Using Sentinel-2 data for Efficient Monitoring and Modeling of Wetland Protected Areas

Iva Ivanova[a], Temenuzhka Spasova[a]*, Nataliya Stankova[a]
[a]Space Research and Technology Institute – Bulgarian Academy of Sciences, Department of Aerospace information, Acad. G. Bonchev Str., Bl. 1, 1113 Sofia, Bulgaria

ABSTRACT

Wetlands are ecologically vital habitats that play a crucial role in supporting biodiversity and providing essential ecosystem services. They are considered to be among the most productive ecosystems on the planet that provide numerous benefits. For the purposes of this study, Straldzha Complex Protected Area, Bulgaria was chosen as the object of investigation. Straldzha Complex Protected Area includes a reservoir and surrounding wetlands and meadows, the remains of the eastern part of the former Straldzha Plateau (the largest plateau ever in Bulgaria). The wetland is sensitive to human activities, related to the water management and unsustainable use of the former plateau as agricultural land.

For the purposes of this study, data from Sentinel-2 satellite of the European Space Agency were used. The monitoring was carried out during the study period 2017 – 2022. An index-based classification was used in the study, utilizing NDVI, NDWI and MSAVI2 indices for classifying the contents within the wetlands boundaries. NDGI model was applied as well, evaluating the vegetation dynamics in the marsh. The obtained results showed successful mapping and monitoring of wetlands. The wetlands are of high importance and should be protected and conserved to maintain the benefits they provide to the environment and society.

The data and results of this research will be able to serve Destination Earth (DestinE), which is an ambitious initiative of the European Union to create a digital model of the Earth that will be used for monitoring the effects of natural and human activities on our planet, prediction of extreme events and adapting policies to the climate challenges. The data and models will serve the Bulgarian initiative for the construction of the Digital Twins, which is being pilot developed in the department of Aerospace Information, Space Research and Technology Institute – Bulgarian Academy of Sciences. Open Data were used in this study, with the aim of promoting the Open science policy and FAIR principles as much as possible.

Keywords: Satellite data, Sentinel-2, Wetlands, Monitoring, Modeling, Indices.

1. INTRODUCTION

A wetland is a land area that is saturated with water, either permanently or seasonally, so that it takes on the characteristics of a distinct ecosystem. This is an ecosystem where water is the main factor upon which ecological conditions and the associated animals and plants depend[1]. Wetlands can be considered as one of the most productive ecosystems on the Earth. Wetlands around the world are facing threats from human activities such as drainage, pollution, and land conversion. Climate change is also a significant threat to the wetlands, as rising sea levels and changes in precipitation patterns can alter the natural balance of these fragile ecosystems. Invasive species and overfishing can also disrupt the delicate balance of wetland ecosystems, threatening the survival of native species and causing long-term damage to the environment. The loss of wetlands can have serious consequences for human communities as well, since wetlands play an essential role in regulating water quality and quantity, providing habitat for wildlife, and supporting important economic activities such as fishing and tourism. Protecting and restoring wetlands is crucial for maintaining the health and well-being of both the natural world and human societies, and requires a concerted effort from governments, NGOs, and individuals around the globe.

The wetlands in Bulgaria cover an area of 133 189, 86 ha.

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1.1. Region of interest

For the purposes of this study, a typical wetland area in Bulgaria was selected – the Straldzha Complex. It includes the Tsarkovski Reservoir, neighboring wet meadows and marshy areas, remains of the eastern part of the former Straldzha Swamp[2] (the largest swamp ever in Bulgaria). It is located in Burgas and Yambol regions (Figure 1). The area covers a total of 2871.82 ha. The reservoir itself is an open water area, partially overgrown with hydrophilic vegetation dominated by bulrush (*Typha spp.*) in its eastern part. It is surrounded by low elevation to the north (234.6 m above sea level) and by flat arable land to the south (around 150 m above sea level). To the west of the reservoir, there are lower-lying areas occupied by wet meadows, marshy areas with a system of drainage canals, and during rainy spring seasons, small temporary boggy ponds. The wet meadows are covered with mesophilic grass vegetation. Strips mainly consisting of poplar (*Populus spp.*), white acacia (*Robinia pseudoacacia*), and some other cultivated species form the only areas with forest vegetation in the region. Straldzha Swamp used to be the largest inland swamp in Bulgaria until the mid-1920s, when its gradual drying out began. At that time, the Dalmatian pelican and Curly pelican had nested there in large numbers, as well as the common crane. By the 1940s, the swamp had completely dried out, despite the working drainage system, a large part of the area still floods and is covered with reeds during rainy years. Today, 143 species have been identified in Straldzha Complex, 50 are listed in the Red Book of Bulgaria. 70 of the species found are with European nature conservation significance (SPEC)[2]. The wetland area is sensitive to human activities related to water management, as well as unsustainable use of the former marshland as agricultural land. Constant drainage of the area reduces the quality of habitats related to providing sufficient space for resting and feeding migratory birds. Part of the territory is planted with cereal crops and intensively treated with artificial fertilizers and pesticides to achieve good yields and remove the reeds. The draining of the remaining wetlands and marshes leads to further loss of valuable habitats. The distillery located near the river causes its waters to be polluted. The temporary drying up of the river, including in winter, does not allow for the full use of the wetland as a resting and feeding place. Hunting and fishing cause distress to birds. The unrestricted and uncontrolled access to the whole territory during the nesting period also causes distress to the nesting birds. In 1998, about 95% of the territory was designated as a CORINE site due to its European importance for the conservation of rare and endangered habitats, plants and animals, including migratory water birds. In 1997, the territory was declared an Important Bird Area by BirdLife International. In 2008, the site was added to the European network of protected areas - NATURA2000 zone.

Figure 1. Location of Straldzha Complex (NATURA 2000), Sentinel 2, 2022

2. DATA AND METHODS

2.1. Data

Data from Sentinel-2 by the European Space Agency (ESA) as part of the Copernicus program were used[3,4]. The mission's objective is to provide global, high-resolution, and multi-spectral images of the Earth's surface. The Copernicus SENTINEL-2 mission comprises a constellation of two polar-orbiting satellites placed in the same sun-synchronous orbit, phased at 180° to each other. It aims monitoring variability in land surface conditions, and its wide swath width (290 km) and high revisit time (10 days at the equator with one satellite, and 5 days with 2 satellites under cloud-free conditions which results in 2-3 days at mid-latitudes) will support monitoring of Earth's surface changes. Generally, Sentinel-2 provides a valuable tool for monitoring and understanding the Earth's surface and can help us take informed decisions about the management and conservation of our planet[1,3,5,6].

The ecological monitoring of Straldzha Complex has been done over a period of six years, from 2017 to 2022. For this purpose, one satellite image was used per year. The selected satellite scenes were taken during the spring-summer season, when the vegetation in the area is well represented.

2.2. Data processing of satellite images

Multiband composite images were created by combining the available 13 channels for Sentinel 2 satellite images. These images were essential for subsequent analysis and processing, as they allowed for the extraction of indices values[4,5,6]. Thus, the territory of Straldzha Complex is visualized and suitable for further processing.

2.3. Index classification

Index classification from satellite images was applied for analyzing the spectral characteristics of satellite imagery, with the aim of identifying and mapping certain features or properties on the Earth's surface. This involves the calculation of various spectral indices, which are derived from the reflectance values of different bands of the satellite imagery. These indices were used to highlight specific features, such as vegetation density, water content, soil moisture, which can be used for various applications[1], including environmental monitoring and management of wetlands. Index classification from satellite images can be performed using various software tools and techniques, including remote sensing software, machine learning algorithms, and image processing techniques.

For the purposes of this research, the following indices were used:

2.3.1. NDVI

Normalized Difference Vegetation Index (NDVI) is a numerical index used to assess the health and vitality of the vegetation cover on the land. NDVI is derived from the remote sensing of vegetation reflectance in the visible and near-infrared bands of the electromagnetic spectrum[7,8].

The NDVI index is calculated using the following formula:

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

where NIR is the reflectance in the near-infrared band and Red is the reflectance in the red band.

The NDVI index is widely used in the agriculture, forestry, and ecology to monitor vegetation growth, estimate crop yields, assess drought conditions, and detect land cover changes.

2.3.2. NDWI

The Normalized Difference Water Index (NDWI)[9] is a satellite-derived index from the Near-Infrared (NIR) and Short Wave Infrared (SWIR) channels. The SWIR reflectance indicates changes in both the vegetation water content and the spongy mesophyll structure in vegetation canopies, while the NIR reflectance is affected by leaf internal structure and leaf dry matter content but not by water content. The combination of the NIR with the SWIR removes variations induced by leaf internal structure and leaf dry matter content, improving the accuracy in retrieving the vegetation water content[10]. 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[11,12]. The NDWI is a remote sensing based indicator, sensitive to the change in the water content of the leaves. As well as NDVI, NDWI is derived from remote sensing data[13,14,15], and it uses the differences in reflectance between two bands of the electromagnetic spectrum to identify the presence of water.

The NDWI index is calculated using the following formula:

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

where SWIR is the reflectance in the Short-Wave infrared band and NIR is the reflectance in the Near-infrared band.

NDWI is widely used in the hydrology, remote sensing, and land cover mapping to identify and monitor the spatial and temporal distribution of surface water in wetlands, rivers, lakes, and coastal zones. It is also useful for detecting changes in water availability and the impacts of climate change on water resources.

2.3.3. MSAVI2

Modified Soil-Adjusted Vegetation Index (MSAVI2)[16] is a vegetation index that aims to reduce the soil brightness effect in remote sensing images and provide a more accurate representation of the green vegetation cover. MSAVI2 is calculated as follows:

$$\text{MSAVI2} = \frac{(2*NIR + 1 - \sqrt{(2*NIR+1)^2} - 8*(NIR - RED))}{2} \tag{3}$$

where NIR represents the near-infrared reflectance and RED represents the red reflectance values of a given pixel in the remote sensing image.

The MSAVI2 is a modified version of the Soil-Adjusted Vegetation Index (SAVI) and takes into account the soil brightness effect in a more sophisticated manner than SAVI. The index is calculated using reflectance values in the near-infrared and red bands, which are typically available in satellite images. The MSAVI2 index is sensitive to changes in vegetation density and provides a more accurate representation of the green vegetation cover than other indices such as Normalized Difference Vegetation Index (NDVI)[16,17].

MSAVI2 is widely used in the agriculture, forestry, and ecological studies, as well as in land cover mapping and classification. It is commonly used with satellite images from sensors such as Landsat, MODIS, and Sentinel-2. The index can provide valuable information on the distribution and density of vegetation[18], which can be used to monitor changes in land cover, evaluate the impact of land-use changes, and support decision-making in land and resource management.

2.4. NDGI

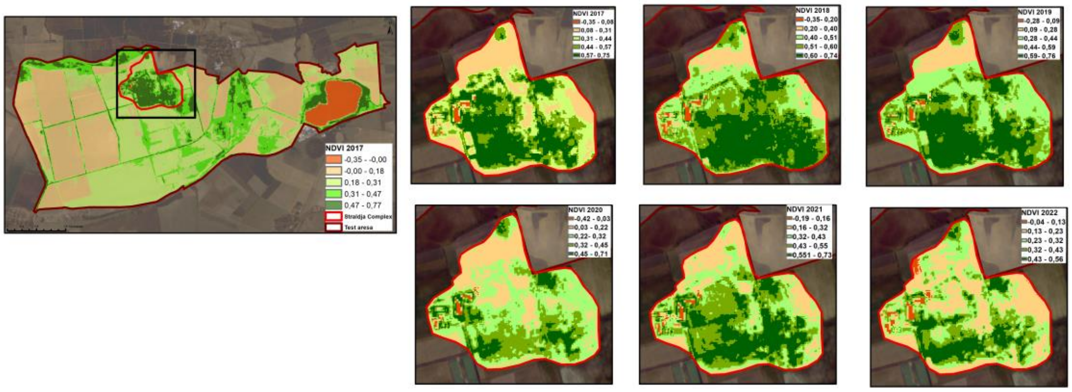
Normalized Differential Greenness Index (NDGI)[19] is an index for assessing the dynamics of vegetation. The NDGI index is derived from the Greenness component from orthogonal image transformation (TCT). Satellite images from Sentinel 2 were used. The approach to define NDGI is based on orthogonalization of satellite images using the Greenness component is based on the spectral reflection characteristics of vegetation. NDGI indicates the dynamics of the change in the state of vegetation using different time periods. NDGI ranges from +1 to -1 and is applicable to assess the development of the vegetation process.

3. RESULTS

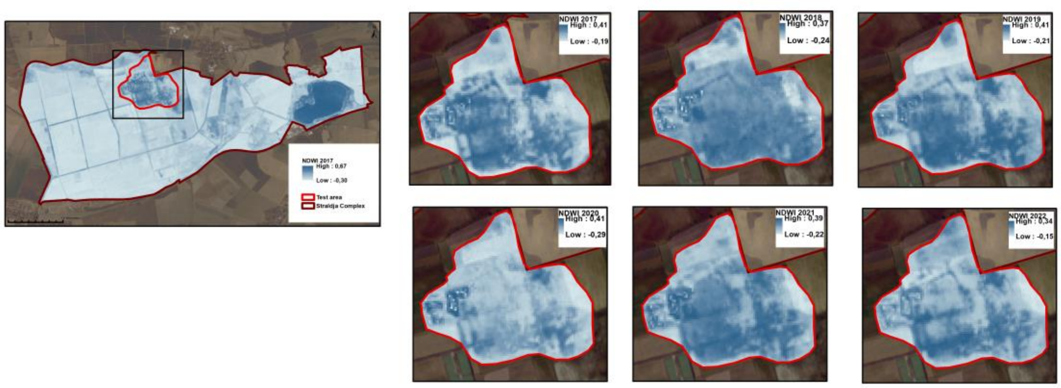
3.1. Results from index application

Figure 2 shows the results of the index classification of satellite images. For this purpose, a test area of the protected zone was chosen, which represents a typical wet meadow area with the presence of small water mirrors. This test area has a smaller territory which will allow for more accurate results for the applied classifications.

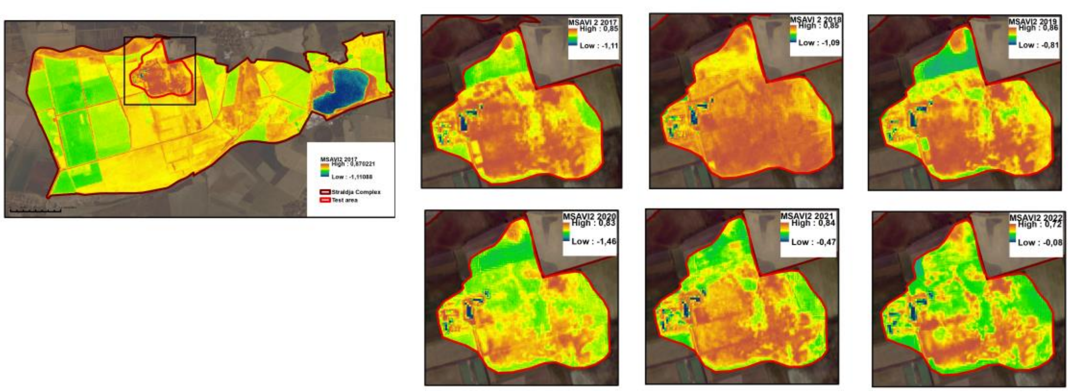
The results obtained from the NDVI classification (Fig. 2a) show the development of the leaf mass over the observed years. NDVI values range from -1 to +1, with higher values indicating denser, healthier vegetation. Negative values of NDVI (brown color) represent non-vegetated areas such as water or bare soil. The closer the value is to +1 (green color), the denser and healthier the vegetation cover is. The results show that the highest vegetation development was observed in 2018 and 2019, where NDVI values were highest - up to 0.76. The sparse vegetation was established in 2020, when the moisture in the test area was the lowest (Fig. 2b). In 2021 and 2022, the area covered by vegetation in the test zone is smaller compared to the previous years (2017-2019), and the NDVI index values decreased to 0.56 in 2022.



a) NDVI



b) NDWI



c) MSAVI2

Fig. 2 Index classification a) NDVI b) NDWI c) MSAVI2

The NDWI product is dimensionless and varies between -1 to +1, depending on the leaf water content, as well as on the vegetation type and cover (Figure 2b). High values of NDWI (dark blue color) correspond to high vegetation water content and to high vegetation fraction cover. Low NDWI values (white) correspond to low vegetation water content and low vegetation fraction cover. In the period of water stress, NDWI decreases (2020).

In Figure 2b it can be clearly seen that a threshold of zero (presented with light blue color) does not extract the small water bodies or the water bodies that contain vegetation[1]. A threshold of -0.41 successfully extracts pixels that contain water, in this case, a mixture of water and vegetation.

According to the obtained results, the highest values of the NDWI classification were acquired in 2017, 2018 and 2019 respectively, and the areas where these values were observed were larger when the vegetation was abundant. In the following years, when there was less vegetation in the test area, the NDWI index showed a smaller area of distribution and lower values. In 2021 and 2022, the index also had lower values - 0.39 and 0.34, but the area of water distribution had increased compared to 2020.

Figure 2c shows the results of the MSAVI2 index classification. MSAVI2 values should be in the range of -1.0 to +1.0, but these values are well beyond -1.0. After verifying the calculations, we have determined that there were no errors and they appear to be correct.

The higher the value, the higher the water content. In order to accurately monitor changes in water content at the pixel or plot level over time, it is necessary to ensure that there are no significant changes in the underlying biomass during the same period (i.e., NDVI or MSAVI2 do not change significantly)[18]. This is because higher biomass can result in higher values for water content indicators, which can make it difficult to distinguish changes in water content from changes in biomass.

The highest values of the index were observed in 2018 - 0.86, they were also high in 2017 and 2019. During this period, high values of the NDVI and NDWI index were also observed. The values decreased to 0.72 in 2022.

3.2. NDGI model application

Fig.3 shows the results obtained by applying the NDGI model for estimating the dynamics of vegetation in the test area in Straldzha Complex at different time intervals for the period 2017-2022. NDGI shows the dynamics of vegetation change over different time periods. NDGI takes values from +1 to -1, which is applicable for assessing the development of the vegetation process, allowing for more precise assessment of the particular moments of the vegetation process[19]. Values of -1 (red color) indicate minimal changes in vegetation, and values of +1 (in green) - maximum changes in vegetation dynamics. Fig. 3 shows that the most changes in the vegetation in the test area are observed for the period 2017/2018 and 2018/2019 (in green) and the results of NDVI show significant vegetation overgrowth. In the following periods, the rates are significantly lower and the territories that cover these low values are larger (in red).

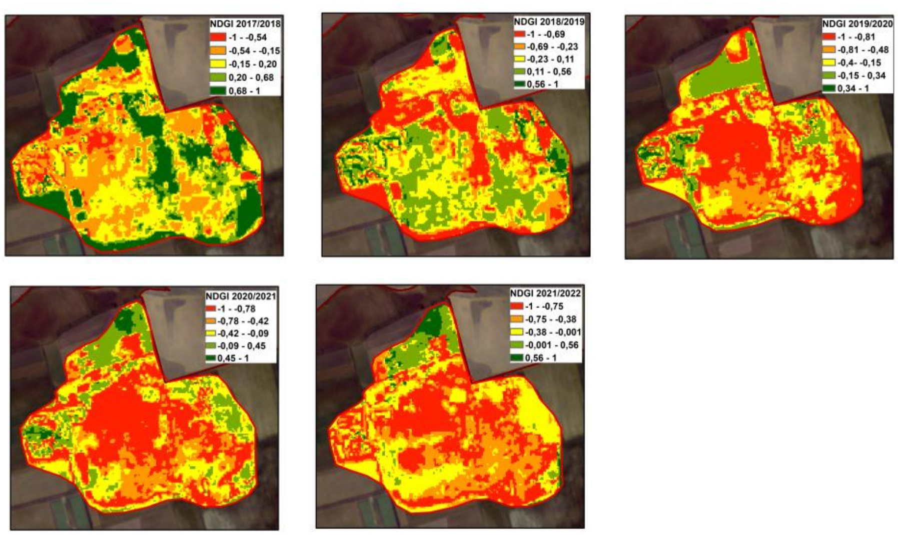
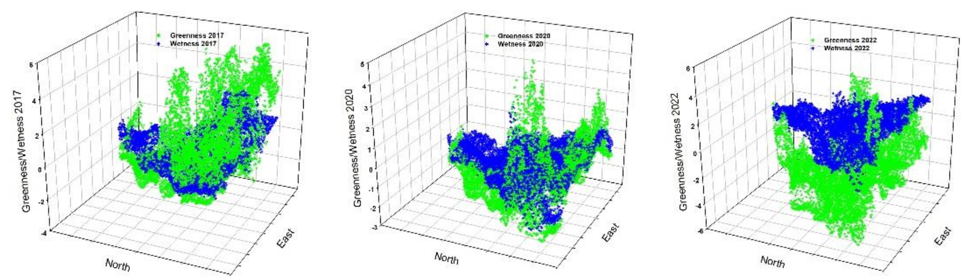


Fig. 3 NDGI model application

3.3. Spatial distribution of vegetation and water

Figure 4 shows the spatial distribution of the components of the earth's surface - vegetation and water, obtained from the TCT model, derived from the Sentinel 2 images for the period 2017-2022. This spatial distribution was made as an example for the years 2017, 2020, and 2022.



a)2017 b)2020 c)2022

Fig. 4 Spatial distribution of vegetation and water

Figure 4a shows the ratio between the two components in 2017, where the Greenness (vegetation component) dominates over the Wetness (water component). In 2020 there was a significant decrease in the Greenness component, while the Wetness was better represented, according to the data. A gradually differentiation of the water component from the vegetation one can be observed in 2022.

4. CONCLUSION

Based on the obtained results from the analysis, it can be inferred that this particular wetland ecosystem undergoes notable changes over the course of time. Monitoring the changes in the wetland during the study period, it has been established that the wetland was in its optimal state during the period between 2017 and 2019. However, in 2020, a drying was witnessed in the area, which led to a decline in the overall condition of the wetland. Nonetheless, there has been a slight improvement in the condition of the wetland in 2021 and 2022. These results suggest that this wetland ecosystem has the natural capacity to recover from environmental disturbances, provided the environmental conditions are suitable for its restoration.

The proposed methodology has numerous practical uses. The results of the current study reveal the progression of a standard wetland and its changes over a six-year observation period. The obtained results provide an accurate monitoring of the wetland over a significant period of time, offering insight into its state and the imperative to implement preservation strategies for its protection and control.

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