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Quantitative assessment of Urmia Lake water using spaceborne multisensor data and 3D modeling

Mehrdad Jeihouni · Ara Toomanian · Seyed Kazem Alavipanah · Saeid Hamzeh

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Abstract Preserving aquatic ecosystems and water resources management is crucial in arid and semi-arid regions for anthropogenic reasons and climate change. In recent decades, the water level of the largest lake in Iran, Urmia Lake, has decreased sharply, which has become a major environmental concern in Iran and the region. The efforts to revive the lake concerns the amount of water required for restoration. This study monitored and assessed Urmia Lake status over a period of 30 years (1984 to 2014) using remotely sensed data. A novel method is proposed that generates a lakebed digital elevation model (LBDEM) for Urmia Lake based on time series images from Landsat satellites, water level field measurements, remote sensing techniques, GIS, and 3D modeling. The volume of water required to restore the Lake water level to that of previous years and the ecological water level was calculated based on LBDEM. The results indicate a marked change in the area and volume of the lake from its maximum water level in 1998 to its minimum level in 2014. During this period, 86% of the lake became a salt desert and the volume of the lake water in 2013 was just 0.83% of the 1998 volume. The volume of water required to restore Urmia Lake from benchmark status (in 2014) to ecological water level (1274.10 m) is 12.546 Bm^3, excluding evaporation. The results and the proposed method can be used by national and international environmental organizations to monitor and assess the status of Urmia Lake and support them in decision-making.

Keywords Urmia Lake · Remote sensing · Lakebed topography · 3D modeling · Long-term monitoring · GIS

M. Jeihouni · A. Toomanian (✉) · S. K. Alavipanah · S. Hamzeh
Department of Remote Sensing and GIS, Faculty of Geography, University of Tehran, Azin Alley. 50, Vesal Str., Tehran, Iran
e-mail: a.toomanian@ut.ac.ir

Introduction

Human existence depends on global water resources. These resources comprise oceans, seas, lakes, surface water (rivers), and groundwater. Generally, seas, lakes, and wetlands collect the surface and groundwater flows of an area. In recent years, sharp changes in the quantity and quality of lakes water have motivated scientists to develop advanced methods to understand lakes ecosystems (Lytras 2007). Continuous monitoring of the characteristics of water resources in short- and long-term time scales are the key to sustainable management. Continuous monitoring increases permanent cognizance of the resource status and reveals their trends. Decision-makers can use this knowledge to make management decisions to preserve, restore, and make optimal use of the resources. Aquatic ecosystems are fragile and vulnerable to damage by many natural and anthropogenic causes. The study of lakes and lake management has become critical to environmental and hydrological studies (Moe et al. 2016; Templar et al. 2016; Al-Fahdawi et al. 2015; Ban et al. 2014; Hacısalihoğlu et al. 2016; Zhang et al. 2017a).

Climate change has affected countries in both arid and semi-arid regions and their water resources. These

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areas are vulnerable to damage associated with climate change because they have limited adaptive capacity for extreme events. Iran has arid and semi-arid climates (Amiraslani and Dragovich 2011) and climate change has recently intensified drought and the water crisis. Accordingly, continuous monitoring of water resources and inland water bodies like lakes is essential.

Urmia Lake is the largest lake in Iran (Hassanzadeh et al. 2012) and the second largest hyper-saline lake in the world (Sima et al. 2013). It is one of the most valuable aquatic ecosystems in the country and has been listed as a Ramsar site and UNESCO Biosphere Reserve (Zarghami 2011). This, however, has changed radically in recent years. The Urmia Lake basin is an important agricultural area with a population of 6.4 million and 76 million people residing within a radius of 500 km (UNEP 2012) that will be adversely affected by the desiccation of the lake.

The status of the lake worsens year by year. It is drying up in response to climatic conditions such as decreasing rainfall and drought and mismanagement of water resources, including the construction of many dams on the rivers that feed the lake and excessive pumping from legal and illegal wells in Urmia basin (Tourian et al. 2015). The water level has decreased 7 m in the last 20 years according to the Iranian Ministry of Energy (IMOE) dataset (Fig.1). These changes have altered the area and water quality of the lake and produced many environmental effects. The drying up of Urmia Lake has become a crisis in northwestern Iran and in neighboring countries because of the influential role of the lake on the ecosystem of the region. If Urmia Lake dries up, the associated ecosystems will be strongly affected; therefore, the drying trend should be controlled.

Authorities as well as academia have proposed many projects to revive and save Urmia Lake. Their main goal is to restore the water level of the lake to its ecological level (1274.10 m) (Urmia Lake Restoration National Committee 2016). To do this, it is necessary to know how much water must be restored to the lake. It is also necessary to understand the effect of the intrusion of saltwater into the surrounding plains. The current study sought answers to the first issue. It is necessary to determine the changes over recent decades and develop a method to calculate the volume of water required for restoration. Urmia Lake plays an undeniable role in regional ecosystems and disagreement regarding changes in the lake and the volume of water for restoration will certainly develop.

The calculation of the volume of the lake would be simple if lakebed topography or lakebed digital elevation model (LBDEM) was available, but this does not exists because it has not been surveyed. Urmia Lake is a hyper-saline lake with an average salinity of about 350 g L^{-1}. This had increased to 551 g L^{-1} by July 2010 at Sharafkhaneh station according to the IMOE dataset. If it is assumed that the LBDEM of Urmia Lake is as surveyed many years ago, the high salinity (350 g L^{-1}), high evaporation and the 30 Bm^3 of negative balance (Urmia Lake Restoration National Committee 2016) means that 10.5 billion tons of salt has been deposited beneath the lake. This would alter the lakebed topography; consequently a new method should be developed to generate the LBDEM with respect to these salt deposits.

Various methods have been developed to monitor water resources. The issue of long-term monitoring and analysis of change is complex. Accurate datasets and appropriate analysis are required, including time series dataset and systems which can store, manipulate,

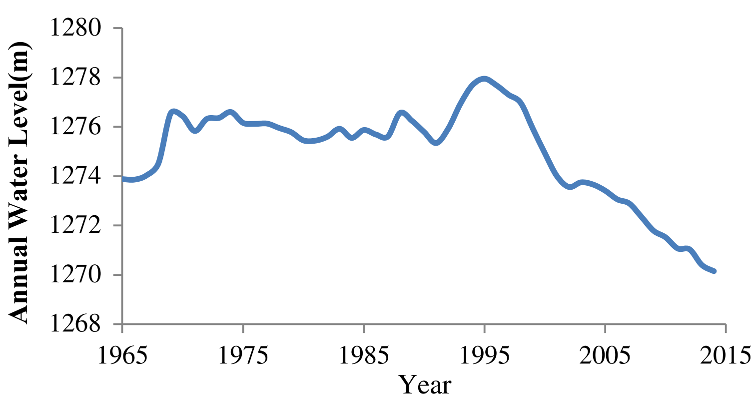


Fig. 1 Urmia Lake water level over the last 50 years

and analyze the data. This highlights the critical roles of remote sensing and the geographic information system (GIS). Remote sensing and GIS are the ideal solutions for such studies and have become efficient tools for long-term studies. Remote sensing satellites have collected periodic and long-term data at different spatial resolutions over recent decades. In addition, GIS integrates information and spatial data toward understanding natural trends and investigates potential changes. Remote sensing provides a fast and cost-effective approach monitoring such changes. The critical role of remote sensing in lake studies has been demonstrated in numerous studies (Alavipanah 2003; Alavipanah 2010; Ovakoglou et al. 2016; Moussavi et al. 2016; Dlamini et al. 2016; Dörnhöfer and Oppelt 2016; Shi et al. 2015; Arsanjani et al. 2015; Doña et al. 2015; Kleinherenbrink et al. 2015; Lu et al. 2013; Mehrian et al. 2016).

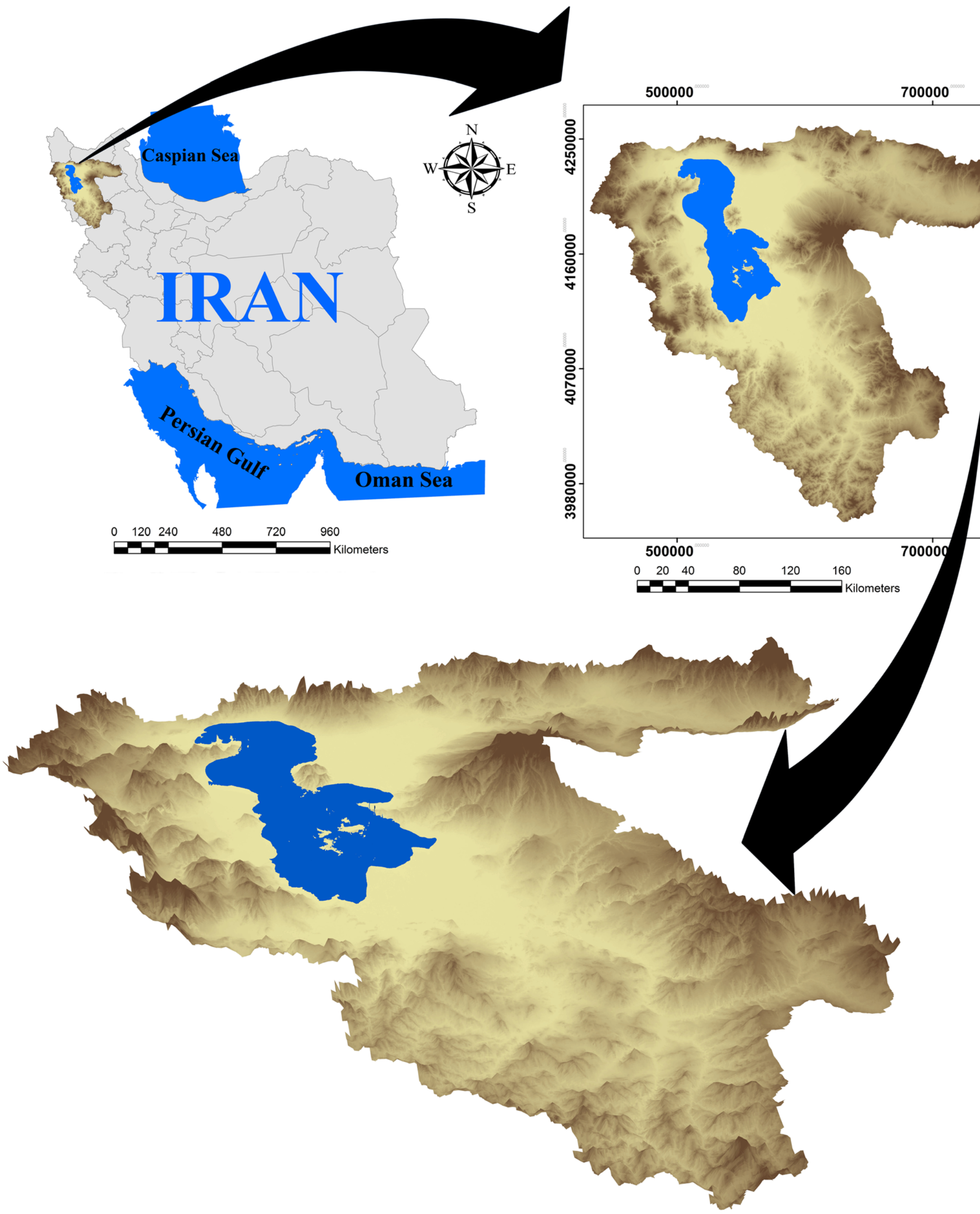


Fig. 2 Location of Urmia Lake in the basin (3D view)

Remote sensing is broadly used for detecting lake change, changes in water bodies, and coastline studies (Ghosh et al. 2015; Kuleli et al. 2011; Restrepo et al. 2012; Ford 2013; García-Rubio et al. 2015; Tourian et al. 2015; Almonacid-Caballer et al. 2016). Many studies have been carried out to estimate lake volume through remote sensing techniques. These include the use of radar altimetry data (Medina et al. 2010; Kleinherenbrink et al. 2015), laser altimetry data (Zhang et al. 2017b), volume-area-elevation relationships (Sima and Tajrishy 2013), and combined use of satellite altimetry and imagery data (Duan and Bastiaanssen 2013; Tourian et al. 2015) and using time series images (Lu et al. 2013). Lu et al. (2013) developed a triangulated irregular network (TIN)-based volume model to calculate the volume of a small lake with an area of 366 km^2. The calculations from this model were time-consuming and the volume was calculated based on the assumption that the inside height of each triangle was the average height of the triangle vertices. This was not the case because of the variations in elevation inside the each triangle. The assumption, therefore, produces a large calculation error for estimation of the volume of large lakes such as Urmia Lake.

The goals of the present study were threefold. The first was the long-term monitoring of Urmia Lake over a period of 30 years (1984 to 2014) by processing Landsat satellites time series images. The second was to present a novel method of generating the Urmia Lake LBDEM using the remotely sensed time series images, field measurements, and GIS and 3D modeling. The third was to calculate the volume of Urmia Lake in previous years and the volume of water required restoring the ecological water level or any water level based on the LBDEM.

This study presents a novel and practicable method of generating LBDEM for desiccating lakes which is applicable for developing countries. The LBDEM could also be generated through field surveys or RADAR and LIDAR instruments, but these approaches are costly.

Study area

Urmia Lake is located in northwestern Iran and between 37°06′ and 38°13′ N latitude and 45°20′ and 45°50′ E longitude (Fig. 2) and its maximum area was approximately 5500 km^2. The mean annual precipitation over the lake is about 350 mm (Sima et al. 2013) and the evaporation rate is high, averaging 1200 mm/year for a 50-year record (Zeinoddini et al. 2009). Urmia Lake

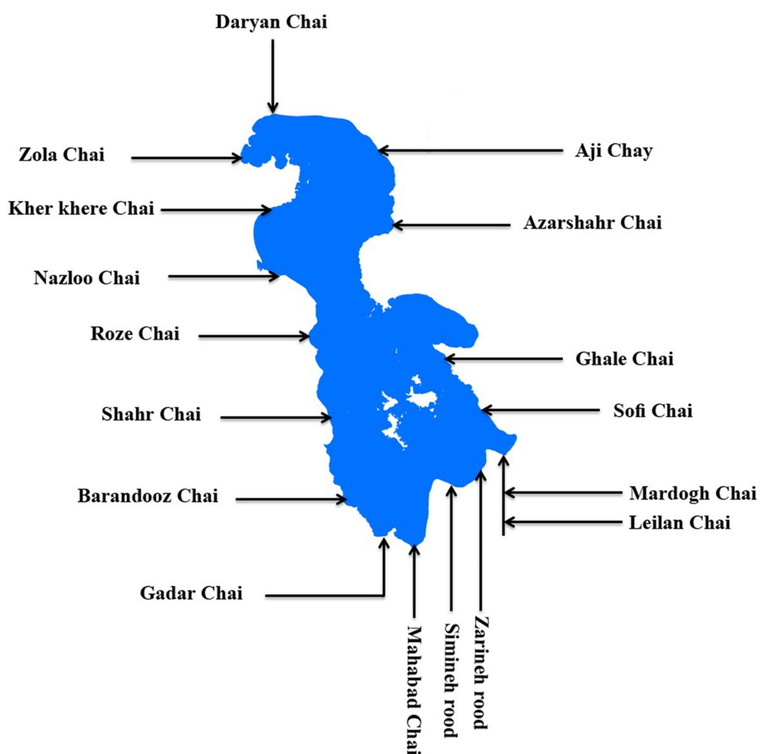


Fig. 3 Location of 17 permanent rivers flowing into Urmia Lake

requires a minimum inflow of 3 Bm^3 each year to balance out annual evaporation (Zarghami 2011). In recent decades, the water level of Urmia Lake has shown a descending trend (Fig. 1); the lake is drying up.

Urmia Lake basin contains 17 permanent rivers, 12 seasonal rivers, and 39 floodways (Hashemi 2008) that flow into the lake. The permanent rivers are shown in Fig. 3. The average annual inflow from the rivers is about 4.6 Bm^3, making them the main source of lake water (Zeinoddini et al. 2009). The building of dams on the permanent rivers has reduced the flow into the lake. The decrease in water level over the last decades provides a good case study for implementing the proposed method.

Materials and methods

Image acquisition

Lack of attention to image acquisition can cause undesirable changes in the results of remote sensing studies (Amiraslani and Dragovich 2013). Ideally, the remotely sensed data used to detect changes in phenomena is

Table 1 Properties of satellite images in this study

Year	Satellite	Sensor	Date	Number of scenes	Spatial resolution (m)
1984	Landsat 5	TM	27 Aug	1	30
			3 Sep	2	
1998	Landsat 5	TM	18 Aug	1	30
			25 Aug	2	
2000	Landsat 7	ETM+	22 Aug	2	30
			31 Aug	1	
2001	Landsat 7	ETM+	25 Aug	1	30
			26 Sep	1	
			5 Oct	1	
2002	Landsat 7	ETM+	6 Sep	1	30
			13 Sep	1	
			29 Sep	1	
2003	Landsat 7	ETM+	4 May	1	30
			11 May	2	
2004	Landsat 7	ETM+	17 Aug	2	30
			26 Aug	1	
2005	Landsat 7	ETM+	13 Aug	1	30
			20 Aug	2	
2006	Landsat 5	TM	24 Aug	1	30
			31 Aug	2	
2007	Landsat 5	TM	15 Jun	2	30
			24 Jun	1	
2008	Landsat 7	ETM+	5 Aug	1	30
			28 Aug	2	
2009	Landsat 5	TM	15 July	1	30
			22 July	2	
2010	Landsat 5	TM	10 Aug	2	30
			19 Aug	1	
2011	Landsat 5	TM	14 Sep	2	30
			23 Sep	1	
2012	Landsat 7	ETM+	17 Sep	1	30
			24 Sep	2	
2013	Landsat 8	OLI	12 Sep	1	30
			19 Sep	2	
2014	Landsat 8	OLI	15 Sep	1	30
			22 Sep	2	

acquired by a remote sensor systems that holds the spatial (and look angle), spectral, radiometric, and temporal resolutions constant. The details of remote sensing fundamentals can be obtained elsewhere (Jensen 2004, 2006). Ideally, remotely sensed data that is acquired by one sensor will have matching spatial (and look angle), spectral, radiometric, and partially temporal resolutions.

All image acquisition principles were taken into account. Because it was important to acquire images on anniversary dates that had minimum of precipitation and cloud covers, the dry months of the region are August and September. Field data from these months also show the minimum water level of the lake. Acquiring images for this period had two advantages; it eliminated precipitation and soil moisture effects and revealed the status of the lake at the minimum water body area and volume each year. It was important to select images showing the minimum area and water level to generate better LBDEM results. To assess the status of Urmia Lake over a period of 30 years using remotely sensed data, images from 17 years were selected based on image acquisition principles and data availability. The lake itself did not fit into a single image frame; thus, three images were mosaicked to create the lake shape. To produce images for 17 years, 51 scenes from Landsat satellites (Landsat 5, 7, and 8) from the TM, ETM+ and OLI sensors were processed. The characteristics of the images used are presented in Table 1.

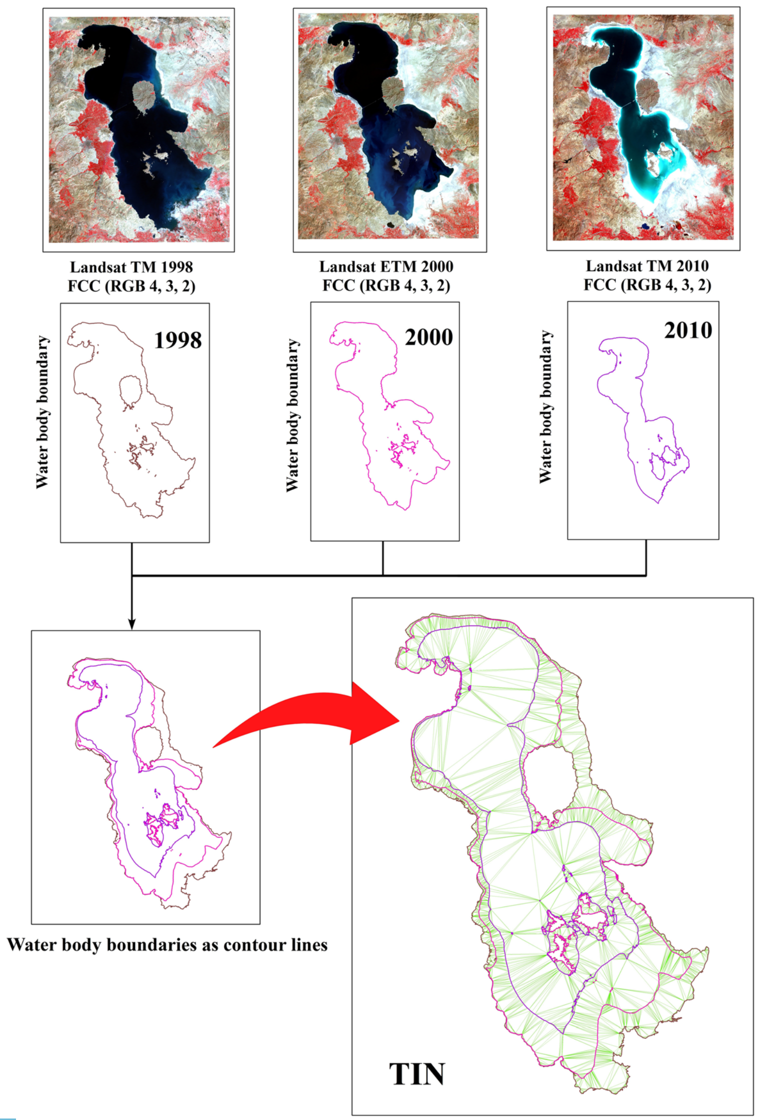


Fig. 4 Schematic of water bodies extraction and generation of contour lines and TIN presentation for 3 years

Image processing and water body extraction

The images were Terrain-Corrected (L1T) products which georeferenced by the United States Geological Survey (USGS) before downloading. The dark object subtraction method for atmospheric correction was first applied to all images, and then the images were mosaicked to generate the lake shape. The water body was extracted from the mosaicked images using the method developed by Stumpf et al. (2003). Details of the method and equations can be found in Stumpf et al. (2003).To increase the accuracy, the extracted water boundaries were visually checked for each year using the NIR band images (Klein et al. 2014). Next, the water bodies were imported into the GIS to change their format from raster to vector and then 3D analysis and modeling was continued in GIS.

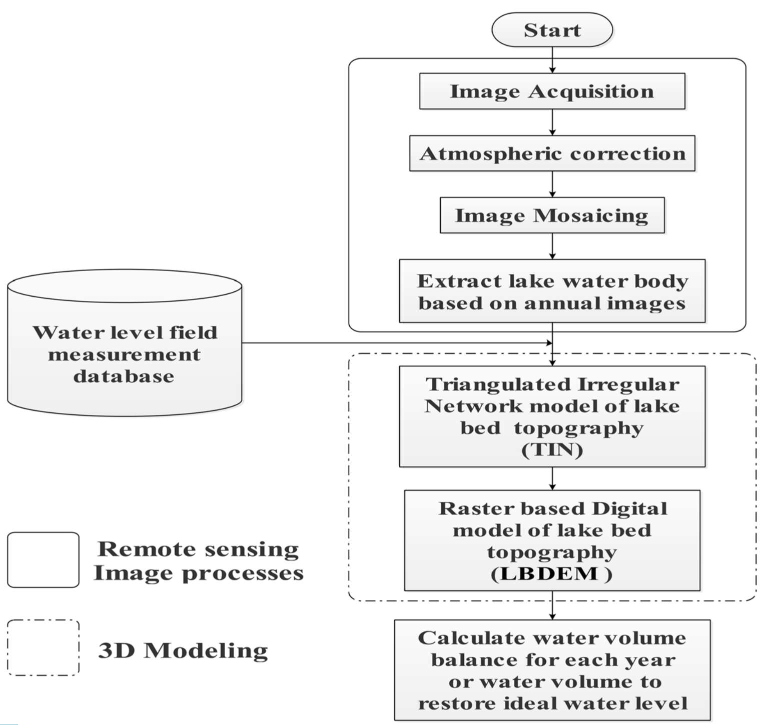
3D modeling

The series of water body boundaries of a lake which exhibits different water levels can be assumed to be contour lines on topographic maps (Feng et al. 2011; Lu et al. 2013). All images were acquired when the lake area was at a minimum level and the water body boundaries were extracted. The existing field measurements of the water level were then used to produce a contour line of the lake bed. Figure 4 shows a schematic presentation of water body extraction and contour line generation for 3 years along with its TIN model.

In GIS, 3D modeling is mainly employed to model and display the earth's surface/subsurface such as for topography or seabed mapping. An explanation of 3D modeling can be found in Li et al. (2005). A TIN is a digital data structure (De Floriani et al. 1985) and a vector-based data model used in GIS for 3D surface modeling (Li et al. 2005) and land surface or seabed representations. A TIN is generated using irregularly-distributed nodes and lines with 3D coordinates (x, y, and z) that are organized in a network of non-overlapping triangles. It is a surface approximation represented by a network of triangular elements with vertices placed at sample locations (De Floriani 1987). Details on TIN modeling can be found in Longley et al. (2005) and Li et al. (2005). TIN modeling is superior to split models (Lu et al. 2013) such as separated contour lines. The TIN model of the lakebed generated from the 17 contour lines reveals the status of the lake over a 30-year period (Fig. 4).

A digital elevation model (DEM) is a raster-based representation of the terrain's surface or any type of phenomena that experiences changes in elevation. A

Fig. 5 Methodology flow chart



DEM is a grid-based model, each grid called a cell. Every cell has a value that denotes its height. DEM is superior to TIN because its grid-based structure facilitates complex and time-consuming calculations and increases the accuracy of estimation. In DEM, each cell at the x and y coordinates provides a value that can be used for calculation. To generate a grid DEM with high quality and accuracy, it is better to generate it from TIN instead of directly interpolated from random samples (Hu et al. 2011). Accordingly the TIN model is a prerequisite to generating LBDEM.

A four-step method was used to generate the Urmia Lake LBDEM and calculate water volume at any water level. The Urmia Lake water body area for each year was first extracted through remote sensing image processing techniques. All 17 water boundaries were integrated with the water level to generate contour lines. The TIN model was generated from the contour lines and was used to generate the LBDEM. The volume of water required to restore the lake was calculated using the LBDEM. The methodology is summarized in Fig.5.

Results and discussion

The status of Urmia Lake was assessed over a period of 30 years to show the trend of change. Its status for each year is shown in Fig. 6 and the water body area for each year is listed in Table 2. The areas of shrinkage and expansion of the lake between years are shown in Fig. 7. As an overview, the change in the coastline of the southern half of Urmia Lake from 1998 to 2014 is shown in Fig. 8.

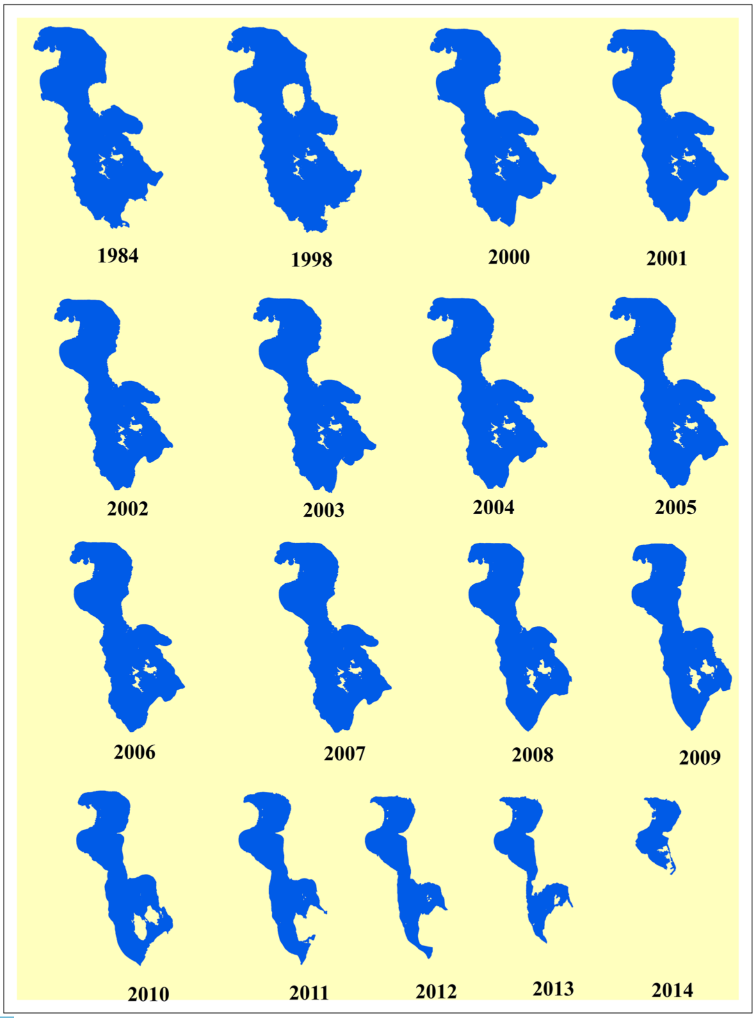


Fig. 6 Variation in Urmia Lake water body from 1984 to 2014

Table 2 Area of Urmia Lake from 1984 to 2014

Year	Area (km^2)
1984	4980
1998	5581
2000	4695
2001	4404
2002	4178
2003	4460
2004	4288
2005	4178
2006	4000
2007	4116
2008	3568
2009	3277
2010	2858
2011	2318
2012	1912
2013	1554
2014	740

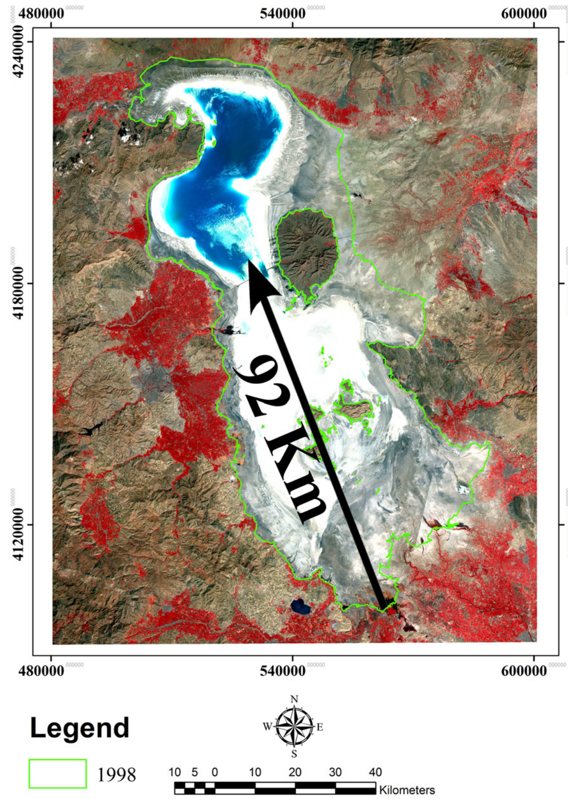


Fig. 8 Retreat of southern coastline from 1998 to 2014 (red denotes agricultural land)

The contours were developed from the water boundaries, the TIN model was produced and the LBDEM was generated using the TIN model. Figure 9 shows the triangular network of TIN, TIN structure without triangular network presentation and LBDEM as the final product. The volume of lake at any water level can be estimated using the LBDEM. The volume of the lake was estimated for 16 of the 17 water levels. Urmia Lake water level in 2014 was 1270.15 m which was the minimum until now. The lowest level (in 2014) was assumed by the model to be the lakebed and was used as the benchmark for volume calculations. All volumes were estimated based on this water level (Table 3). The model then calculated the volume of water required to restore any water level from this benchmark of 1270.15 m. For instance, the volume of water required to restore the water level from 1270.15 (in 2014) to 1273.18 (in 2007) is 8.629 Bm^3. The model can estimate the volume between two arbitrary water levels, the negative balance for 2014 from any year or water level and lake area at any water level. Table 3 and Fig. 10 summarize the volume of water required to restore the

Fig. 7 Area (km^2) of shrinkage and expansion of lake between years (blue denotes expansion and red denotes shrinkage)

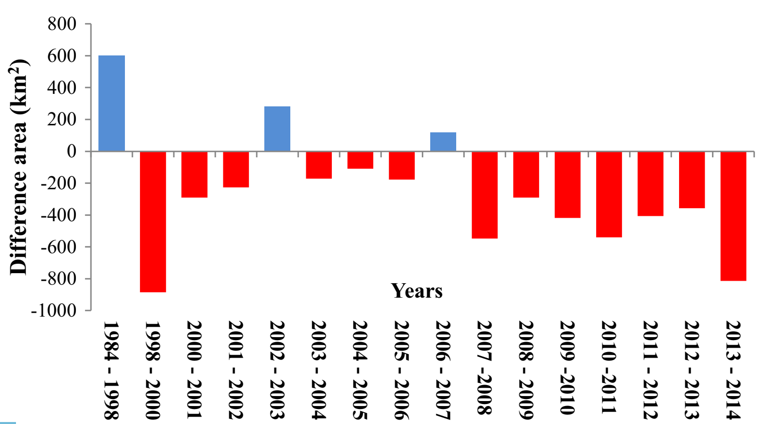
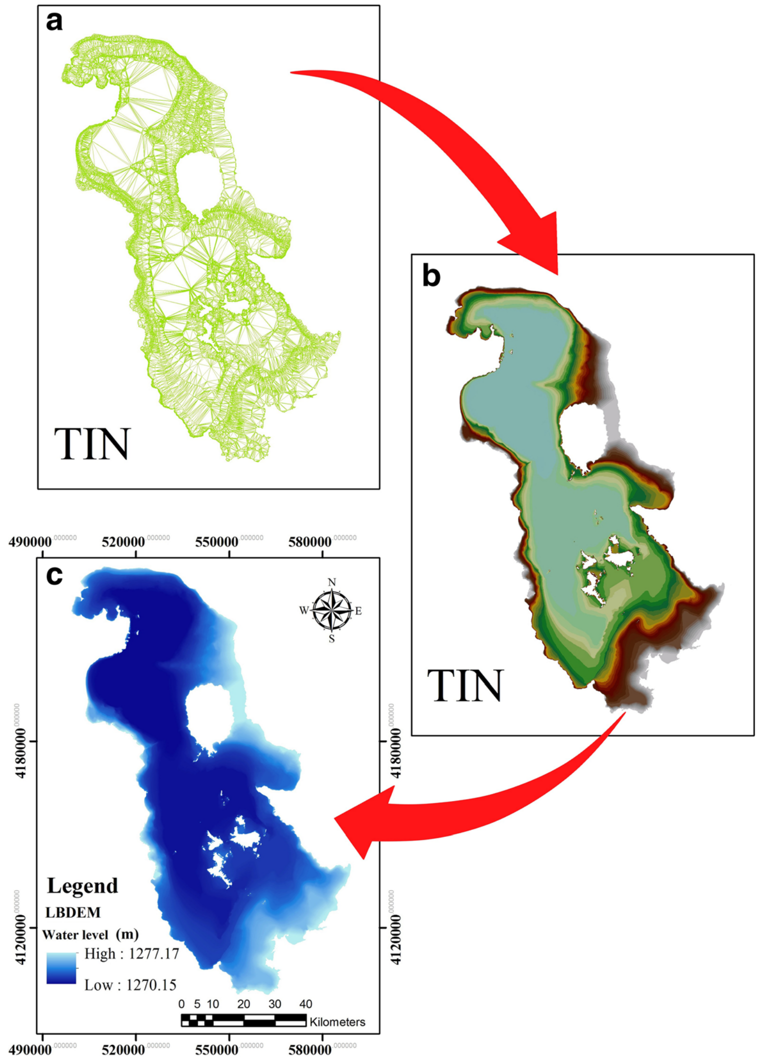


Fig. 9 a Triangular network presentation of TIN, b simple TIN presentation, and c final LBDEM



water level in a given year. Figure 11 shows the negative and positive balance of Urmia Lake volume between years.

Figure 6 and Table 2 reveal that the area of Urmia Lake has decreased drastically over the study period. The area of the lake decreased from 5581 km^2 in 1998 (maximum area for the 30 years) to 740 km^2 in 2014. This signifies an 86% decrease in the lake during this period. Figure 7 shows that the southern coastline has receded about 92 km from its location in 1998, demonstrating a severe decrease in area and desiccation of the lake. The LBDEM indicates that the topographic changes in the southern half of the lake are much less than in the northern half. These topographic conditions exacerbated the lake's backward move in the southern half. This heterogenic topography is reflected in the polynomial trend between lake's water level and surface area (Fig. 12) and indicates a non-linear relationship between water level and area. Table 3 can be used to compare the volume of lake water between 1998 and 2013 to reveal the magnitude of this disaster. The volume of lake water in 2013 was just 0.83% of the 1998 volume.

The LBDEM shows that the volume of water required restoring Urmia Lake from benchmark status in 2014 to the 1998 maximum water level and the ecological water level (1274.10 m) is 27.881 and 12.546 Bm^3, respectively. The volume of water required to restore Urmia Lake from its current water level of 1270.70 m (30 June 2017) to the ecological water level is

Table 3 Volume of water to restore the lake to status of past years based on lake status in 2014

Year	Volume of water to restore lake based on 2014 status* (Bm^3)
1984	19.188
1998	27.881
2000	16.196
2001	12.456
2002	9.873
2003	12.767
2004	10.805
2005	9.873
2006	7.534
2007	8.629
2008	5.160
2009	3.688
2010	2.705
2011	1.504
2012	0.684
2013	0.232

*Urmia Lake water level in 2014 was 1270.15 m which was the minimum until now and this year was the benchmark for volume calculations

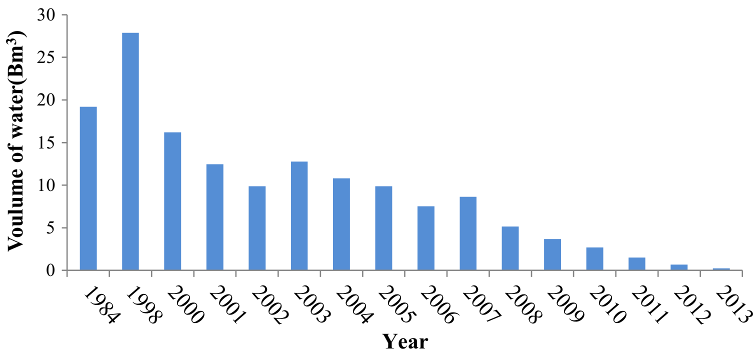
11.813 Bm^3. This is a vast volume of water and its supply will not be easy.

The relationships between Urmia Lake volume and water level and volume and lake surface area were assessed and regression equations were generated having high coefficients of determination (R^2) of 0.999 and 0.993, respectively (Figs. 13 and 14). These equations were just developed from the relation between lake volume with water level and surface area, to accurately calculate the volumes for use in decision-making the volume should calculated from the LBDEM. The estimated volumes are only the net volume required to restore the lake and do not consider evaporation. The evaporation rate in the area is much higher than the precipitation rate. Accordingly, in restoration process the amount of evaporation should be also considered and calculated.

The high salinity of Urmia Lake (350 g L^{-1}) means that desiccation of the lake has increased the size of the salt deserts surrounding it (Golabian 2011). This salt is carried by the wind and produce salt storms (UNEP 2012) such as those observed as the result of desiccation of the Aral Sea (Golabian 2011). Around the Aral Sea area, salt storms have reduced crop production and yield and resulted in negative social and economic consequences and an increase in respiratory illnesses and eye problems (Micklin 2007). Urmia Lake is located in a densely-populated region of northwestern Iran that includes the city of Tabriz, the largest the largest industrial city in northwestern Iran, city of Urmia, and thousands of hectares of agricultural land (denoted in red in Fig. 8).

Salt storms represent severe health hazards to residents of the region (Golabian 2011). They also deposit salt on the surrounding agricultural land and alter the physicochemical properties of the soil and cause secondary soil salinization. Soil salinization decreases soil and crop productivity and will destroy crop land and exacerbate desertification. The storms do not only impact regional health, but also affect the livelihoods of regional farmers and these consequences are only those described for the Urmia Lake watershed. On the larger scale, the lake is central to a populated area that includes southern Caucasia, northern Iraq and eastern Turkey (Golabian 2011). Urmia Lake is a ticking salt bomb, which the salt storms and disastrous consequences threaten an area that extends far beyond northwestern Iran (Golabian 2011).

Fig. 10 Trend of change in Urmia Lake volume over study period based on LBDEM



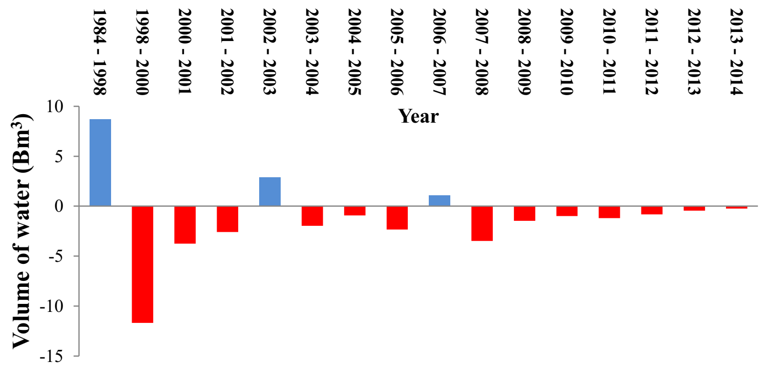


Fig. 11 Negative and positive balance of Urmia Lake volume between years

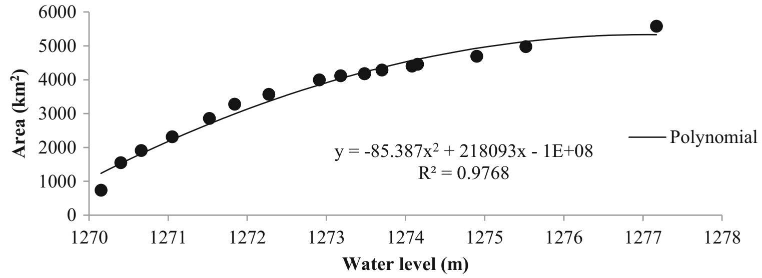


Fig. 12 Relation between Urmia Lake water level and surface area

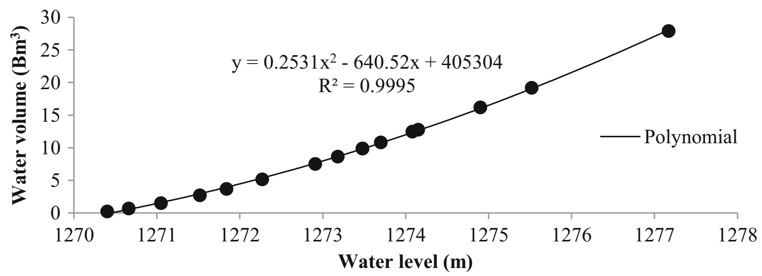


Fig. 13 Relation between Urmia Lake water level and volume

The groundwater of the plains surrounding Urmia Lake has experienced a negative balance and saltwater intrusion into the aquifers has been reported by Jeihouni (2015). Jeihouni (2015) discussed that increasing the water level intensifies saltwater intrusion and rendering the groundwater unusable. Groundwater is crucial in the semi-arid climate of the area for agricultural purposes and saltwater intrusion threatens the agriculture in the

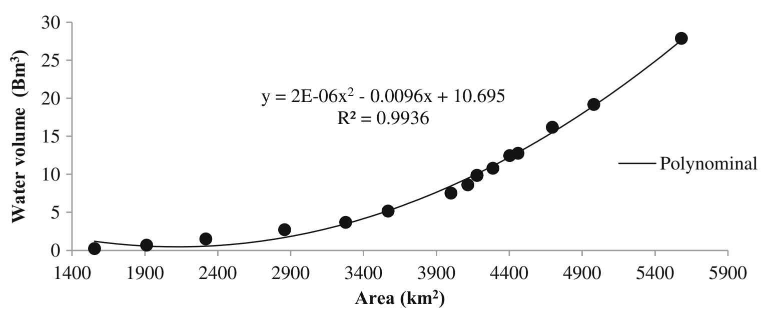


Fig. 14 Relation between Urmia Lake surface area and volume

surrounding plains. The focus must not be limited to restoring the lake, but the spread of water must also be taken into account. More research is needed to understand the complexities of the restoration of Urmia Lake.

Conclusion

The current study developed a method of estimating the volume of water to restore Urmia Lake water levels. The goals of this study were to generate a LBDEM of Urmia Lake and calculate the water volume at any water level using LBDEM to facilitate lake status assessment. The method of generating the LBDEM was the innovation of this study. For this purpose, time series images of Landsat satellites were combined with field water level measurements to generate the LBDEM by employing image processing algorithms, GIS and 3D modeling techniques. The monitoring and assessment of the area and volume of Urmia Lake shows a descending trend over a 30-year period. The lake area decreased from 5581 km^2 in 1998 to 740 km^2 in 2014. The volume of water required restoring Urmia Lake from benchmark status in 2014 to the ecological water level is 12.546 Bm^3 and the lake volume in 2013 was just 0.83% of the 1998 volume.

The results of this study clarify the magnitude of the disaster, which will influence an area far beyond that of northwestern Iran. Urmia Lake should be restored, but the process is complex because of the lake's unique conditions. The present study proposed a novel approach to calculate the volume of water required to restore Urmia Lake to any water level, such as to its ecological water level. The generated LBDEM answers the one of the most important questions about restoring Urmia Lake. The proposed method and the results of this study can be used as a basis by national and international organizations such as the Urmia Lake National Restoration Committee and United Nations Environment Programme to obtain comprehensive and quantitative information about Urmia Lake to assist in the difficult task they face.

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