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Spatiotemporal assessment of suspended sediment concentration and salinity in Lake Urmia using satellite imagery and remote sensing

Mehran Dadashzadeh [1], Alireza Mojtahedi*[1], Javad Parsa [2]

[1]University of Tabriz, Faculty of Civil Engineering, Tabriz, Iran
[2]University of Tabriz, Faculty of Agriculture, Tabriz, Iran

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Abstract

Lake Urmia is considered as the largest salt water lake in Iran. Due to climate change and human activities in the lake's basin, the salinity of the lake has risen to more than 300 g/L during recent years, and large areas of the lake bed have been desiccated. Consequently, awareness of the hydro-ecological factors during the last few decades is crucial for identifying the problems. In the present study, the impacts of changes in suspended sediment concentration and saline features are explored using satellite imagery and remote sensing. The main purpose of this study is to conduct supervised monitoring in order to evaluate the Urmia Lake crisis with regard to human-involved factors such as the construction of the causeway. The results highlight an alarming increase of saline features around the lake during the studied period, from 287.718 km^2 in 2000 to 3006.5 km^2 in 2015. Also, it is concluded that the SSC has increased in the lake during recent years. The results of this study confirm that anthropogenic factors can be considered as the main cause of the crisis.

1. Introduction

Urmia Lake is one of the largest hyper-saline lakes in the world, with considerable ecological, environmental, and cultural value. Its watershed is an important agricultural region with a population of around 5 million people. Over the past few years, the lake's surface area and water level have been declining. The decline is generally attributed to a combination of climate change, increased water diversion for irrigated agriculture within the lake's watershed, and mismanagement (AghaKouchak et al. 2015; Hassanzadeh et al. 2011; Khatami 2013; Okhravi et al. 2017; Mojtahedi et al. 2022). Also, a causeway has been built across the lake with a gap of less than 2000 m, which may decrease the water circulation between the northern and southern halves of the lake.

Satellite imagery during the recent 17-year period illustrates the water retrogradation and the expansion of saline features around the lake. As the surface water continues to shrink in size, more of the lakebed and salt will be exposed (Garousi et al. 2013). Of the serious salinization effects, one can mention the ecological threats caused by the lake bed turning into a salt-covered wasteland and the consequent soil erosion (Pitman and Läuchli 2002). Considering the importance of the problem, a comprehensive analysis of the changes in dominant parameters is essential for the control and management of the lake, and the evaluation and implementation of effective restoration methods require appropriate spatial information. Thus, remote sensing methods are able to provide valuable information to conduct a comprehensive monitoring strategy, which is crucial for ecological management. In recent years, several studies have been carried out using satellite imagery and remote sensing technologies to develop monitoring procedures for the lake.

Mitchell (2013) used remote sensing technology and Landsat 5 and Landsat 8 satellite imagery to study changes in the water area and saline features of Urmia Lake and concluded that the saline features had increased by 898 km2 from 1998 to 2013. Khademi et al. (2015) studied the saline features around the lake using Landsat satellite imagery, remote sensing, and spatial analysis. The study of Landsat satellite images over a 13-year period illustrated a very rapid increase in saline features, and that the area of salt marsh in 2011 was approximately 26 times that of 1998. Chaudhari et al.

* **Corresponding Author**

(mehrandadashzadeh@tabrizu.ac.ir) ORCID ID 0000– 0001– 9521– 7330
*(a.mojtahed@tabrizu.ac.ir) ORCID ID 0000– 0002– 7917– 434X
(jparsa@tabrizu.ac.ir) ORCID ID 0000– 0002– 4993– 4475

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(2018) studied the natural and human-induced changes in the hydrology of the Urmia Lake basin based on remote sensing data, ground observations, and a hydrological model. The results indicated that the reduction in lake volume is primarily due to direct anthropogenic alterations.

Various factors have been mentioned which affect the crisis. In general, scientists believe that a combination of drought, climate change, increased water diversion for irrigated agriculture within the lake's watershed, mismanagement, and the constructed causeway are the most important causes of the lake's decline (Abbaspour et al. 2012; Shadkam et al. 2016). This study attempts to monitor the crisis by exploring the impact of key features such as the salinity and suspended sediment concentration (SSC) via satellite imagery, remote sensing, and fieldwork.

2. Method

In the present study, a spatio-temporal analysis is performed for the last decade of data (2000-2015) obtained from Landsat and MODIS satellite images integrated into Geographical Information System (GIS) software. The ArcGIS 10.3 package is used for calibrating, analyzing, and characterizing the recorded images to be used for decision-making and problem management.

2.1. Detection of causeway impacts on suspended sediment concentration and salinity

A 1.25 km-long dike-type causeway has been built across the lake to provide road access between the western and eastern provinces and divides the lake into northern and southern basins. Some scientists and environmental experts have suggested that this has decreased circulation within the lake and subsequently flow and salinity regimes are affected (Karbassi et al. 2010; Dadashzadeh et al. 2020). In this study, the effects of the construction of the causeway are investigated by evaluating the changes in two parameters, which include the saline features (around the causeway and shoreline of the lake) and the suspended sediment concentration, as described in the following sections.

2.1.1. Analyzing changes in suspended sediment concentration

The research uses Landsat 5, 7 and 8 satellite imagery to study changes in the SSC of Urmia Lake from 2000 to 2015. The images are calibrated using the expressed equations and the lake boundary is determined from the 1999 image. Due to the large size of the Landsat imagery in the full scene and to reduce computational volume, all images are masked and cropped using this boundary and areas outside the border are removed. Also, to quantify the SSC, the water boundary of each year should be determined and salts should be removed. In this regard, the supervised classification is applied to the images using the Linear Mode SVM algorithm. The method of research uses three types of spectral transformation for suspended sediment that is Normalized Suspended Material Index (NSMI), Normalized Differences Suspended Sediment Index (NDSSI), and Band Ratio (BR).

2.1.2. Change detection of saline features

In this study, Iso-cluster unsupervised classification and then supervised classification are implemented by conducting field visits. When setting a land cover map, it is necessary to take many GPS points of different features. To cover a study area with a representative set of sampled points, a schedule plan must be made before going out to the field. In this work, points such as samples of saline fields around the lake are located and marked by a Garmin 62 GPS. In addition, GPS points are taken at locations like road crossings, etc. to help create a coordinate system and for geo-referencing. Cloud-free images captured during the period of the fieldwork are ordered. After classifying the images, they are used to determine the ranges of salinity around the causeway and lake.

On the other hand, Landsat 5, 7 and 8 satellite imagery are used to study changes in saline features as the process worked in the SSC estimation. Radiometric correction of satellite imagery is carried out and the lake boundary is determined from the 1999 image. Then, all images are masked and cropped using this boundary. Therefore, the images are in the same size and number of pixels. ArcGIS and ENVI software programs are used to determine the lake boundary and to crop and mask images, respectively. To quantify the saline features in the lake, Brightness Index (BI) and Salinity Index (SI) are applied to images. After applying the indices, saline feature areas and the number of pixels are calculated for each image. MATLAB coding is performed to calculate area, number of pixels and total saline features from masked index results.

3. Results and discussion

3.1. Estimation of suspended sediment concentration

This section presents the results of applying the algorithm to determine the SSC in Urmia Lake. In this study, 3 typical indices are used to determine sediment content. The average results of each index are calculated to investigate the changes in SSC over the considered period (2000-2015) and the results are presented in Figure 1. The lower the NSMI and BR values, the cleaner the water, and the larger these values indicate the increase in SSC in the study area. The values of these indices have increased per year, indicating the increment in sedimentation rate, as shown in Fig. 1. Also, both BR and NSMI indices have provided better results compared to NDSSI.

3.2. Evaluation of saline features

In this study, satellite imagery is used to investigate the changes in areas of saline soils and the range of salinity around the causeway from 1999 to 2016. Development of the salinization area is visualized in Figure 2 for the years 1999 and 2016. The observed changes in the area were compared with consideration of the lake shapefile for 1995 (when the lake reached its maximum expansion during the studied period), as the base area.

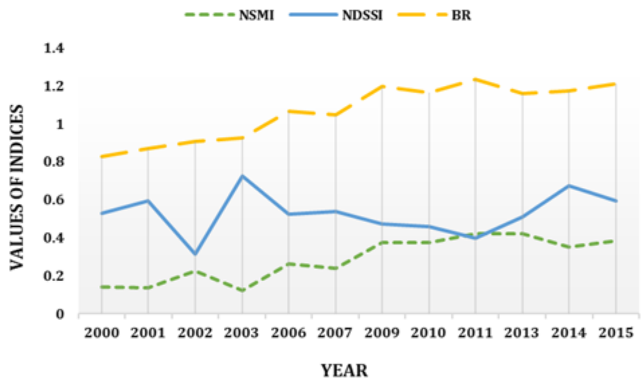

Figure 1. Average of sediment indices results for the years 2000 to 2015

Furthermore, the saline features around the lake are quantified using two types of spectral transformation for the period 2000-2015. After applying the proposed algorithm, the number of salt pixels, salt area, and the number of fresh salt pixels are calculated to evaluate the salinity increase and drought spread in Urmia Lake. The total number of pixels detected as saline features has increased during the studied period. That is, the drought has developed and more parts of the lake have been turned into a salt pan. The results indicate a significant increase in saline features around the lake during the studied period, from 287.718 km^2 to 3006.5 km^2 and consequently a decrease in lake water.

As previously mentioned, Lake Urmia salt is classified into two categories of fresh and old salt. Figure 3 indicates the number of pixels of fresh salt obtained by the algorithm. The number of pixels related to fresh salt has been added each year, reflecting the expansion of saline features in the lake.

As is clear from the results presented in Figure 3, the values of SI and BI indices have increased in the boundary during the studied period. The incremental trend of indices values demonstrates a considerable increase in saline features around the lake. Also, Figure 3 illustrates a reasonable agreement between the results of the two indices. For visual comparison, maps of the salinization areas are provided according to the results of the indices. The maps obtained from the SI index are illustrated in Figure 4 for the years 2000 and 2015.

4. Conclusion

There are many studies showing that human activities can be considered one of the main factors responsible for the ecological crises of lakes and wetlands in arid or semi-arid regions around the world. During recent decades, Urmia Lake has also experienced dramatic changes in its watershed. These factors include climate change, land-use changes, increased water diversion for irrigated agriculture within the watershed, construction of a causeway across the lake, several dams on the rivers around the lake, etc. The relationship between the lake's crisis and hydrological drought and anthropogenic factors is a challenging problem for the local population and governmental organizations, noting the hierarchy in planning and making final decisions. However, there are not yet enough detailed studies on temporal and spatial change detection to conclude with certainty which of the anthropogenic and climate factors is the main cause of the crisis. This study has tried to investigate the problem, and the following results can be concluded based on the observations.

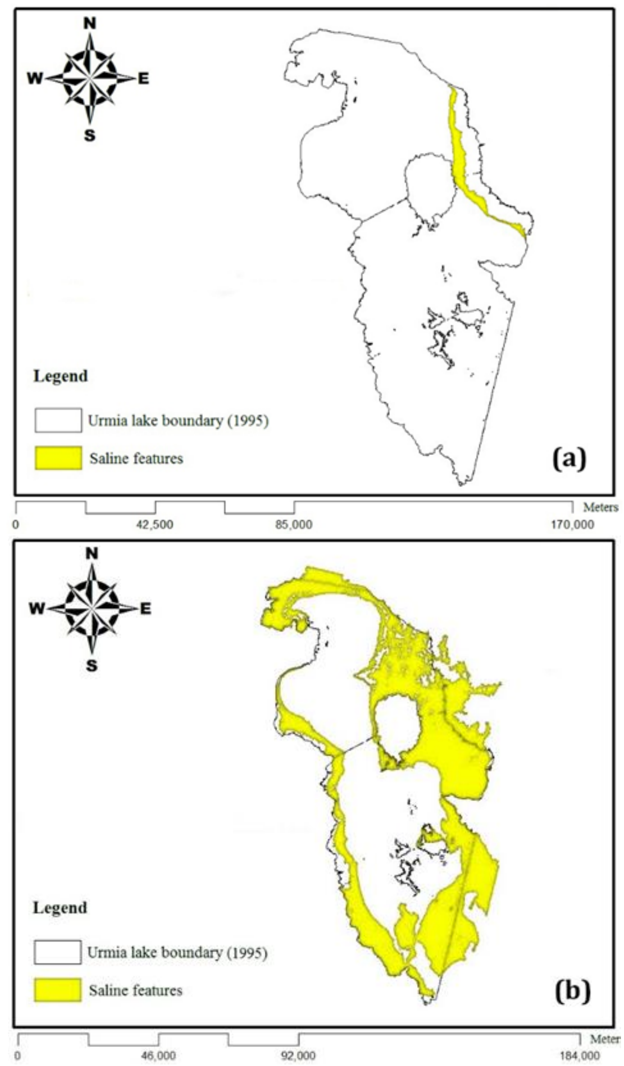

Figure 2. Maps of the salinization areas for the years, a) 1999 and b) 2016

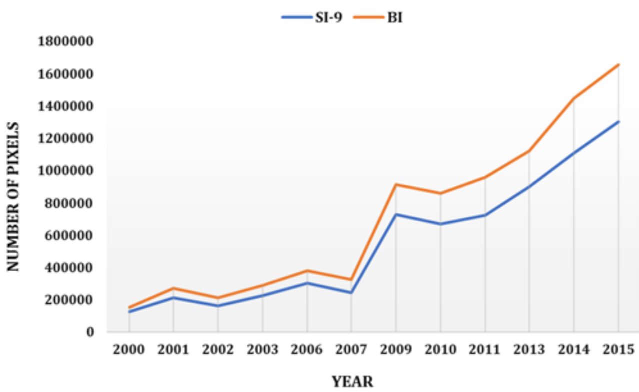

Figure 3. The number of pixels related to fresh salt

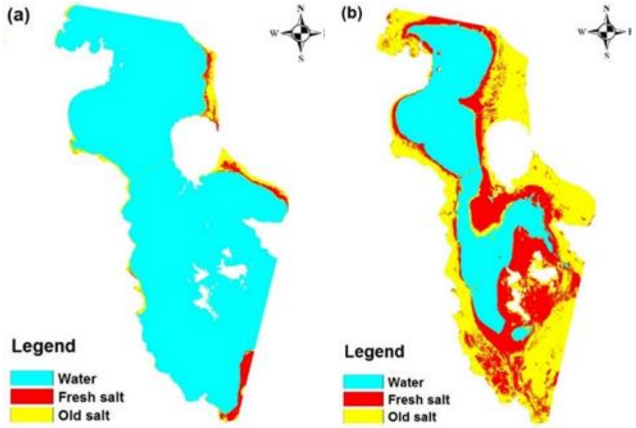

Figure 4. Maps of the salinization areas obtained from SI index for the years, a) 2000 and b) 2015

The results show that there is a notable increase in saline feature areas around the lake during the studied period, from 287.718 km^2 in 2000 to 3006.5 km^2 in 2015. The results warn that the continuation of the crisis of reduced water volume will lead to collapse of the lake's ecosystem as well as salt storms which could have serious negative impacts on the regional environment and public health. Considering the importance of the problem, maps of potential high-salinity areas are essential for the control and management of the environmental risks in the lake region.

Furthermore, the SSC and saline features have been investigated using satellite imagery over the past 15 years, from 2000 to 2015. In this regard, the algorithms have been implemented on the images and the results are analyzed. The results demonstrate that the SSC has increased in the lake during recent years. By analyzing the images and the amount of SSC around the causeway, it had no significant impact on the SSC pattern.

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