ATLANTIS PRESS
Atlantis Highlights in Material Sciences and Technology (AHMST), volume 1
International Symposium "Engineering and Earth Sciences: Applied and Fundamental Research" (ISEES 2019)

Changes in the Trophic State Of Lake Valencia (Venezuela) from 2013 to 2019 According to Remote Sensing And Modelling Data

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Abstract **– Lake Valencia is the second most important natural freshwater basin in Venezuela. The expansion of industrial and agricultural activities and population growth over the past four decades has accelerated the process of eutrophication of the lake waters at such a rapid rate that it cannot be compensated by natural processes at present. Continuous monitoring of the trophic state of the lake, including remote sensing, is mandatory for collection of hydrobiological information, which allows developing effective strategies for monitoring and improving the quality of the lake's waters. Development and validation of a model for estimating the concentration of A-chlorophyll and the trophic state of Lake Valencia through the visible and near-infrared spectrum engaged multispectral satellite images Landsat 8 OLI in the present study. The results of measuring A-chlorophyll concentration at four sampling stations conducted in 2011 were also used. The proposed model showed a positive correlation of r^2 = 0.77 for the study conditions. A-chlorophyll concentration was estimated using a grid of 778 points located within the perimeter of the lake and on the basis of the proposed model. The A-chlorophyll concentration increased by 11.48% from 2013 to 2019. The eutrophic state of Lake Valencia, characterized by TSI = 68.238 at the date of the last monitoring (20 February 2019), was confirmed.**

Keywords – remote sensing; a-chlorophyll; trophic status index; multispectral images; Landsat 8 OLI.

I. INTRODUCTION

Aquatic ecosystems, under natural conditions or where anthropogenic interference has a controlled effect, changes in parameters such as flow rates and the biogeochemical structure of water are controlled primarily by geological and climatological characteristics of environment. Thus, the ecosystem's own dynamics can generally compensate for the effects caused by extreme natural phenomena [17], either hydrological in the case of long droughts or severe storms with a low return period, or physical in the case of fires or tectonic movements. Human activities, mainly industrial, agricultural and domestic, directly affect the concentration of nutrients that are transported to permanent water basins by natural watercourses, surface or underground.

When the concentration of dissolved nutrients in the water system exceeds natural levels (mainly phosphorus (P) and nitrogen (N)), algae and aquatic plants begin to grow rapidly, the biogeochemical cycle of the aquatic environment. Eutrophication is a serious threat to water quality, leading to the death of endogenous biota which was part of this ecosystem [27] to the accumulation of biogenic sediments and reproduction of pathogenic organisms.

The trophic status index (TSI) proposed by Carlson (1977) is commonly used to determine the trophic state or eutrophication level in a water basin [5]. The TSI proposed by Carlson ranges from 0 to 100 and takes into account 4 degrees of eutrophication: oligotrophic (TSI < 30), mesotrophic (30 ≤ TSI <60), eutrophic (60 ≤ TSI < 90) and hypereutrophic (90 ≤ TSI ≤ 100). TSI is determined by various water quality parameters such as: Secchi disc transparency, A-chlorophyll concentration, and total phosphorus concentration. Table 1 Formulae for determining TSI. (Carlson, 1977) according to water quality parameters.

TABLE I. Formulae for determining TSI (Carlson, 1977)

Eutrophication parameters	Carlson, 1977
Secchi Disk, Ds, m	$TSI_{Ds} = 60 - 14.41*Ln(Ds)$
Total phosphorus, P_T, mg/l	$TSI_{Pt} = 4.15 + 14.42*Ln(P_T)$
A-chlorophyll, Cla, mg/m^3	$TSI_{Cla} = 30.6 + 9.81*Ln(Cla)$

Three methods are currently used to study and monitor the main parameters that characterize the trophic status and quality of continental waters: on-site measurements, remote sensing methods and mathematical models [7]. On-site measurements provide accurate information on a wide range of water quality parameters at specific points and at specific times but require investment of financial and time resources. Remote sensing methods are cost-effective. They allow ~~you~~ to analyse the entire water basin and constantly monitor the water quality, assessing the parameters that can be determined by its optical properties. Remote sensing methods are widely used to assess the eutrophication degree of internal waters and A-chlorophyll content. Empirical mathematical models based on water quality data obtained for specific points at different times are used to analyse the dynamics of these parameters and estimate them soon.

This study applied multispectral images from the Landsat 8 OLI sensor to develop and validate a trophic state assessment model concerning Lake Valencia. The accuracy of the developed model was evaluated on the basis of measurements of A-chlorophyll concentration carried out in situ by Lopez [16] at 5 sampling stations in 2011.

II. Study Area

Lake Valencia is located in the North of Venezuela, surrounded by the Cordillera de La Costa mountain range, in the States of Carabobo and Aragua (Fig. 1 Study area. Location of Lake Valencia).

Lake Valencia is the largest natural freshwater basin of the Andorian type in South America [2] and the second largest lake in Venezuela. Its area currently is 365 km2, the maximum estimated depth is 39 m, the average is 21 m, the basin area is 3150 km2, the absolute surface height is 412 m. On the shores of the lake there are two main industrial cities of Venezuela: Maracay and Valencia, with an approximate population of 1.39 million inhabitants by 2018 [11, 12].

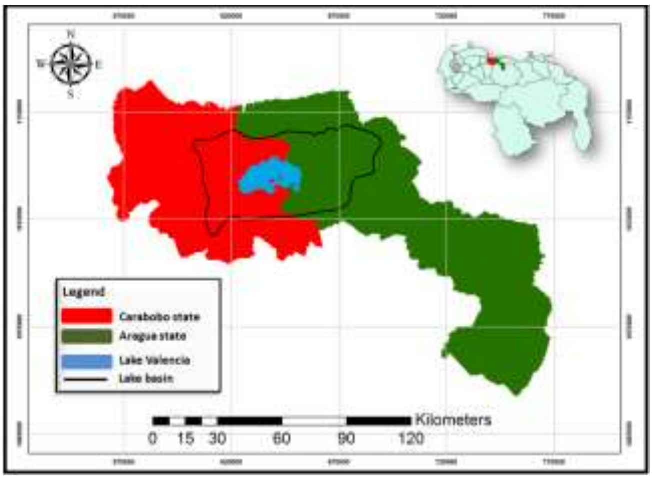

Fig. 1. Study area. Location of Lake Valencia.

The climate in the basin of Lake Valencia is predominantly sub-equatorial with 2 conditional seasons: a dry season from November to April and a rainy one from May to October. The average annual temperature in the lowland of the basin is 24.5–27 ºC. The average monthly temperature at the end of the dry period is 33.4 °C, while in the mountainous part the average annual temperature is 14 – 15 °C. The average annual rainfall in the basin is 1000 – 1800 mm in the mountainous areas, while in the depression of Lake Valencia it is about 900-1300 mm. The average annual evaporation is from 900 to 2000 mm, the highest values of evaporation are from February to May [11, 12].

The expansion of industrial and agricultural activities and population growth over the past four decades has accelerated the process of eutrophication of the Valencia waters at such a rapid rate that it cannot be compensated by natural processes now. A comprehensive study of Lake Valencia basin has been conducted since 1978 by the Ministry of environment and natural resources [19]. Studies conducted by the Ministry in the last two decades confirm that the deterioration of water quality is the main consequence of discharges of household and industrial waste, which leads to the existing level of extremely high pollution [20-22].

III. Methods and Materials

Methods for assessing the content of A-chlorophyll based on the relationship between the spectral properties of aquatic vegetation and the dispersion of radiation in water with solid particles in ~~the~~ suspension were widely studied [3, 4, 6-10, 23, 25, 26, 28, 31-33]. These and previous studies show, on the one hand, that the spectral behaviour of A-chlorophyll is characterized by strong absorption of reflectivity in the wavelength regions of the blue and red spectrum. This, in turn, confirms that the use of satellite remote sensing is an advantageous and effective method of obtaining accurate information for determination and monitoring of the trophic state of inland waters.

Other parameters, such as turbidity and solids content in the suspension, have also been evaluated with high accuracy using remote sensing techniques [1, 13-15, 24, 29]. The authors recommend referring to relevant links mentioned above to get more information about the physical properties and algorithms used to evaluate these parameters employing remote sensing techniques.

A. *Materials*

As shown by Oyama [25], to more accurately determine the content of A-chlorophyll through multispectral images, it should be taken into account that each pixel consists of phytoplankton, suspended solids and pure water. Accounting for the characteristics of the case study on Lake Valencia, ~~including~~ inland waters with A-chlorophyll content greater than 10 $\mu g{*}L^{-1}$, high turbidity and between wavelengths of 0.450 µm and 0.690 µm [10] demonstrated that the ratio ~~of radii b~~etween wavelengths from 0.685 µm to 0.745 µm was successful in estimating the A-chlorophyll content.

Based on these spectral principles and taking into account radiometric and spatial advantages, Landsat 8 OLI multispectral images were selected to analyse the trophic state of Lake Valencia. These images have been available since 2013 on the USGS (United States Geological Survey) portal.

Two multispectral images were used. The first of them corresponds to November 2013, as it is the closest in time to the measurements made on-site [16] in the dry season during January 2011, which were used in developing the working model. The second image, obtained by Landsat 8 on 20 February 2019, was used to analyse the current trophic conditions of Lake Valencia during the study period between 2013 and 2019. Table 2 shows Landsat 8 OLI images and gives a list of images used in the case study.

TABLE II. Landsat 8 OLI images

Number	Landsat 8 OLI images	Date
1	LC08_L1TP_004053_20131118_20170428_01_T1	18.11.2013
2	LC08_L1TP_004053_20190220_20190220_01_RT	20.02.2019

To process multispectral images, ENVI 5.1 software was used to perform atmospheric correction from the flash module and ArcGIS 10.1 software, to calculate trophic state based on images with atmospheric correction and their corresponding geographic processing.

B. *Methods*

The work on pre-processing of images included two stages: the first corresponds to conversion of the digital level values taken by the satellite multispectral sensor into the radiance values, and the second is the atmospheric correction to obtain the values of reflectivity on the surface. For this purpose, ENVI 5.1 software was used to allow automatic radiometric calibration of Landsat 8 products based on the information contained in the metafile of each image. After the radiance values were obtained, the atmospheric correction was performed using the flash module of the ENVI 5.1 software ~~and~~ a tropical atmospheric model with aerosol dispersion in rural areas. Thus, the reflectivity values were obtained on the surface for each of the multispectral images, which can be used to perform appropriate calculations to estimate the content of A-chlorophyll.

Depending on the water quality conditions of Lake Valencia, a model was developed to estimate A-chlorophyll concentrations using Landsat 8 OLI bands 2, 3, 4 and 5 (equation 1).

$$Cl\text{-}a = e^{\wedge}((B3/B2+B3/B4+B5/B4)) \quad \text{(equation 1)}$$

Here (Cl-a) is the A-chlorophyll concentration in mg/m^3, B2 is the band corresponding to the blue colour, B3 is the band corresponding to green, B4 is the band corresponding to red, and B5 is the band corresponding to near infrared. Table 3 represents the Bands used to develop the model. Source: USGS, the used bands and their corresponding wavelengths and resolution are present.

TABLE III. Bands used to develop the model. Source: USGS, 2018 [30]

Band	Name	Wavelength (µm)	Spectral resolution (m)
2	Blue	0.452 - 0.512	30
3	Green	0.533 - 0.590	30
4	Red	0.636 - 0.673	30
5	Near infrared	0.851 - 0.879	30

After the A-chlorophyll concentration was determined in equation 1, a statistical analysis was carried out between the results obtained and the on-site measurements in January 2011. Out of 5 sampling stations, the stations E1, E2, E4 and E5 were selected for the analysis because they showed the most statistically reliable results [16].

To obtain a more accurate estimate of the average concentration of A-chlorophyll in the proposed model, each of the processed scenes of Landsat 8 has applied the grid of 778 points distributed in the area of the lake where the concentration of A-chlorophyll has been determined. Figure 2 Sampling stations and the grid. The trophic state is considered by the equation proposed by Carlson [5] to determine TSI as a function of the average concentration of A-chlorophyll (table 2).

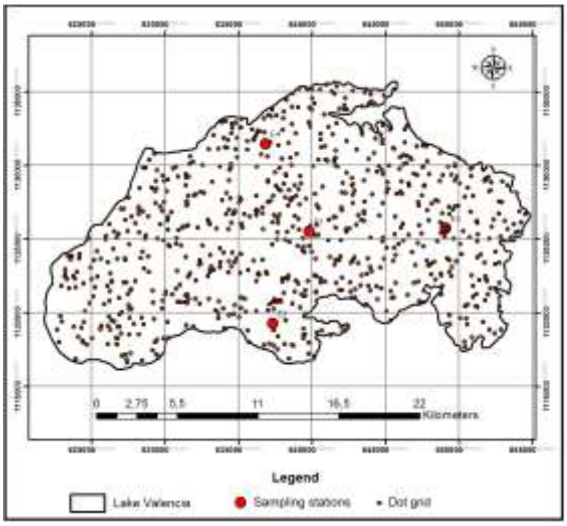

Fig. 2. Sampling stations and stipple grid.

IV. Results

The proposed model presented a good positive linear correlation $r^2 = 0.77$ regarding the values determined on site. Table 4 shows the coordinates of the sampling stations and A-chlorophyll concentrations determined locally for each station and estimated by equation 1 18.11.2013.

TABLE IV. Coordinates of sampling stations and A-chlorophyll concentrations by two methods of determination.

Sampling point.	Coordinate system		A-chlorophyll at the place of measurement, mg/m³, 2011	A-chlorophyll estimated by model, mg/m³, 2013
	N	***E***		
E1	639820.00	1125527.90	37.19	43.36
E2	637318.10	1119282.00	42.2	69.36
E4	636844.90	1131475.90	39.07	34.08
E5	649101.60	1125750.00	36.11	25.69

The results show an increase in A-chlorophyll concentration by 11.48% during the study period (from 2013 to 2019). According to TSI = 68.238 on the date of the last monitoring (20 February 2019), Lake Valencia regime is classified as eutrophic. A-chlorophyll distribution maps for each processed scene show that A-chlorophyll dispersion on the lake surface has increased significantly over the past six (6) years, confirming deterioration of water quality and the eutrophic state of lake. From 2013 to 2019, the average concentration of Cl-a (mg/m^3) increased from 41.051 to 46.372, and the TSI index increased from 67.042 to 68.238. The spatial change in chlorophyll concentration from 2013 to 2019 is shown on the maps based on the GIS system based on acquired data (figure 3 Concentration and distribution of A-chlorophyll in Lake Valencia on 18.11.2013 and figure 4 Concentration and distribution of A-chlorophyll in Lake Valencia on 20.02.2009).

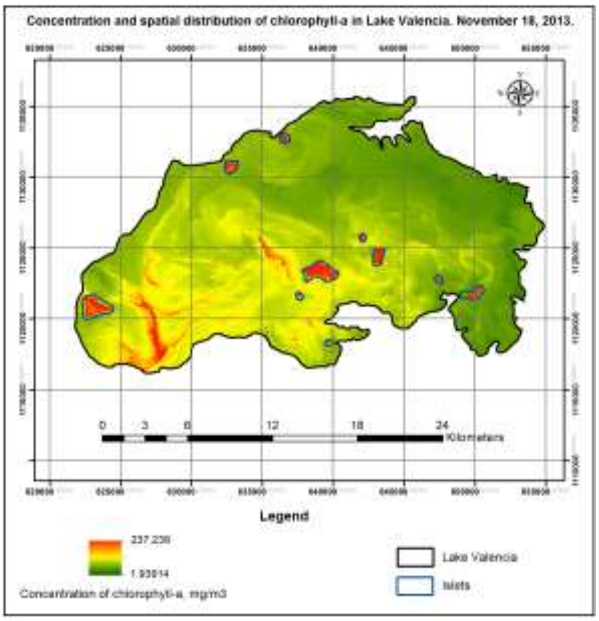

Fig. 3. Concentration and distribution of A-chlorophyll in Lake Valencia on 18.11.2013.

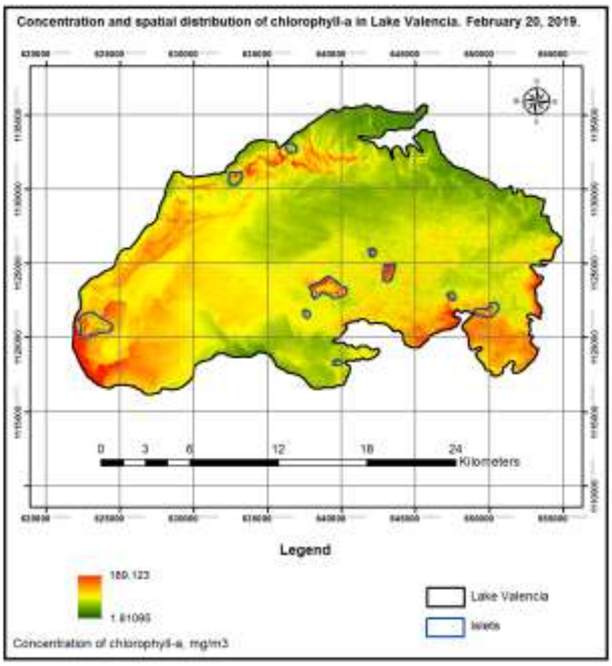

Fig. 4. Concentration and distribution of A-chlorophyll in Lake Valencia on 20.02.2009.

V. CONCLUSIONS

According to the results obtained in this study, the average concentration of A-chlorophyll in Lake Valencia in February 2019 is 46.372 mg/m^3 with eutrophic status TSI=68.238. The model proposed in this paper works well and can be used to monitor trophic status and determine A-chlorophyll concentrations through Landsat 8 OLI images with an accuracy of r^2=0.77 and an approximate frequency of 16 days corresponding to the temporal resolution of the satellite in Lake Valencia and others.

Taking into account the spatial resolution of Landsat 8 OLI (30 m) products, it is recommended to use this model only for continental waters with trophic state TSI ≥ 30. We consider that the ability of this model to detect absorption at wavelengths in the spectrum of blue (0.400 µm) and red (0.600 µm) has not yet been determined in pure waters with low A-chlorophyll concentration.

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