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SHABLA-EZERETS LAKE MONITORING FOR THE PERIOD 2017–2024 USING SENTINEL DATA

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Abstract

This study presents an 8-year monitoring assessment of the Shabla-Ezerets Lake Complex, located on Sarmatian limestones in northeastern Bulgaria, approximately 5 km northeast of the town of Shabla. The lake complex is part of the protected area "Shabla Lake" and comprises two adjacent coastal estuarine lakes — Shabla and Ezerets — which are interconnected by an artificially excavated canal. In recent years, high-resolution satellite imagery and data from the European Space Agency's Sentinel satellites have been instrumental in monitoring the ecological and hydrological dynamics of the complex. These data provide valuable long-term information on water resources, enabling the analysis of trends such as fluctuations in water levels, changes in vegetation cover, and the identification of potential pollution sources. This study utilizes data from Sentinel-2 and Sentinel-3 satellites to evaluate the spatiotemporal dynamics of the area over the period 2017–2024, offering insights into environmental changes and contributing to effective conservation and management strategies.

Introduction

Shabla-Ezerets Lake is part of the Protected Area "Shabla Lake." It is located in the northeasternmost part of Bulgaria, approximately 18 km from the Bulgarian-Romanian border and 3–5 km northeast of the town of Shabla, Dobrich Province. The area represents a wetland complex that includes two coastal limans —Shabla Lake and Ezerets Lake—interconnected by a canal, as well as adjacent sand dunes, grasslands, forest and shrub vegetation, and cultivated agricultural lands. The Protected Area "Shabla Lake" covers an area of 5,312.4 decares [1].

The area is listed under the Ramsar Convention as a wetland of international importance, particularly as a habitat for waterfowl, under the name "Shabla Lake." The entire territory is also included in BirdLife International's list of Important Bird Areas in Europe under the name "Shabla Lake Complex" [2]. Shabla Lake Complex is part of the European ecological network NATURA 2000, designated as site BG0000156 (Fig. 1).

Shabla-Ezerets Lake is among the most significant wetlands in Bulgaria. It is a representative example of natural coastal estuarine lakes along the western Black Sea.

Fig. 1. Location of Shabla-Ezerets Lake

In the wetland, one Bulgarian endemic plant species and four Balkan endemic species can be found, along with 23 other species of significant national and international conservation importance. The wetland's greatest importance lies in its role in preserving avifauna. The overwintering populations of several waterfowl species and the numbers of other species during migration have contributed to the international recognition of the wetland as a Ramsar site [1].

The protected area is located along the Via Pontica migration route and provides favorable conditions for feeding and resting for numerous migratory bird species. Conservation and management objectives for the protected area focus on the long-term preservation of its unique and representative ecosystems and biological communities, in accordance with the National Biodiversity Conservation Strategy [1, 2].

An essential aspect of wetland conservation is the restoration and maintenance of the natural balance in aquatic ecosystems, as well as the preservation of the natural water regime in the wetland, which is critical for maintaining the ecological functions and biodiversity of the area. Management goals for the protected area include reducing eutrophication processes in the lake by implementing measures to decrease the concentration of nutrients in the aquatic ecosystems and restoring a water regime closer to the natural one. The management of aquatic vegetation aims to increase open water areas through rotational mowing and grazing by cattle, which helps slow eutrophication and creates better conditions for biodiversity [1]. Keeping up-to-date and comprehensive scientific knowledge about natural processes and ecosystem conditions is a vital component of effective area management.

Data and Methods

Data from Sentinel-2 and Sentinel-3 developed by the European Space Agency as part of the Copernicus program were utilized [3–5]. The mission is designed to deliver high-resolution, multispectral images of the Earth's surface on a global scale.

The use of satellite data, particularly from the Sentinel mission, is essential for monitoring wetlands due to its ability to provide high-resolution, multispectral imagery on a regular basis. Sentinel satellites enable the detection of changes in vegetation, water levels, and land cover, offering valuable insights into the dynamics and health of wetland ecosystems [4]. This data supports effective conservation, management, and restoration efforts, helping to address environmental challenges and ensure the sustainability of these critical habitats [6].

Ecological monitoring of Shabla-Ezerets Lake has been conducted over an eight-year period, from 2017 to 2024. For this purpose, one satellite image was used per year. The selected satellite scenes were taken during the spring (April–May), when the vegetation in the area is most prominent (Table 1). Multiband composite images were generated by stacking the 13 available channels from Sentinel-2 satellite data. These images were essential for subsequent analysis and processing, as they allowed for the extraction of indices values.

Land Surface Temperature (LST), derived from infrared radiation, represents the radiative temperature of the Earth's surface. Based on data from Sentinel-3 SLSTR (Sea and Land Surface Temperature Radiometer), LST is not equivalent to air temperature, which is typically included in daily weather forecasts [7]. LST retrieval algorithms achieve an accuracy of 1 K, especially at night when differential surface heating is absent [7]. Since the Shabla region was studied in the spring, significant differences in sensor-measured temperature are observed between morning (around 8:00 Central European Time) and evening (20:00 Central European Time) recordings.

LST data are crucial for monitoring climate change. Research on the impacts of climate change is particularly important for modeling potential scenarios of how climate variations could affect thermal variations of the Earth's surface. The data used are from Sentinel-3A and Sentinel-3B (Table 1), and the SLSTR thermal bands utilized for SST retrieval (the three infrared channels S7, S8, and S9 at 3.74 µm, 10.85 µm, and 12 µm) are also employed for LST retrieval in the SLSTR Level-2 products. Algorithms for deriving LST using split-window radiances are sufficiently advanced to achieve an accuracy of 1 K, particularly at night when differential surface heating is absent [8].

Table 1. Image acquisition dates

Sensor	***Acquisition Date***
Sentinel 2 A	*3 May 2017*
Sentinel 2 A	*3 May 2019*
Sentinel 2 A	*12 April 2021*
Sentinel 2 A	*2 May 2022*
Sentinel 2 B	*7 May 2023*
Sentinel 2 A	*26 May 2024*
Sentinel 3 A	*3 May 2019*
Sentinel 3 A	*12 April 2021*
Sentinel 3 B	*26 April 2024*

Spectral index classification of satellite imagery was utilized to analyze the spectral properties of Earth's surface features, enabling their identification and spatial mapping. This method involves computing specific spectral indices derived from the reflectance values of multiple bands captured by the satellite sensors. These indices are particularly effective in emphasizing key surface characteristics, such as vegetation cover, water presence, and soil moisture levels, which are critical for diverse applications, including ecological monitoring and wetland management [8–13]. The following spectral indices were used in the current research: Normalized Difference Vegetation Index, Normalized Difference Water Index, and Normalized Differential Greenness Index.

The Normalized Difference Vegetation Index (NDVI) is a numerical index used to assess the health and vitality of vegetation cover on land. NDVI is derived from the remote sensing of vegetation reflectance in the visible and near-infrared bands of the electromagnetic spectrum [10, 11]. The NDVI index is calculated using the following formula:

(1) $$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

where NIR is the reflectance in the near-infrared band and RED is the reflectance in the red band of the visible spectrum.

Normalized Difference Water Index (NDWI) is a satellite-derived index from the near-infrared (NIR) and shortwave infrared (SWIR) channels [14, 15]. NDWI is sensitive to the change in the water content of the leaves. The combination of NIR with SWIR removes variations induced by leaf internal structure and leaf dry matter content, thereby improving the accuracy in retrieving vegetation water content [11, 16]. The amount of water available in the internal leaf structure largely controls the spectral reflectance in the SWIR interval of the electromagnetic spectrum. SWIR reflectance is therefore negatively related to leaf water content. In addition to NDVI, NDWI is derived from remote sensing data, utilizing the differences in reflectance between two bands of the electromagnetic spectrum to identify the presence of water [11, 15, 16]. NDWI is useful for detecting changes in water availability and the impacts of climate change on water resources. NDWI is calculated using the following formula:

(2) $$NDWI = \frac{(SWIR - NIR)}{(SWIR + NIR)}$$

In the current research, the Tasseled Cap Transformation (TCT) model was implemented utilizing data acquired from the Sentinel-2 satellite. This orthogonal transformation technique is designed to convert the spectral information from satellite imagery into distinct spectral components, referred to as spectral indices [17]. Widely recognized in remote sensing, the TCT model has demonstrated effectiveness across numerous applications related to environmental monitoring and analysis [18]. Notably, the TCT coefficients are sensor-specific, necessitating their adaptation to the spectral characteristics of the Sentinel-2 multispectral instrument used in this research. The output of the TCT process generates multi-band images composed of three primary components — Wetness, Brightness, and Greenness. Following their derivation, each component undergoes further decomposition for detailed analysis [4, 8, 9].

The Normalized Differential Greenness Index (NDGI) is an index used to assess the dynamics of vegetation [19]. The NDGI index is derived from the Greenness component obtained through orthogonal image transformation (TCT) using satellite images from Sentinel-2. The NDGI reflects changes in the state of vegetation over different time periods. NDGI ranges from +1 to -1 and is applicable to assess the development of the vegetation process [19]:

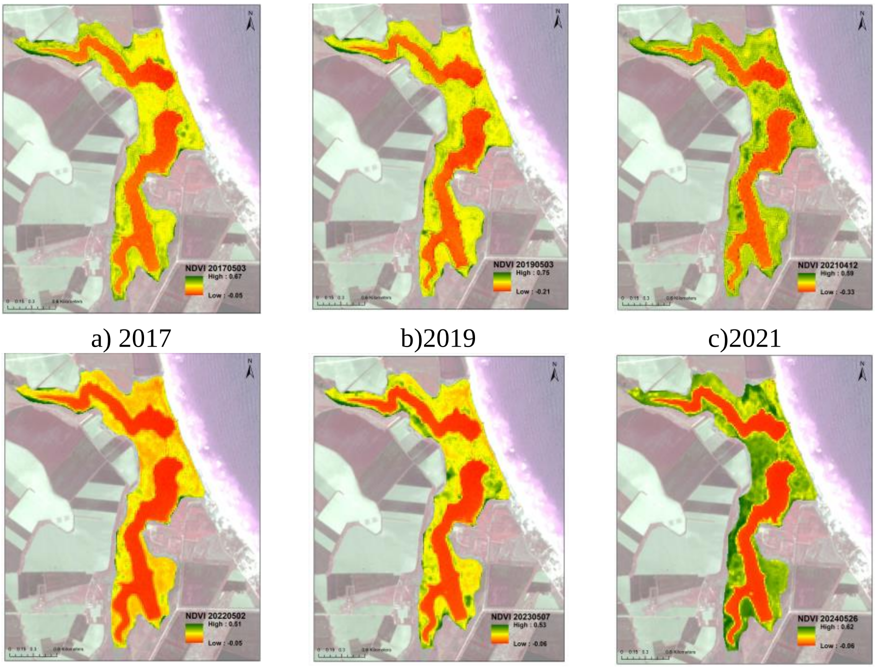
(3) $$NDGI = \frac{GR_n(t_2) - GR_n(t_1)}{|GR_n(t_2)| + |GR_n(t_1)|}$$

where $GR_n(t_1)$ and $GR_n(t_2)$ represent the normalized values of the Greenness components at time points t_1 and t_2, respectively, and $|GR_n(t_2)|$ and $|GR_n(t_1)|$ represent the absolute values of the same components [19].

Results

NDVI classification

The analysis of the NDVI for Shabla-Ezerts Lake was conducted on six different dates spanning the period from 2017 to 2024 (Fig. 2).



a) 2017 b)2019 c)2021

d) 2022 e) 2023 f) 2024

Fig. 2. NDVI classification

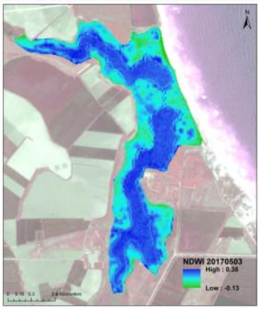
The NDVI index is used to assess the condition of vegetation cover, with its value ranging from -1 to 1 (corresponding to red and green colors). Values between 0.2 and 0.5 indicate sparse vegetation. Values above 0.5 indicate dense and healthy vegetation. Low values signal reduced or degraded vegetation and the presence of water or bare surfaces.

In 2017 (Fig. 2a), NDVI values ranged between -0.05 and 0.67. High values were observed mainly in the peripheral areas, indicating active and healthy vegetation. Low values in the central water body indicate the presence of open water areas or regions with sparse vegetation cover. In 2021 (Fig. 2c), a decline in maximum NDVI values compared to 2017 suggests potential vegetation degradation or an expansion of water areas and water bodies. By 2022 (Fig. 2d), most vegetation exhibited values between 0.3 and 0.5, indicating moderately developed vegetation, whereas lower values highlighted affected or degraded zones. In 2024 (Fig. 2f), NDVI values ranged from -0.06 to 0.62, suggesting partial recovery of vegetation cover relative to 2021. The maximum values approached those of 2017, indicating some improvement in ecological conditions, although areas with low values, likely linked to water bodies, remain.

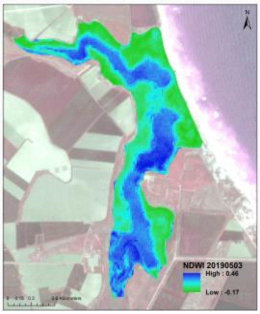
NDWI classification

The NDWI index reveals annual variations in the quantity and extent of water within the region (Fig. 3). High NDWI values, represented by blue shades, indicate the presence of water or wetland areas. Green shades reflect less saturated wetland zones or transitional areas. Local differences in green and blue regions between the figures may suggest changes in water distribution or the effects of climatic or anthropogenic activities.

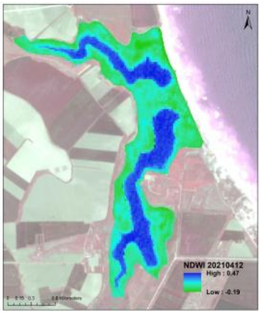
From 2017 to 2021 (Fig. 4a, b, c), a trend of increasing maximum NDWI values (from 0.38 to 0.47) is observed, which may indicate an expansion of water areas or an improvement in their condition. The minimum values become lower over the years, possibly reflecting the presence of transitional zones around the lake with varying moisture characteristics. The data are from the spring months (April and May), suggesting that the increase in water areas could be linked to increased rainfall.



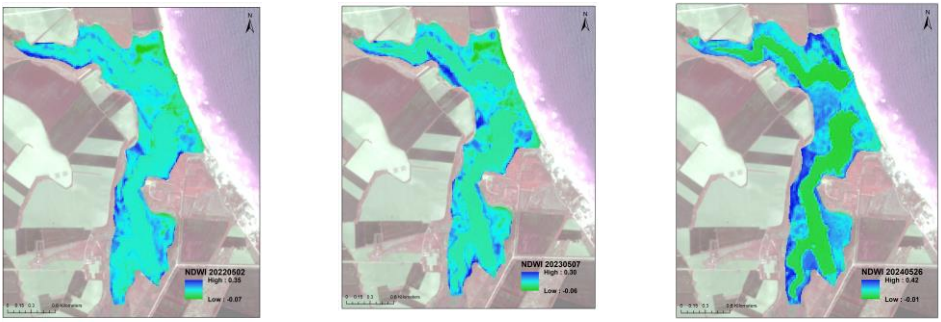
a) 2017



b) 2019



c) 2021



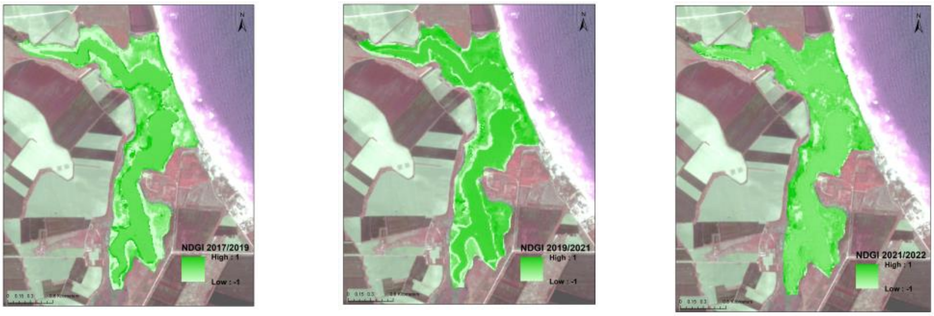
d) 2022 e) 2023 f) 2024

Fig. 3. NDWI classification

Between 2022 and 2024 (Fig. 4d, e, f), some fluctuations in NDWI values are noticeable. In 2022 (Fig. 4d), the NDWI values range between -0.07 and 0.35. Compared to 2021, these values are lower, which may indicate a reduction in water quantity or wetland areas during this period. In 2023, the NDWI values are at their lowest (0.30), suggesting a possible decrease in water reserves or drought conditions. By 2024 (Fig. 4f), the maximum value rises to 0.42, implying an increase in areas with high values (open water bodies). The higher maximum value indicates the presence of more open water bodies or a significant reduction in impurities.

NDGI classification

The obtained results, which present the NDGI values for various periods (2017/2019, 2019/2021, 2021/2022, 2022/2023, 2023/2024) (Fig. 4), enable an analysis of vegetation development dynamics. The NDGI assesses the intensity of vegetation, with higher values (positive, dark green) indicating more developed vegetation, and lower values (negative, light green) indicating reduced or absence of vegetation.



a) 2017/2019 b) 2019/2021 c) 2021/2022

d) 2022/2023

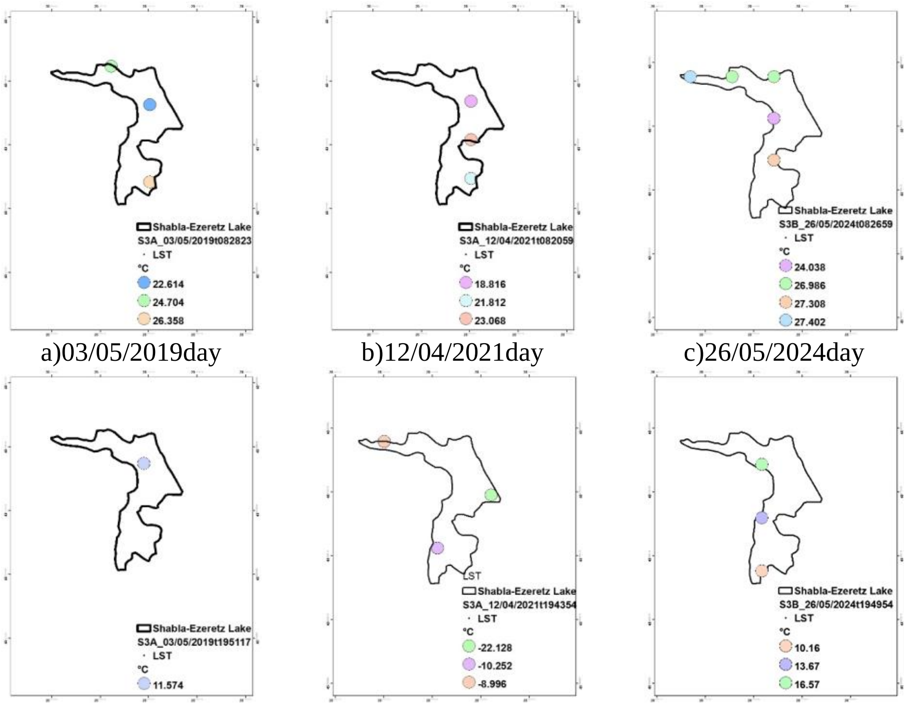
e) 2023/2024

Fig. 4. NDWI classification

For the period of 2017/2019 (Fig. 4a), the green areas are more limited in extent compared to the subsequent periods. During 2019/2021(Fig. 4b), a significant increase in green areas was observed, including within the water bodies. For the period of 2021/2022 (Fig. 4c), the green areas continued to expand, covering a larger portion of the territory. This could be due to natural factors such as specific climatic conditions, human activities, or processes of eutrophication. For the 2023/2024 period (Fig. 4e), an expansion of areas with high NDGI values (dark green color) is observed, compared to 2022/2023 (Fig. 4d). This suggests that the vegetation around the lake has increased or become denser during the past period. Areas with lighter green shades and negative NDGI values remain relatively stable, indicating that these regions are minimally affected or have not undergone significant changes during the observed periods. The increase in vegetation is most noticeable near the lake's shores and in certain inland sections. The elevated NDGI values around the periphery of the water bodies may indicate the expansion of terrestrial vegetation. The presence of dense vegetation in the coastal zones (high NDGI) can, in turn, act as a filter for nutrients, limiting their transfer into the water bodies and thus slowing down eutrophication. Although NDGI does not directly measure these parameters, an indirect analysis of the vegetation surrounding the water bodies can help identify early signs of such processes.

LST results

For a better understanding of the causes of these changes, more detailed data, such as climatic factors from Sentinel-3 SLSTR, have been analyzed (Fig. 5). Based on the LST data, it can be summarized that the area of interest falls within a region with relatively high LST values, which is typical for northeastern Bulgaria during this time of the year. Even in early May, temperatures in the northeast can reach up to +40°C. The minimum values for the specific granules are almost identical, ranging from -46 °C to -48 °C.



a)03/05/2019day b)12/04/2021day c)26/05/2024day

d)03/05/2019night e)12/04/2021night f)26/05/2024night

Fig. 5. LST day and night point images, Sentinel 3 SLSTR, ESA

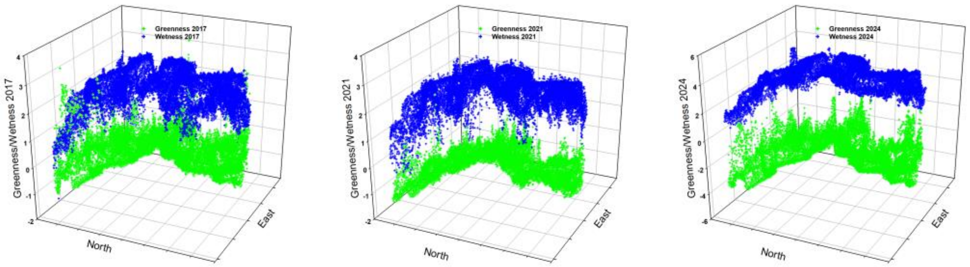
Another characteristic of the area around the lake is that within its territory, temperatures can range from 22 to 26°C for 2019 during the day (Fig. 5a), 18 to 23°C for 2021 during the day (Fig. 5b), and 24 to 27°C for 2024 during the day (Fig. 5c). This indicates that different processes occur in the northern and southern parts of the lake. However, there is no strict pattern observed, such as the north being consistently warmer than the south or vice versa (Fig. 5).

The differences between daytime and nighttime LST values are drastic.
A constant value was observed for the entire lake only in 2019 (Fig. 5d). In the evening image, large differences in the values of the night images for 2021 (Fig. 5e) and 2024 (Fig. 5f) were observed.

High temperatures stimulate the growth of algae and other organisms, accelerating the process of eutrophication. In the presence of increased nutrient levels, these organisms reproduce rapidly. At lower temperatures, biological processes slow down, which can limit the rate of eutrophication. It is evident that temperature affects the water's ability to retain oxygen. Warm water holds less dissolved oxygen, worsening conditions for aerobic organisms, such as fish and other aquatic life. The lack of oxygen is a result of eutrophication, leading to the decline or collapse of aquatic ecosystems. During the warmer months, a warmer surface layer was observed, which disrupts circulation in the bottom layers. This, combined with the presence of decaying organic matter accumulated as a result of eutrophication, depletes oxygen levels in the water.

Spatial distribution of vegetation and water

The graphs presented depict the temporal dynamics of vegetation (greenness) and water (wetness) components in the Shabla-Ezerets Lake area, as determined by the TCT model, for the years 2017, 2021, and 2024 (Fig. 6).



a) 2017 b)2021 c)2024

Fig. 6. Spatial distribution of vegetation (greenness) and water (wetness)

The green and blue points represent greenness and wetness components, respectively, plotted against spatial coordinates (North-East) to capture spatial variability. In 2017 (Fig. 6a), the greenness (green points) was distributed mostly between values of -1 and 2, indicating moderate vegetation cover. The distribution suggests relatively uniform vegetation cover with some variation near the lower range. Wetness (blue points) was concentrated between 1 and 3, indicating stable water presence across the area (Fig. 6a). The wetness values suggest moderate water retention levels without any significant anomalies.

In 2021 (Fig. 6b), the greenness component exhibited a slight decrease in values compared to 2017 (Fig. 6a), with values clustering closer to 0 and 1. This trend may indicate vegetation stress or a reduction in plant cover, potentially attributed to seasonal variations, anthropogenic activities, or climatic effects. The wetness component remained relatively consistent with 2017; however, it demonstrated slightly broader variability, extending below 1. These observations may suggest minor fluctuations in water levels or localized drying trends.

In 2024 (Fig. 6c), greenness exhibited a further reduction, with values ranging from -2 to 2, indicating increased variability and more negative values. This trend suggests potential degradation of vegetation cover, possibly due to environmental stressors, salinity changes, or pollution. Wetness values demonstrated an upward trend, ranging between 2 and 4, and extending up to 6 in some areas. This may reflect increased water retention, potentially associated with precipitation patterns, hydrological changes, or flooding events. Wetness values generally increased, suggesting rising water levels or greater moisture content, which might be indicative of hydrological shifts or climatic influences. The diverging trends between greenness and wetness point to potential ecological imbalances, warranting continuous monitoring and targeted conservation efforts.

Discussion

Ongoing, consistent monitoring using index classification is crucial for tracking long-term changes in the Shabla-Ezerets Lake ecosystem. Additionally, it is recommended to implement measures to control eutrophication and regulate the water regime, with the goal of enhancing the condition of vegetation and biodiversity in the region. The combined analysis of NDWI and NDGI provides insights into the dynamics of water and vegetation over time.

The interaction between NDWI and NDGI indicates that, while water bodies experience fluctuations, the surrounding vegetation has grown, impacting nutrient cycling and water quality. Monitoring these indices together provides early indicators of ecological changes, such as eutrophication, which can impact water clarity, oxygen levels, and the overall ecosystem balance. The temporal analysis of greenness and wetness components in the Shabla-Ezerets Lake ecosystem reveals notable trends in vegetation and water dynamics over the study period. The observed decline in greenness values suggests increasing stress on vegetation, potentially linked to environmental degradation, human influence, or climatic variations. Conversely, the rise in wetness values may indicate changes in hydrological regimes, including higher water retention and possible flooding events.

LST can play a key role in analyzing the intensity and effects of eutrophication. In the context of climate change, rising temperatures and LST in the area of the water body are likely to exacerbate the issue of eutrophication, placing greater pressure on ecosystems and water resources. Higher temperatures accelerate the decomposition of organic matter, releasing more carbon dioxide, ammonia, and methane. This not only intensifies the process of eutrophication but can also degrade water quality. Certain species of algae proliferate more rapidly at elevated temperatures, as evidenced by LST data. These "blooms" are a direct result of the combination of eutrophication and water warming (Fig. 5).

Further investigations are recommended to ensure the sustainable management of the Shabla-Ezerets Lake ecosystem. These should include detailed field studies to validate remote sensing data and identify specific drivers of vegetation degradation. Continuous monitoring using advanced satellite imagery and higher-resolution data is crucial for detecting subtle environmental changes.

Additionally, implementing conservation measures such as controlling pollution sources, managing water inflows, and promoting vegetation restoration can help reduce negative impacts and maintain the region's ecological balance.

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МОНИТОРИНГ НА ШАБЛЕНСКО-ЕЗЕРЕЦКО ЕЗЕРО ЗА ПЕРИОДА 2017–2024 Г. ПО ДАННИ ОТ SENTINEL

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Резюме

Това изследване представя 8-годишна мониторингова оценка на Шабленско-Езерецко езеро, разположено върху сарматски варовици в Североизточна България, на около 5 км североизточно от град Шабла. Езерото е част от Защитената територия "Шабленски езерен комплекс", който се състои от две съседни крайбрежни лиманни езера — Шабленско и Езерецко — които са свързани помежду си с изкуствено изкопан канал. През последните години спътникови изображения с висока разделителна способност и данни, предоставени от спътниците от серията Sentinel на Европейската космическа агенция, имат важна роля в наблюдението на екологичната и хидроложката динамика на комплекса. Тези данни позволяват събирането на ценна дългосрочна информация за водните ресурси, улеснявайки анализа на тенденции като колебания в нивата на водата, промени в растителната покривка и идентифициране на потенциални източници на замърсяване. Настоящето изследване използва данни от спътниците Sentinel-2MSI и Sentinel-3SLSTR, с цел да се оцени пространствено-времевата динамика на района за периода 2017–2024 г., предоставяйки информация за промените в околната среда и допринасяйки за ефективни стратегии за опазване и управление.