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Modern methods of monitoring estuarine waters on the example of the Tiligul Estuary

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Abstract. Manual monitoring of the eutrophication status of water bodies such as estuaries is a rather difficult task. Drone technology can be used to assist in monitoring any water body. This study was conducted with the aim of applying remote sensing methods based on unmanned aerial vehicles (UAVs) to obtain eutrophication indicators in the waters of the Tiligul Estuary. The information was based on data collected by drones on the level of eutrophication and the state of marine areas. A DJI Phantom 4 Pro drone was used to collect data from the air. Four sampling points were selected for testing, where the normalised vegetation difference index and normalised turbidity difference index were evaluated. Exsitu data, such as nitrate concentration and phosphate concentration, were also obtained. A trophic status index was calculated to describe the algae content in the estuary. The UAV hyperspectral images were orthorectified and georeferenced in Agisoft PhotoScan software and the normalised difference vegetation index values were evaluated in ArcGIS. The results showed a correlation between the vegetation difference index values and the concentration of nitrogen and phosphorus with coefficients of 0.7079 for phosphorus concentration and 0.7004 for nitrogen concentration, respectively. This study confirmed the applicability of remote sensing for water resource management using UAVs, which is characterised as a fast and simple methodology. A qualitative assessment and control of environmental parameters during the solution of environmental monitoring tasks for marine areas and coastlines was proposed. It was noted that mathematical and simulation modelling methods contribute to the formation of functional and information models, and system analysis methods are also used to identify structural relationships between components of complex systems. The results of the study will enable the further use of UAVs and other remote sensing methods for monitoring and forecasting the state of estuaries and marine areas

Keywords: marine environment monitoring; unmanned aerial vehicles; estuary; coastal zone management; eutrophication

Introduction

Preserving the ecological safety of marine areas and coastal zones is important for countries with access to the sea. In the context of increasing anthropogenic pressure on marine ecosystems, global climate change and growing transport traffic, it is extremely important to continuously monitor the state of water resources and coastal ecosystems. Timely detection of environmental threats and man-made accidents (oil spills, chemical pollution, changes in water temperature and

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salinity, erosion processes) makes it possible to minimise damage and mitigate the consequences. In this context, modern mobile monitoring information systems are of particular importance. Mobile monitoring platforms – such as unmanned aerial vehicles (drones), automated marine buoys and specialised boats with sensors – enable field research, which is particularly important for regions with hard-to-reach coastal areas. The use of mobile information systems facilitates more accurate tracking of environmental parameters, monitoring of biodiversity, prevention of natural disasters (such as storm surges and floods) and control over compliance with international environmental standards.

The development of information systems for monitoring marine and coastal areas is being actively studied in scientific circles. Scientists analyse technical solutions, improve data collection methods and develop algorithms for the rapid detection of environmental threats. Various methodologies, mechanisms, principles and approaches have been developed to assess the state of the environment during environmental monitoring using aerospace technologies. An analysis of the experience of scientists H. Zhang *et al.* (2022), who studied aquatic ecosystems, has shown that their protection and rehabilitation is only possible with the active use of relevant information technologies in the management of water bodies.

As noted in the work of I. Afán *et al.* (2022), being fundamental to global biodiversity and critical to human well-being, aquatic ecosystems are characterised by their profound diversity, which is due to a multitude of environmental conditions and complex population structures. This inherent complexity requires nuanced monitoring to ensure conservation, protection and restoration. However, existing monitoring methods face significant challenges in capturing the full extent of this complexity, which hinders effective ecosystem management. Traditional methods, including remote sensing using satellites and on-site measurements, have provided valuable information, but advances in computer IT technologies in the information age are prompting change. According to researchers O. Trofymchuk *et al.* (2014), global threats such as biological invasions, climate change, intensified land use and water depletion further emphasise the urgency.

These challenges highlight the need for more modern monitoring approaches that can provide high-resolution data in real time at different spatial scales. Given these challenges and achievements, an integrated approach incorporating state-of-the-art technologies, including UAVs and advanced algorithms, is rapidly becoming the new frontier in capturing the multifaceted dimensions of aquatic ecosystems. Although UAVs are increasingly being used in common scenarios in aquatic ecosystems, such as habitat surveys, algal bloom monitoring, vegetation monitoring, and animal behaviour observation, K. Wu *et al.* (2019) emphasised that the potential of these technologies to revolutionise ecosystem monitoring remains understudied, especially in the integration of different types of UAVs for comprehensive multi-scale monitoring.

The work of scientist C. Yang (2022) indicates that combining aerial photographs with specific limnological support provides a comprehensive approach to assessing the state of the estuary. Thus, some studies address a number of limnological aspects related to the ecological status using UAV imagery; for example, the dynamics of helophytes (*Phragmites*) in estuaries, submerged macrophytes in shallow estuaries, or algal blooms in reservoirs and estuaries. The aim of this work was to present the results of using drones in the context of monitoring estuary waters using the example of the Tiligul Estuary.

Materials and Methods

The object of this study was the Tiligul Estuary, located in the Mykolaiv region. Like most estuaries in the Northern Black Sea region, the Tiligul Estuary has traditionally been subject to significant anthropogenic influence. Figures 1-2 show the geographical location and bathymetric map of the Tiligul Estuary.

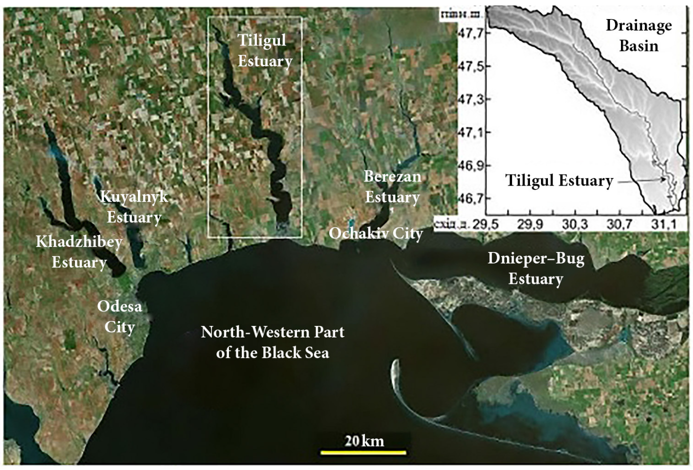

Figure 1. Geographical location of the Tiligul Estuary and its catchment basin

Source: created by the authors based on D. Kushnir & Y. Tuchkovenko (2021)

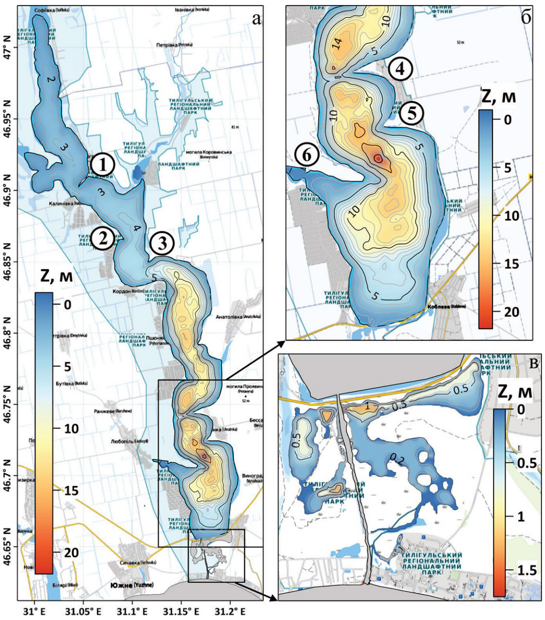

Figure 2. Bathymetric map of the Tiligul Estuary (isobaths in metres) at a water level of minus 0.4 mBS. WGS-84 horizontal coordinate system

Note: 1 – Lyubopil Spit; 2 – Chervonoukrainska Spit; 3 – Chilova Spit; 4 – Ranzeva Spit; 5 – Anatolivska Spit; 6 – Kordonska Spit; 7 – Shyrokyna Spit; 8 – Kalynivska Spit; 9 – Strilka Spit

Source: created by the authors based on D. Kushnir & Y. Tuchkovenko (2021), L. Hurets *et al*. (2021)

In this study, a DJI Phantom 4 Pro drone was used to take aerial photographs of the relevant sampling area. The drone was equipped with a 20-megapixel camera. The attached camera is capable of eliminating shutter distortion when shooting fast-moving objects or flying at high speeds, resulting in sharp and vivid photos and videos (Zhang *et al*., 2023). This equipment can withstand wind gusts of 6 m/s. A Sony Alpha ILCE-5100 camera with a resolution of 20.0 Mpx was used. Possible eutrophication at each sampling point was analysed by processing and interpreting visually and digitally. The orthorectified mosaic served as a platform for creating the NDVI image. To improve the concept of spatial distribution of NDVI in the estuary, only parts of the sampling point area were covered. A colour composite image was created, which highlighted changes in index values (Mokin, 2005).

Figure 3 shows a map of the Tiligul estuary in the area of protected sand spits with examples of trajectories that the quadcopter must follow for monitoring studies. In particular, the green outline marks the area of artificial reef research; the yellow outline marks the research of vegetation cover, including areas of red-listed species, monitoring of violations of the protection regime; the blue outline marks bird counting. Figure 4 shows a block diagram including the main stages of image acquisition and analysis that are followed to obtain a useful geomatics product for assessing the level of eutrophication.

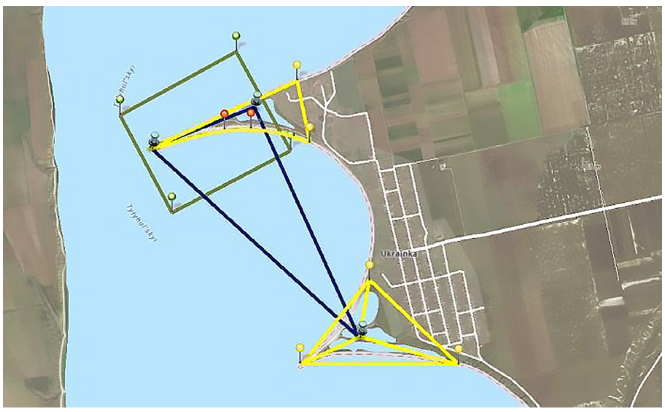

Figure 3. Map showing possible quadcopter trajectories for environmental monitoring and sampling points for analysis

Source: created by the authors

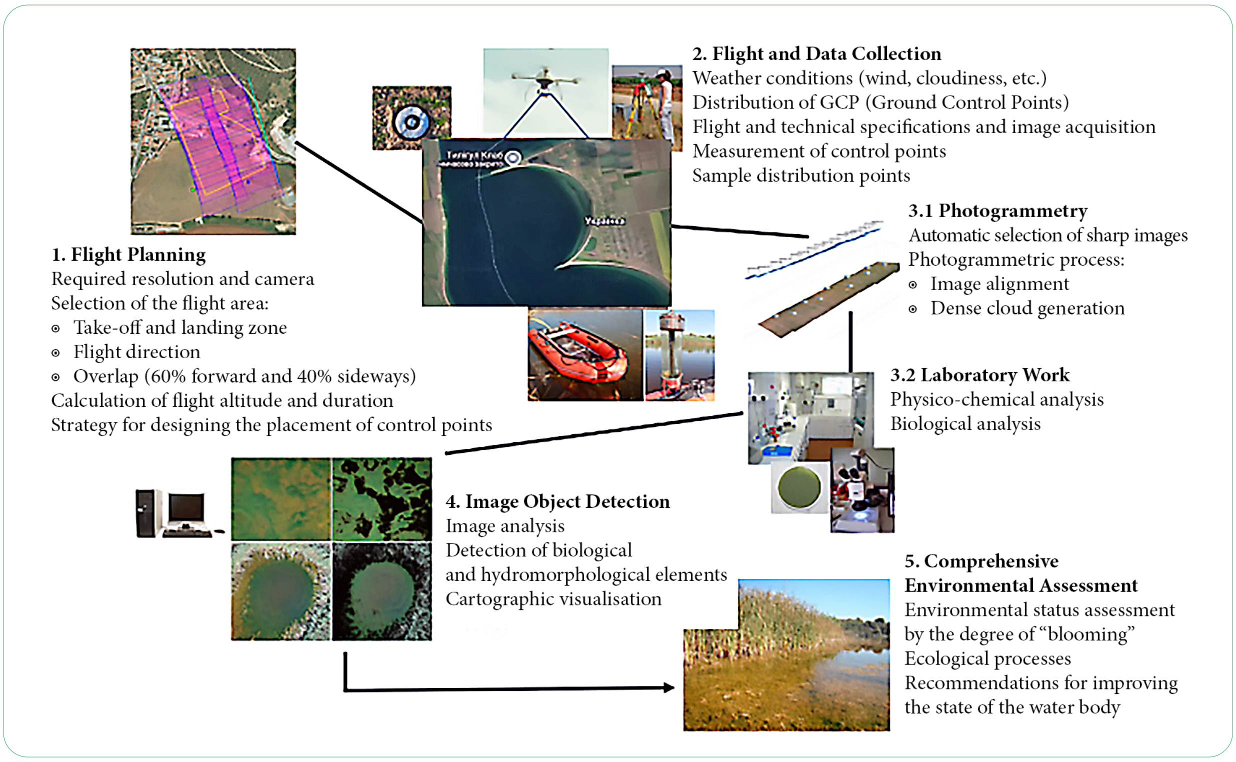

Figure 4. Block diagram showing the main steps in acquiring and analysing images to obtain a geomatics product. GCP, ground control point; RTK GPS, real-time kinematic global positioning system

Source: created by the authors

The ground sampling distance (GSD) was calculated to obtain a target image resolution of 2.5 cm based on the camera's focal length, taking into account the maximum flight altitude of 120 m in accordance with Spanish airspace regulations. Ten targets (radius 0.20 m) were evenly distributed and measured in the flight area to obtain final georeferenced images (orthoimages) (Zou *et al.*, 2014). The location of the target centroids was measured using a Leica Global Positioning System (GPS) 1200 (Leica Geosystems AG, Heerbrugg, Switzerland) linked to a permanent Global Navigation Satellite System (GNSS) reference station (ERGNSS, 2008). The calculated accuracy of the GNSS real-time kinematic (GNSS-RTK) system was 0.02 m for planimetry and 0.03 m for altimetry (Ownby *et al.*, 2021).

Flights and image processing were performed according to the methodology proposed by J.I. Córcoles *et al.* (2013) and D. Hernández-López *et al.* (2013). Eight UAV flights were conducted during the annual cycle from July 2023 to July 2024. Flights began around noon to minimise solar glare and shading, as well as to optimise visibility conditions for groundwater and submerged vegetation, and to maximise visibility of the deep water column. Image processing included automatic selection of non-blurred images and the following photogrammetric process: photo alignment, dense cloud construction, grid construction, and texture construction. For each flight, an orthomosaic of georeferenced RGB images was created for the main purpose of quantifying the total macrophyte coverage in the estuary and the degree of eutrophication (Sidabutar *et al.*, 2020). The normalised difference turbidity index (NDTI) was used to determine different degrees of turbidity and was calculated according to S.H. Patel *et al.* (2018):

$$\text{NDTI} = \frac{(\text{Red Band 1} - \text{Green Band 2})}{(\text{Red Band 1} + \text{Green Band 2})}. \quad (1)$$

From the orthophoto with georeferencing, the normalised difference vegetation index (NDVI) image was used for the entire sampling point from the index adaptation, as shown in the equation (2):

$$\text{NDVI} = \frac{\text{Band 4} - \text{Band 1}}{\text{Band 4} + \text{Band 1}}, \quad (2)$$

where Band 4 – the near-infrared band; Band 1 – the red band.

The NDVI values for the sampling points were obtained by linear regression of the Landsat 8 OLI 0.655 μm/0.56 μm (Band 3/Band 2) ratio with the natural logarithm of the measured NDVI values. A polynomial equation was used to calculate the NDVI values for each sampling point based on the results of the Landsat C3/C2 band ratio (Foste & Vaneeckhaute, 2021):

$$(\text{NDVI}) = 7.1354(\text{C3/C2})2 - 11.761(\text{C3/C2}) + 5.2004. \quad (3)$$

Several studies that used NDVI to determine the eutrophic status of water bodies were used to calculate NDVI values. The NDVI values were also used to correlate with chlorophyll-a (Chl-a) concentrations. The study also demonstrated the use of Landsat 8 OLI band ratio data to predict Chl-a concentrations. A correlation model between NDVI values and N and P concentrations was identified to compare field measurement data with remote sensing data. The Trophic Status Index (TSI) describes the algae content in estuary water. The Carlson equation is used to calculate the trophic status of sampling points in the Tiligul Estuary with Chl-a concentration values. As mentioned, the NDVI has a strong linear dependence on Chl-a values. Therefore, the TSI can be calculated (4):

$$\text{TSI NDVI} = 10\,[6 - (2.04 - 0.68\ln_{(NDVI)}) / (\ln^2)]. \quad (4)$$

To calculate the TSI, input values obtained using linear regression between the obtained NDVI data and the B3/B2 ratio of Landsat 8 OLI images are used, since the blue-green band ratio is commonly used in oceanic and moderately turbid coastal waters. The authors of this study also considered nitrogen and phosphorus as some of the most important elements for the life of microorganisms. When determining the total phosphorus content, the samples were not filtered or preserved. The duration of the period between sampling and analysis is not regulated. Immediately before the study, the sample was vigorously shaken and then mineralised. In the case of determining the total content of dissolved phosphorus compounds, the water was pre-filtered through a membrane filter with a pore size of 0.45 μm.

The samples were mineralised using potassium persulphate, which oxidises organophosphorus compounds to oxidation state +5 in an acidic environment, forming orthophosphate ions PO_4^{3-}. The latter were determined photometrically. The method is suitable for the analysis of colourless and slightly coloured estuarine waters. The indophenol method was used to determine the nitrogen concentration in estuary water. This spectrophotometric method is based on the interaction of ammonia with phenol and hypochlorite, resulting in the formation of indophenol, which exhibits a distinct blue colour in an alkaline environment. The highest colour intensity occurs in a solution containing 0.3 M NaOH and 0.8% phenol. The colour intensity is measured at a wavelength of 625 nm. When analysing solutions containing ammonia at a concentration of 1 ppm, the standard deviation of the results is 0.03 ppm.

Results

Analysis of orthophotos ensures that the images cover the entire sampling area. High NDVI values indicate a greater difference between red and near-infrared radiation, while low NDVI values indicate a small difference between red and near-infrared signals (Mažeikienė & Šarko, 2022). This situation occurs when there is little photosynthesis or when there is very little reflection of light in the near-infrared range. It can be seen that all NDVI values for water from all sampling points are in the middle range. This indicates that the estuary water has experienced a state of low photosynthetic activity, and the chlorophyll level in the estuary water is average (Da Costa *et al.*, 2020). The average NDVI value obtained as shown in Table 1.

Table 1. Average NDVI values

Date of observations	Sampling point	NDVI
27 July 2023	1	0.40
	2	0.50
	3	0.38
	4	0.47
8 November 2023	1	0.38
	2	0.41
	3	0.34
	4	0.40
5 March 2024	1	0.37
	2	0.44
	3	0.36
	4	0.40
18 June 2024	1	0.37
	2	0.41
	3	0.36
	4	0.42

Source: created by the authors

It can be seen that sampling points 2 and 4 have higher NDVI values for the four sampling dates, which means that these two sampling points have slightly higher chlorophyll levels compared to the other sampling points. NDVI values can be observed by the colour shade in the images to show different NDVI levels from the side, as shown in Figures 2-5. A darker colour means a high NDVI value and contains a large amount of chlorophyll (Fig. 5).

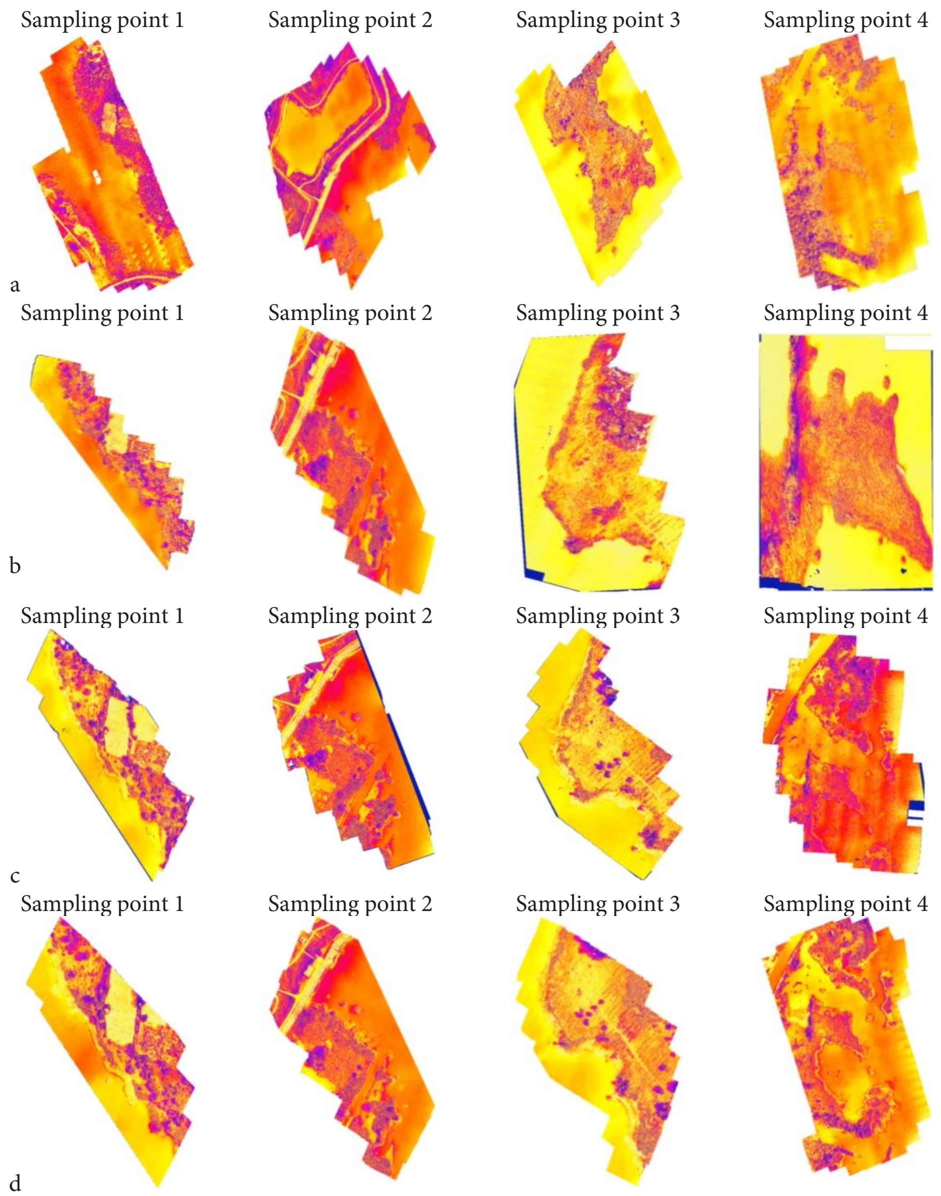

Figure 5. Images of NDVI in different areas of the sample

Note: a – 27 July 2023; b – 8 November 2023; c – 5 March 2024; d – 18 June 2024

Source: created by the authors

Although some sampling points have low NDVI values, the colour becomes darker compared to sampling points with higher index values. This is due to the reflection coefficient of red light in the near-infrared range, which makes the colour darker (Zhang *et al.*, 2023). However, this will not have a significant impact or a large difference in the NDVI value, which will not affect the results (Costa *et al.*, 2019). The pixels that appear in the NDVI were identified as vegetation, and this was associated with water turbidity. The colour tone in the images reflects different levels of turbidity from the side, as shown in Figure 6. While the NDVI values are in the middle range, the NDTI values are also in the middle range, which does not indicate a high level of turbidity.

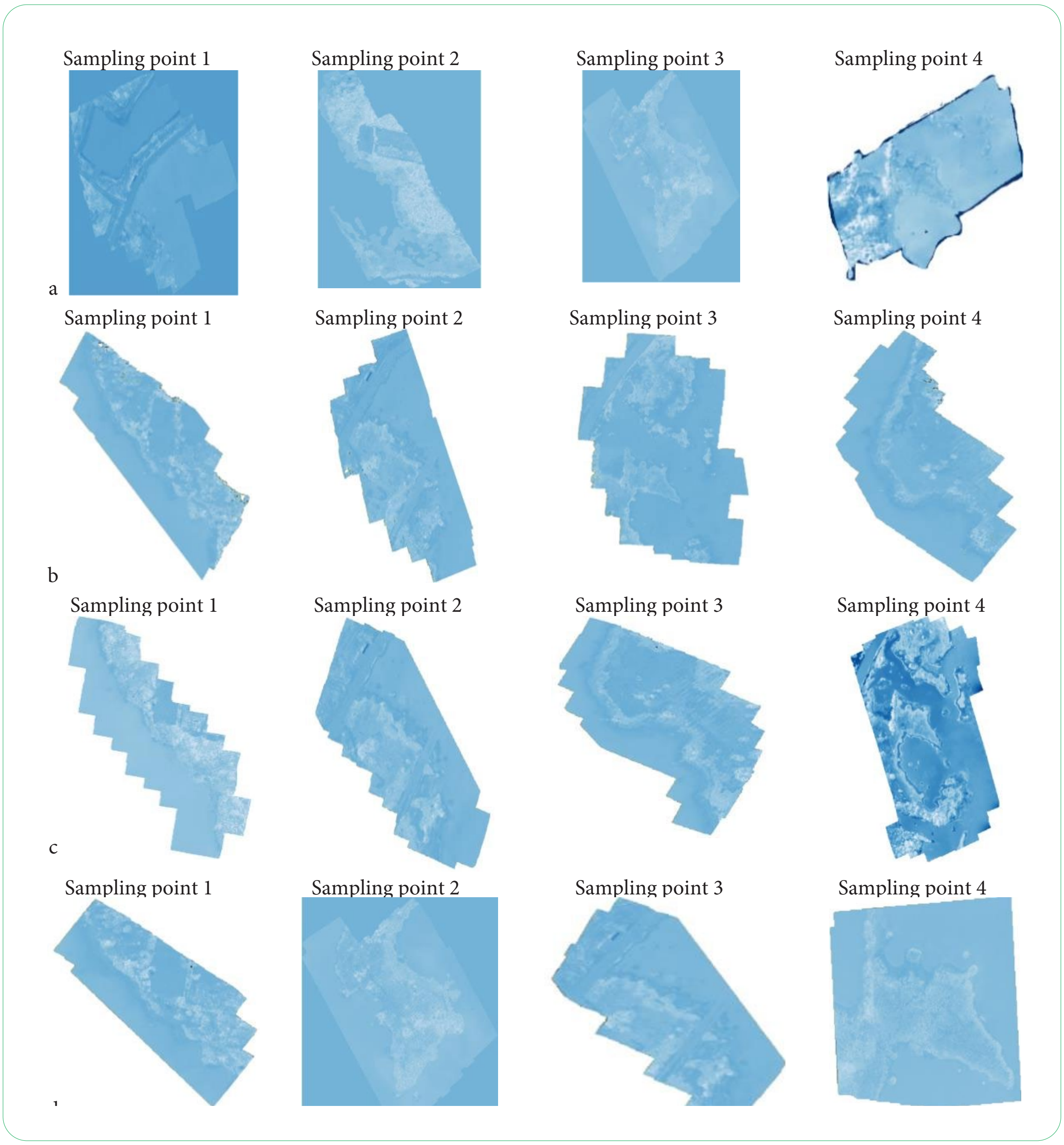

Figure 6. Images of different areas of the estuary

Note: a – 27 July 2023; b – 8 November 2023; c – 5 March 2024; d – 18 June 2024

Source: created by the authors

When comparing the samples, sampling point 4 is more turbid. Higher NDTI values were recorded in the area near the estuary coast due to the interference of aquatic vegetation. Higher turbidity values can be explained by backscattering in the estuary water column, which causes an increase in suspended particles (Denisova *et al.*, 2020). From this point of view, the proposed method is more effective for studying the turbidity of water bodies than conducting measurements on site, which would be very expensive and difficult. As shown in Figure 7, the correlation model produces the best result, which was a second-order polynomial function curve returning a correlation a R^2 equal to 0.7115. This revealed an acceptable linear dependence with a correlation R^2 equal to 0.51 (Aguilar-Ascon, 2020).

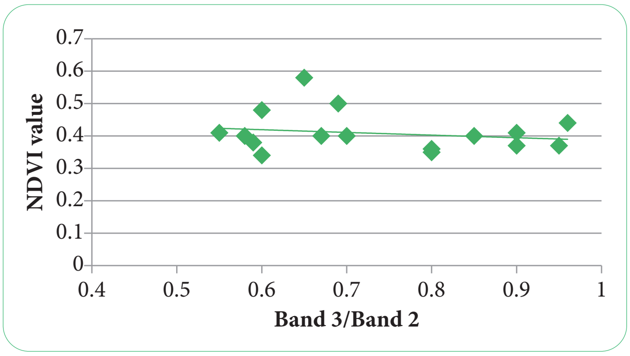

Figure 7. Correlation model between NDVI values and Band 3/Band 2

Source: created by the authors

Since the data on the Landsat 8 OLI and NDVI band ratios have a linear dependence on Chl-a, this study demonstrated a correlation between NDVI and the 0.655 μm/0.56 μm band ratio (Band 3/Band 2). This indicates that NDVI may be equivalent to Chl-a concentration in this particular case. As a result, the regression line showed a strong relationship between NDVI and the 0.655 μm/0.56 μm band ratio, returning a correlation R^2 of 0.7115 (Ajala *et al.*, 2023). The trophic status of water bodies can be evaluated based on the TSI value calculated as shown in Table 2.

Table 2. Trophic status index (TSI) for all sampling points

Date of observations	Sampling point	TSI
27 July 2023	1	21.54
	2	21.09
	3	21.29
	4	22.70
8 November 2023	1	21.15
	2	21.29
	3	20.41
	4	21.80
5 March 2024	1	20.82
	2	20.74
	3	20.75
	4	21.63
18 June 2024	1	20.90
	2	21.65
	3	20.70
	4	22.49

Source: created by the authors

Based on the calculated TSI values (20-40 TSI), all sampling points can be considered mesotrophic estuaries. This indicates that the sampling area has some algae turbidity, which reduces its aesthetic appeal. However, this condition will not lead to oxygen depletion in deep water horizons and is safe for hydrobionts under these conditions. The results showed that vegetation indices based on UAV images are similar to those obtained from ground sensors and cameras. This study also demonstrates the applicability and reliability of NDVI as an important tool for monitoring water quality in aquatic environments. Nitrogen and phosphorus are the main nutrients in the eutrophication process; therefore, it is important to determine the concentration of nitrates and phosphates in water bodies. Eutrophication begins when the concentration of nitrogen in water reaches 0.3 mg/L and the concentration of phosphorus reaches 0.02 mg/L (Ownby *et al.*, 2021). From the results presented, it can be seen that the concentration of nitrates and phosphates at all sampling points exceeds 0.3 mg/L and 0.02 mg/L, respectively. These values are presented in Table 3. They show that the sampling area is in a mesotrophic state with slight eutrophication. The excess of nutrients promotes algae growth in this location (Ajala *et al.*, 2023).

Table 3. Concentrations of N and P at all sampling points

Date of observations	Sampling point	Nitrates, NO^{3-} (mg/L)	Phosphates, PO_4 (mg/L)
27 July 2023	1	0.15	1
	2	0.43	0.9
	3	0.06	0.6
	4	0.44	1.9
8 November 2023	1	0.13	0.8
	2	0.45	1.1
	3	0.04	0.5
	4	0.41	1.7
5 March 2024	1	0.11	0.7
	2	0.43	1.3
	3	0.05	0.3
	4	0.42	1.6
18 June 2024	1	0.09	0.6
	2	0.43	0.9
	3	0.06	0.4
	4	0.44	1.7

Source: created by the authors

For the correlation between NDVI values and N concentration, it has an inverse correlation R^2 equal to 0.7004, while the correlation R^2 between NDVI values and P concentration is 0.7079. From the correlation model created, it can be seen that P concentration and N concentration have almost the same relationship to NDVI, but in this study, the correlation of P concentration is slightly higher, i.e., high P concentration can lead to high Chl-a concentration and cause eutrophication. This statement was confirmed by research in the work of S. Stefanni *et al.* (2022) conducted on mitigating estuary eutrophication. They argued that to mitigate eutrophication, phosphorus content should be reduced instead of nitrogen. Although controlling nitrogen content also failed to eliminate the reduction in estuary eutrophication, reducing phosphorus content is more important than reducing nitrogen content. The main limitation of the method used in this study was wind speed. Wind tolerance depends on the equipment, in particular its size and weight. With the equipment used here (Microdrones md4-1000, 1.2 kg), flights were performed at wind speeds below 2 m/s. Higher wind speeds can result in blurred images. During the study period, flights were not possible on 12.3% of days due to unfavourable weather conditions, such as high wind speeds. Cloud cover and lighting also affect the results.

In the work of M.W. Letshwenyo & T.V. Sima (2020), it was recommended to perform flights at noon, around 12:00 solar time. Water transparency or turbidity is the main limitation associated with the condition of the water body, which affects the maximum depth visible in UAV images. As a rule, RGB cameras are used under normal lighting conditions and clear water. As noted in the work of C.A Knight (2021), submerged lake vegetation can be classified to a depth of 2.5 m, but changes in turbidity can affect the maximum resolution in terms of depth. In the studied water body, features at a depth of 4 m were detected under clear water conditions, making this methodology very useful for detecting lake stratification processes and for mapping deep-water macrophytic communities.

In the work of S.O. Akinnawo *et al.* (2023) confirmed that eutrophication caused by nitrate and phosphate runoff from agricultural land, wastewater from aquaculture ponds, and municipal and industrial discharges is a serious problem due to its significant contribution to socio-economic and environmental health problems. In the work of P.C. Sonarghare *et al.* (2020), it was reported that the emergence of a dead zone due to the effects of eutrophication (consisting of algal blooms and hypoxia) leads to the loss of aquatic biodiversity. Algal blooms are sometimes referred to as “red or brown tides” depending on the colour of the algae, and the organism responsible for red tides is called cyanobacteria. In addition, it has been noted that cyanobacteria produce harmful substances, such as off-flavours and toxins, which are potentially dangerous to the health of both humans and wildlife. Furthermore, C.A. Knight (2021) confirmed that cyanobacterial blooms are one of the serious consequences of eutrophication, causing coastlines and as well as boat hulls with a foul-smelling film, leading to odour and taste problems in water bodies, thereby rendering them unsuitable for desired use due to their potential danger to wildlife and the population.

In addition, environmental studies conducted in European countries between 2015 and 2021 showed that, according to estimates, only 40-60% of the nitrates and phosphates applied in fertilisers were used by plants. The remaining percentage is reportedly washed into runoff that reaches water bodies, with a phosphate load into European seas of 0.26-0.30 TgP/year (Matei & Racoviteanu, 2021; Pytka-Woszczyło *et al.*, 2022). Further research by L.P. Astuti *et al.* (2022) on the level of eutrophication in the Jatiluhur reservoir, conducted in 2022, showed that the trophic status index (TSI) and trophic index (Trix) exceed 4 and 50, respectively. This indicates an eutrophic-hypertrophic level, characterised by high chlorophyll-a and total phosphorus content in the Jatiluhur reservoir. Based on the study, the following can also be said. A fairly effective method against water “blooming” in Europe is the use of modern LG Sonic ultrasonic technology. This method was studied in the work of S.H. Melnyshenko *et al.* (2023). By 2025, this technology will be used in 55 countries around the world. It is recognised as environmentally friendly and highly effective, eliminating algae and blocking their further growth to the “blooming” stage. At the same time, LG Sonic is completely safe for fish and humans.

A biological method of combating water eutrophication, often used in artificial reservoirs, has also demonstrated high efficiency in European countries. The essence of this method is to introduce herbivorous fish into water bodies, which consume blue-green algae, thereby reducing the intensity of “blooming”. This method not only improves the ecological condition of the water body, but also provides an opportunity to breed fish economically without spending money on feed. Competition for space and resources in the context of sustainable aquaculture development involves the development of closed recirculation systems, the use of offshore farms, including cages, platforms and ropes for shellfish farming, and the integration of future aquaculture projects into a comprehensive zoning and management strategy. Strategic management is key to the recovery and progress of Ukraine’s fisheries. Its effectiveness depends on the correct choice of strategic development vector, taking into account specific political, organisational and economic conditions and opportunities, as well as the development of effective regulatory mechanisms.

Conclusions

The use of remote sensing by UAVs in monitoring the eutrophication process offers many advantages over conservative monitoring methods. The results of this study allow establishing – a correlation between the data for the NDVI image obtained during the UAV flight and the estimated values of the Landsat 8 satellite. This study also correlates NDVI values with N and P concentrations obtained from field data. A mathematical model was created and acceptable coefficients of determination (R^2) were obtained, namely 0.7115, using the correlation between NDVI and the Landsat 8 OLI band ratio using a second-order polynomial function. This second-order polynomial function also provides a mathematical model based on the correlation between NDVI values and N and P concentrations, which has coefficients of 0.7079 for P concentration and 0.7004 for N concentration.

The results can serve as a starting point for further research and expand the study of the impact of other indicators, such as water turbidity, suspended solids, estuary depth, and background influence. Since the TSI value obtained as a result of the study showed the Tiligul estuary to be in a mesotrophic state, this study proposed long-term monitoring of water quality conditions and recommended the implementation of appropriate management plans to support aquaculture and other activities in the estuary. The results of on-site measurements differ slightly from the results of remote sensing. This is because algae growth is sometimes dominated by light attenuation from inorganic turbidity. Thus, this discrepancy illustrates the need to develop a specific method that depends on the specific conditions of the estuary during the study. It was emphasised that the use of alternative tools in monitoring aquatic environments is particularly important for the application of preventive and corrective measures that can be taken to minimise socio-economic impacts.

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Conflict of Interest

None.

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Сучасні методи моніторингу лиманних акваторій на прикладі Тилігульського лиману

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Анотація. Ручний моніторинг стану евтрофікації водних об'єктів, таких як лимани, є досить складним завданням. Технологія дронів може бути використана для допомоги в моніторингу будь-яких водойм. Це дослідження було проведено з метою застосування методів дистанційного зондування на основі безпілотних літальних апаратів (БПЛА) для отримання показників евтрофікації у водах Тилігульського лиману. Основу інформації становлять дані, зібрані дронами, стосовно рівня евтрофікації та стану морських просторів. Для збору даних з повітря використовувався дрон DJI Phantom 4 Pro. Для тестування було обрано чотири точки відбору проб, де оцінювали нормалізований індекс різниці рослинності та нормалізований індекс каламутності різниці. Також були отримані дані Exsitu, такі як концентрація нітратів і концентрація фосфатів. Було розраховано індекс трофічного стану, який описує вміст водоростей в лимані. Гіперспектральні зображення БПЛА були орто-випрямлені та геоприв'язані в програмному забезпеченні Agisoft PhotoScan та оцінці значення нормалізованого різницевого вегетаційного індексу в ArcGIS. Результати показали кореляцію між значеннями індексу різниці рослинності та концентрацією азоту та фосфору зі значеннями коефіцієнтів 0,7079 для концентрації фосфору та 0,7004 для концентрації азоту відповідно. Це дослідження підтвердило застосовність дистанційного зондування для управління водними ресурсами за допомогою БПЛА, що характеризується як швидка та проста методологія. Запропоновано якісну оцінку й контроль параметрів довкілля під час розв'язання задач екологічного моніторингу морських акваторій і прибережжя. Зазначено, що методи математичного та імітаційного моделювання сприяють формуванню функціональних й інформаційних моделей, а також застосовуються методи системного аналізу для виявлення структурних зв'язків між компонентами складних систем. Отриманні результати проведеного дослідження дадуть змогу в подальшому використовувати БПЛА та інші способи дистанційного зондування для моніторингу та прогнозування стану лиманних та морських акваторій

Ключові слова: моніторинг морського середовища; безпілотні літальні апарати; естуарій; управління прибережною зоною; евтрофікація