gazyetov

Contributing authors: Eleftherios Katsikis, Yulia Rudka, Ioannis Manakos, Volodymyr Medinets, Serhii Snihirov, Tetiana Pavlik, Nataliia Kovalova, Alla Mileva, Valentyna Khitrich, Oleksandr Abakumov, Oleg Voroniuk, Pavlo Snihirov, Iryna Yakuba, Olena Pauzer, Yevgen Cherkez, Inna Soltys, Olga Konareva

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EXECUTIVE SUMMARY

Study area and environmental concerns

The Ukrainian pilot area studied within this assessment included the Dniester river delta with the adjacent estuary; a significant part of the pilot embraces the Lower Dniester National Nature Park.

The study area faces many environmental challenges such as nutrient pollution affecting drinking and irrigation water quality and ecosystems functioning, disruption of river water flow (due to impacts of hydropower plants and changing climate) affecting habitats/ biodiversity and agricultural water supply and all this causes aquatic vegetation overgrowth over summertime with associated environmental and economic concerns.

What has been done?

Satellite images (LandSat 5 and 8, Sentinel 2) and historical field data on aquatic vegetation were collected for 2009-2020.

4 field campaigns in the Dniester Estuary and the Bile Lake were conducted for detailed mapping the emergent, floating and (semi-)submerged aquatic plants by unmanned aerial vehicles (UAVs) equipped with RGB and multispectral sensors in the selected sub-sites.

Vegetation samples were also collected to quantify plant biomass and nutrient contents.

VHR space images were used to accurately quantify emergent and floating plant species cover and their densities in the selected sites.

Space-born and aerial images/ orthophotomosaics were processed by various approaches (manual, SCP, CERTH-developed) to differentiate different aquatic types and species and determine inter- and intra-annual changes in their covers.

What has been concluded?

Emergent vegetation cover was quite stable over the time in the Dniester Estuary, while deltaic lakes were more vulnerable (*e.g.* the Bile lake areas decreased by 16% since 1984.

The river mouth areas were highly affected by overgrowth of floating vegetation; a gradual pronounced increase of its cover was detected from 2000 to 2019, while a decrease was recorded since 2020 onwards.

The first ever a high resolution map of aquatic vegetation cover in the Bile lake have been created (based on UAV-images).

The nutrient content in the main aquatic species growing in the two different pilot subareas have been quantified within the project.

Accumulation of the nutrient by emergent and floating aquatic vegetation in the summer time (at mature development stage) for areas of the Dniester estuary and Bile lake has been quantified.

VHR aerial and space-born images were found to be highly credible for distinguishing floating vegetation species/ their cover densities and detailed vegetation map build-up.

High resolution satellite image use were shown to be relevant for local authorities to monitor inter-annual and seasonal changes of vegetation cover in large areas.

Aquatic vegetation (both emergent and floating) have been found to be a crucial source of nutrient (nitrogen, potassium and phosphorus) in the pilot currently causing negative impacts on ecosystem but potentially being a valuable resource for agricultural and energy sectors at sustainable usage.

DEFINITION AND ABBREVIATIONS

Aquatic vegetation or **water vegetation** – this term includes all types of emergent, floating and submerged vegetation growing within water body and its boundary area.

Algae – this term includes cellular, lower weed form with no distinguishable stem of leaf.

Emergent vegetation or **emersent vegetation** or **'wetland' vegetation** – this term includes plants growing in shallow waters with leaves or steams above the water (mainly presented by reeds in the Ukrainian pilot site).

Floating vegetation – this term includes growing *unattached (non-rooted)* or *rooted plants* with floating leaves; this may also include *submerged vegetation at specific condition* when (i) water level decrease and stems/ leaves lie on the water surface, (ii) when it overgrows and their long stems/ leaves lying within the water surface (interface between water and air).

Phytoplankton or **microalgae** – this term includes autotrophic microscopic aquatic algae.

Submerged vegetation – this term includes plants growing entirely below and up to the water surface.

Wetlands – this term according to the Ramsar Convention defines as *"…wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters."*

1. INTRODUCTION

Freshwater ecosystems, being a valuable resource of ecosystem services for local population wellbeing and regional economy (*e.g.* tourism, aquaculture, hydropower generation, drinking water from freshwater systems), are ones of the most vulnerable to the anthropogenic impacts (Sutton *et al.*, 2011). Surface stream waters (*e.g.* rivers and estuaries) mainly function as a transporter/ carrier of received nutrients and other organic/ mineral substances through to the stream within catchment (from agriculture, industry, municipal and domestic activities and atmosphere) and further to larger river and/ or finally to deltaic areas and the sea (Rouholahnejad *et al.*, 2014; Medinets *et al.*, 2017). While low stream or still waters (*e.g.* lakes and ponds) are even more vulnerable to received nutrients and other substances and are of subject to their consumption by aquatic vegetation and accumulation in bottom sediments (OECD, 2017; Teshager *et al.*, 2017; Vinten *et al.*, 2017).

The core driver of ecological concerns in many transboundary river catchments, including the Dniester, is excessive nutrients load of anthropogenic origin as a result of agricultural, industrial (via wastewater discharges and re-deposition of gas emission), domestic (via sewage discharges) and other anthropogenic activities (*e.g.* Medinets *et al.*, 2015, 2016, 2017, 2020), which leads to a significant increase of eutrophication in the lakes, deltaic areas and estuaries (Dereziuk, 2019; Kovalova *et al.*, 2018a,b, 2019). Moreover, temperature increase and rain pattern alteration under changing climate together with fluvial water flow disturbance due to up-regulation with hydro power constructions often inforce and intensify negative impacts on biodiversity, biological resources and ecosystem services. Along with algal blooms, all this is subjected to the overgrowth of aquatic vegetation, which is often observed in vulnerable deltaic areas, lakes and estuaries.

Emergent, floating and submersed aquatic vegetation are natural components of most water bodies (Fig. 1). Aquatic plants play important role in aquatic ecosystem functioning, while might also be a source of additional serious challenges under changing climate, especially in flow-disturbed and/ or nutrient-polluted water bodies.

Positive effects of aquatic vegetation

Under 'normal' condition aquatic plants provide a lot of benefits to aquatic ecosystems, such as uptake of nutrients and heavy metals; oxygenation of waters; atmospheric carbon storage; retain suspended matter and harmful organics; trophic support (via direct consumption by grazers or contributions to the detrital food web); provision of surfaces for algal and invertebrate attachment; fish breeding with further predation refuge for small fish (Boyer *et al.*, 2013; Hussner *et al.*, 2017). Uptake of nutrient and heavy metals by all types of aquatic vegetation as well as mechanically retain suspended matters (with further degradation/ detoxification of most of organic pollutants) by dense emergent vegetation plays an important role in water body self-purification capacity (Sadchikov, 2004; Hu and

Li, 2021; Gula *et al.*, 2022). *E.g.*, Morozov (2001) showed that oil decomposition in the presence of aquatic plants was 3-5 times faster. This can be due to the fact oil substances

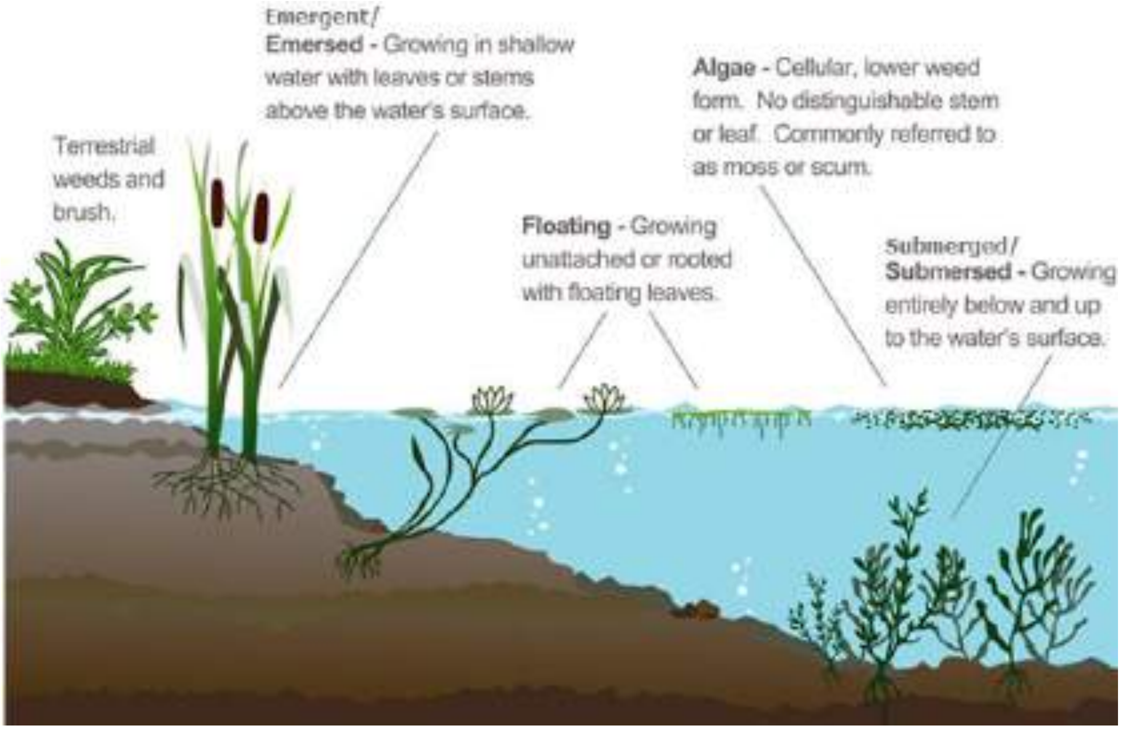

Figure 1: Definition of various aquatic vegetation types (INVAS, 2022).

together with mineral and organic suspensions form larger compounds on plant surfaces, after being deposited they are decomposed by benthic organisms (Morozov, 2001). It was demonstrated that dense plantations of reeds (*Phragmitis sp.)* and cattails (*Thypha sp.*) were potentially able to retain up to 90% of suspended matter from livestock discharges (Krotkevich, 1982) as well as sustain water clarity (Sadchikov, 2004). Aquatic vegetation actively uptakes nutrients from sediments and/or water column and thus in many regions are used as a tool for removing nutrients from aquatic system if aquatic plants accumulated with nutrients are mechanically removed/ collected from the water body until senescence stage (Malik, 2007). Although the uptake rate of different nutrient, organic and mineral substances is type- and species-specific. *E.g.*, submerged vegetation uptake phosphorus 2-10 times rapidly compared to emergent plants (Einor and Dmitrieva, 1984). They showed that emergent vegetation uptakes phosphorus mainly by roots rather than all underwater tissues. Submerged species (*e.g. Egeria densa*) presented in moderation were suggested to oxygenate waters for fish breeding (Cook and Urmi-Konig, 1984). Moreover, large macrophytes may act as antagonists to microalgae, preventing algal blooms, by releasing biologically active substances, such as phytoncides and antibiotics. In addition, some native and invasive macrophytes possess aesthetic appeal for tourists unless adverse effects of their overgrowth, which we will talk about further, do not exceed their visual attractiveness.

Negative effects of aquatic vegetation

However, overgrowth or blooms of floating and submerged aquatic vegetation often lead to harmful consequences for water quality, biodiversity, ecosystem functioning and services provision via decreasing dissolved oxygen level, increasing pH, reducing light penetration, slowing water velocity (while increasing water temperature), increasing siltation rates (in slow streams), serving as mechanical substrates for filamentous algae, clogging or hampering navigation channels/ areas using for fishing and touristic purposes, losing recreational/ touristic attractiveness. Also, negative effects tend to emerge more pronouncedly in the case of non-native species invasion (when the invaders are at high densities and cover large areas) leading to unwished alterations in a number of factors, inter alia nutrient dynamics and food web. Submerged species forming the thick beds are often responsible for substantial reduction of dissolved oxygen level at night due to the lack of photosynthetic oxygen production for respiration needs. At the same time thick mats of floating vegetation may also lead to dissolved oxygen decline through drawdown at night, hamper of gas exchange at water-air interface (Madsen, 1997; Perna and Burrows, 2005), shading photosynthetic macrophytes and phytoplankton (Malik, 2007) as well as at senescence stage, when plant decomposition requires a high biological oxygen demands leading to hypoxia (Greenfield *et al.* 2007). Notably, oxygen level decrease in bottom waters may increase mobility of phosphorus, contributing to its release from sediments and further accumulation via mainly porewater uptake by submersed, emergent and floating plants (Cornwell *et al.*, 2014). On one hand macrophyte blooms may impact trophic chains by changing composition and number of invertebrates, proving more food for carnivorous fish, on the other – thick beds of submerged plants are suggested to hinder invertebrate food resource for fish and simultaneously increase predation risk for fish compared to other habitats (Nobriga *et al.*, 2005; Brown and Michniuk, 2007). Moreover, floating vegetation can increase the surface area for colonization of epiphytic invertebrates and attract fish, which both can serve as a food for certain birds until a plant cover becomes highly dense (Brendonck *et al.*, 2003). Complications of navigation of small vessels, engaged in touristic activity and commercial/ amateur fishing, due to excessively dense vegetation mats effect regional economics.

Most of above mentioned effects of aquatic vegetation are applicable for the Dniester delta area with the adjacent estuary – a Ukrainian pilot site within the PONTOS project. The surface water from the Dniester is known to be an important source of drinking and irrigation for the South-Western Ukraine and the large part of Moldova with totally more than 5 mln population. In large municipalities treated surface water is used for drinking, while in rural areas groundwater is the main source. Magnitudes of water discharge in the Dniester, a precipitation-fed river system, are directly depended on amounts of snowfalls and rainfalls over the year deposited to the catchment. During last decades the tendency of precipitation decrease was observed in the upper part of the basin (OSCE, 2005). In dry years the Lower Dniester received even lesser water than it naturally should owing to a highly regulated flow up-streams. There are four large water storage reservoirs (Dniestrovskoe, Bufernoe, Dubossarskoe and Kuchurganskoe) in the Dniester catchment, operating of which has a high priority and where the frequency and amount of water releases from storages are often less than minimally required (OSCE, 2005). All this leads to a vast of environmental concerns impacting ecosystem state and quality of ecosystem services down-streams (OSCE, 2005; Medinets *et al.*, 2020a). Deltaic areas are the most vulnerable as they act as a sink for and largely exposed to nutrient and chemicals coming from the entire basin, are extremely dependent on (environmental and technical) water releases from storage reservoirs upstream and thus highly sensitive to climate change (disturbed rain-pattern and warming) impacting water quality, biodiversity, ecological services (including fishing). Lower Dniester National Nature Park covers a large part of deltaic wetlands, which play multiple significant roles i) as biodiversity hotspots, including endangered species from the 'Red Book' list, ii) in suspended substances accumulation leading to partially water 'purification' from nutrients, mineral and organic chemicals, and iii) in air quality and greenhouse gas balance via reactive and greenhouse gas emission affected by biochemical processes and natural fires/ human-related dry reed burning.

This highly productive but very vulnerable catchment area is faced with multiple challenges to find a working pattern how to improve environmental state and effectively protect wildlife biodiversity, while sustainably providing ecological services to the locals. We hypothesize that study of changes in the aquatic vegetation cover and quantification of nutrient accumulation by them is highly demanded for development of scientifically-based region-specific aquatic vegetation management strategies, which application in practice might be a strong sustainable option to facilitate solving environmental problems as well as provides added value in terms of additional source of nutrients for agriculture in the region. Moreover, a user-friendly online tool based on free-accessed space-born data for identification of emergent and floating aquatic vegetation cover in the Dniester deltaic area verified with in-situ data is developed within the PONTOS project and, we believe, will be a valuable instrument for a vast of local stakeholders and decision-makers.

The main purposes of this assessment are:

I. To estimate (inter-annual) changes in the area of emergent and floating vegetation cover during 2009-2021 in the Ukrainian pilot with identification of the most vulnerable to overgrowth areas
II. To estimate annual dynamics of changes in emergent and floating vegetation cover over 2021
III. To contribute the development of the automatic tool for the emergent and floating vegetation cover mounted in the PONTOS platform and provide in-situ data for algorithm tuning and data verification

There are also specific goals we have covered within this study:

i. To identify aquatic vegetation species using very high resolution (VHR) satellite images and unmanned aerial vehicle (UAV) mosaics (at selected sub-sites)

ii. To quantify the biomass of and nutrient accumulation in different types/ species of aquatic vegetation in pilots (at selected sub-sites)
iii. To identify (semi-)submersed vegetation and to assess their area/density using UAV and satellite VHR images (at selected sub-sites)

2. MATERIAL AND METHODS

2.1. Study area

Ukrainian Pilot area (PONTOS-UA) is located in the north-western part of the Black Sea consisting of two joint study sub-areas: the coastal line (PONTOS-UA_1) and the Dniester river delta (PONTOS-UA_2) (Fig. 2a). This assessment was performed in PONTOS-UA_2, which includes the Dniester river delta area and adjacent estuary (approx. 1800 km2) through which it is connected with the Black Sea (Fig. 2b). A significant part of this area belongs to the Lower Dniester National Nature Park (Fig. 2b).

Figure 2: Location of the Ukrainian pilot sub-sites PONTOS-UA_1 and PONTOS-UA_2 (a) as well as location of the territory of the Lower Dniester National Nature Park (dashed area) within the PONTOS-UA_2 (b).

The Dniester is a transboundary river, which flows through three countries; starting in Poland (covering ~0.4% of its river basin), further going through Ukraine (totally ~72.6% of its river basin) and Moldova (~27% of its river basin) until returning back to the Ukraine before discharging into the Black Sea. The river basin lies on 7 oblasts (administrative regions) of the Ukraine and on more than half the territory of Moldova (59%; of the 11 administrative regions and the Transdniestrian area). The importance of the Dniester to the South-Western part of Ukraine and Moldova is hard to overestimate, since it is the main source of both drinking and irrigation water for those regions.

The Dniester river catchment consists of rubbly soil in the mountain forests, soddy podzolic soil in foothills of Carpatians, grey forest soil in the Podol uplands and black podzolised soil in the lower areas. Black soils are predominantly found in the Moldovan part of the Dniester Basin, which is dominated by agricultural land (76% agricultural land, of which 59% is arable). Agricultural land in the arid area of the Odesa oblast (covering the pilot area) are composed of both black soils and chestnut soils. In total *ca.* 67% of the Dniester Basin (in the Ukrainian territory) is involved in agriculture activity (78% of this is arable). Mineral fertilizer application was estimated to be between 45 and 46 kg N ha^{-1} yr^{-1} within Odesa region, and 25 to 100 kg N ha^{-1} yr^{-1} within the republic of Moldova (organic and manure fertilizer and N content were not reported) (UKRstat, 2015; Statistica.MD, 2015). A key concern is that poor soil management practice in a basin, and often inappropriate fertilizer and chemicals application schemes (type, method, rate and timing) may cause N losses via atmospheric emission as well as nutrient and chemical losses via leaching and surface runoff to the hydrosphere.

The pilot area has a temperate continental climate. Annual mean air temperature is 10.5 C (period of 2000-2014) varying from 8.4 C to 12.5 C (Medinets *et al.*, 2016). The long-term average annual precipitation sum was 464 mm (2000-2014), but varied substantially over the last years from 420 mm (in 2020) to 771 mm (in 2021). The atmospheric total N (TN) deposition rate is moderate at ca. 11.4 kg N ha-1 y-1 (Medinets *et al.*, 2020b) with circa 67% contribution from organic constituents; such large contribution is also observed for open waters in the northwestern part of the Black Sea (Medinets and Medinets, 2012; Medinets, 2014).

2.2 In-situ observations

2.2.1 Direct vegetation boundaries measurements

In this assessment we used the historical data of direct measurements based on field GPS tracking of aquatic vegetation boundaries by using a boat performed in the north part of the Dniester estuary by the Odesa National I.I. Mechnikov University (ONU) on an annual basis (in July) over 2010-2020. This approach included the following stages:

- Tracking of the boundaries of emergent and floating vegetation with the boat-mounted GPS device of Eagle SeaCharter 640CDF GPS with horizontal accuracy of 3-5 meters (when it was impossible to distinguish floating vs. dense semi-submerged vegetation, a sum of both was indicated as a floating vegetation);

- Visual assessment of emergent and floating vegetation, its types and areas covered with a photo report;
- Post-expeditionary processing of geolocation data was carried out: downloading GPS data and converting them into a coordinate system suitable for GIS software;
- In a GIS software (ArcGIS or QGIS), the position of the aquatic vegetation boundaries was checked and manual corrected (where required) using available space images (LandSat 5, 7, 8 and Sentinel 2) due to the fact that in some areas it was not possible to bypass the aquatic vegetation polygons on a boat (small vessel) because of dense vegetation cover or the presence of other difficulties;
- Spatial analysis of aquatic vegetation polygons was performed using a GIS software (ArcGIS or QGIS): the introduction of corrections for the indentation of a boat from the vegetation boundaries, the production of digital maps of emergent and floating vegetation cover, analysis of spatiotemporal variations of emergent and floating aquatic vegetation in certain sectors of the Lower Dniester delta (Fig. 3)

Figure 3: Location of sectors used for spatiotemporal analysis of the emergent and floating vegetation cover in the deltaic part of the Lower Dniester.

2.2.2. Air-born mapping and data processing

Within the PONTOS project the ONU conducted a series of field surveys for mapping of vegetation cover using the unmanned aerial vehicles (UAVs) in the PONTOS-UA_2 over 2021. Two types of UAVs were used: i) DJI Phantom 4 Pro v.2.0 with RGB sensor (1" CMOS with effective pixels 20 MP), purchased by the ONU within the PONTOS project, and ii) DJI Phantom 4 Multispectral equipped with 6 sensors (VisRGB, Blue: 450 nm ± 16 nm; Green: 560 nm ± 16 nm; Red: 650 nm ± 16 nm; Red edge: 730 nm ± 16 nm; Near-infrared: 840 nm ± 26 nm; each having 1/2.9" CMOS with effective pixels 2.08 MP).
Free software was used for high resolution mapping: 1) DJI GS Pro on Mac OS for the Multispectral UAV and 2) DJI Pilot on Android for the RGB UAV. The operational height of flight during mapping was set on 120 m above the ground for the RGB UAV and 50 m for the Multispectral UAV to get an accurate set of high resolution georeferenced images for the Bile lake and the selected sites in the Dniester estuary (see Fig. 4). The retrieved sets of images were pre-processed to combine into corresponding orthophotomosaics using the specific software Pix4Dmapper, purchased by the ONU within the PONTOS project. Further detailed processing of RGB and multispectral mosaics differs.

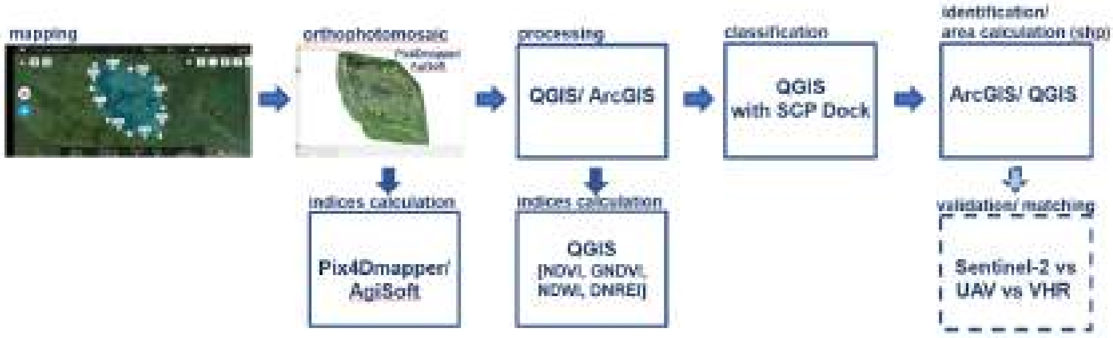

Figure 4: General workflow of in-situ airborn data retrieval and processing.

2.2.2.1. RGB orthophotomosaic processing

We used RGB orthophotomosaics to identify the temporal variation of different types/ species of emergent and floating vegetation cover in the Bile lake. The workflow for the classification of the aquatic vegetation types/ species based on RGB orthophotomosaics includes the following stages:

- to coarse RGB-orthomosaic resolution to 0.5 m per pixel in QGIS;
- to manually prepare an AOI shapemask by selecting an area without shooting errors, artifacts and noise;
- to vectorize a raster image of a 0.5m-coarsened RGB orthomosaic in the Vextractor application by creating a shapefile and cropping it along the boundaries of the AOI shapemask;

- to manually correct the ArcGIS/QGIS-generated vegetation and water shapefile for land cover classification using the expert's judgment, photographic material from the survey site and Sentinel-2 images retrieved for the same day;
- to calculate areas in ArcGIS/QGIS, compose and export output maps to graphical format;
- to carry spatial analysis using the ArcGIS/QGIS tools to identify seasonal variability in the distribution of aquatic vegetation cover presenting by different species.

2.2.2.2. Multispectral orthophotomosaic processing

We used orthophotomosaics obtained for different bands of spectrum and a set of vegetation and water indices calculated out of those bands to identify the temporal (and spatial) variation of different types/ species of emergent and floating vegetation cover in the selected site of the Dniester estuary and the Bile lake. The workflow for the classification of the aquatic vegetation types/ species based on multispectral orthophotomosaic includes the following stages:

- to coarse single-band orthomosaics resolution to 0.5 m per pixel in QGIS;
- to produce a custom multispectral mosaic from a combination of single-band mosaics of Green-NIR-RedEdge in QGIS;
- to prepare an AOI shapemask by selecting an area without shooting errors, artifacts and noise as well as a water mask based on threshold values in the longest wavelength RedEdge band;
- to calculate and crop along the boundaries of the AOI-shapemask vegetative and water indices (NDVI, GNDVI, NDWI, NDREI; see below) as well as to prepare ready-made maps of those indices in QGIS/ArcGIS;
- to carry out a step-by-step classification of different aquatic vegetation species/ types in a multispectral mosaic by using the Semi-Automatic Classification Plugin (SCP) tool in QGIS, then to distinguish them into separate rasters;
- to stitch rasters of aquatic vegetation species and water in QGIS with further their vectorization into a shapefile;
- to correct any errors in QGIS/ArcGIS, to calculate areas covered by different aquatic vegetation species/ types and water, to layout output maps.

The following indices were tested to be potentially used for aquatic vegetation identification and/ or separation against water:

- GNDVI is a Green Normalized Difference Vegetation Index, where the Green region of the spectrum with a wavelength of 540-570 nm and the near infrared (NIR) region are used:

  $$GNDVI = (NIR - Green) / (NIR + Green).$$

  GNDVI is more sensitive to chlorophyll than widely used NDVI and is often used for crop development assessment, identification of plants under stress and at the wilting stage.

- NDWI is a Normalized Difference Water Index designed to study water surfaces. The index can vary from -1 to 1, identifying the green vegetation in a range of -0.1 to 0.4. Green and NIR regions of spectrum are used for NDWI calculation:

  NDWI = (Green - NIR) / (Green + NIR).

  NDWI is widely used in agriculture to detect flood events in fields/ flooded agricultural land, to monitor irrigation efficiency as well as to identify wetland and to assess water turbidity.
- NDREI is a Normalized Difference Red Edge Index used for measuring the chlorophyll content in plants. A combination of NIR and Red Edge (located between visible Red and NIR) regions of the spectrum are used for its computation:

  NDRE = (NIR - RedEdge) / (NIR + RedEdge).

  Such a band combination makes NDRE extremely sensitive to chlorophyll concentration in the plant tissues.

2.2.3. Aquatic vegetation sampling and analysis

We sampled the representative plots from different typical vegetation polygons at the selected sites in summer months of 2021 within the PONTOS project. We used a 50x50 cm plastic frame upon vegetation sampling to extract the vegetation biomass inserted in the frame area. Further on, the samples were qualitatively and quantitatively analysed in the ONU's laboratory. Species composition was identified, fresh (wet) biomass and dry biomass following drying out at 80°C in an oven were measured as well as nutrient (nitrogen, phosphorus and potassium) contents in plant biomass of each species were determined in the samples.

2.3 Space-born data

2.3.1 SCP-based processing of the very high resolution (VHR) images

The VHR images were purchased from Maxar Technologies Inc. within the PONTOS project (Table 1).

Table 1: The list of the very high resolution (VHR) images purchased and used for aquatic vegetation identification.

VHR image details	Date	Area
WorldView-2, Image ID: 103001005AA52B00, 8 multyspectral bands - 1.84 m; panchromatic band - 0.46 m	17.07.2016	Bile lake
WorldView-2, Image ID: 103001005A2FD600, 8 multyspectral bands - 1.84 m; panchromatic band - 0.46 m	30.07.2016	Dniester estuary
WorldView-2, Image ID: 10300100C23EDB00, 8 multyspectral bands - 1.84 m; panchromatic band - 0.46 m	20.07.2021	Dniester estuary
WorldView-2, Image ID: 10300100C3635F00, 8 multyspectral bands - 1.84 m; panchromatic band - 0.46 m	31.07.2021	Bile lake

The general workflow (Fig. 5) for processing the VHR images to classify the aquatic vegetation types/ species in the Bile lake and the Dniester estuary included the following specific steps:

- to open multispectral and panchromatic images in QGIS/ArcGIS;
- to perform the pansharpening sequentially for channels B4-B3-B2, B6-B7-B5 and B8-B7-B1 (as RGB) using the Gram Schmidt algorithm specialized for WorldView-2 to improve the multispectral component resolution to the one of panchromatic image (0.46 m);
- by opening consecutive combinations of B4-B3-B2, B6-B7-B5 and B8-B7-B1 in QGIS/ArcGIS to allocate each pansharpened band into a separate raster to obtain a set of improved bands;
- to calculate the GNDVI, NDWI, NDREI indices (see description above) using pansharpened bands in QGIS;
- using the Semi-Automatic Classification Plugin (SCP) in QGIS, to classify water in detail first, then in turn, creating masks of water and each aquatic plant species and distinguishing them into separate rasters;
- to manually create a shape-mask of the boundary between emergent vegetation and water using the threshold value in the NIR2 (or SWIR) band, which is attributed to the zone of maximum absorption by water;
- to merge aquatic plant and water classification rasters into multichannel one and then vectorize it into a shape-file;
- using QGIS/ArcGIS to correct any errors, to calculate areas covered by different aquatic vegetation species/ types and water, to layout output maps.
- to carry spatial analysis using the ArcGIS/QGIS tools to identify seasonal variability //in the distribution of aquatic vegetation cover presenting by different species.

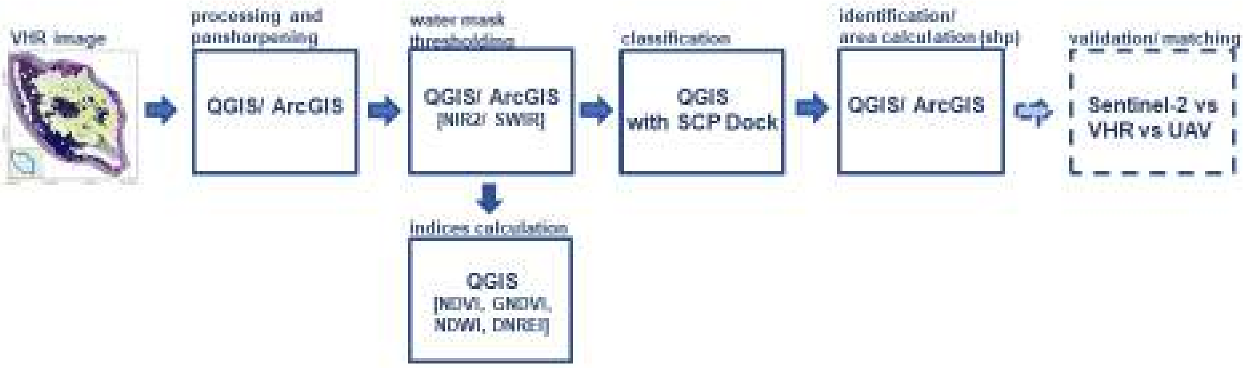

Figure 5: General workflow of the very high resolution image processing.

2.3.2. Processing of satellite images using CERTH-developed algorithm

The unsupervised clustering method has been developed by Centre of Research and Technology Hellas (CERTH) within the PONTOS project to estimate i) open water ii) emergent vegetation cover and iii) floating vegetation cover. This method was applied for and tuned on Sentinel-2 level-2A products (2017-2021) as well as initially tested on

LandSat 5 (2009-2011) and 8 (2013-2016) images. The general workflow of satellite image processing is outlined in Fig. 6.

Figure 6: General workflow of the very high resolution image processing.

The determination of open-water and different types of aquatic vegetation includes the following steps:

i. The first step is to identify the open-water using the SWIR's band histogram threshold (Fig. 7). SWIR is better for delineating water in wetlands, since it less sensitive to sediment-filled waters and therefore more suitable for delineating the boundaries between water and dry ground in shallow wetland areas.

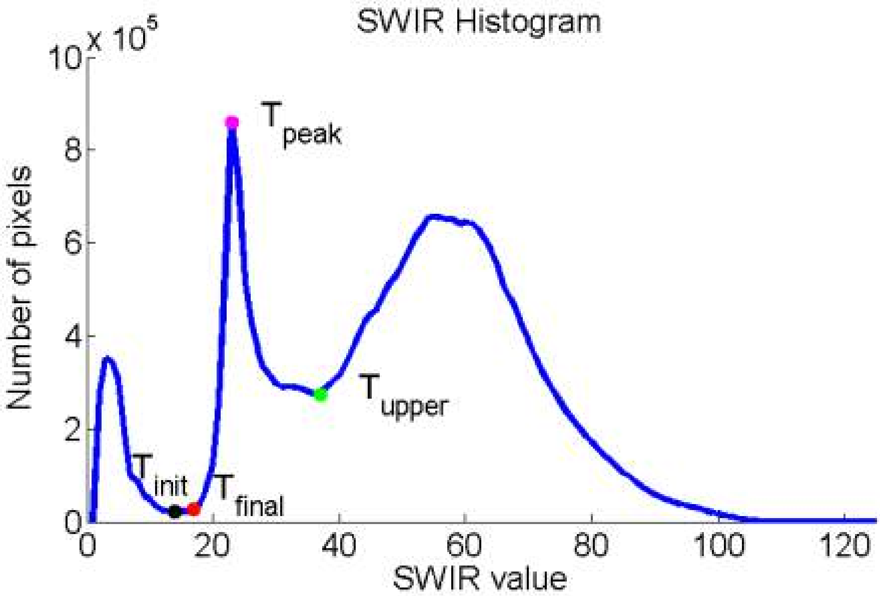

Figure 7: SWIR's band histogram.

The T_{final} value is identified in the first deep valley of the histogram and represents the open-water threshold. All pixels with SWIR values smaller than the T_{final} are classified as water.

ii. The next step is to calculate the MNDVI's histogram and detect the MNDVI's threshold in the first deep valley which is over the value 0.25 (Fig. 8). The MNDVI (Modified Normalized Difference Vegetation) Index is estimated, using Band 7 and Band 5 of Sentinel-2:

$$MNDVI = (Band\ 7 - Band\ 5) / (Band\ 7 + Band\ 5)$$

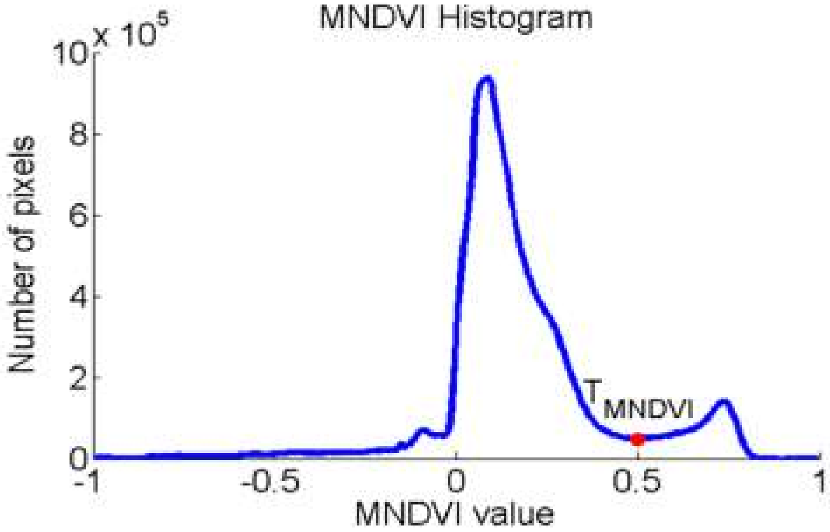

Figure 8: MNDVI's histogram.

Pixels are classified as emergent vegetation if the conditions below are applied:
a) SWIR value is greater than T_{final} smaller than T_{upper}
b) MNDVI value is greater than T_{MNDVI}
Rest pixels are initially classified as land.

iii. The final step is to calculate the Index (Band 5 – Band 7) / (Band 5 + Band 7) and calculate its histogram (Fig. 9).

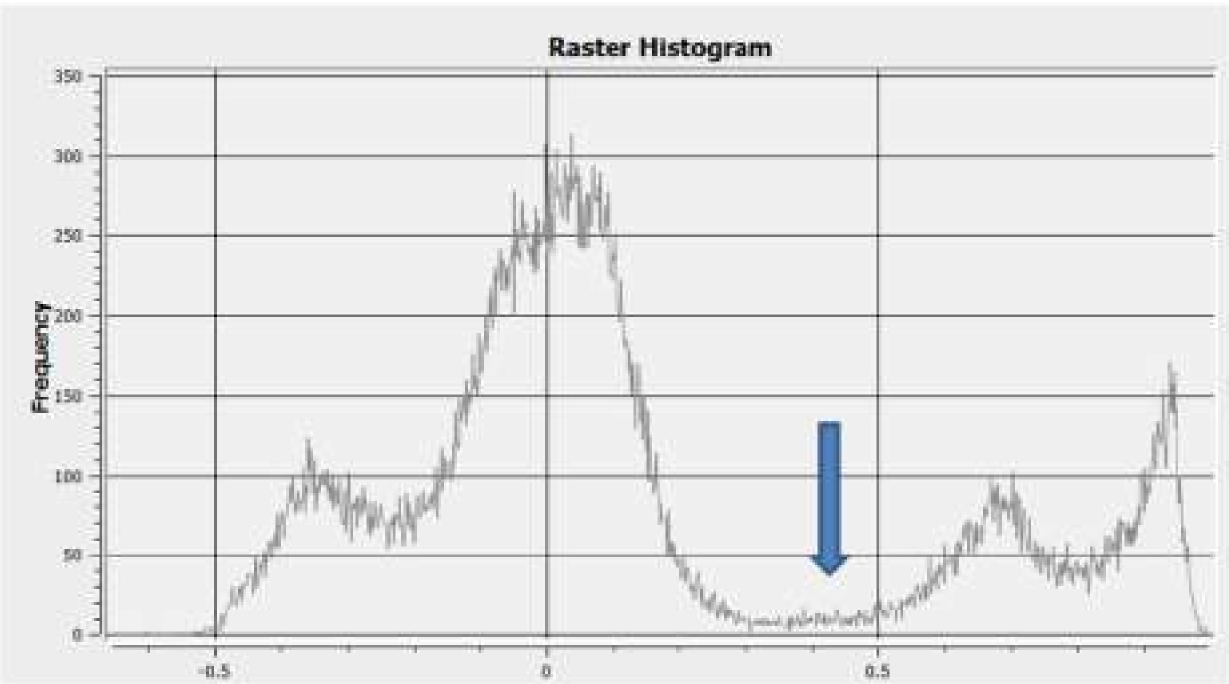

Figure 9: Raster histogram.

The threshold is detected in the first deep valley for values greater than 0. Pixels are classified as floating vegetation if the conditions below are applied:
a) Initially classified as land
b) Index (Band 5 – Band 7) / (Band 5 + Band 7) values are greater than index threshold.

All steps are carried out through the enhanced Watermask module, which for PONTOS needs is enriched with the workflow in step (iii). Due to the inability of the software to automatically detect an optimal minimum value out of the range in the valley suggested in step (iii), the user has to iteratively (test and error process) and manually on screen identify the best minimum value for each area of interest, which discriminates best the floating aquatic vegetation. This value has to be entered in the code of the Watermask module by the user/programmer.

3. RESULTS

3.1. In-situ data

A combination of historical and measured in the framework of the PONTOS project datasets was used to explore spatiotemporal variations of emergent and floating aquatic vegetation cover in the Dniester river delta and adjacent estuary (the Ukrainian pilot area) in this assessment. Also, within the large pilot area, two representative sub-areas, the Bile lake and the north-east part of the Dniester estuary, were selected to perform enhanced measurements and monitoring.

3.1.1. Historical field data derived with boat surveys

Dniester estuary

During 2010-2020 the Regional Centre of Integrated Environmental Monitoring (RCIEM) of the ONU monitored the boundaries of the aquatic vegetation in the upper part of the Dniester estuary within summer campaigns carried out annually between late July – early August in a framework of series of national projects dedicated to the Lower Dniester river investigations. The studied area was divided into 5 sectors according to the geohydromorphological characteristics (Fig. 3):

- Sector A: a north part of Dniester estuary with extensive wetland area on the right bank of the river;
- Sector B: the territory between two branches (Deep Turunchuk and Dniester) of the Dniester river;
- Sector D: the territory of the Dniester branch mouth with adjacent area
- Sector E: the territory of the left bank of the Dniester branch and the Karaholsky bay
- Sector F: an open water central part of the Dniester estuary

Early estimates of aquatic vegetation in July 2000 and 2005 were carried out by manual analysing LandSat satellite images using expert's judgement of research staff working in that area (Fig. 10-11). From 2010 onwards processed results were mainly based on in-situ monitoring data (Fig. 12-16). The exception was areas with a mixture of floating and dense (semi-)submerged vegetation in 2010, which as well as those 'earlier' data of 2000 and 2005 were evaluated remotely (Fig. 10-11). Further on, the pronounced polygons of a 'soup' of floating and dense (semi-)submerged vegetation were observed sporadically in sectors B and D (near the mouths of two Dniester river branches) in 2015, 2019 and 2020 (Fig. 13, 14, 16). Areas covered by those plants varied substantially: larger values were shown for 'earlier' satellite-estimated years of 2000, 2005 and 2010 (range: 31.8-70.6 km^2), while lower values of 8.6-16.4 km^2 were indicated for 'recent' years (2015, 2019 and 2020), where vegetation cover was measured during field campaigns (Fig. 17). We found that emergent vegetation cover (Fig. 18) was quite stable over the time (and within the certain sectors) in the region with a deviation from 0.5% to 1% only. The maximum cover of 89.4 km^2 was estimated for 2000, while minimum area covered (88.4 km^2) with that type of vegetation was detected in 2011. During the past 20 years a positive tendency of emergent vegetation cover increase (r^2=0.7064; $p<0.05$) was observed (Fig. 18).

Figure 10: Areas covered by aquatic vegetation in the Dniester estuary in July 2000 (a) and 2005 (b) [- water; - emergent veg.; - floating veg.; - a mixture of floating + (semi-)submerged veg.; dashed line – rough estimates].

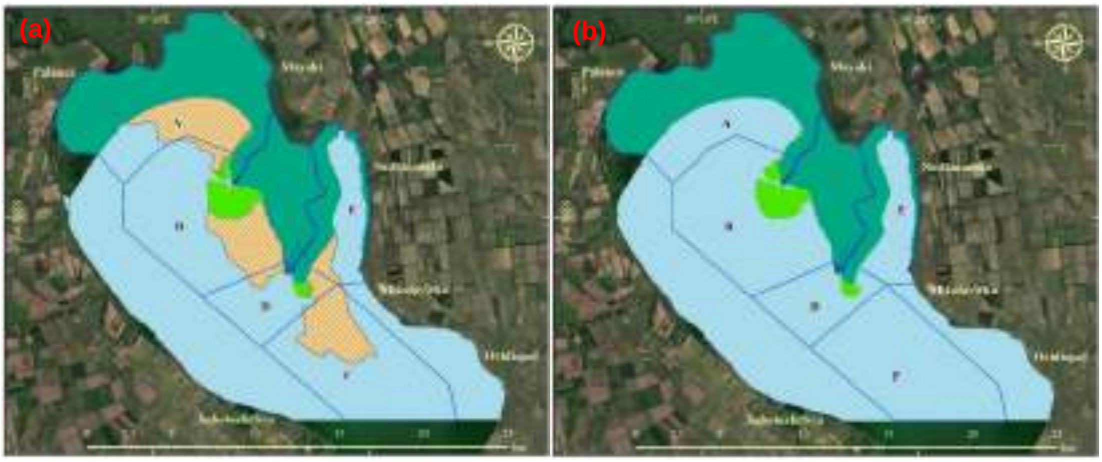

Figure 11: Areas covered by aquatic vegetation in the Dniester estuary in July 2010 (a) and 2011 (b) [- water; - emergent veg.; - floating veg.; - a mixture of floating + (semi-)submerged veg.; dashed line – rough estimates].

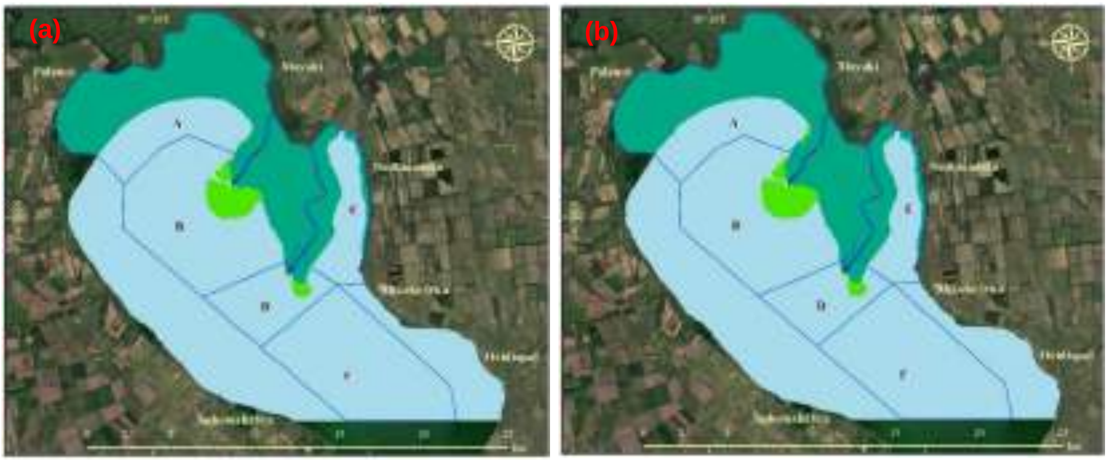

Figure 12: Areas covered by aquatic vegetation in the Dniester estuary in July 2012 (a) and 2013 (b) [- water; - emergent veg.; - floating veg.; - a mixture of floating + (semi-)submerged veg.; dashed line – rough estimates].

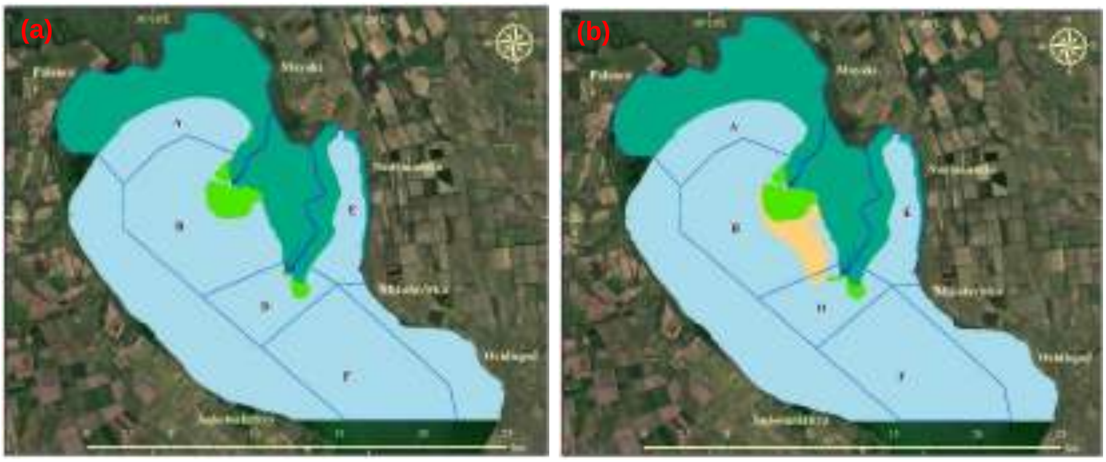

Figure 13: Areas covered by aquatic vegetation in the Dniester estuary in July 2014 (a) and 2015 (b) [- water; - emergent veg.; - floating veg.; - a mixture of floating + (semi-)submerged veg.; dashed line – rough estimates].

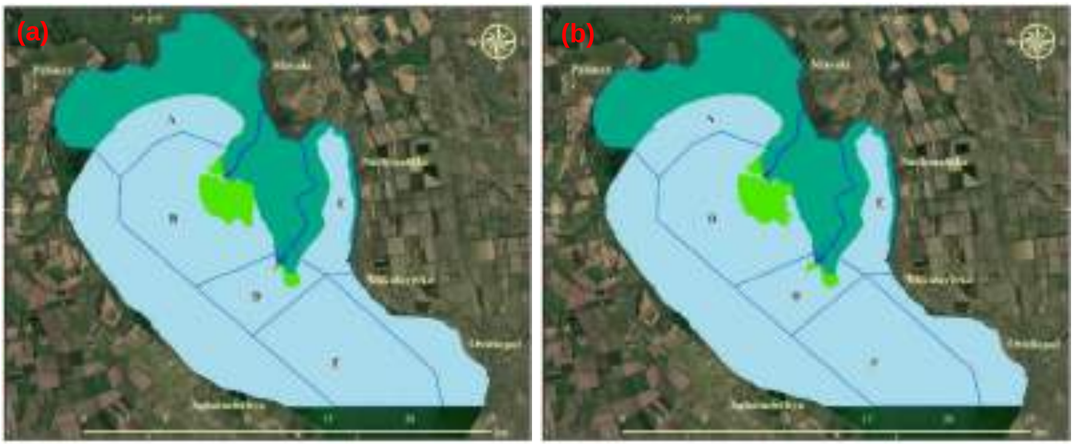

Figure 14: Areas covered by aquatic vegetation in the Dniester estuary in July 2016 (a) and 2017 (b) [- water; - emergent veg.; - floating veg.; - a mixture of floating + (semi-)submerged veg.; dashed line – rough estimates].

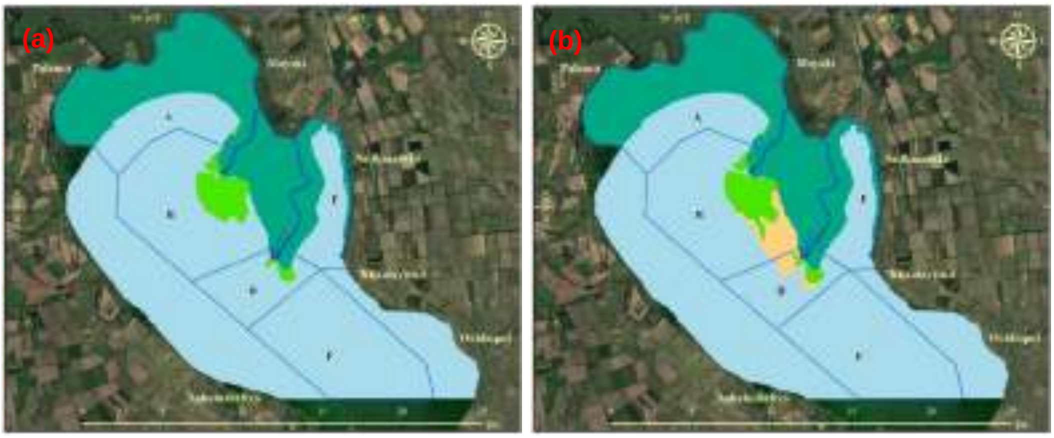

Figure 15: Areas covered by aquatic vegetation in the Dniester estuary in July 2018 (a) and 2019 (b) [- water; - emergent veg.; - floating veg.; - a mixture of floating + (semi-)submerged veg.; dashed line – rough estimates].

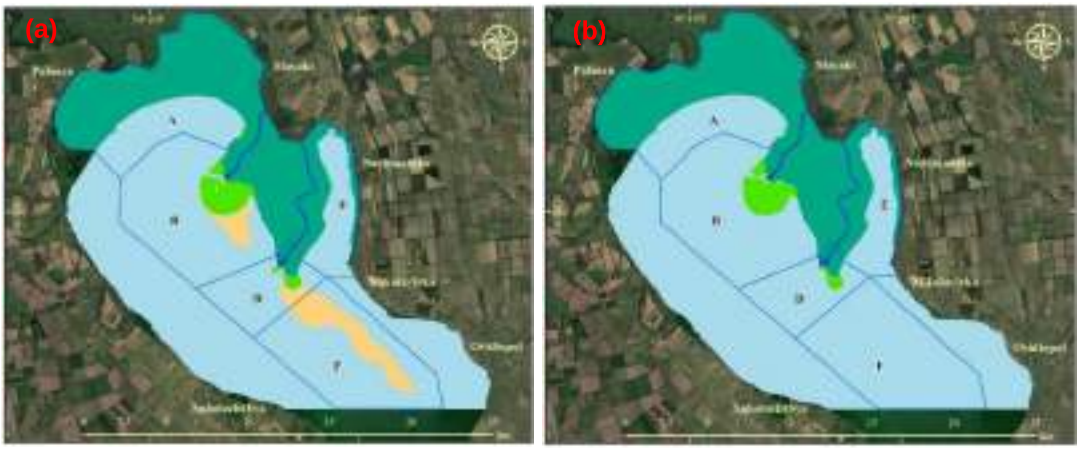

Figure 16: Areas covered by aquatic vegetation in the Dniester estuary in July 2020 (a) and 2021 (b) [- water; - emergent veg.; - floating veg.; - a mixture of floating + (semi-)submerged veg.; dashed line – rough estimates].

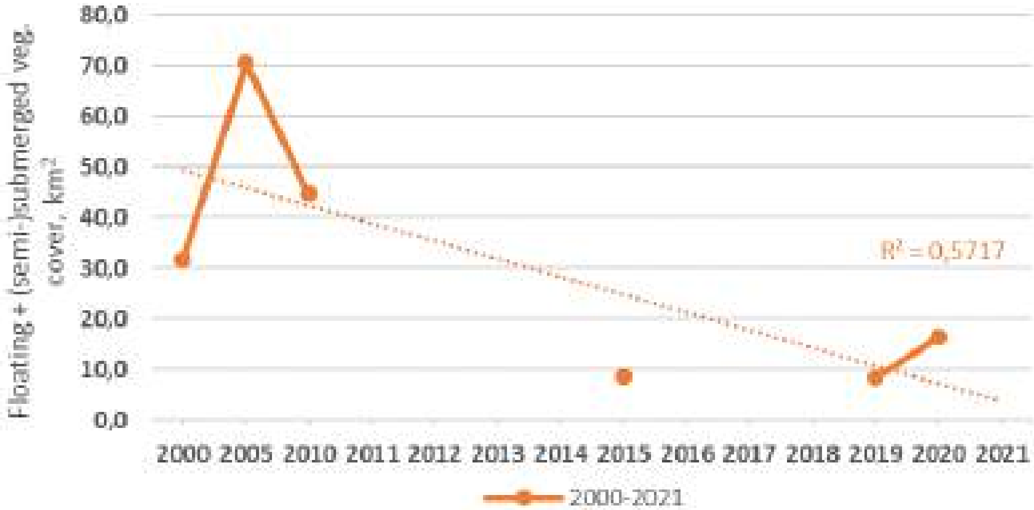

Figure 17: Areas covered by a mixture of floating and (semi-)submerged vegetation in the Dniester estuary over 2000-2021.

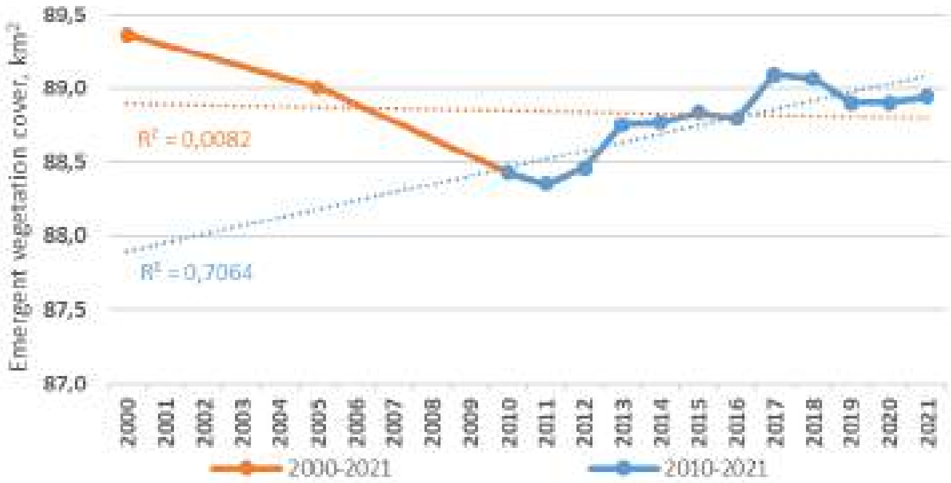

Figure 18: Areas covered by emergent vegetation in the Dniester estuary over 2000-2021.

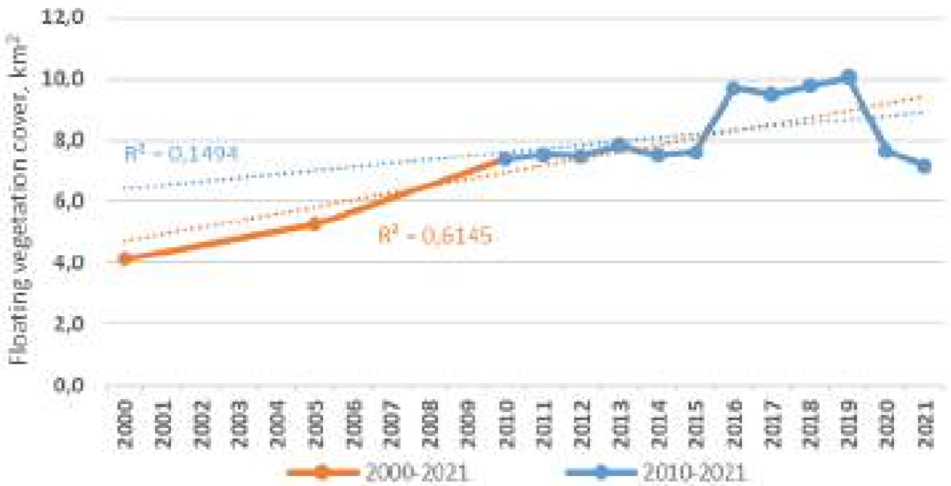

Figure 19: Areas covered by floating vegetation in the Dniester estuary over 2000-2021.

Fig. 19 shows the evolution of floating vegetation since 2000 onwards. The river mouth areas (sectors B and D) were highly affected on overgrowth of floating vegetation in summer time. We detected a gradual pronounced increase of the area covered with floating vegetation from 4.1 km^2 in 2000 to 10.1 km^2 in 2019. Whilst, since 2020 we have recorded this plant type coverage decrease up to 7.2 km^2. Inter-annual variation of vegetation cover near the Dniester branch mouth (sector D) was larger (variation coefficient (VC): 32.3%) than that (VC: 21.8%) near the Deep Turunchuk branch mouth (sector B).

Bile lake

Since 2004 the Bile lake, a unique biodiversity hotspot in the Dniester delta, has been on a focus of the RCIEM of the ONU. Monitoring of the boundaries of the emergent vegetation carried out during summer campaigns together with the LDNNP.

Early estimates of the lake area bordered by emergent vegetation in 1984, 1990, 1995, 2000, 2005 and 2010 were carried out by manual analysing LandSat satellite images using expert's judgement of research staff working in that area (Fig. 20-22). From 2011 the combination of two methods, direct measurements and estimates from satellite images, were used for the lake boundary determination (Fig. 23-27) because overgrowth of floating plants covering a large part of the lake hampered the effectiveness of field measurements in summer time.

Figure 20: Boundaries of the emergent vegetation in the Bile lake in July 1984 (a) and 1990 (b).

Figure 21: Boundaries of the emergent vegetation in the Bile lake in July 1995 (a) and 2000 (b).

Figure 22: Boundaries of the emergent vegetation in the Bile lake in July 2005 (a) and 2010 (b).

Figure 23: Boundaries of the emergent vegetation in the Bile lake in July 2011 (a) and 2012 (b).

Figure 24: Boundaries of the emergent vegetation in the Bile lake in July 2013 (a) and 2014 (b).

Figure 25: Boundaries of the emergent vegetation in the Bile lake in July 2015 (a) and 2016 (b).

Figure 26: Boundaries of the emergent vegetation in the Bile lake in July 2017 (a) and 2018 (b).

Figure 27: Boundaries of the emergent vegetation in the Bile lake in July 2019 (a) and 2020 (b).

Figure 27: Boundaries of the emergent vegetation in the Bile lake in July 2021.

We found that the lake area was decreasing in time due to overgrowing with emergent vegetation. From 1984 to 2005 we estimated area reduction by 5% only, while over the last 16 years this process intensified and reached 11% (Fig. 28). Overall, the total lake area decreased by 16% from 1.17 km^2 in 1984 to 0.98 km^2 in 2021. Despite manually processed satellite images with a resolution from 60 to 10 m per pixel were shown to be a valuable source of a reliable estimation of the lake area evolution over the time.

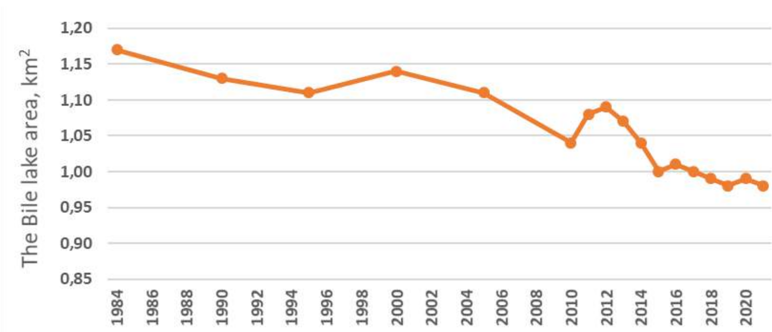

Figure 28: Changes of the Bile lake boundaries during 1984-2021 (estimated for July).

3.1.2. Airborn field data

From April to September 2021 within the PONTOS project, the RCIEM of the ONU conducted 8 field trips and carried out accurate mapping in the selected sub-areas (in the Bile lake and in the north-east Dniester estuary) by using the UAVs to identify the cover of different aquatic plant species and to estimate their dynamics over study period. We found that there was no floating vegetation detected in April 2021, which started to appear in May (unfortunately due to bad weather condition at times when Sentinel-2 (S-2) satellite where above the pilot area, we did not perform any field surveys in May). However, from June to September 2021 we collected 20 high resolution aerial datasets (9 with RGB and 11 with multispectral sensors) to be composed into orthophotomosaics and further processed.

We found that the quality of every initial aerial image depended on weather conditions (wind speed, wind gust, partial cloudiness, waves) upon mapping and brightness was very important characteristic for further processing as both impacted the image stitching to an entire orthophotomosaic. Mosaics with fuzzy (unfocused) fragments, stripes with chessboard effects, offset stitching of tiles of spectral bands as well as those mapped under plant senescence period led to misprocessing in ArcGIS/QGIS (Fig. 29). In total, 5 out of 11 multispectral mosaics were successfully processed with Semiautomatic Classification Plugin (SCP) to determine water and different aquatic vegetation species.

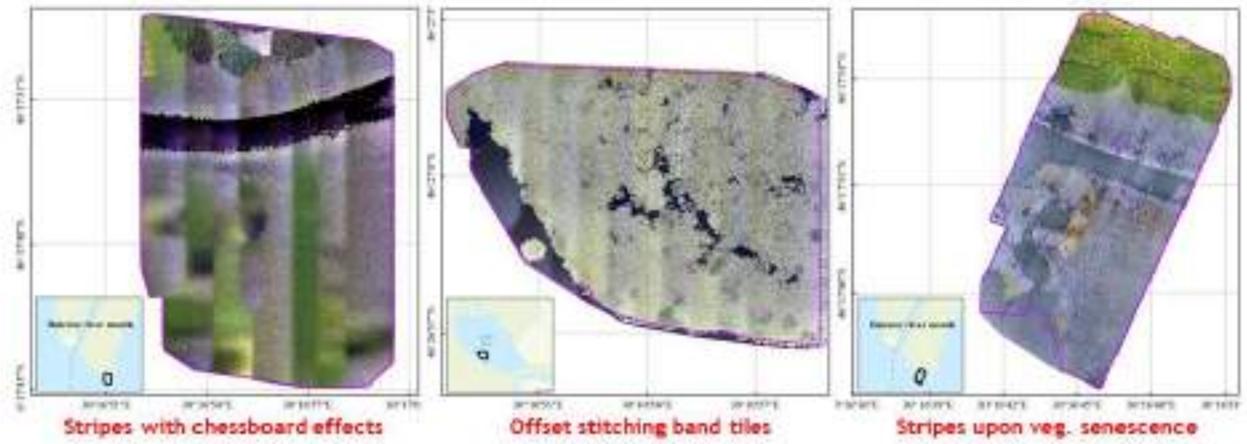

Figure 29: Examples of mismatched orthophotomosaics

Also, we confirmed that using SCP is still time-consuming process as each orthophotomosaic should be classified separately (at least the current version) as they substantially differ in spectral characteristics, reflectance, brightness, color intensity etc.

Dniester estuary

For the selected representative sub-area in the north-east part of the Dniester estuary we identified the distribution of two dominant species of floating aquatic vegetation (*Nuphar lutea* and *Trapa natans*) and quantified areas covered (Fig. 30). We found that N. lutea covered 45.0% and T. natans 36.2% of the area, while the water spaces in-between where below 19%. Thus *Nuphar-Trapa* ratio of 1.24 can be considered as a representative for floating aquatic polygons adjacent to river mouths (sectors B and D).

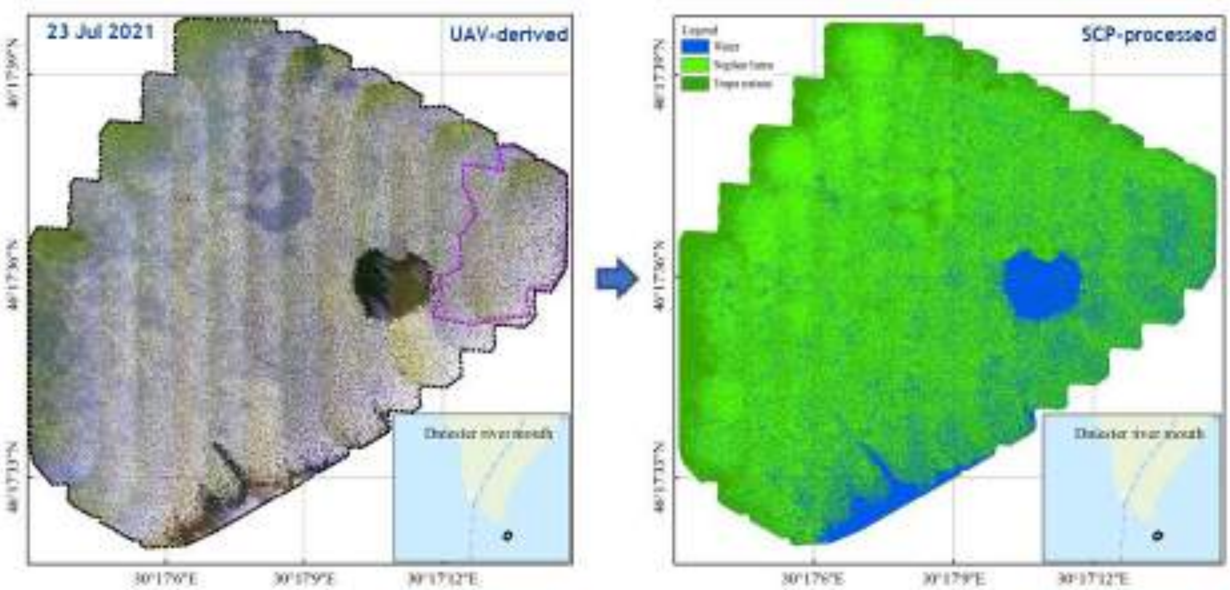

Figure 30: Floating aquatic species determination in the UAV-derived mosaic (July 23, 2021) processed with the SCP tool.

Also, we showed that semi-submerged and submerged vegetation, presented by *Ceratophyllum demersum* can be satisfactory identified in a high resolution UAV-derived mosaics and that its density can be quantified by using either SCP tool (Fig. 31) or water/ vegetation indices, *e.g.* NDWI and NDREI (Fig. 32). We observed that on July 23[th], 2021 (semi-)submerged *C. demersum* covered not more than 3% of the area.

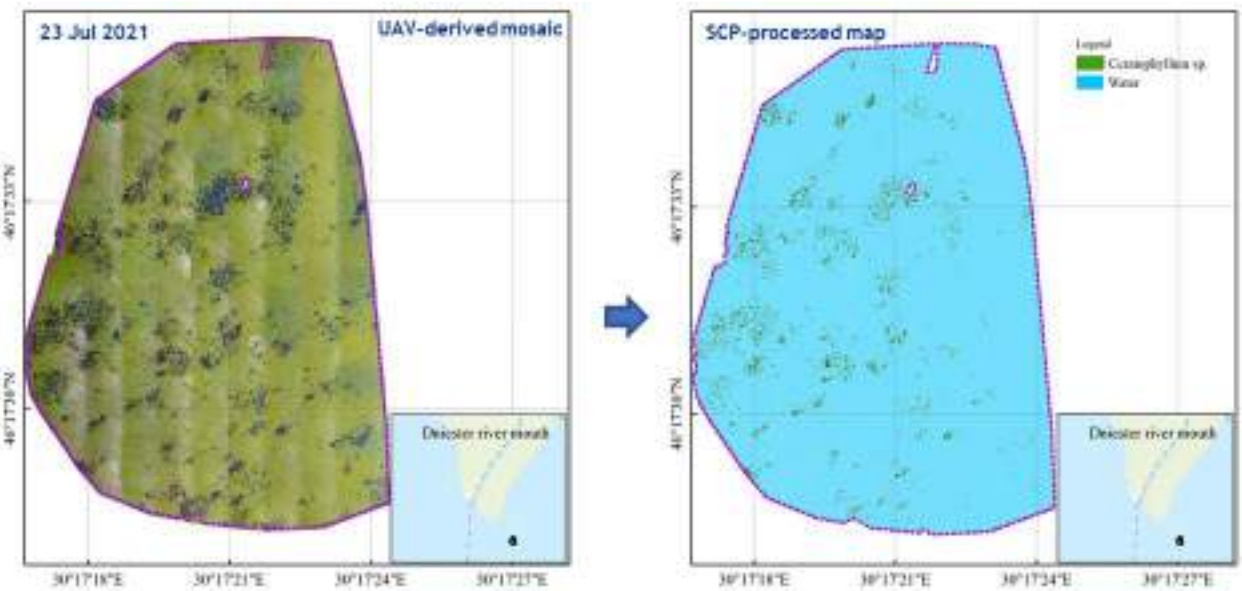

Figure 31: Floating aquatic species determination in the UAV-derived mosaic (July 23, 2021) processed with the SCP tool.

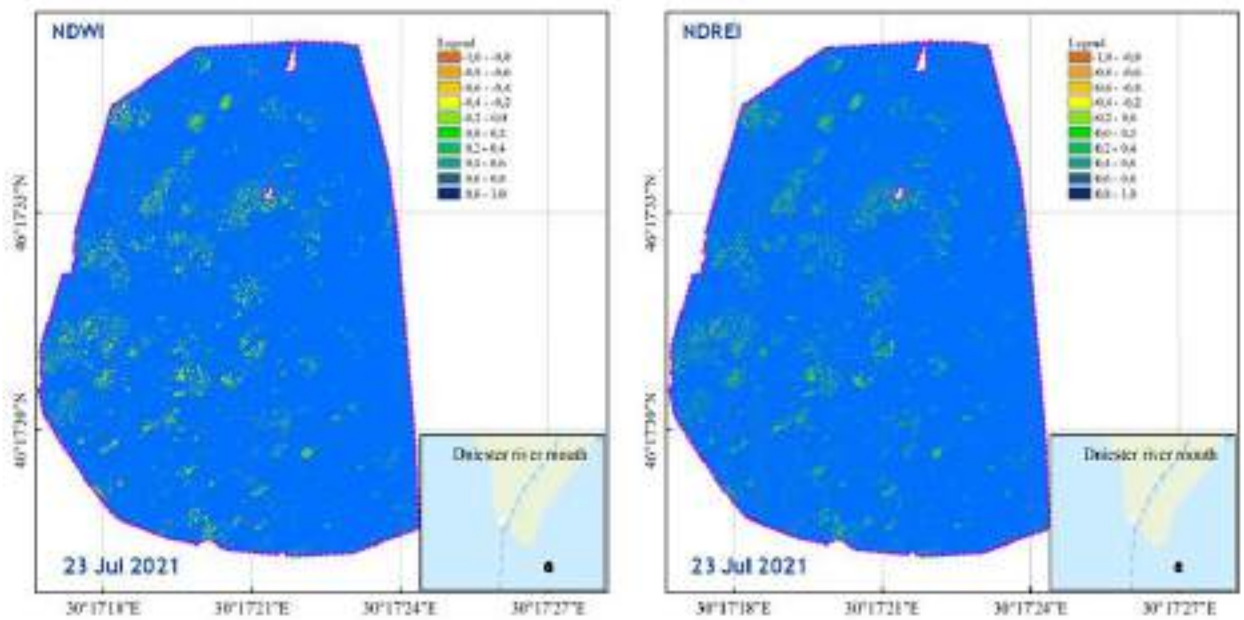

Figure 32: Floating aquatic species determination in the UAV-derived mosaic (July 23, 2021) by using NDWI and NDREI.

Bile lake

In the representative area of the Bile lake (North-west part) we identified the distribution of the dominant floating aquatic species *Nuphar lutea* interspersed with *Nymphaea alba* (Fig. 33). We found that *N. alba* was composed only 11.4% of the area covered with floating vegetation. Also, in the south-east part of the lake we identified the larges cluster of *Trapa natans* (Fig. 34). It was located around the channel going to the river and covered

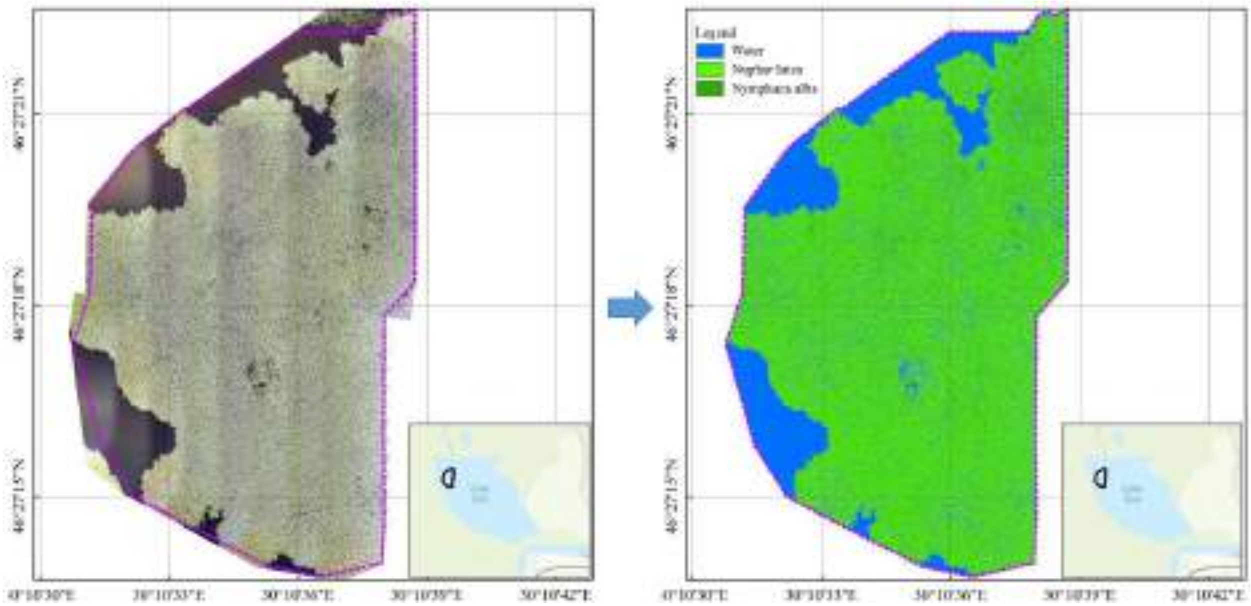

Figure 33: Floating aquatic species determination in the Bile lake site from the UAV-derived mosaic (July 26, 2021) processed with the SCP tool.

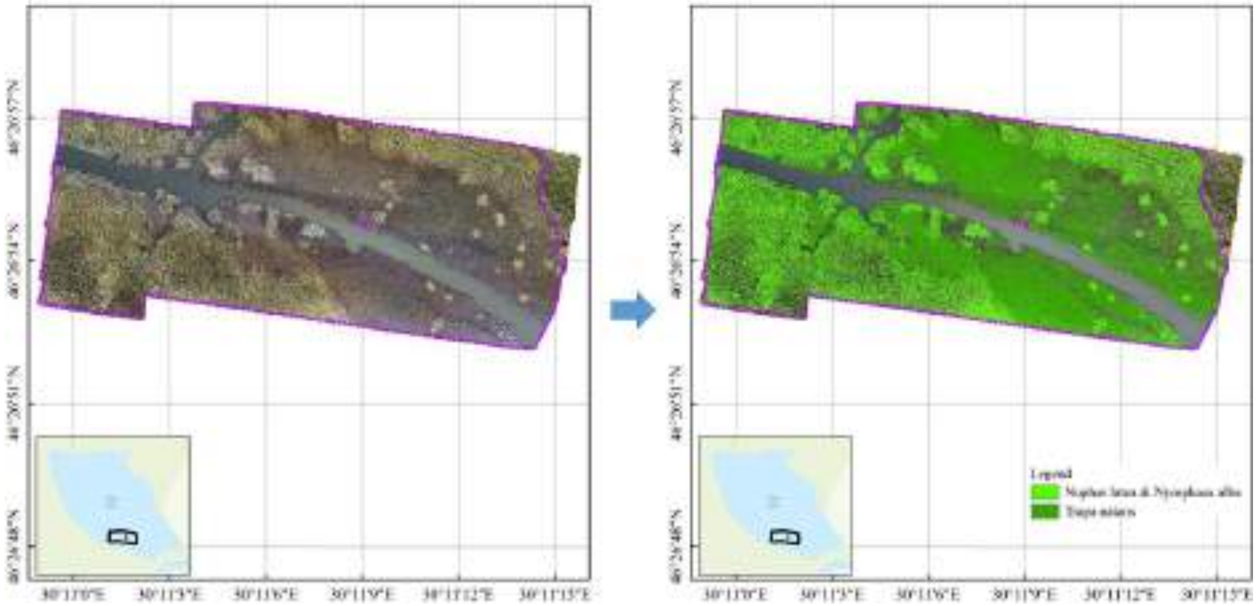

Figure 34: Floating aquatic species determination in the Bile lake site from the UAV-derived mosaic (September 9, 2021) processed with the SCP tool.

the area of 11 646 m^2. *T. natans* cover was quite homogenic surrounded mainly by *N. lutea* (interspersed by *N. alba*), which sometime formed well-marked foci in the water chest nut carpet.

Moreover, using the SCP tool we managed to distinguish submerged species *Ceratophyllum demersum* in the UAV mosaic (Fig. 35). By the beginning of September this species had well developed biomass within the lake water column and covered around 80% of the bottom.

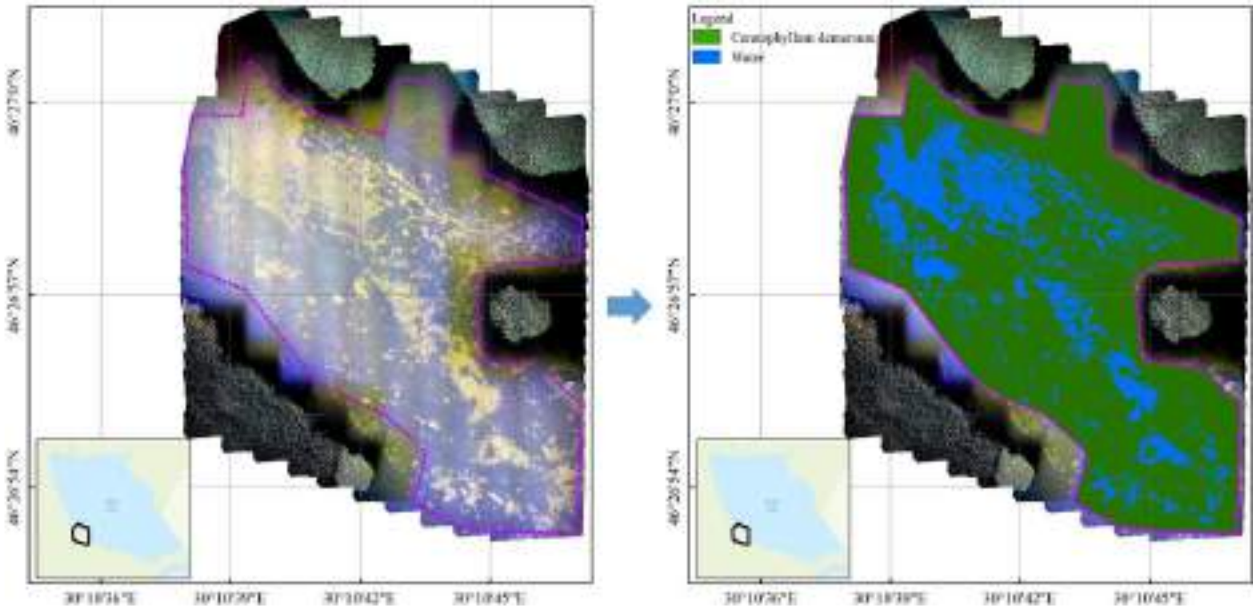

Figure 35: Floating aquatic species determination in the Bile lake site from the UAV-derived mosaic (September 9, 2021) processed with the SCP tool.

Using a RGB-photomosaic of the entire Bile lake with resolution of 5cm per pixel after coarsening to 50 cm under the routine processing, we scrupulously identified all basic vegetation species and retrieved first ever detailed vegetation map for this unique water body (Fig. 36). We quantified that *N. lutea*, being the dominant species, covered 56.0% of the lake area followed by *T. natans* (2.5%), *N. alba* (1.7%) and *C. demersum* (1.4%).

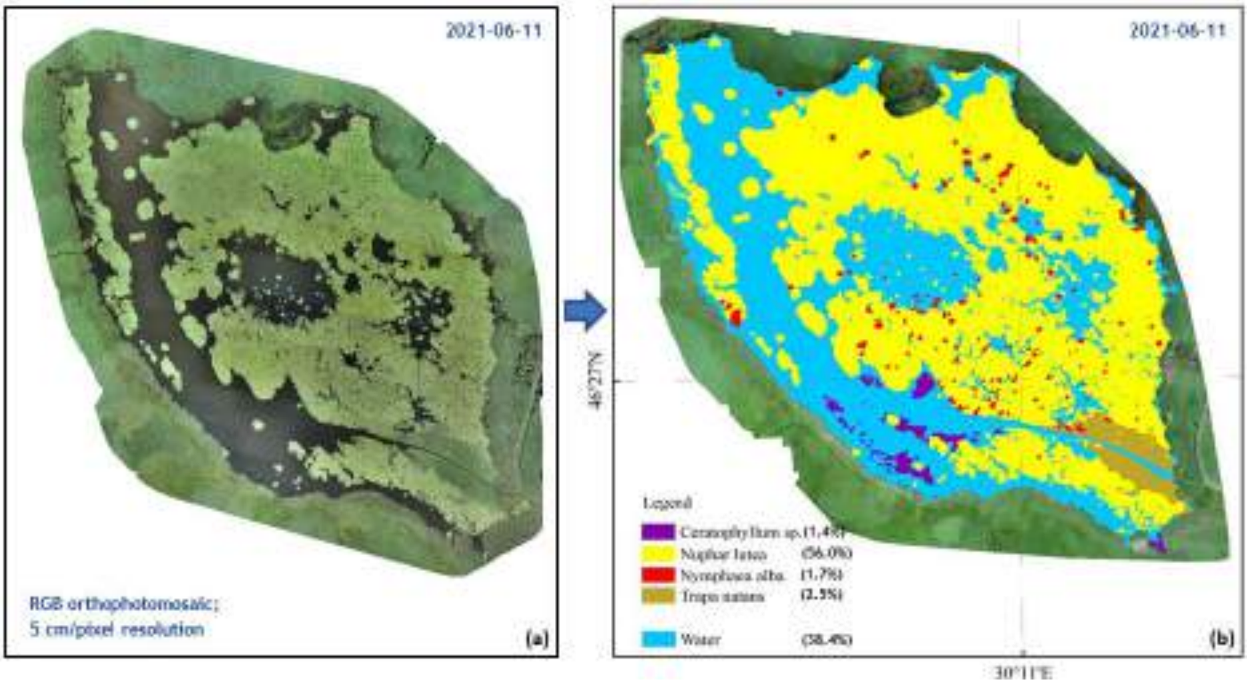

Figure 36: The UAV-derived RGB-ofthophotomosaic dated on June 11, 2021 (a) and the map of aquatic vegetation cover in the entire Bile lake (b).

Moreover, we managed to identify three types of land cover in UAV-derived RGB-orthphotomosaics of the entire lake after coarsening to 30 cm per pixel by using semi-automatic SCP tool classification plugin (Fig. 37).

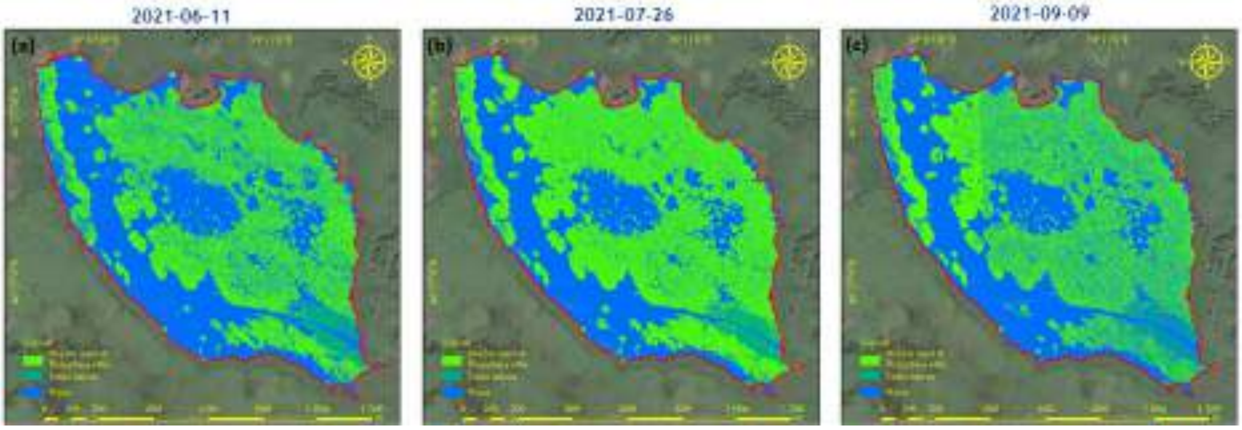

Figure 37: Maps of basic aquatic vegetation cover of the entire Bile lake in June (a), July (b) and September (c) 2021 based on UAV-derived RGB-orthophotomosaics processed with SCP.

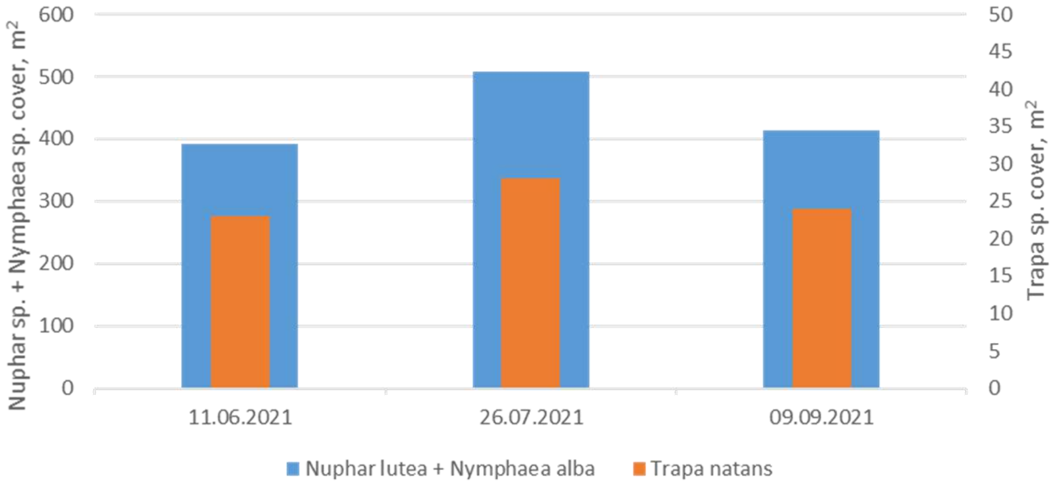

Figure 38: Comparison of the basic aquatic vegetation cover dynamics in the Bile lake over June – September 2021.

This significantly facilitated the processing of the RGB-mosaics and allowed us to quantify seasonal dynamics of prevailing types of floating vegetation *T. natans* and *N. lutea* interspersed with *N. alba*. We clearly showed that maximal cover of both types of floating vegetation was in late July then decreased by the early September (Fig. 38).

3.1.3. Biomass and nutrient content in aquatic vegetation

Samples of main aquatic vegetation species were collected in the Bile lake and the Dniester estuary in July, 2021. Wet and dry biomasses were quantified per sampled area (Table 1). We found that emergent species *Phragmites australis* and floating species *Trapa natans* had 1.8 and 1.3 times higher biomass in the Dniester estuary than those in the Bile lake. Whist *Nuphar lutea* produced 1.4-fold more leaf biomass in the lake ecosystem. Other species (*C. demersum, N. alba, T. angustifolia*) did not show any significance difference in biomass across study areas.

Table 1: Nutrient content in aquatic vegetation species of the Bile lake and Dniester estuary (samples were taken on July 26, 2021).

Species	Water body	N, mg N g^{-1} dry matter	P, mg P g^{-1} dry matter	K, mg K g^{-1} dry matter
Phragmites australis (Cav.) Trin. Ex Steud	Bile lake	1.81±0.05	0.072±0.001	1.01±0.07
	Dniester estuary	1.85±0.09	0.073±0.002	0.92±0.05
Typha angustifolia L.	Bile lake	2.12±0.11	0.082±0.002	0.91±0.07
	Dniester estuary	1.87±0.07	0.078±0.002	0.92±0.09
Nuphar lutea (L.) Smith	Bile lake	2.62±0.13	0.070±0.002	1.42±0.12
	Dniester estuary	2.18±0.15	0.069±0.002	1.62±0.10
Nymphaea alba L.	Bile lake	2.41±0.09	0.066±0.001	1.43±0.13
	Dniester estuary	2.13±0.12	0.067±0.001	1.33±0.09
Trapa natans L.	Bile lake	2.77±0.11	0.076±0.003	1.30±0.17
	Dniester estuary	2.24±0.15	0.078±0.003	1.61±0.13
Ceratophyllum demersum L.	Bile lake	3.17±0.12	0.075±0.003	1.61±0.15
	Dniester estuary	2.95±0.07	0.080±0.003	2.00±0.17

Regarding nutrient contents, the concentrations of nitrogen (N) and potassium (K) in the corresponding species varied more pronouncedly between two study areas than that of phosphorus (P). We reported that all plants sampled in the Bile lake accumulated in their tissues higher N (1.10-1.24-fold) except *P. australis*, where N content was stable across the whole deltaic area (Fig. 39-41). At the same time estuarine *T. natans* and *C. demersum* removed 1.24-fold more K that he plants growing in the lake.

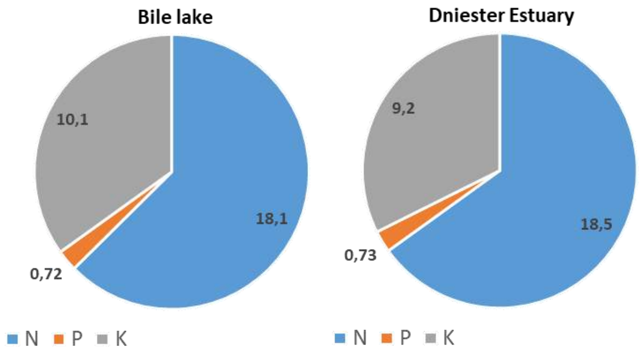

Figure 39: Nutrient content (mg L^{-1}) in the emergent vegetation *Phragmitis australis* sampled in the Bilke lake and Dniester estuary in July, 2021 [N: nitrogen; P: phosphorus, K: potassium].

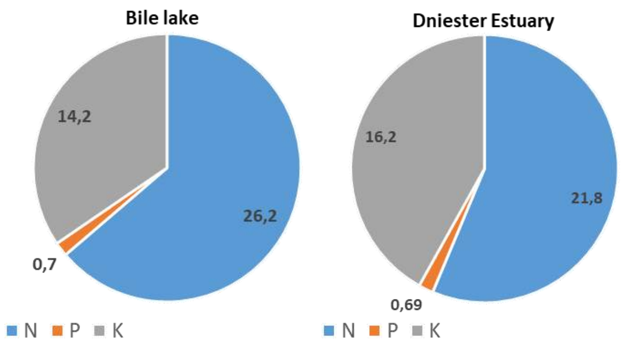

Figure 40: Nutrient content (mg L^{-1}) in the floating vegetation *Nuphar lutea* sampled in the Bilke lake and Dniester estuary in July, 2021 [N: nitrogen; P: phosphorus, K: potassium].

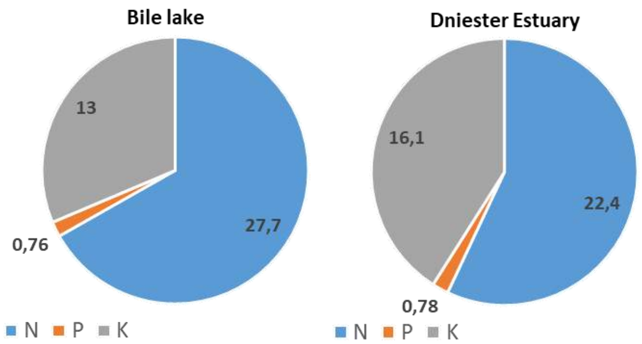

Figure 41: Nutrient content (mg L^{-1}) in the floating vegetation *Trapa natans* sampled in the Bilke lake and Dniester estuary in July, 2021 [N: nitrogen; P: phosphorus, K: potassium].

3.2. Space-born data

Within the PONTOS project we used two types of satellite images: free-access high resolution ones derived from Sentinel and Landsat missions covering the period of 2009-2021 as well as very high resolution (VHR) ones purchased in Maxar Technologies covering selected areas at certain dates.

3.2.1. Aquatic vegetation determination with very high resolution satellite images

The VHR multispectral images have been purchased within the project to estimate the accuracy of different aquatic species determination in two sub-areas. Two images from the WorldView-2 satellite covering the Bile lake area and dated by July 17, 2016 and July 31, 2021 were processed. For the Bile lake, we managed to identify floating species of *T. natans, N. alba* and *N. lutea* in July 2016 and 2021 by using the SCP tool (Fig. 42a, b). We found that T. natans cover was 1.6-fold larger in 2021 (33468 m^2) compared to that in 2016 (21029 m^2), while the area covered by *N. lutea* and *N. alba* decreased by 5% due to formation of open water area in the middle of the lake (see Fig. 42b).
Despite the areas with submerged vegetation might be visually distinguish in both true-color VHR images, the SCP plug-in was able to partially detect *C. demersum* in July 2016 only (Fig. 42).

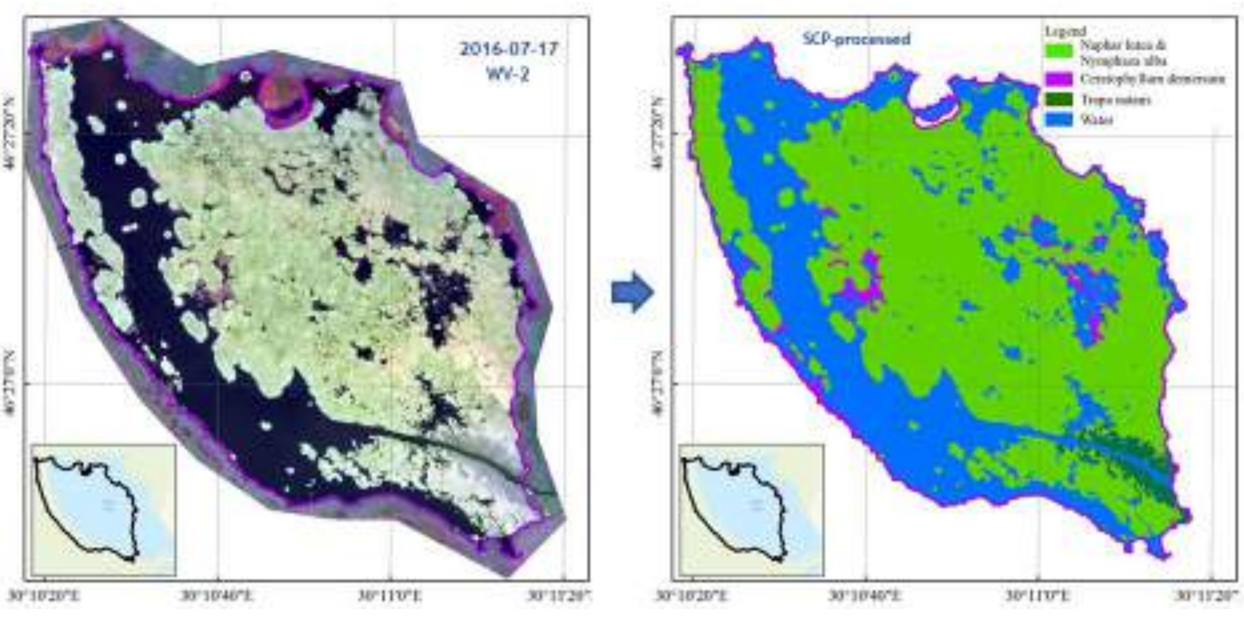

Figure 42a: Floating and submerged aquatic species determination in the Bile lake site from the VHR image derived from WorldView-2 satellite (July 17, 2016) and processed with the SCP tool.

For the Dniester estuary, specifically the sub-area of floating vegetation polygon in the vicinity of the Dniester river mouth, we managed to classify and identify the emergent

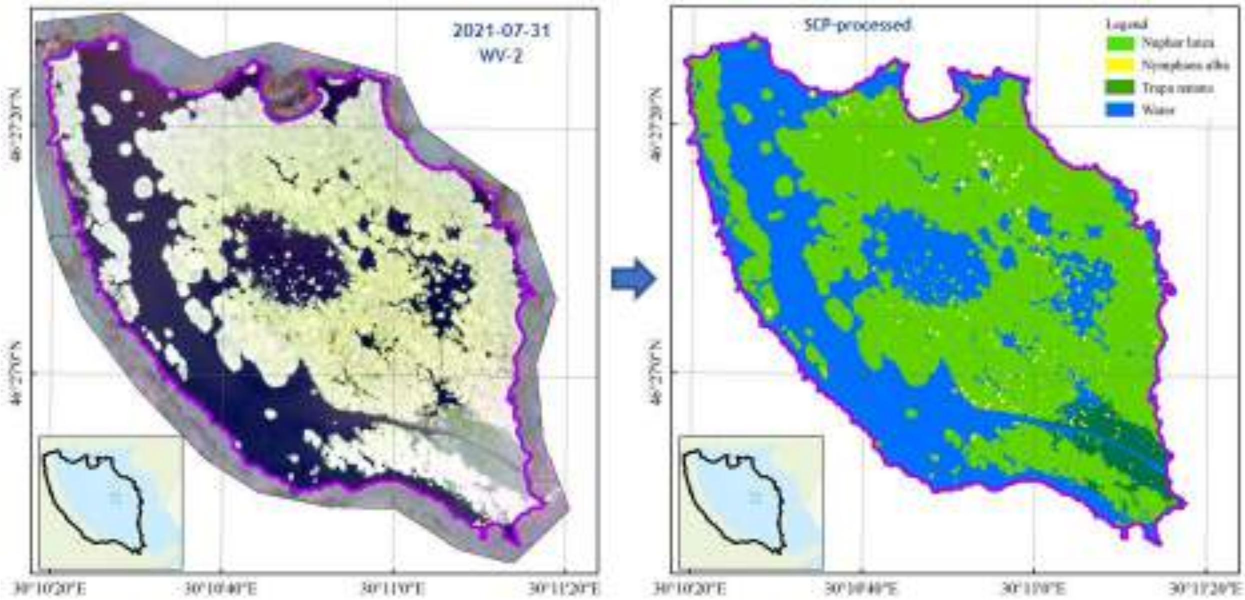

Figure 42b: Floating and submerged aquatic species determination in the Bile lake site from the VHR image derived from WorldView-2 satellite (July 17, 2016) and processed with the SCP tool.

vegetation (*Ph. communis*) and floating vegetation species (*T. natans* and *N. lutea*) (Fig. 40). We found that the ratio of Trapa to Nuphar was 2.9. However, so far we failed to classify submerged plants by using SCP in this particular image, despite it might be seen in a true-color image (Fig. 43).

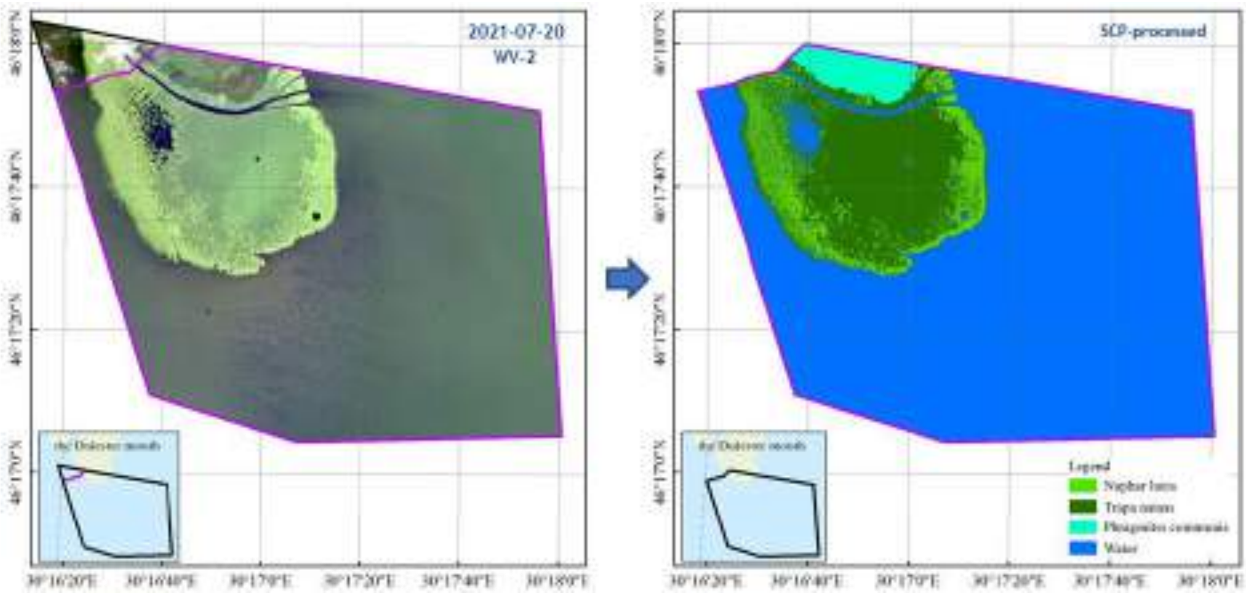

Figure 43: Emergent and floating vegetation species determination in the Dniester estuary (near the Dniester river mouth) from the VHR image derived from WorldView-2 satellite (July 20, 2021) and processed with the SCP tool.

3.2.2. Aquatic vegetation determination with free-access satellite images

In the framework of the PONTOS we downloaded all available images for the targeted pilot area. We were mainly focused on available 'good-quality' July/ August images (the times when vegetation in its mature stage) covering 2009-2020 derived from LandSat-5 (2009-2011), LandSat-8 (2013-2016) and Sentinel-2 (2017-2020) missions (Fig. 44-47). Images were processed with the unsupervised clustering method, which was developed by Centre of Research and Technology Hellas (CERTH) within the PONTOS project to estimate i) open water ii) emergent vegetation cover and iii) floating vegetation cover. In-situ data were used for validation and further tuning/ adjustment of the CERTH-developed.

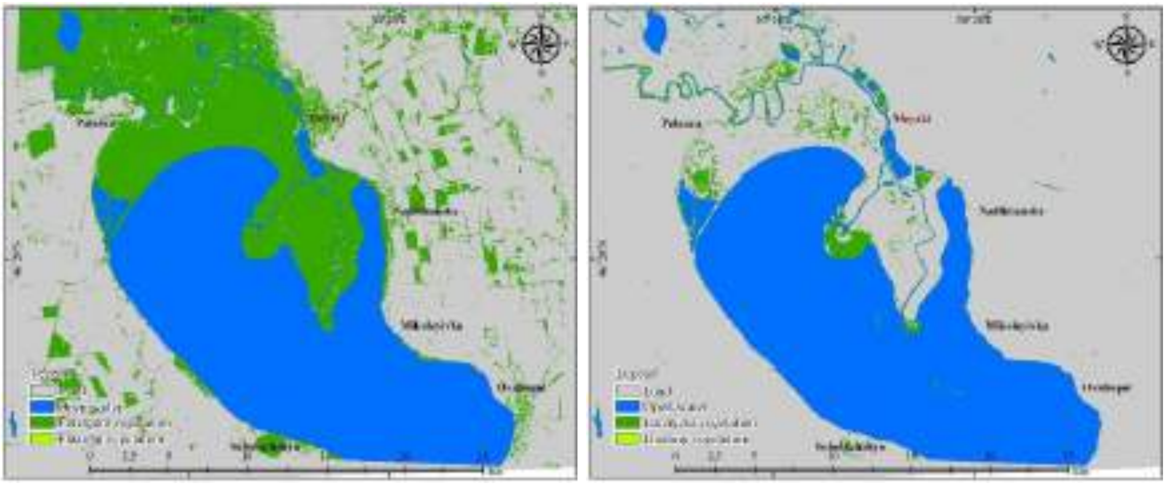

Figure 44: Emergent and floating aquatic species determination in the Ukrainian pilot from the high resolution images of LandSat-5 satellite (August 4, 2009 – left; August 7, 2010 - right) processed with the CERTH-developed approach.

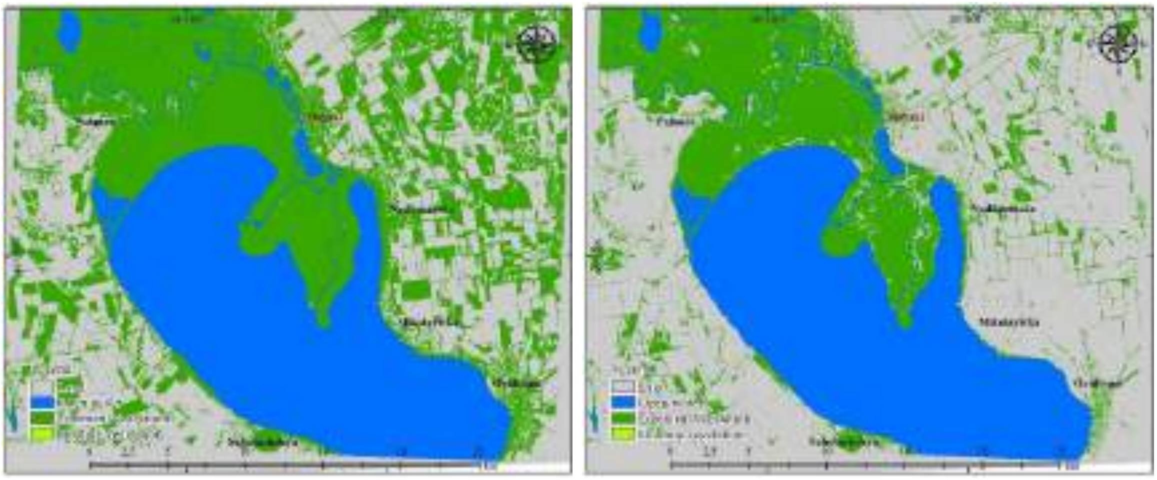

Figure 45: Emergent and floating aquatic species determination in the Ukrainian pilot from the high resolution images of LandSat-5 (July 9, 2011 – left) and LandSat-8 satellites (August 15, 2013 - right) processed with the CERTH-developed approach.

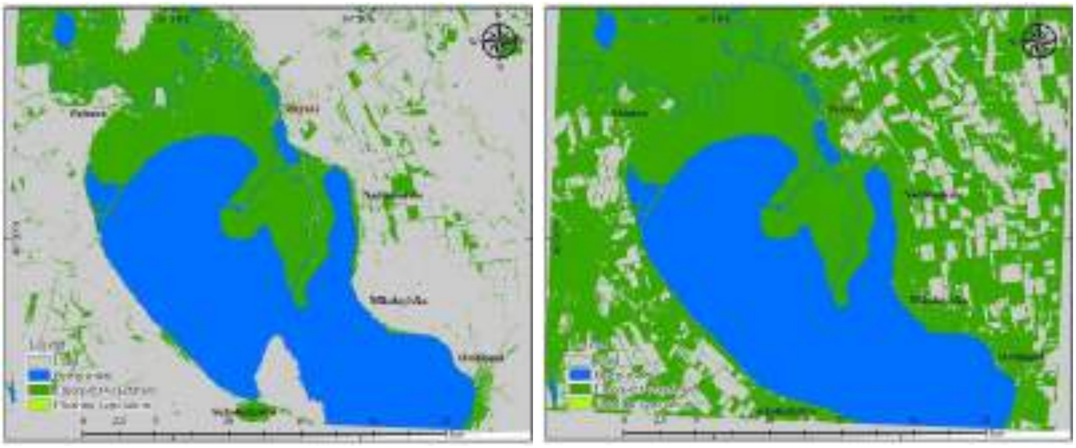

Figure 46: Emergent and floating aquatic species determination in the Ukrainian pilot from the high resolution images of LandSat-8 satellite (August 2, 2014 – left; July 20, 2015 - right) processed with the CERTH-developed approach.

Figure 47: Emergent and floating aquatic species determination in the Ukrainian pilot from the high resolution images of LandSat-8 (August 22, 2016 – left) and Sentinel-2 satellites (July 22, 2017 - right) processed with the CERTH-developed approach.

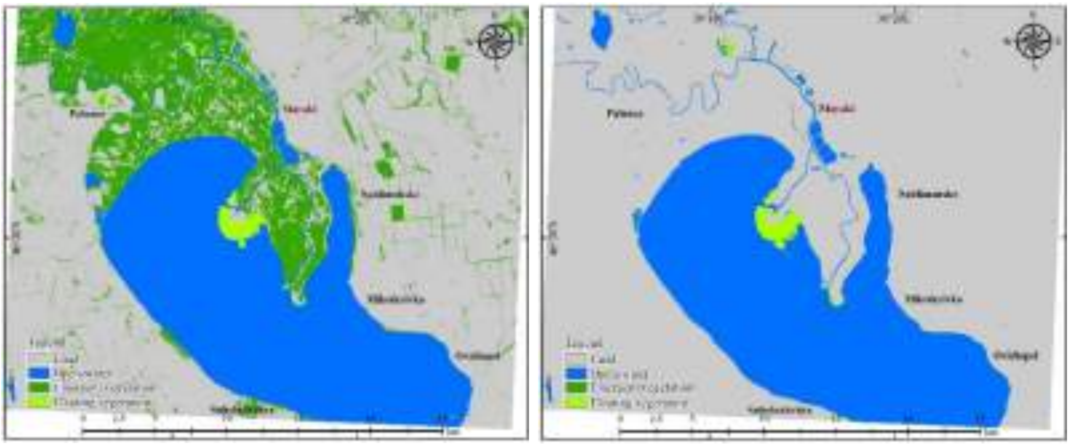

Figure 48: Emergent and floating aquatic species determination in the Ukrainian pilot from the high resolution images of Sentinel-2 satellite (August 11, 2018 – left; July 2, 2019 - right) processed with the CERTH-developed approach.

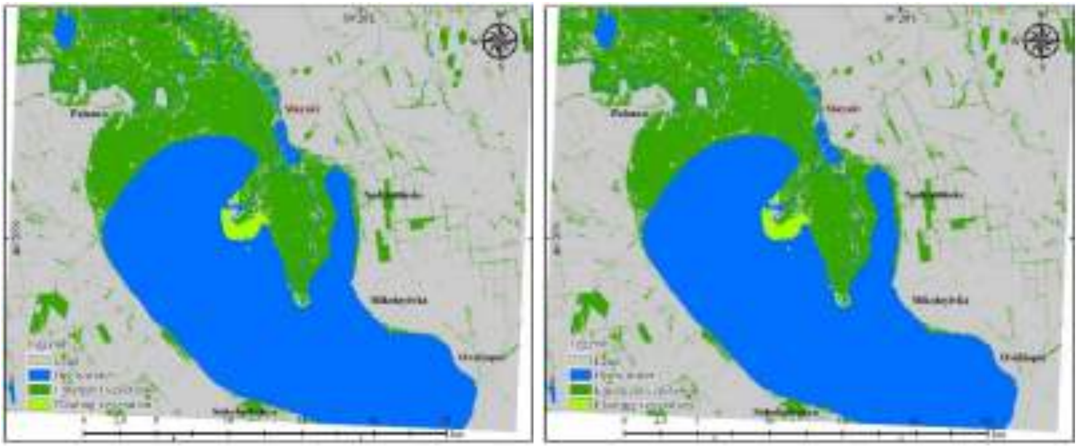

Figure 49: Emergent and floating aquatic species determination in the Ukrainian pilot from the high resolution images of Sentinel-2 satellite (August 5, 2020 – left; August 5, 2021 - right) processed with the CERTH-developed approach.

We have found that due to spectral characteristics threshold values representing open water, land, emergent and floating vegetation varied and to use ‘standard’ threshold can hardly be possible. Also, due to overlapping spectral characteristic of wet leaves & water and dry leaves & land and emergent & floating vegetation, the algorithm might misrecognize the real ‘land-cover’. For the LandSat-5 images of 2009 (Fig. 44) and 2011 (Fig. 45) we found that both aquatic vegetation types as well as land vegetation were marked as emergent vegetation, *i.e.* we could not distinguish floating vegetation out. In 2010 (Fig. 44) we define most of floating vegetation in Dniester mouth areas, but it was marked as emergent one, while ‘real’ emergent vegetation had similar characteristics to the land and could not be identified properly; therefore, more scrupulous tuning is needed to process such type of images. In all LandSat-8-derived images (Fig. 45-48) the floating vegetation was not being able to distinguish from emergent aquatic one; also terrestrial vegetation on non-harvested agricultural fields was misidentified as emergent. Similar was observed after processing the Sentinel-2 image of 2017 (Fig. 47). However, since 2018 the CERTH approach was able to distinguish the floating vegetation cover in Sentinel-2 images, although not in a full extend (perhaps due to sensitivity to the vegetation stage; drier plants were not recognized). The detection of emergent aquatic vegetation was likely also quite sensitive to a plant development stage (senescent vegetation was not detected). In August 2018 (Fig. 48), 2020 and 2021 (Fig. 49), floating vegetation was partially identified near ‘Deep Turunchuk’ mouth (upper river mouth), while only thin area of floating plants was defined in the vicinity of ‘Dniester’ mouth (lower river mouth). However, if in 2018 the rest of ‘real’ floating vegetation was misidentified as land, then in 2020 it was referred to emergent vegetation; we suppose that it depends on dry and/or senescent status of floating vegetation.
At the same time, in 2019 the CERTH-method could not define any emergent vegetation in the pilot, most probably because of prolong drought period resulted in water level decrease (Fig. 48).

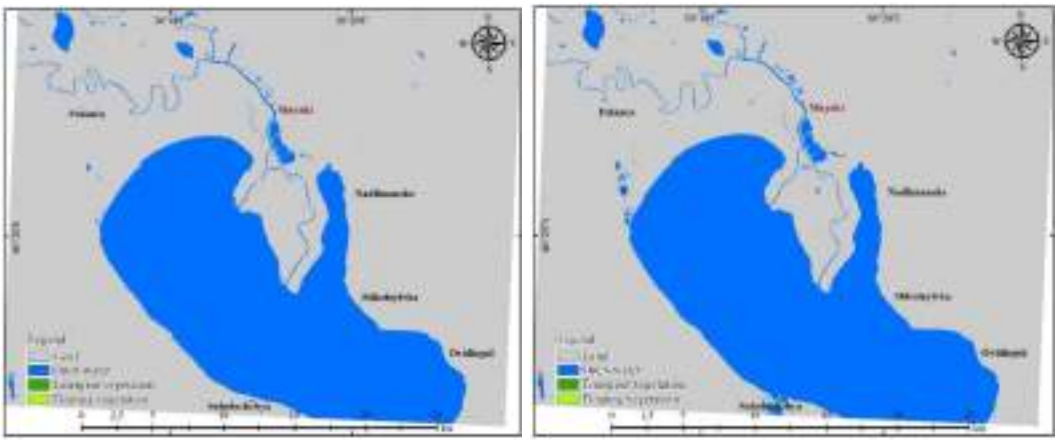

Figure 50: Emergent and floating aquatic species determination in the Ukrainian pilot from the high resolution images of Sentinel-2 satellite (January 2, 2021 – left; February 26, 2021 - right) processed with the CERTH-developed approach.

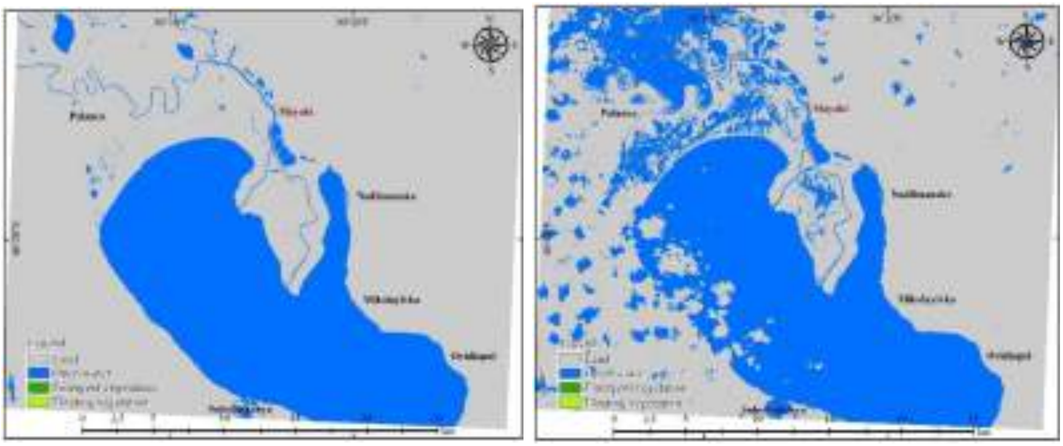

Figure 51: Emergent and floating aquatic species determination in the Ukrainian pilot from the high resolution images of Sentinel-2 satellite (March 8, 2021 – left; April 22, 2021 - right) processed with the CERTH-developed approach.

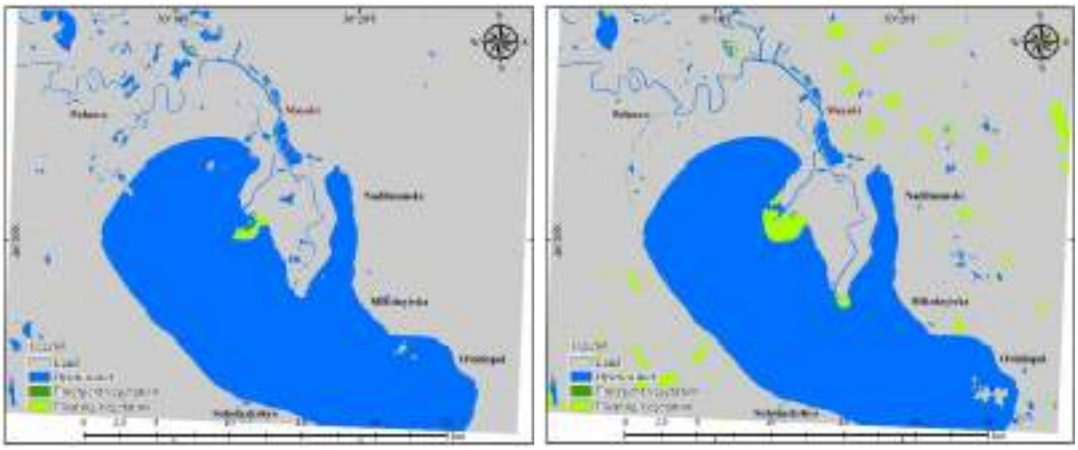

Figure 52: Emergent and floating aquatic species determination in the Ukrainian pilot from the high resolution images of Sentinel-2 satellite (May 22, 2021 – left; June 26, 2021 - right) processed with the CERTH-developed approach.

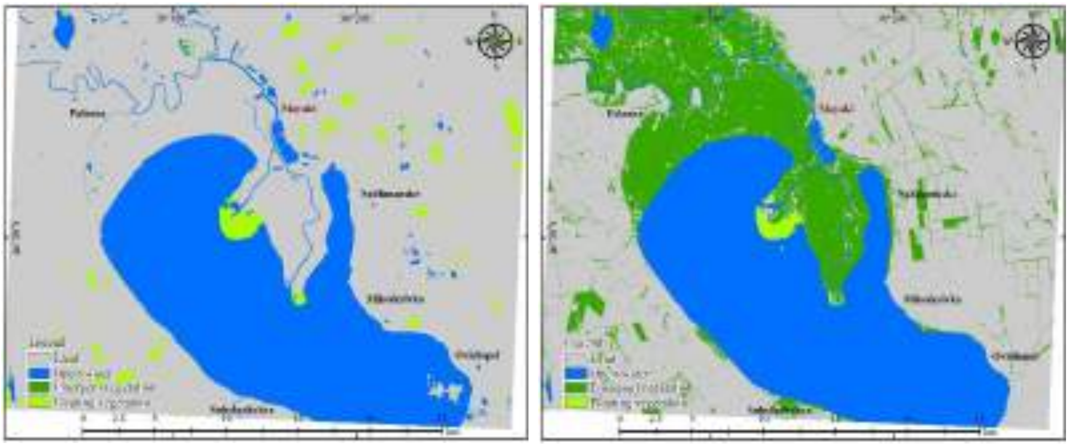

Figure 53: Emergent and floating aquatic species determination in the Ukrainian pilot from the high resolution images of Sentinel-2 satellite (July 26, 2021 – left; August 5, 2021 - right) processed with the CERTH-developed approach.

Figure 54: Emergent and floating aquatic species determination in the Ukrainian pilot from the high resolution images of Sentinel-2 satellite (September 9, 2021 – left; October 29, 2021 - right) processed with the CERTH-developed approach.

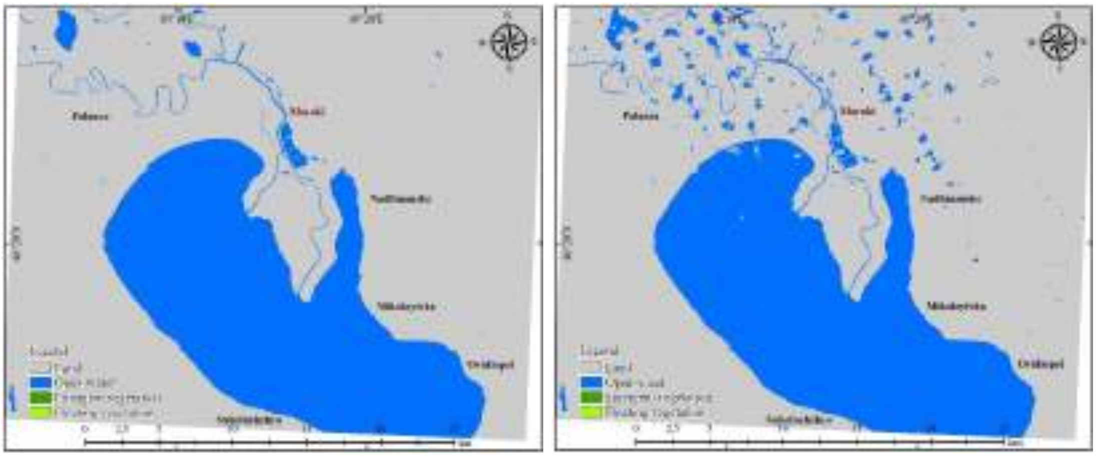

Figure 55: Emergent and floating aquatic species determination in the Ukrainian pilot from the high resolution images of Sentinel-2 satellite (November 3, 2021 – left; December 23, 2021 - right) processed with the CERTH-developed approach.

For the year of 2021 we processed Sentinel-2 images in a monthly manner to study seasonal dynamics. The images obtained over January-March clearly showed no fresh green vegetation cover in the pilot (Fig. 50, 51). The April image was not good enough and had multiple artefacts (land/ open water misdetected) after processing due to cloudiness and could not be used for further analysis without cleaning at a pre-processing stage (Fig. 51). In images from May and June 'fresh' floating vegetation was quite accurately identified within the estuarine and lake areas (Fig. 52). However, in June 2021 some agricultural fields had similar spectral characteristics and were misidentified as floating vegetation. Light cloudiness also impacted the land cover determination; this needs to be taken into account and cleaned at a pre-processing stage. Later on, in July surroundings of floating vegetation polygons were identified as 'floating vegetation cover' most probably because they consist of 'fresher' green plants compared to the core areas of those polygons and/or other reasons impacting spectral characteristics of this image (Fig. 53). Processed images from August and September showed quite well reproduction of both emergent and floating vegetation cover, although 'inner' parts of floating vegetation polygons were misinterpreted as emergent vegetation (Fig. 53, 54). In September the gradual disappearance of floating vegetation polygons near mouths of the 'Deep Turunchuk' (western one) and 'Dniester' (eastern one) tributaries was shown. From October to December, the CERTH-method identified no 'green' vegetation covers neither floating nor emergent in the Ukrainian pilot.
In the current version of the CERTH-method, the boundaries of open water in the estuary and river were rather accurately defined with the coefficient of variation of 1.85%. This data is ready to use for assessing annual and seasonal water area dynamics. To use other data, such as emergent and floating vegetation further tuning of the method is required.

4. DISCUSSION

4.1. Aquatic vegetation determination

Within this assessment we have collected and then tested various datasets obtained by using different methods with different spatial (and temporal) resolution. We found that historical in-situ data on emergent and floating vegetation collected by the Regional Centre for Integrated Environmental Monitoring of the Odesa National I.I. Mechnikov University using a boat with GPS-tracker within annual summer campaigns (during July/August) over the Dniester Delta area represented a valuable continuous dataset, specifically for the inter-annual emergent plant cover dynamics. It showed that areas covered by emergent vegetation, mainly presented by *Phragmitis australis* were quite stable (88.8 km^2) in the Dniester estuary over the last 20 years (annual fluctuation did not exceed 1.0%; Fig. 18). Whilst small water bodies (like lakes) in the deltaic area were likely more vulnerable to emergent vegetation overgrowth. *E.g.* we observed a pronounced reduction (by 16%) of the Bile lake area from 1984 onwards (Fig. 28).

We reported on the intensification of this process from 2005 to 2010 and then from 2012 to 2021, which appeared to be related to weak/ no flushing of the wetland areas (surrounding the lake) at a low water (dry) years caused by redistribution of rainfall pattern from spring – early summer to late summer – early autumn and aggravated by hydro power structures and their operation procedure (impacting water flow by filling reservoirs and decreasing ecological water release from those reservoirs to downstream areas). Meanwhile, due to the technical limitations of this in-situ method (using boat surveys) those data could be used as indicative to roughly outline areas (to be more precisely boundaries of areas) of floating vegetation in the Dniester estuary. To fill this gap and estimate the affordability, the different types of remote sensing data were retrieved and tested within this assessment. We found that very high resolution orthophotomosaics (3-5 cm $pixel^{-1}$) derived from the UAV mapping may provide a plenty of detailed information on aquatic vegetation. However, the quality of initial aerial images was highly depended on weather conditions and brightness upon mapping campaign (see section 3.1.2; Fig. 29). Therefore, intellectual (semi-)automatic processing, *e.g.* using Semiautomatic Classification Plugin (SCP), was shown to be very sensitive to derived orthophotomosaic quality as well as impacted on credibility of the final results. Also, in case of intention to compare the UAV-derived data with satellite images or use them for validation of space-born images, the cloudiness condition might be another critical limitation, *e.g.* we faced over May 2021, when we were not able to meet appropriate conditions for mapping. However, we confirmed that both RGB and multispectral UAV orthophotomosaics potentially might be used to identify different types and species of aquatic vegetation using SCP. We stated that for small water objects as the deltaic lakes (≤1.5 km^2) it is feasible to carry out a detailed mapping with further accurate determination of aquatic vegetation species. *E.g.* within this assessment we obtained the first ever detailed vegetation map of the Bile lake based on the RGB orthophotomosaic (Fig. 36), which has been shared with the Lower Dniester National Nature Park authority and will be used as a basic map for further monitoring of this unique lake. Furthermore, we demonstrated seasonal dynamics in changes of *T. natans* and *N. lutea* interspersed with *N. alba* stating that maximal cover of both types of floating vegetation was observed in late July (and perhaps remains high until the first decade/ middle of August) then decreased by the early September (Fig. 38).

Based on those SCP-processed maps we carried out detailed in order to identify the changes of average density cover of main types of floating vegetation in trial plots over June-September (Fig. 56).

We observed an intensive growth in the interface between *N. lutea* and *T. natans* since 11th of June, followed by a substantial increase of *N. lutea* and a slight decrease of *T. natans* cover in 26th of July most probably due to some Trapa plants were shaded/ covered by large leaves of Nuphar. Then in the early September a cover decrease of both

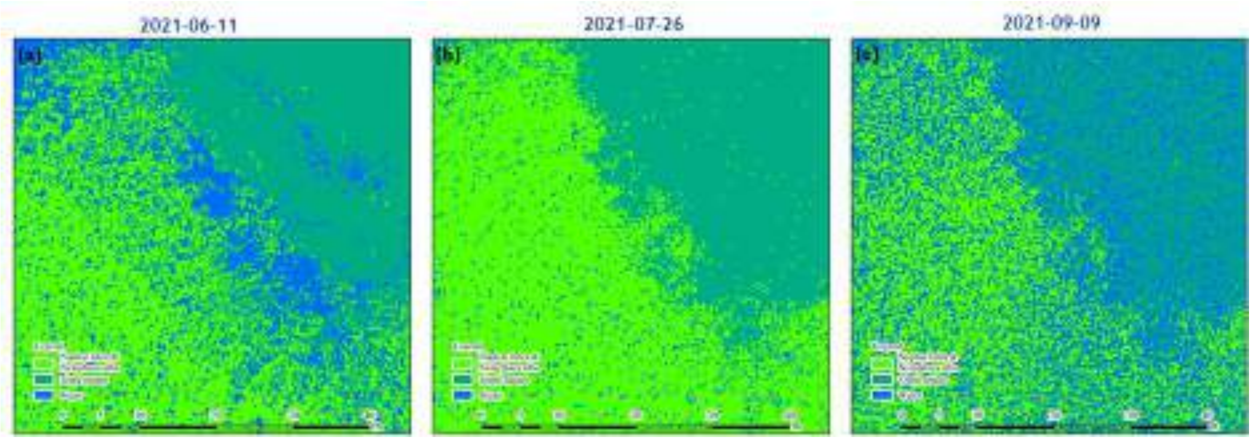

Figure 56: Floating vegetation cover map of trial plots (51.4m x 51.4m) within the Bile lake in June (a), July (b) and September (c) 2021 based on UAV-derived RGB-orthophotomosaics processed with SCP.

vegetation types was registered likely owing to senescence stage, however due to a larger vegetation period water chestnut cover prevailed (Fig. 56, 57). This clearly showed that when both yellow water lilly (*N. lutea*) and water chestnut (*T. natans*) are presented, Trapa can be shaded/ not easily detected with remote sensing techniques and its real biomass might be larger than estimated.

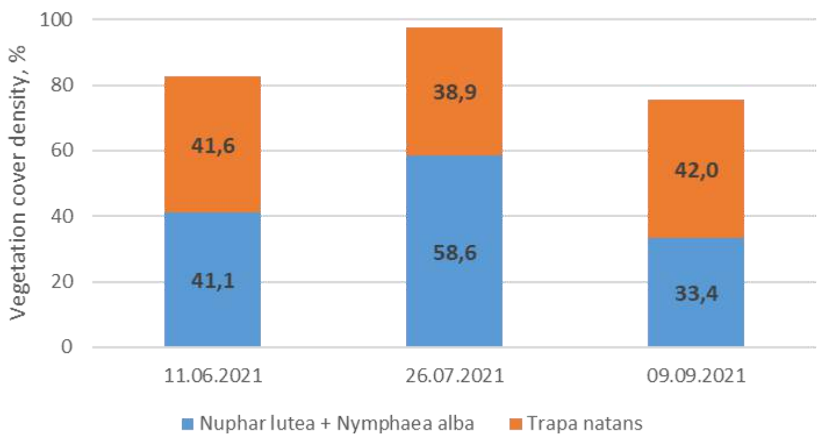

Figure 57: Floating vegetation cover (%) in trial plots (51.4m x 51.4m) of the Bile lake in June, July and September 2021.

After processing three VHR images (from the WorldView-2 satellite) purchased within the PONTOS, we may confirm that these commercial products were responded quite well to land cover classification with SCP tool (Fig. 42a,b, 43), although conceded in determination of less presented floating species and submerged vegetation. We found that it is likely that floating vegetation was slightly overestimated in the VHR images (Fig. 42b) compared to the UAV-mosaics (Fig. 37) perhaps due to lesser threshold of detection of water interspaces between floating plants (Table 2).

Table 2: Comparison of UAV and VHR images for aquatic plants determination in the Bile lake (July 2021).

Land cover/ species	UAV (RGB) 2021-07-26 [SCP]	VHR (multispectral) 2021-07-31 [SCP]
Nuphar lutea	53.6%	59.5%
Nymphaea alba		
Trapa natans	3.0%	3.5%
Ceratophyllum demersum	-	-
Open water	43.4%	37.0%

Data retrieved from the VHR image processing for the Dniester estuary plot (a sub-area of floating vegetation polygon in the vicinity of the Dniester river mouth) gave us valuable information on the cover ratio of the dominant floating plants (*T. natans* and *N. lutea),* which might be further use to quantify nutrient content in floating vegetation polygons (Fig. 43).
Overall, taking into account the cost of VHR images we suppose that their use is reasonable for study areas with middle-to-large size only, meanwhile for the relatively small areas (≤1.5 km^2) the use of UAV-mosaics seems to be more feasible in terms of both cost-effectiveness and detalisation.

Within PONTOS project we were ambitiously aimed to make basic steps in development of an approach, which may enable us to determine emergent and floating vegetation types from free-access high resolution images from Sentinel-2 and LandSat satellites. For this specific purpose the unsupervised clustering method was developed by Centre of Research and Technology Hellas (CERTH) to be applied for Sentinel-2 level-2A products as well as initially tested on LandSat images and was further tuned by using in-situ historical and retrieved-within-project data. We found that as a first approximation the CERTH-developed method might work quite well with Sentinel-2 images to determine both emergent and floating vegetation, however under limited 'ideal' conditions, *i.e.* when the threshold for all land cover categories were very accurately adjusted and cloud correction was applied (*e.g.* Fig. 53, 54). Also, we stated that due to spectral characteristics threshold values representing open water, land, emergent and floating vegetation varied and to use 'standard' threshold can hardly be possible. Also, due to overlapping spectral characteristic of wet leaves & water and dry leaves & land and emergent & floating vegetation, the algorithm might misrecognize the real 'land-cover'. In addition, the detection of emergent aquatic vegetation was likely also quite sensitive to a plant development stage (senescent vegetation was often not detected). Nevertheless, we assume that within the PONTOS we did make the first step towards the development of a robust approach for different aquatic types determination using (semi-)automatic algorithm, which we believe will be substantially improved within the next projects and will enable to identify not only emergent and floating, but also submerged vegetation in deltaic areas.

4.2. Vegetation cover and biomass

On the one hand excess nutrient loads of anthropogenic origin to the Dnister basin (Medinets *et al.*, 2015, 2016, 2017, 2020) lead to a significant increase of eutrophication in the lakes, deltaic areas and estuaries (Dereziuk, 2019; Kovalova *et al.*, 2018a,b, 2019) as well as are subjected to the overgrowth of aquatic vegetation. On the other hand aquatic plants are the valuable pool of the source of nutrient, which might be used in agricultural and energy sectors (OECD, 2017). Therefore, based on the results obtained within this assessment we quantitatively estimated a capacity to store nitrogen (N), phosphorus (P) and potassium (K) in different species of aquatic vegetation in the Dniester estuary and the Bile lake areas (Table 3).

Table 3: Nutrient content (kg per ha^{-1}) in different aquatic plant species per covered area in the Dniester estuary and the Bile lake (sampled in July 2021)

Species	Water body	N content, kg N ha^{-1} dry matter	P content, kg P ha^{-1} dry matter	K content, kg K ha^{-1} dry matter
Phragmites australis (Cav.) Trin. Ex Steud	Bile lake	272	10,8	152
	Dniester estuary	2042	80,6	1016
Typha angustifolia L.	Bile lake	314	12,1	135
	Dniester estuary	277	11,5	136
Nuphar lutea (L.) Smith	Bile lake	76	2,0	41
	Dniester estuary	63	2,0	47
Nymphaea alba L.	Bile lake	81	2,2	48
	Dniester estuary	71	2,2	44
Trapa natans L.	Bile lake	69	1,9	32
	Dniester estuary	72	2,5	52
Ceratophyllum demersum L.	Bile lake	92	2,2	47
	Dniester estuary	96	2,6	65

We showed that *P. australis* growing in the wetlands of the Dniester estuary represented a huge source of N (2042 kg N ha^{-1}) and K (1016 kg K ha^{-1}), approx. 7.5-fold higher than that surrounded the Bile lake. Despite, *T. angustifolia* had a rather high content of nutrients in its tissues, it is not considered as a valuable resource due to its limited coverage in study area. Meanwhile floating and submerged vegetation accumulated nutrients in comparable amounts in ranges of 63-96 kg N ha^{-1}, 41-65 kg P ha^{-1} and 2.0-2.6 kg K ha^{-1} (Table 3).

We quantified that above water part of **floating vegetation** of the small **Bile lake** (area of 0.94 km^2) accumulated in their tissues ca. **4.05 tons N, 2.2 tons K** and **0.11 tons P** from the water ecosystem in July 2021. At the same the aquatic vegetation of **the Dniester estuary** (studied sectors area of 256.4 km^2; Fig. 16b) was able to eliminate up to **18.2 thousand tons N, 9.0 thousand tons K** and **0.7 thousand tons P with emergent plants** and approx. **49.7 tons N, 36.0 tons K** and **1.7 tons P with floating vegetation** from the water-sediment continuum as estimated for July 2021. At the absence of smart sustainable management practice those in-plant accumulated nutrients during the summer time are re-deposited to the aquatic system in autumn causing negative impacts on ecosystem in the next spring instead of being used as nutrient-reach agents, *e.g.* in agriculture.

4.3. Impact on and applicability for local stakeholders

During the PONTOS project lifetime, in parallel with assessment conducting the active routine work with stakeholders was going on (totally, 11 target groups of stakeholders representing by 60 entities have been reached). ONU actively cooperated with stakeholders, regularly informed them about achievements, developments and gained experience, and identified their requirements, wishes and needs during a series of events organized within the PONTOS project.

We have familiarized the practitioners from regional and local authorities, state agencies and national parks as well as young scientists from universities and research organizations with the basics of the Environmental Observations, explained from case to case when and how low, high and very high resolution images might be used and why in-situ measurements are of necessity at the beginning of study of the targeted area and in some particular cases. We also showed them on the practical examples how to deal with freely available space-born data in their every day work, we trained them on the hands-on sessions with advanced approaches, which they will further be able to use in their work. All these steps are essential ones for the ‘new generation of stakeholders’ enable to ‘read’ and evaluate data quality provided (field campaign and assessments), monitoring agencies (seasonal/ annual reports) in order (i) to better understand weak and strong points and credibility of available data, (ii) to lean on science-based evidences upon developing strategies and making decisions.

Moreover, Local Public events organized within the PONTOS allowed us to underline the topical environmental issues in the region, particularly aquatic vegetation overgrowth in the Dniester estuary and deltaic lakes, and with the support of local public to trigger policy makers, regional and local authorities to pay more attention on them.

The results of this assessments have been shared with the relevant regional decision-makers and local stakeholders to provide science-based evidences on changes in emergent and floating aquatic vegetation cover, species composition and nutrient accumulation by different species in order to be used for annual reports, evaluations, strategic planning and regional development. Specifically, the ONU signed six Memorandums of Understanding with the active regional actors:

- Basin Management Authority of Water Resources for the Black Sea Rivers and the Lower Danube (Odesa, Ukraine)
- Centre of Ecological Safety, LLC (Odesa, Ukraine)
- Odesa State Environmental University (Odesa, Ukraine)
- Hydrometeorological Centre of the Black and Azov Seas (Odesa, Ukraine)
- Lower Dniester Natural Nature Park (Odesa Region, Ukraine)
- Department of Engineering Protection of City Territory and Development of Coast under Odesa City Council (Odesa, Ukraine)

Besides, the interactive PONTOS platform developed within the project has been presented to stakeholders, who also have been trained online how to operate the platform. We expect that the PONTOS platform use will have a high impact, because it extremely facilitates the use of available Environmental Observation in a user-friendly manner via access to both historical and real time data. In addition, the corresponding manual for the Platform operation use has been issued in English and planned to be translated to Ukrainian until the end of the PONTOS project.

The PONTOS team really hopes that after the Victory of Ukraine, in a complicated post-war period the PONTOS outcomes (developed platform and achieved assessment results) will be of a high demand and help the regional and local authorities to make weighted research-based decisions and develop evidence-based long-term sustainable strategies for regional development.

5. CONCLUSION

We stated that emergent vegetation cover was quite stable over the time in the Dniester Delta area (deviation < 1.0% only), while deltaic lakes were found more vulnerable, *e.g.* the Bile lake areas decreased by 16% since 1984. However, over the past 20 years a positive tendency of emergent vegetation cover increase was observed for the entire area.

The river mouth areas were highly affected on overgrowth of floating vegetation in summer time. A gradual pronounced increase of floating plant cover was detected from 2000 to 2019, while a cover decrease was recorded since 2020 onwards.

The nutrient content in the main aquatic species growing in the two different pilot subareas was quantified within this assessment

Accumulation of the nutrient by emergent and floating aquatic vegetation in the summer time (at mature development stage) for areas of the Dniester estuary and Bile lake was quantified.

Very high resolution aerial and space-born images/mosaics processed with Semiautomatic Classification Plugin (SCP) tool were found to be highly credible for detailed monitoring with distinguishing floating vegetation species and their cover densities.

Free-access high resolution satellite images and Level 1 products (mainly derived from Sentinel 2 satellite Copernicus program) were shown to be a highly relevant tool (after accurate setting up the thresholds) for local authorities to monitor inter-annual and seasonal changes of vegetation cover and provide science-based evidences for accurate decision-making.

Aquatic vegetation (both emergent and floating) have been found to be a crucial source of nutrient (nitrogen, potassium and phosphorus) in the pilot currently causing negative impacts on ecosystem but potentially being a valuable resource for agricultural and energy sectors at sustainable usage.

We believe that data generated within this assessment and also available through the interactive PONTOS platform will facilitate ongoing everyday work of local authorities and expand public awareness to the problems caused by aquatic plant overgrowth and help to look up the potential 'hidden' benefits at implementing sustainable management in the pilot area.

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