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Using satellite data to extract volume–area–elevation relationships for Urmia Lake, Iran

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ABSTRACT

Urmia Lake in the northwest of Iran is the second largest hyper-saline lake worldwide. During the past two decades, a significant water level decline has occurred in the lake. The existing estimations for the lake water balance are widely variable because the lake bathymetry is unknown. The main focus of this study is to extract the volume–area–elevation (V–A–L) characteristics of Urmia Lake utilizing remote sensing data and analytical models. V–A–L equations of the lake were determined using radar altimetry data and their concurrent satellite-derived surface data. Next, two approximate models, a power model (PM) and a truncated pyramid model (TPM), were parameterized for Urmia Lake and checked for accuracy. Results revealed that in comparison with the satellite-derived reference volume–elevation equation, the PM slightly over-predicts the volume of Urmia Lake while the TPM under-estimates the lake storage. Variations of the lake area and volume between 1965 and 2011 were examined using the developed V–A–L equations. Results indicated that the lake area and volume have declined from the historical maximum values by 2200 km^2 and 33 km^3, respectively. To restore Urmia Lake to a level to maintain ecological benefits, 13.2 km^3 of water is required. This study demonstrates the use of remote sensing data of different types to derive V–A–L equations of lakes. Substituting satellite-derived V–A–L equations for common empirical formulas leads to more accurate estimations of a lake water balance, which in turn, provides insight to water managers for properly assessing and allocating water resources to downstream ecosystems.

Introduction

Urmia Lake is the second largest hyper-saline lake worldwide. It is located in a closed basin between 37° 04′ N and 38° 17′ N latitude and 45° E and 46° E longitude in the northwest of Iran. It has an historical maximum surface area of 5700 km^2 (Alipour, 2006). Urmia Lake was declared a wetland of international importance by the Ramsar Convention in 1971(Ramsar Convention website). Moreover, because of its ecological importance, the lake is defined as a National Park and International Biosphere Reserve (Abbaspour and Nazaridoust, 2007). Urmia Lake is situated in a semi-arid area, having a mean annual temperature of 11.2 °C, an average precipitation and evaporation rate of 341 and 1200 mm/yr, respectively (Djamali et al., 2008). Aquatic biodiversity is limited by the lake's high salinity. The most significant aquatic biota in the lake is a brine shrimp species, *Artemia urmiana* and no flora other than phytoplankton is found within the lake (Ghaheri et al., 1999). There are four major islands in the south part of the lake which are considered protected areas by the Iran Department of Environment (Fig. 1). These islands are important destinations for various migratory birds including flamingos, pelicans, spoonbills, ibises, storks, avocets, stilts and gulls. There are also two very rare species of mammals which are sheltered and preserved on the islands of Urmia Lake: Yellow Persian deer (*Dama mesopotamica*) and a variety of sheep (*Ovis Orientalis gimelini*).

During the last two decades the lake water level has significantly dropped mainly due to over-exploitation of upstream rivers and ongoing drought (Eimanifar and Mohebbi, 2007; Hassanzadeh et al., 2011). Retreat of Urmia Lake from its original shoreline is not only a hydrological concern, but it also presents serious challenges for water quality, conservation, human health and economics. For example, the decrease in volume has caused the salinity level of the lake to exceed the tolerable salinity threshold of *A. urmiana*. Population growth rates of *A. urmiana* are expected to decline as most of the species physiological activities will cease due to the increased salinity (Agh et al., 2008; Asem and Rastegar-Pouyani, 2010). Another consequence of the lake desiccation is the expansion of its islands, which has resulted in land bridges between some of the islands and the east shores. This has caused that some species of Persian Fallow Deer to flee from the islands to nearby villages. Moreover, precipitation of dissolved salts has produced salt crusts covering the black organic mud of the lake bed, particularly at the shorelines (Alipour, 2006). These dried coastal salt lands

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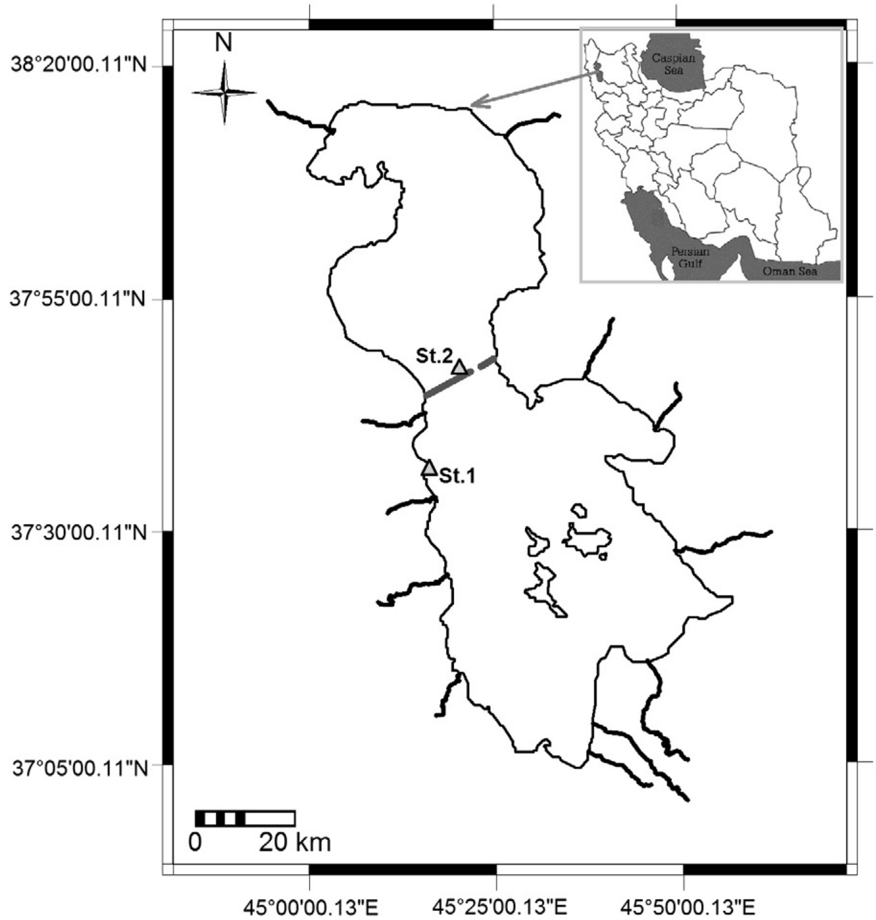

Fig. 1. Urmia Lake and the previous (St.1) and current locations (St.2) of the water level gauge. Solid line across Urmia Lake by St. 2 marks location of a causeway.

can create salt dusts that then are dispersed over the surrounding agricultural and residential areas when they are exposed to strong winds. It has been estimated that the 76 million people living within a 500 km radius of the lake will be at risk of such windblown salt-storms (UNEP and GEAS, 2012).

To overcome such challenges, it is essential to setup a comprehensive integrated water management plan which takes into account all elements of the basin's water budget and can balance demands for human use and ecosystem requirements. The integrated management plan of Urmia Lake was established in May 2010 under the United Nations Development Program/-Global Environmental Facility/ Iran Department of Environment joint project for conservation of Iranian Wetlands (Department of Environment, 2010). Within this framework, it is noted that a volume of 3.1 km^3 of water needs to enter the lake annually in order to keep its water level at the minimum ecological level of 1274.1 m. This level was defined to meet the hydrological and water quality conditions ($NaCl < 240$ g/L) required to preserve *A. urmiana*, as the main ecological feature of Urmia Lake (Abbaspour and Nazaridoust, 2007).

One of the principal shortcomings of that study, which is considered as the base point for the lake restoration, is lack of sufficient knowledge about the lake bathymetry. Accuracy of the volume–area–elevation (V–A–L) and salt balance equations applied in that study is highly questionable because of large uncertainties in the few data used to derive them. A comprehensive bathymetric survey has never been conducted in Urmia Lake. Because the lake is shallow and hyper-saline, movement of ships and boats is prohibited. Thus, eco-sounder measurements cannot be applied over the whole lake. A few hand soundings have been made by local researchers, but these are insufficient to generate a Digital Elevation Map (DEM) of Urmia Lake.

Analytical models expressing the volume–elevation relationship of water bodies from minimal field data can serve as geometric depression models in simulation studies (Nilsson et al., 2008). Application of analytical models in hydrologic studies to predict wetland volume characteristics has been considered for many years (Singh and Woolhiser, 2002). A number of researchers have developed different models for various types of water bodies. These models can be categorized into two major types: Power Models (PM) and Truncated Pyramid Models (TPM). O'Connor (1989) parameterized PMs for several lakes and reservoirs in the United States to simulate variation of dissolved solids. Wise et al. (2000) developed a volume–elevation (V–L) PM for an isolated marsh wetland. Furthermore, Hayashi and van der Kamp (2000) introduced a PM to represent the area–depth relations of ephemeral ponds and wetlands in small natural depressions. A PM was developed by Nilsson et al. (2008) to describe volume–elevation (V–L) relationships for different types of wetlands in the United States and Canada. Likewise, the TPMs have been applied by limnologists and fisheries biologists to compute volumes of lakes and wetlands (Taube, 2000). For example, Shjeflo (1968) used a truncated pyramid formula to verify that wetland volumes developed from specific topographic maps were accurate. Moreover, the TPM is currently used by several global lake databases such as the HYDROWEB (http://www.LEGOS.obs-ip.fr/soa/hydrologie/HYDROWEB) to calculate volume variations for a number of lakes.

Analytical models require some data from the lake V–A–L to be developed or validated, although not as intensive as bathymetric studies. Remote sensing appears to be an ideal method to acquire data for analytical models. Several researchers have confirmed the potential of remote sensing data to extract detailed information of wetlands such as wetland size, shape, type and extent (e.g. Cavalli