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Monitoring Urmia Lake Area Variation Using MODIS Satellite Data

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ABSTRACT

Urmia Lake is a large hyper-saline lake located in the northwest of Iran. It plays an important role in the hydrology, climate and ecology of its surrounding regions. In recent years, the water level of Urmia Lake has been dropped significantly. This study investigates the seasonal and annual variations of the lake area from 2000 to 2011 using remote sensing data. MODIS imageries of Normalized Differential Vegetation Index (NDVI) were used to extract the water surface area of the lake. Results reveal a significant decline in the lake area during the last past 12 years. Analysis of the seasonal images shows that maximum and minimum areas of Urmia Lake usually occur in winter and autumn, respectively. This study confirms the successful application of MODIS-NDVI products for retrieving the variation of the large lakes area with an acceptable spatial and temporal resolution.

Key words: *Urmia Lake, Lake Area, MODIS, NDVI*

1. Introduction

Lakes as key elements of hydrologic cycle play an important role in meteorology, ecology and economy of their surrounding regions. Moreover, they are highly responsive to natural changes and anthropogenic impacts (Bai et al., 2011; Cretaux et al., 2011). One of the major threats to lakes ecosystem worldwide is the insufficient inflows due to the excessive use of water in the basins which in turn results in the lakes shrinkage (Ramsar Convention Secretariat, 2007). Such concerns are intensified in developing countries in semi-arid regions where regional water balance has been affected by intense abstraction of water in upstream rivers to meet agricultural demands (Bai et al., 2011). To achieve a better understanding of both human-induced and climatological impacts on lakes, it is a prerequisite to monitor principal characteristics of lakes such as water level and surface area (Cretaux et al., 2011).

Ground surveying, aerial photography and remote sensing are among the approaches that have been used in lake mapping. Nevertheless, expense and time requirements for ground-based monitoring make it inefficient to monitor more than a limited area of lakes. Also, accessing to remote locations or difficult terrains is problematic in field surveys (Bai et al., 2011). Aerial photography; however, is more acceptable than field survey specifically in distant regions, requires large number of photos to cover the whole region and huge amount of processing which in turn is costly and time consuming (Alesheikh, 2007). In preference to the two mentioned approaches, remote sensing can be effectively used to assess ongoing dynamics and detect the changes over a reasonable period of time. Furthermore, remotely sensed data can be obtained, interpreted and analyzed quite easily (Bai et al., 2011). Examples of remote sensing application in lake studies include mapping lakes spatial extent, monitoring lakes water quality and estimating evaporation (Prata, 1990; Vuglinskiy, 2009).

There are several satellites providing images with different spatial and temporal resolutions that have been applied for mapping surface area and detecting changes. Having a high spatial resolution of 4 m, IKONOS and QuickBirds satellite imageries are suitable to trace changes at local scale (Sawaya et al., 2003). For lower spatial resolution demanded studies, Landsat TM (30m) and ETM^+ (15-30 m) still supplies high spatial resolution data and have been used in many studies for spatial extent mapping of lakes (Taheri Shahriani et al., 2005; Alesheikh, 2007; Bai et al., 2011). However, these applications of high resolution data are restricted due to the coarse temporal resolution and high cost of data acquisition (Sakamoto et al., 2007).

MODerate Resolution Imaging Spectroradiometer (MODIS) instrument onboard the Terra (EOS AM) and Aqua (EOS PM) satellites, was launched in 1999. Having a recurrence period of 1 to 2 days, MODIS is able to properly map temporal variations of large water bodies with an acceptable spatial resolution (250-500m). Application of MODIS data to monitor temporal and spatial variation of lakes is limited. Peng et al. (2005) used MODIS images of Dongting Lake in China from 2002 to 2003 (13 images) to find a relationship between lake surface area and water level and analyze the influence of lake area variation on water level. Also, few studies have reported the successful use of MODIS data to extract the spatial extent of flooded and irrigated area as well as the temporal changes (Thenkabail et al., 2005; Sakamoto et al., 2007).

This study investigates the application of MODIS imageries to monitor the spatial and temporal variations of Urmia Lake surface area between 2000 and 2011. First, clear sky MODIS-NDVI/Terra images are ordered and processed to obtain NDVI maps of the study region. Second, seasonal surface areas of the lake are extracted from NDVI maps. Then MODIS-derived surface areas are validated against the reported values of Urmia lake area from HYDROWEB database, which have been acquired using high-resolution images and radar level data. Finally, seasonal and inter-annual variations of Urmia Lake area are assessed.

2. Study Area

Urmia Lake is a closed hyper-saline lake situated between the 37° 04′N to 38° 17′N latitude and 45° E and 46° E longitude in the northwest of Iran. It has a surface area between 5000 and 6000 km^2 depending on evaporation and water inflows. The deepest part of the lake is hardly deeper than 4 m. It is located in a semi-arid area, having a mean annual temperature of 11.2°C, average precipitation and evaporation rate of 341 and 1200 mm/yr, respectively (Djamali et al., 2008). There are four major islands in the south part of the lake named Kabudan, Arezu, Ashk and Espir which are considered as protected areas by the Environmental Protection Organization (Figure 1).

During the last decade the lake ecosystem has been threatened by a significant water level drop which is mainly due to the over-exploitation of upstream rivers for irrigation as well as drought. One of the consequences of the lake desiccation is the expansion of the islands so that some of them are attached together. Moreover, dried coastal salt lands have a potential of creating salt dusts over the surrounding agricultural and residential areas when they are exposed to strong winds. Therefore, monitoring spatial variations of the lake is of high importance since it can reflect regional changes occurring by climate and human activities. Additionally, having a relatively long-term historical time series of the lake surface can help water resources managers to plan for the lake rehabilitation.

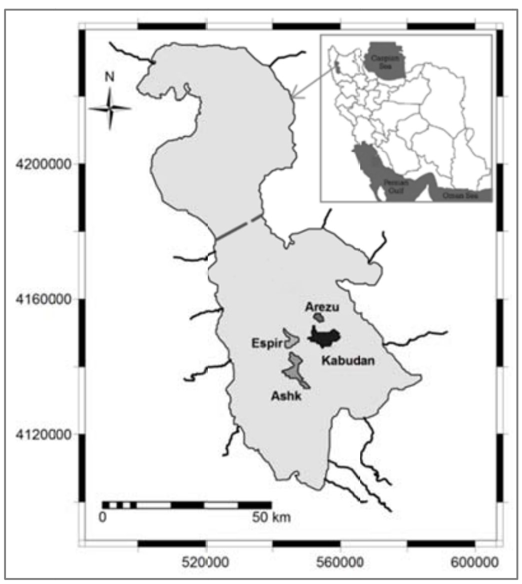

Figure 1. Study Area

3. Methodology

A number of image processing techniques have been developed to extract spatial extent of lakes and wetlands from remote sensing data including: Band-ratio (Yongwei et al., 1993), Histogram Thresholding (Lascassies et al., 1994), Normalized Different

Vegetation Index (NDVI), Wetness Index, Statistical classification methods (unsupervised and supervised Classification) (Heckbert, 1982; Richards,1993) and separation based on color composite images. In addition, some researchers used a combination of methods to improve the accuracy of results (Alesheikh et al., 2007; Taheri Shahriani et al., 2005). They are mostly based on the different optical response of water bodies and other land covers such as vegetation, soil and rock. While reflectance of water is approximately equal to zero in reflective infrared spectrum (0.7-3µm) (Engman and Gurney, 1991), the reflectance of majority of land covers is greater than zero. Hence, using appropriate bands of different sensors (e.g. band 7 of Landsat-MSS; Band 4 of Landsat-TM), water bodies can be separated from surrounding lands (Kite and Pietroniro, 2000).

Taheri Shahriani et al. (2005) compared various methods to map the spatial extent of Hirmand, Sabury and Poozak lakes in the southeast of Iran. They applied the threshold of NDVI map with visual interpretation of false color composite (FCC) image as a reference to evaluate other processing methods. Moreover, they concluded that in all of the processing methods using different multi spectral images, estimation can be improved through the combination with NDVI map (Taheri Shahriani et al., 2005). Another reason for selecting NDVI thresholding method in this study is the availability of MODIS-NDVI satellite images with an appropriate temporal resolution (16 days) and a satisfactory spatial resolution (nominal 250×250 m) to monitor both seasonal and within year variations of Urmia Lake surface area.

MODIS-NDVI products (MOD/MYD16Q1, version 5) were obtained from the NASA Active Archive Center. Between 2000 and 2011, one cloud-free image was chosen for each season as a representative of the lake extent during the whole season. Overall, 48 MODIS-NDVI satellite imageries were processed. Since, inter-seasonal variation of the lake area is not of high extent, this presumption does not seem to be so unrealistic. Then using HEG to GOS software images were resampled to the UTM coordinate system zone 38, with a 250×250 m spatial resolution and reformatted from HDF to GEOTiff. Next, GEOtiff images were imported to ILWIS3.3 environment for further processes containing: Preparing a sub-map of the lake location, geometric correction and separation of the lake boundary from shallow saline coastlines by thresholding NDVI map and producing polygon maps. Subsequently, the area and perimeter of the lake and corresponding islands can be extracted from the histograms of the polygon maps.

NDVI is a normalized index primarily developed to monitor the presence and condition of green vegetation cover over different land types. It is formulated as follow:

$$NDVI = \frac{NIR - VIS}{NIR + VIS}$$

where NIR and VIS are the near infrared and visible bands of a satellite sensor, respectively. NDVI values range between -1 and 1. Increasing positive NDVI values indicate dense green vegetation cover, while near-zero values and decreasing negative values represent non-vegetated features such as barren surfaces (rock and soil), water, snow, ice, and clouds (Tucker et al., 1991). Open water bodies, have high negative

NDVI values. However, values of MODIS-NDVI products range from 0 to 1 and negative values are shown as undefined. Thus, the lake boundary can be distinguished as a border of undefined values, whereas the surrounding salt lands presented by near-zero NDVI values. Furthermore, few patches can be observed inside the lake having positive NDVI values. These are either islands or salt hills which have been created as a result of salt precipitation.

4. Results and discussion

4.1. Results

The seasonal areas of Urmia Lake and its corresponding islands from 2000 to 2011 are presented in Figures 2 and 3, respectively. The lake surface area has been constantly decreases from winter to autumn, in almost every year. The higher rate of precipitation in winter following by the snow-melt runoffs during spring, leads to an increase in the water level and surface area of Urmia Lake. Then, from summer till the end of the year, the lake starts shrinking as a result of limited amount of inflows and high rate of evaporation.

Unlike the lake, its islands have been expanded during the past 12 years (more than 50%), so that some of them such as Arezu and Kabudan are currently attached together. Usually, the islands area increases from winter to summer and autumn. This trend is more evident in the period between 2007 and 2011. Although the MODIS-NDVI products can also be used to map the islands of Urmia Lake, the accuracy is much lower than that of the lake itself. That is due to the fact that the total area of the lake main islands is about 100 km^2. In other words, as the spatial extent of the object mapped decreases, mapping errors increase. Nevertheless, since there is no reliable source to serve as reference values, those extracted values of islands area cannot be validated.

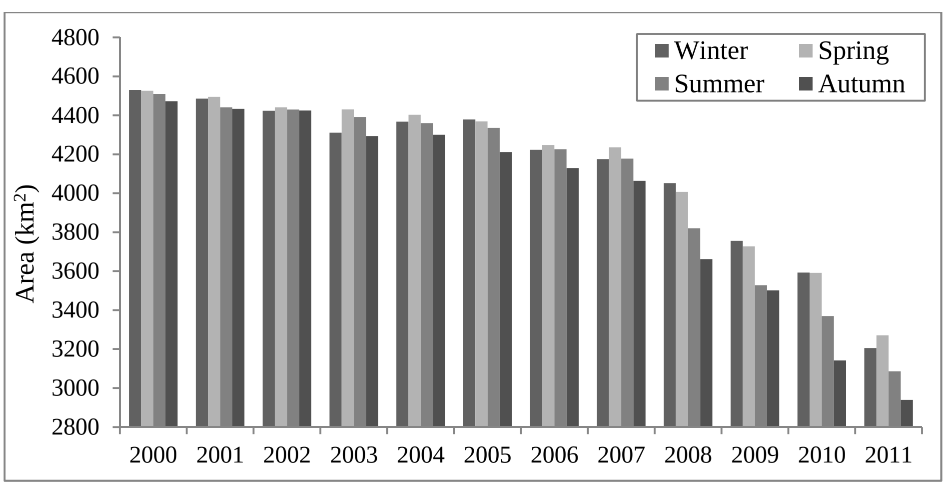

Figure 2. Seasonal variation of Urmia Lake surface area from 2000 to 2011

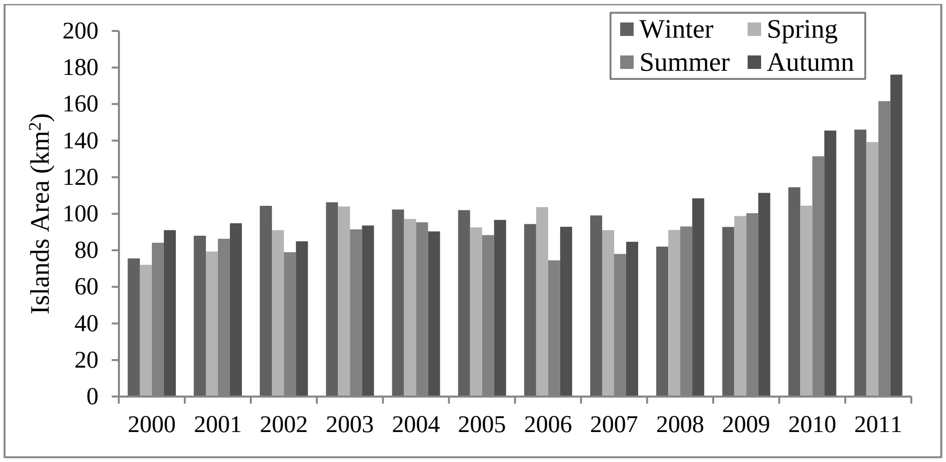

Figure 3. Seasonal variation of Urmia Lake islands area from 2000 to 2011.

Table 1. Range of seasonal variations in the area of Urmia Lake and its corresponding islands (km^2).

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Lake	57	62	18	138	103	167	118	172	390	254	451	332
Islands	19	15	25	15	12	14	29	21	26	19	41	37

Apparently, the range of seasonal variation in the spatial extent of the lake has been significantly raised from 57 km^2 in 2000 to 451 km^2 in 2010 (Table 1). Similarly, the range of within year variations of the islands area has been broadened. Therefore, in recent years not only the lake surface has been declined but also the lake encounters more stress in terms of intra-annual area changes. This can be an indication of the harsher variability in the lakes water inputs (precipitation and evaporation) as well as evaporation losses.

According to the inter-annual area variation, depicted in Figure 5, two different declining trends can be distinguished in the lake surface area. The first one is a slight decreasing trend with a slope of -0.13 from 2000 to 2006; while the latter is a sharp linear diminishing trend (with a slope of -0.71) between 2007 and 2011. In other words, from 2000 to 2006 the decline in Urmia Lake water surface is insignificant, whereas since 2007 the lake has been drying up with an average rate of 154 km^2/season.

4.2. Validation

To validate the extracted area from MODIS-NDVI products, surface data of Lake Urmia from the HYDROWEB database (http://www.LEGOS.obs-mip.fr/soa/hydrologie/ HYDROWEB) were applied. HYDROWEB database contains satellite altimetry data for around 150 large lakes and reservoirs worldwide (Cretaux et al., 2011). Employing several high resolution multispectral satellite imageries (e.g. Landsat-TM/ETM$^+$) and the corresponding satellite altimetry data, a rating curve function (dh/ds) which is the variation of water level with respect to the variation of surface in a given time span was calculated. Next, applying this rating curve function to the near continuous level data, acquired from satellite radar altimetry, the surface variation of the lakes over the time span of the altimetry data (ranging from 1-2 days for big lakes) were estimated. Currently, a prototype based on 20 lakes including Urmia Lake has been developed at LEGOS (Vuglinskiy, 2009). Thus, the validation strategy used in this study is to compare extracted surface area of the lake with the extent determined using high resolution images such as TM/ETM^+, with an error less than 1% (Harris, 1994), from LEGOS database. Among numerous surface area data of the lake, those which were coincident with processed MODIS-NDVI images were selected for comparison, leading to 15 total match-ups.

Scatter plot of MODIS-derived lake surface area versus LEGOS database of Urmia Lake area is illustrated in Figure 4. Additionally, to assure the long-term consistency MODIS-derived lake surface areas which were nearly coincidence with LEGOS database is plotted in Figure 5. Except the year 2000, MODIS-derived surface areas reasonably resemble the trend of areas obtained from high resolution TM/ETM^+ images, having a correlation coefficient of 0.95 and a cool bias 524 km^2. Moreover, two performance measures RMSE and Nash-Sutcliff coefficient were calculated. Both measures indicate a satisfactory accordance (RMSE=130, NASH=0.95) of MODIS-derived lake area compared with LEGOS database.

The lake area has been extracted from MODIS-NDVI data with an accuracy of 1.4% relative to Landsat TM/ETM^+ images. Aside from the sensor and images typical inaccuracies, some part of the error may arise in discriminating shallow salt lands from the lake boundary. Although the spatial resolution of MODIS-NDVI images is approximately 8 times lower than TM/ETM^+ images, they can be applied to monitor the variation of lakes area with a slightly higher error. Therefore, when sparse high resolution satellite images are freely available for detection of large lakes spatial extent, MODIS-NDVI data can be confidently substituted.

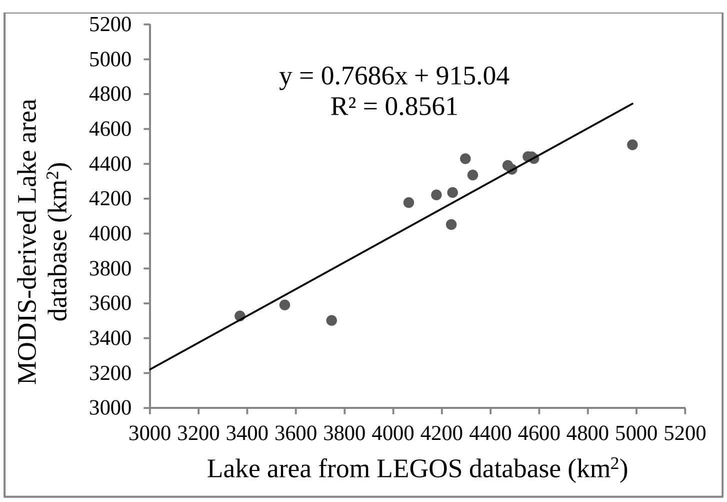

Figure 4. Comparison of MODIS-derived surface area and TM/ETM^+ in Urmia Lake

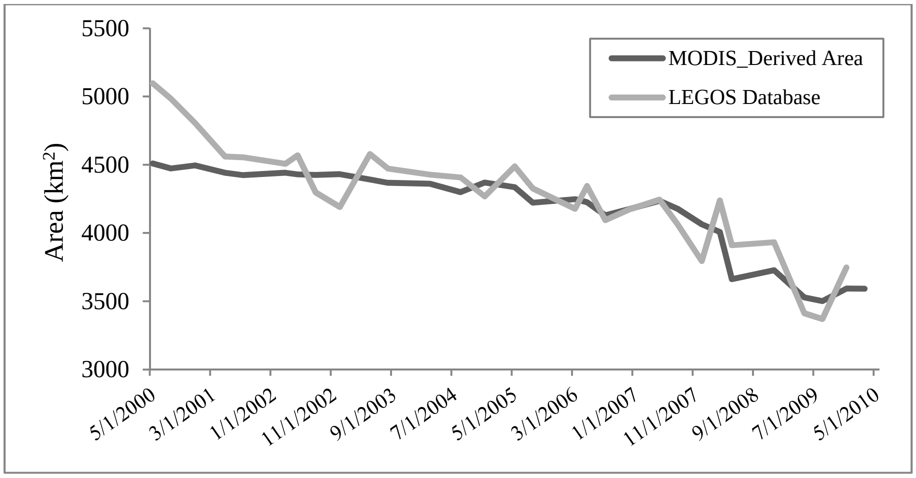

Figure 5. Long term variations of Urmia Lake surface area based on MODIS-derived and LEGOS data.

5. Conclusions

Monitoring the spatial and temporal variation of lake surface area is of high importance particularly in large lakes like Urmia Lake, Iran. Using remote sensing data of MODIS-NDVI the surface area of Urmia Lake examined between 2000 and 2011 and their accuracy were compared to values extracted from high resolution images. The following conclusions can be derived based on the results of this study:

- MODIS-NDVI images can be confidently used to monitor the spatial extent of large lakes with a moderate spatial resolution and adequate temporal resolution.
- In sparse of high-resolution satellite images such as Landsat TM/ETM$^+$, MODIS-NDVI images can be applied for lake mapping with an acceptable error (2.4%).
- During the past 12 years Urmia Lake has been desiccated more than 1500 km^2, which approximately equals a 35% reduction.
- Based on the seasonal analysis, the lake area typically maximizes in winter or spring and then continuously reduces to reach its minimum in summer and autumn.

Through providing a relatively long-term data base of Urmia Lake surface area, results of the current study can assist policy makers to appropriate management of water and ecosystem resources at local and regional scales.

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