Assessing Spatio-temporal Changes of Floating Aquatic Vegetation in Lake Sevan Using Landsat Imagery and Vegetation Indices

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Abstract
This research was carried out as part of the "Copernicus assisted environmental monitoring across the Black Sea Basin – PONTOS" project, which aimed to support and enhance environmental monitoring in the Black Sea Basin region by utilizing Earth Observation products obtained from satellite, airborne, and ground sources. The project team evaluated the environmental monitoring system in pilot sites across Armenia, Greece, Georgia, and Ukraine. The current study focused on assessing changes in wetland and floating vegetation cover from 2009-2015 in Lake Sevan, the largest freshwater source in Armenia and one of the project's pilot sites. Monitoring spatio-temporal changes in aquatic vegetation is crucial for understanding the ecological and socioeconomic functions of lake ecosystems, and requires standardized methods. In order to identify floating aquatic vegetation in Lake Sevan, this study utilized Landsat TM and OLI imagery that were acquired during the main growing season from middle May to middle September of the years 2009-2015. To enhance the classification process, vegetation indices such as the Normalized Difference Vegetation Index (NDVI), Normalized Difference Aquatic Vegetation Index (NDAVI), and Normalized Difference Water Index (NDWI) were applied. The findings of this study indicate that medium-resolution Landsat and similar satellite images, which are freely available, can be effectively used to monitor spatiotemporal changes in lakes in a reproducible and continuous manner. However, it was also discovered that algal blooms can significantly hinder the accurate detection of floating vegetation from satellite imagery.

Keywords: Aquatic floating vegetation, Earth Observation, Lake Sevan, Landsat, Vegetation Index

1. Introduction

Aquatic vegetation is a diverse group of photosynthetic organisms that grow permanently or periodically in wetlands, the shoreline of lakes and along streams [1] [2] [3] and [4]. They are a natural part of every lake ecosystem and serve many purposes in a lake, can help the migration and circulation of elements, purify water quality, and limit the growth of algae [5]. They are an integral part of aquatic ecosystems and play an important role in immobilizing pollutants, regulating oxygen production and global carbon cycle, stabilizing sediments and protecting shore erosion [4] [6] and [7].

Aquatic vegetation can be classified into four functional groups as emergent (EAV), floating-leaved (FAV) and rooted, free-floating, and submerged (SAV), based on their growth form, morphology, and adaptation to the environment [8] and [9]. Figure 1 shows classification schemes for aquatic vegetation types. The impact of anthropogenic stressors and climate change on water-level and aquatic vegetation has been evident in recent decades. The interaction between anthropogenic stressors, land-use change, and water-level variability affects aquatic macrophytes to a great extent [10]. Therefore, it plays a critical role in protecting the biodiversity and ecological balance of freshwater ecosystems such as lakes and rivers [11]. Distribution and composition of macrophyte communities are influenced by nutrient load, and climatic and hydrological conditions such as spatial and temporal variations of water level [4] [12] and [13]. Lake water level changes provide an opening for seedling recruitment for perennial emergent aquatic plants [14] and [15].

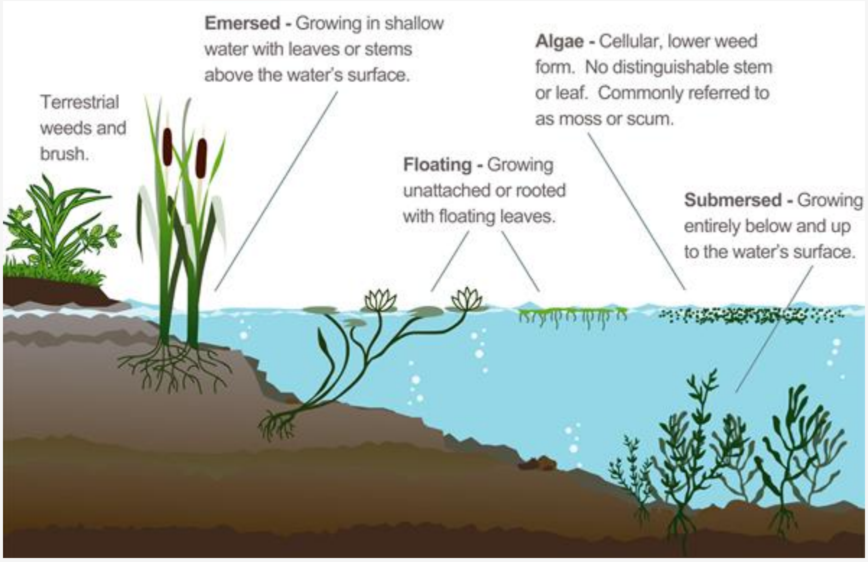

Figure 1: Classification of different types of aquatic vegetation [16]

Climatic conditions such as temperature and rainfall fluctuations also affect germination rates of aquatic vegetation [4] [17] and [18]. Timely recording and mapping of spatio-temporal distribution and composition of macrophytes is necessary to understand factors which influence distribution and composition of macrophytes [19]. Conventional field survey approaches for macrophyte monitoring can give good estimates and provide reliable and reproducible taxonomic information [20] [21] and [22]. However, these methods cannot capture whole-lake macrophyte cover or their patchy distribution and are hindered by technical and logistical limitations [23] and [24]. Alternative approaches such as remote sensing techniques and the use of satellite imagery can provide data covering large areas in space and time [19] [25] and [26].

Different remote sensing techniques have been developed to systematize the identification and change detection of aquatic vegetation from satellite data [27] and [28] and recent advances in satellite image resolution make it possible to classify multiple species with higher accuracy level [29] [30]. Recent developments in specifically designed vegetation indices for aquatic vegetation have improved identification and detection of macrophytes from medium resolution satellite images [26] [28] [31] and [32].

Remote sensing is one of the most useful tools for mapping and studying vegetation because of the advantages of synoptic view (in time and space) compared to traditional in situ survey. Remotely sensed vegetation indices (VIs) derived from airborne and satellite images represent a powerful and effective way to monitor vegetation status, growth, and bio-physical parameters. This is especially true for aquatic ecosystems; whose characterization is extremely time-consuming and expensive. This work runs a comparison of different VIs in mapping floating vegetation and assesses the capabilities of three indices to analyze aquatic ecosystems: The Normalized Difference Vegetation Index (NDVI), Normalized Difference Aquatic Vegetation Index (NDAVI) and the Normalized Difference Water Index (NDWI).

2. Study Area

Lake Sevan is the largest water body in Armenia. It is an alpine freshwater lake situated at more than 1,900 meters (6,234 ft) above sea level and is vital for Armenia's economy, tourism, agriculture, and other industrial sectors. It also has a significant cultural and recreational value for the country. The water volume and surface area of Lake Sevan have varied significantly over the past century. Since the early 1930s, Soviet authorities sought to exploit the lake to fulfill their ambitious plans for industrialization and modernization of agriculture. It was planned to implement the project in 2 stages. In the first phase, the water level of the lake would decrease by 50 meters, and the surface of the water mirror would be reduced to seven times (Big Sevan would dry completely). In the second phase, the use of water resources to irrigate Ararat valley has been planned, as a result, the water outflow (around 700 million cubic meters per year) from the lake would be carried out.

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After these, about 1000 sq.km of land would be vacated for agricultural purposes in the Gegharkunik region. Also, 130,000 hectares of agricultural land in Ararat Valley should be irrigated at the expense of Lake Sevan waters.

Thus, in the 1930s, the reduction of Lake Sevan had begun. During the 1st stage, the scientists recorded that the lake's ecological status suffered faster than it was supposed to be. The lake had been deprived of more than 40% of the water reserves within the next 10 years, with a maximum depth not exceeding 80 m (formerly 99 m). By the mid-1990s, the water level had decreased by around 19 meters and was subject to eutrophication, an increase in the concentration of phosphorus, nitrogen, and other plant nutrients.

In addition, the vacated areas were not suitable for agricultural use, as well as the lake's water was poorly suitable for irrigation due to the high concentration of magnesium and carbonate. There was a need to restore the lake's water reserves at the expense of other rivers being transferred to Lake Sevan. Since 1981, the Arpa-Sevan tunnel was built and part of Arpa River (South part of Armenia) water moved to the Sevan Lake. As a result of these fluctuations in the water level in the lake, the land cover of the area has changed significantly: the coastal zones of the lake were covered with water until the 1930s, then by land after the 1930s and, finally, to this day, they continue to be covered with water (after 1981s). As of 2019, the surface area of the Sevan Lake is 1 279 sq.km with 38.3 cubic km of water volume. The "blooming" of the Sevan Lake was continuing to be recorded, in 2018 covering the whole lake, due to the active eutrophication processes.

2.1 Lake Vegetation

Vegetation cover of the lake. Sevan has been repeatedly studied since the very beginning of hydrobiological studies on the lake [33] [34] [35] and [36]. As a result of these works, the species composition of macrophytes, distribution by water area and depth, production was identified, and changes due to a decrease in the water level in the lake were also shown. The flora of Lake Sevan basin is represented by 32 species from 27 genera and 21 families of cryptogamous and vascular macrophytes. The first ones include microscopic green, yellow-green siphon and char algae, mosses, 11 species in total from 9 genera and 7 families [33].

The second group of plants is more diverse - 21 species from 18 genera and 14 families. The leading families in terms of the number of taxa are Potamogetonaceae Dumort, Cyperaceae Juss., Lamiaceae Martinov, Lemnaceae S.F. Gray, Poaceae Barnhart, Ranunculaceae Adans., genus Potamogeton L., Lemna L. (2). The water fraction (hydro-, hygro-/helo- and hydro-/hygro-helophytes) includes almost all macroalgae and mosses. In the ecological spectrum, the majority of flora species (25 species, or 78.1%) belong to plants traditionally classified as aquatic. All species of macroalgae are typical hydrophytes. Almost all of the listed species of mosses are found in the waters of the lake and at considerable and even great depths [33] [34] and [35]. Among the vascular plants, the most diverse are the aquatic groups: hydrophytes and helophytes. Plants of waterlogged and humid habitats are represented by hygrophytes (6 species). The ratio of the number of hydrophytic species of vascular plants to the number of all their species is equal to 71.4% [33]. It shows the specifics of the reservoir - a mountainous, deep-water lake without overgrowing coastal shallow waters, which does not allow moisture-loving coastal species to penetrate into the water.

3. Data and Methods

3.1 Satellite Data Acquisition and Image Pre-Processing

Cloud free TM L2 and OLI L2 data with a resolution of 30 m were downloaded using QGIS Semi-Automatic Classification Plugin (SCP) (the path/row is 169/032 respectively). Only images with less than 10% cloud cover were selected for this study. A total of 5 OLI images and 2 TM without cloud coverage on AOI during warm season (May-September) from 2009 to 2015 were selected to ensure throughout the entire growth period of floating vegetation (Figure 2). All acquired images were referenced in the World Geodetic System (WGS84) datum. Details and specifications of satellite images used in this study are presented in Table 1. All downloaded satellite images were imported into the Semi-automatic Classification Plugin (SCP) for QGIS. Radiance values were converted into surface reflectance based on the image-based dark object subtraction (DOS) atmospheric correction approach in the SCP [37]. A radiometric correction was also applied using the plugin (SCP) to remove radiometric defects, haze and to improve the visual impact of true and false color composites.

The lake extent with aquatic and semi-terrestrial vegetation was delineated and digitized based on visible spectral-radiometric differences in the images. The Bing Satellite Map was used for the validation. The images were clipped using the digitized polygons shapefile (Figure 3).

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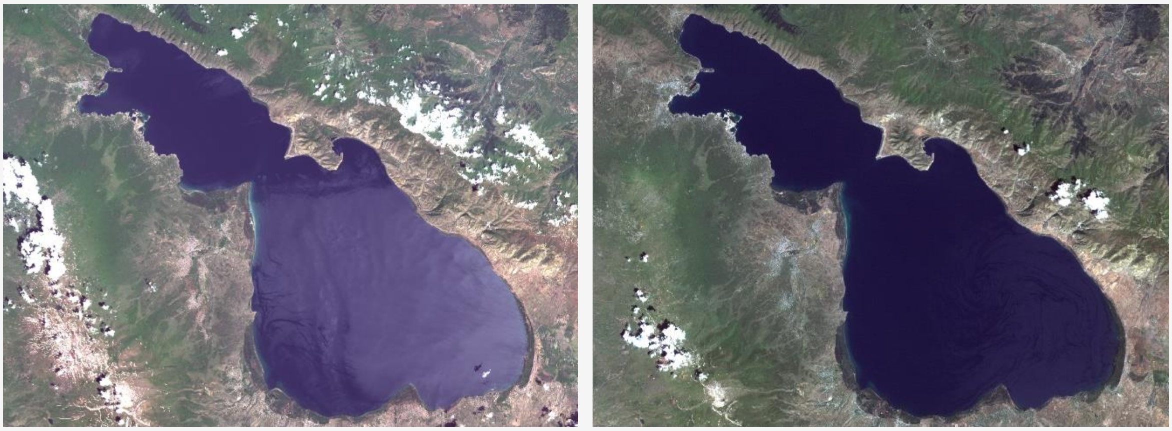
Table 1: Landsat image data information

Season	Sensor	Product ID	Date
Spring	OLI/TIRS	LC08_L1TP_169032_20140517_20170422_01_T1	17.05.2014
Summer	TM	LT05_L1TP_169032_20090604_20161025_01_T1	04.06.2009
	TM	LT05_L1TP_169032_20110728_20161009_01_T1	28.07.2011
	OLI/TIRS	LC08_L1TP_169032_20130615_20170503_01_T1	15.06.2013
	OLI/TIRS	LC08_L1TP_169032_20130701_20170503_01_T1	01.07.2013
	OLI/TIRS	LC08_L1TP_169032_20150621_20170407_01_T1	21.06.2015
Autumn	OLI/TIRS	LC08_L1TP_169032_20150909_20170404_01_T1	09.09.2015



(a) (b)

Figure 2: Landsat TM and OLI images in natural color composite: (a) 2011-07-28, (b) 2015-06-21

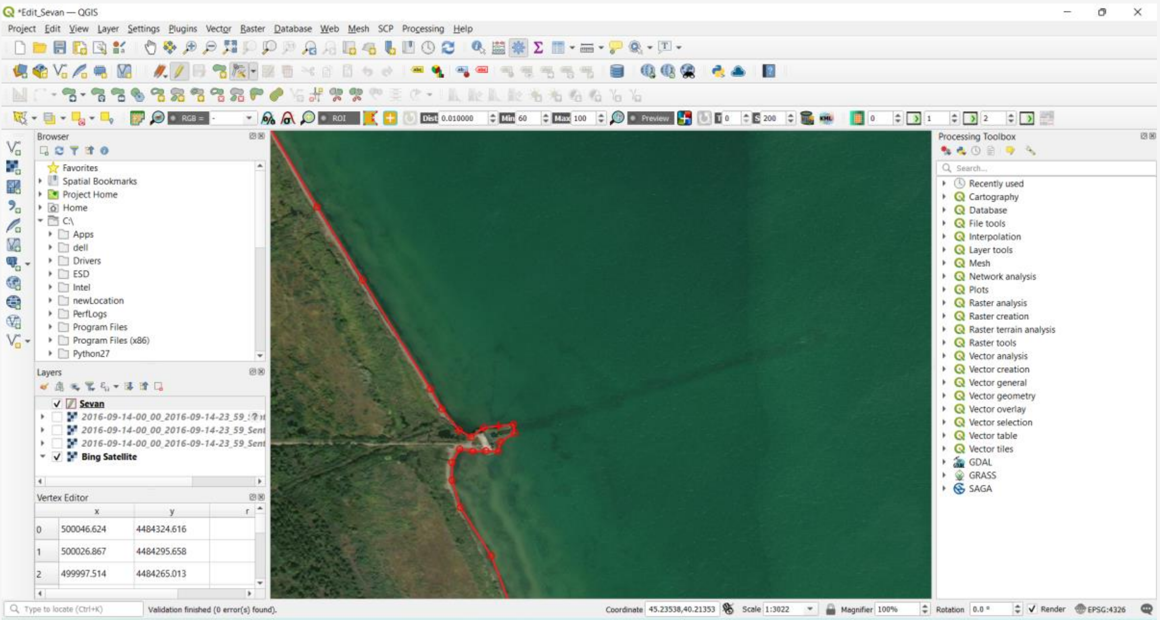


Figure 3: Lake shoreline validation on Bing satellite map

3.2 Vegetation Indices

Currently, it is a common method to use remote sensing data combined with various classification strategies to extract floating vegetation. Unfortunately, methods based on classifications need to rely on numerous measured samples to obtain satisfactory results, and such methods have proven to be inefficient [38]. Therefore, scholars have attempted to design various vegetation indices that are sensitive to aquatic vegetation. In addition, many vegetation indices for identifying and enhancing aquatic vegetation based on the spectral differences of aquatic vegetation types and different sensor features have been promoted, such as the Normalized difference vegetation index (NDVI) [39] and [40], perpendicular vegetation index (PVI) [41], modified normalized water index (MNDWI) [42], floating leaf vegetation sensitive spectral index (FVSI), planktonic algae vegetation index (floating algae index, FAI), macro aquatic vegetation index [28] and [43] (Macro Algae Index, MAI), submerged aquatic vegetation sensitive spectral index (SVSI), normalized difference aquatic vegetation index (NDAVI) [32] and water adjusted vegetation index (WAVI) [17] and [32]. Most of these involve ratios between differences and sums of the visible and near-infrared (NIR) spectral bands [44]. However, the relatively weak differences in NIR band range between EAV and FAV make it difficult to further distinguish them, and also, it is difficult to eliminate the interference caused by algal blooms. Furthermore, several types of aquatic vegetation have similar spectrum curves [45], which makes it hard to distinguish different vegetation accurately using only the spectral index. To overcome these difficulties, phenological features have been combined to identify various aquatic vegetation [17]. In summary, although the existing methods can extract the aquatic vegetation above the water surface, but few methods are able to the further distinguish between EAV and FAV. In fact, it is necessary to further distinguish EAV and FAV because the dissimilar roles in water ecological environment.

One of the most commonly used is the Normalized Difference vegetation Index (NDVI) which has been mostly used to capture terrestrial vegetation characteristics including growth and above ground biomass [39]. In addition to NDVI, we have applied the Normalized Difference Aquatic Vegetation Index (NDAVI) and the Normalized Difference Water Index (NDWI) which are designed to capture aquatic vegetation spectral response [28] [32] and [46]. The extracted water surfaces were also visually inspected and validated. The equations of different vegetation and water indices (Table 2) were calculated using the band calculation tool in SCP.

4. Results and Discussion

4.1 Floating Vegetation Extraction and Mapping

In recent years, the floating vegetation of Lake Sevan has experienced significant changes due to various factors. Using the three different vegetation indices proposed in this report and the TM and OLI images to extract the annual distribution range of floating vegetation cover in the Lake Sevan from 2009 to 2015 (Figure 4), we analyzed the spatial distribution patterns and trends of floating vegetation. As demonstrated in the Figure 5, the floating vegetation above the water surface of Lake Sevan in case of all tree vegetation indices exhibited an overall trend of slowly from decline 2009 to 2013. A slight decrease in AW in Lake Sevan can be associated with an intensive increase in the lake level over the period 2007-2013. However, after that, the trend changes slightly.

Vegetation Indices values were selected from 10 random points from areas away from the coastal zone (where the concentration of floating vegetation is mainly observed) of lake Sevan to compare the ability of different floating vegetation indices to distinguish floating vegetation during algal blooms. Among the floating vegetation indices, it can be seen from the chart (Figure 7) that NDAVI, NDVI, and NDWI have significant differences between distribution of the values.

Table 2: Vegetation indices for identifying aquatic vegetation

Indices (abbreviation)	Formula	Reference
Normalized difference vegetation index (NDVI)	$NDVI = \frac{NIR - Red}{NIR + Red}$	[39]
Normalized Difference Aquatic Vegetation Index (NDAVI)	$NDAVI = \frac{NIR - Blue}{NIR + Blue}$	[32]
Normalized Difference Water Index (NDWI)	$NDWI = \frac{Green - NIR}{Green + NIR}$	[46]

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(a) (b) (c)

Figure 4: Examples of the VI maps (a) NDVI, (b) NDAVI, (c) NDWI

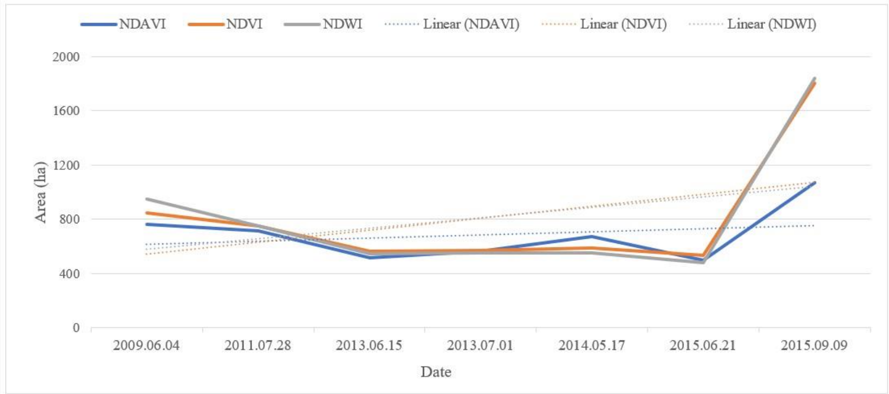

Figure 5: Dynamics of change in floating vegetation 2009-2015

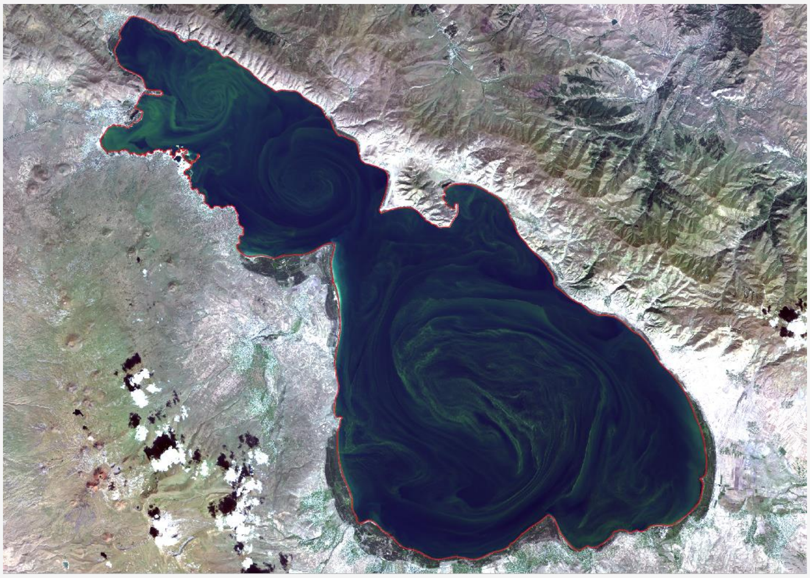

Figure 6: The natural-color composite OLI image - 09.09.2015

The NDAWI values are mostly distributed within the range of values that are typical for the water surface. Therefore, this index has the smallest deviation. In the case of NDVI and NDWI, the values are distributed very unevenly, but with a distinct deviation towards the ranges where vegetation is reflected. It worth also empathize that the algal bloom and floating vegetation can be accurately distinguished based on the adoption of the SWIR band. Previous studies have determined that EAV and FAV usually contain high concentrations of cellulose and lignin, which have a significant impact on the reflectance in the NIR and SWIR bands, with sensitive bands appearing at wavelengths of 930, 1,075, 1,275, 1,650, and 2,220 nm [47] and [48].

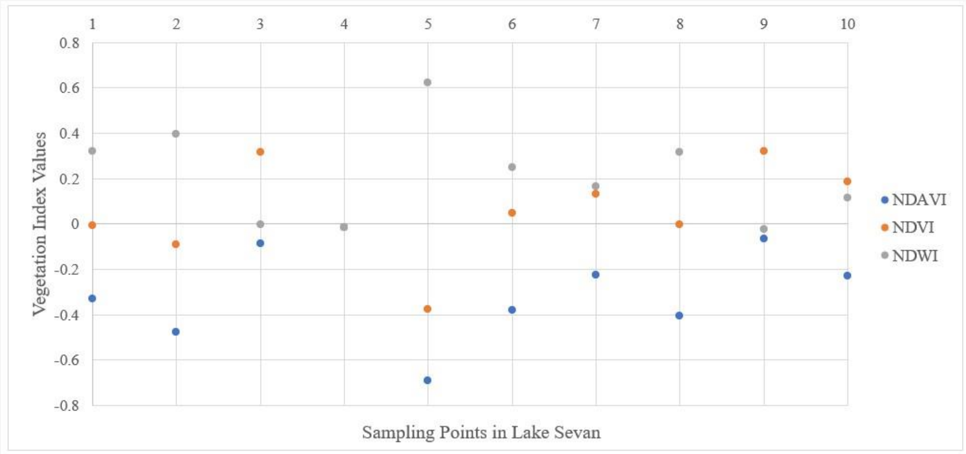

Figure 7: Distribution of values for different VIs

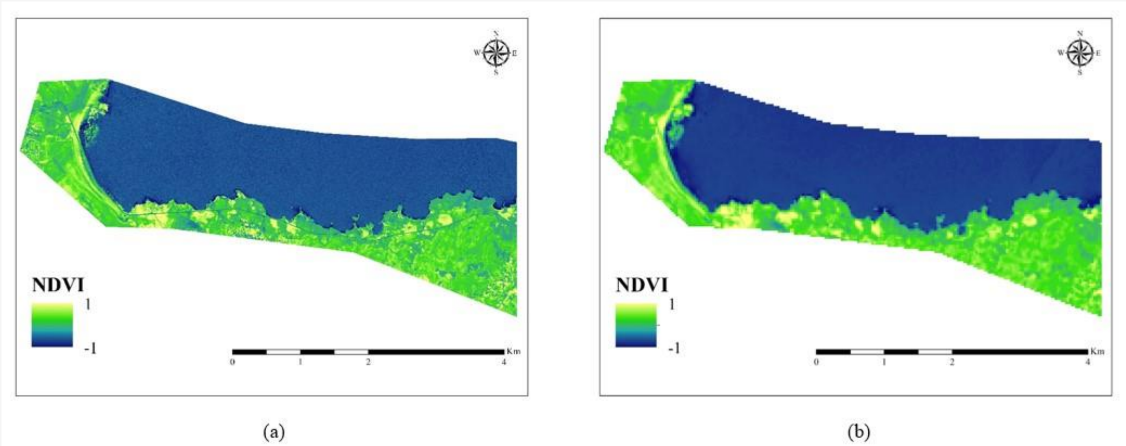

Figure 8: The Comparison of NDVI Maps of the North-Western Shore of Lake Sevan: (a) GeoEye-1, (b) Landsat OLI

Although algal contain high concentrations of chlorophyll, they almost do not contain cellulose and lignin; therefore, algal bloom present significant differences in the SWIR bands than those of EAV and FAV. Furthermore, due to the high concentration of water content in the leaf components of EAV and FAV, the reflectance exhibits a characteristic peak at the central wavelengths of 1,200, 1,450, 1,650, 1,850, and 2,015 nm which are not observed in the algal blooms [48] [49] and [50].

4.2 Validation

Available very high-resolution (VHR) satellite imagery purchased from Maxar Technologies Inc. was used to verify the results. For the target time period, only one image tile was available for the pilot site of Armenia captured by GeoEye 1 satellite. GeoEye-1 simultaneously captures 0.41m panchromatic (black & white) and 1.65m multispectral (color) digital imagery.

It has 5 spectral band - Pan: 450-800 nm; Blue: 450-510 nm; Green: 510-580 nm; Red: 655-690 nm and Near IR: 780-920 nm. Overall accuracy is estimated < 3m CE90 at nadir. The used image was captured on August 02, 2014. The area is the north-west coast of the Lake Sevan between Sevan town and Norashen village. Landsat OLI image dated August 12, 2014 was chosen for comparative analysis. Landsat OLI image extracted by GeoEye-1 image borders.

The statistical comparison of vegetation index maps shows that Landsat images provide up to 67% of the result of GeoEye-1 images for highlighting floating vegetation (Figure 8). Considering the resolution of Landsat images is approximately 18 times lower than that of images suitable for high-detail studies, it is important to note that while Landsat images may not be optimal for determining the species composition of floating vegetation, they can still yield results of sufficient precision for evaluating changes in objects and phenomena over time.

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5. Conclusion

This study demonstrated the potential of combining remote sensing imagery with field data to examine the long-term spatio-temporal changes in floating vegetation within Lake Sevan. The use of moderate-resolution images and various vegetation index analyses yielded moderate results. These findings suggest that medium-resolution Landsat and similar satellite images can be utilized to effectively monitor the spatio-temporal changes of lakes in a reproducible and continuous manner. Furthermore, the study highlights the role of anthropogenic disturbances and fluctuations in water levels in driving changes in the cover of floating vegetation in Lake Sevan. It is worth noting that the vegetation indices obtained from medium-resolution satellite images primarily identify EAV, which predominantly grows in the coastal zone rather than in deep lagoons. The dominant species in Lake Sevan were found to be Butomus umbellatus and Potamogeton pectinatus. One of the key takeaways from this study is that algal blooms can pose a significant challenge when attempting to accurately detect floating vegetation using satellite imagery, particularly when using automatic or semi-automatic machine learning algorithms. To overcome this issue, it is recommended to either avoid using images captured during the blooming season (mid-summer to mid-autumn) or utilize more advanced scientific approaches, such as developing algorithms that adopt the SWIR band.

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