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A spaceborne multisensor approach to monitor the desiccation of Lake Urmia in Iran

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ABSTRACT

Lake Urmia, a hypersaline lake in northwestern Iran, is under threat of drying up. The high importance of the lake's watershed for human life demands a comprehensive monitoring of the watershed's behavior. Spaceborne sensors provide a number of novel ways to monitor the hydrological cycle and its interannual changes. The use of GRACE gravity data makes it possible to determine continental water storage changes and to assess the water budget on monthly to multi-annual time scales. We use satellite altimetry data from ENVISAT and CryoSat-2 to monitor the lake water level. Moreover, we employ optical satellite imagery to determine the surface water extent of the lake repeatedly and at an appropriate time interval.

Our altimetry results indicate that, on average, the lake has lost 34 ± 1 cm of its water level every year from 2002 to 2014. The results from satellite imagery reveal a loss of water extent at an average rate of 220 ± 6 km^2/yr, which indicates that the lake has lost about 70% of its surface area over the last 14 years. By combining water level from altimetry, surface water extent from satellite imagery and local bathymetry, we ascertain the changes in lake volume. Results indicate that the lake volume has been decreasing at an alarming rate of 1.03 ± 0.02 km^3/yr. The water volume of the lake behaves differently from the water storage of the whole basin captured by GRACE. Our results show that the onset of a drought in 2007 over this region together with an increase in the rate of groundwater depletion caused a new equilibrium level for water storage of the whole basin. Comparing the results from GRACE and the obtained water volume in the lake with in situ groundwater level data reveals the anthropogenic influences on an accelerated lake desiccation. In fact, our monitoring approach raises critical issues regarding water use in the basin and highlights the important role of spaceborne sensors for any urgent or long-term treatment plan.

1. Introduction

The Urmia Lake is located in the northwest of Iran between the two Iranian provinces of East and West Azerbaijan. It was the largest inland body of salt water in the Middle East and the largest permanent hypersaline lake in the world with an area varying from 5200 to 6000 km^2 in the twentieth century (Zarghami, 2011; Hassanzadeh, Zarghami, & Hassanzadeh, 2012). The lake and its basin is home to many species including a unique brine shrimp species *Artemia urmiana* (Karbassi, Bidhendi, Pejman, & Bidhendi, 2010). However, in the recent past the lake and its corresponding basin have suffered from an environmental disaster. It has been reported that the surface area and the lake's water level have been declining since 1995 due to various climatic and anthropogenic reasons (Delju, Ceylan, Piguet, & Rebetez, 2013; Karbassi et al., 2010). The lake contains an estimated 8 billion tons of salt. In the case of a complete desiccation, releasing this amount of salt by windborne transport could lead to an ecological, agricultural, and social catastrophe, not only in Iran, but also in neighboring countries such as Turkey, Iraq and Azerbaijan (Pengra, 2012). The drastic decline of lake surface area has been acknowledged and quantified by many research groups reporting a decrease of about 60% in less than a decade (Eimanifar & Mohebbi, 2007).

Hassanzadeh et al. (2012) stated that changes in inflows due to the climate change and overuse of surface water resources are responsible for 65% of the desiccation, the construction of four dams on upstream rivers is responsible for 25%, and reduced precipitation accounts for 10%. The overuse of surface water resources and especially groundwater extraction was the subject of a study by Voss et al. (2013) over a broader region, the Tigris–Euphrates–western Iran region, including the Urmia Lake basin. They quantified an alarming rate of decrease in total water storage of approx. -27.2 ± 0.6 mm/yr between 2003 and 2009. Forootan et al. (2014) proposed a statistically-based signal separation procedure to separate terrestrial and surface water storage changes in the GRACE signal over a broad region encompassing Iran. They obtained a groundwater loss of 11.2 mm/yr over the Lake Urmia region, which is actually the highest rate among the six regions studied in Iran. In a similar study, Joodaki, Wahr, and Swenson (2014) stated that most of the long-term water loss in Iran is due to a decline in groundwater storage,

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where they quantified 25 ± 3Gt/yr as the rate of mass loss due to groundwater depletion. However, one cannot compare the aforementioned values as they are estimated over different regions. Further, Delju et al. (2013) mainly focused on climatic change over the basin. They quantified a decrease of 9.2% for mean precipitation and an increase of 0.8 °C for maximum temperature over the past four decades. Of course, the decrease in precipitation and increase in temperature caused a drought in this region (Trigo, Gouveia, & Barriopedro, 2010), which, together with the increasing demands of irrigation, accelerate the rise of salinity in the lake to more than 300 g/L i.e. 8 times saltier than typical seawater during recent years (Asem, Mohebbi, & Ahmadi, 2012).

Moreover, a causeway was built across the lake (middle of the lake) to connect the two cities of Tabriz and Urmia starting from 1979 to 2008 with only a 1500-m gap for water to move between the northern and southern halves of the lake. This causeway was also identified by previous studies as one of the reasons as the desiccation initially started from southern part of the lake (Eimanifar & Mohebbi, 2007). From these previous studies (Delju et al., 2013; Eimanifar & Mohebbi, 2007; Golabian, 2011; Hassanzadeh et al., 2012; Karbassi et al., 2010; Voss et al., 2013; Zarghami, 2011), we summarize the different reasons for the drying up of the lake (1) increased extraction of groundwater for irrigated agriculture within the lake's watershed, (2) reduced precipitation, (3) the construction of a causeway across the lake, (4) dam construction and (5) climate change.

This study uses a spaceborne multisensor approach to monitor and quantify the desiccation of Lake Urmia. Here we analyze and combine, for the first time over Lake Urmia and its wider basin area, the water storage change time series from GRACE, surface water level time series over different parts of the lake from ENVISAT and CryoSat-2 altimetry, surface water extent time series from optical imagery (MODIS) together with in situ data of groundwater and hydrological fluxes to reconstruct the lake's hydrological cycle.

Satellite altimetry and satellite imagery for the analysis of water volume variation have been combined by several studies. Duan and Bastiaanssen (2013) estimated water volume variations in Lake Mead (U.S.A.), Lake Tana (Ethiopia) and Lake IJssel (The Netherlands) from four operational satellite altimetry databases and satellite imagery data. Michailovsky and Bauer-Gottwein (2013) employed satellite altimetry and imagery to develop a rainfall runoff model of the Zambezi River basin for inflow forecasting. Recently, Baup, Frappart, and Maubant (2014) combined high-resolution satellite images and altimetry to estimate the volume changes of small lakes in France, which are mainly used for irrigation purposes.

Singh, Seitz, and Schwatke (2012) included mass changes from GRACE in addition to the geometric variables from satellite altimetry and optical imagery, demonstrating the combination of physical and geometrical observations. The application of the GRACE data for hydrological purposes has been growing since 2002 e.g. Döll et al. (2014), Longuevergne, Scanlon and Wilson (2010), Riegger, Tourian, Devaraju and Sneeuw (2012) and Schmidt et al. (2008). It captures water storage change over landmasses, which is a useful indicator of climate variability and human impact on the environment. However, GRACE can resolve water storage changes if the signal variability is larger than its uncertainty level of 7–10 mm (Riegger et al., 2012).

Here, we use the same sensors as Singh et al. (2012), but differ from their methodology. Instead of concentrating only on the lake surface area, we take a holistic view of the lake and its basin, thereby enabling us to study the hydrological cycle and its balance. Further, we also make full use of the complementary hydrological data that is available for the Urmia basin: precipitation, evapotranspiration and in situ groundwater data. The use of such complementary data allows us to study the anthropogenic influences, as will be shown later. Our results from spaceborne sensors would be of great importance for mitigation planning of the ongoing environmental disaster over the Urmia Lake basin. On top of this, we also demonstrate the utility of GRACE in regions far below its spatial resolution but with a strong seasonal signal. This, we believe, characterizes our current study.

The paper starts with a description of complementary hydrological data sets in Section 2. Section 3 describes our approach to analyzing the surface water extent of the lake using satellite imagery. In Section 4 we explain the data sets and our method to derive the lake's water level from satellite altimetry. The results from satellite altimetry and satellite imagery, together with local bathymetry data, are used in Section 5 for computing total water volume in the lake. Sections 3–5 deal with monitoring the quantities over the lake itself, while Section 6 discusses estimation of equivalent water height over the whole basin using GRACE. We extensively analyze and quantify the desiccation of the lake in Section 7, where the estimated time series of water volume over the lake and over the whole basin are investigated toward desiccation monitoring. Section 8 will summarize and conclude the results of this study.

2. Data

Apart from the spaceborne data needed to monitor the lake's desiccation, we also need precipitation, evapotranspiration and groundwater data for a better analysis and interpretation of hydrological behavior over Lake Urmia and its basin (Fig. 1). Table 1 summarizes all datasets and sensors that are used in this study.

2.1. Precipitation

Among available precipitation data, the Global Precipitation Climatology Center (GPCC) seems to deliver better datasets around the world (Lorenz & Kunstmann, 2012; Riegger et al., 2012). However, our pre-analysis over this region showed that the data from the Global Precipitation Climatology Project (GPCP) provides a slightly higher compatibility with other hydrological data. Moreover, the GPCC data is only available up to 2010, which impedes our hydrological analysis after 2011. Therefore, in this study we use the monthly $2.5^\circ \times 2.5^\circ$ data sets of the GPCP data, version 2.2. Our confidence in using a global data set has increased after comparing it with in situ precipitation data of 1996–2003 over the lake basin and obtaining a good agreement (not shown here).

2.2. Evapotranspiration

Evapotranspiration is typically available from models or remote sensing only. The models are available from different sources, which range from simple empirical to complex ones including radiative energy balance models. Among the data from the Global Land-surface Evaporation from Amsterdam Methodology (GLEAM) (Miralles et al., 2011), ECMWF (Berrisford, & for Medium Range Weather Forecasts, 2009; Simmons, Uppala, Dee, & Kobayashi, 2006) and MOD16 from MODIS (Mu, Heinsch, Zhao, & Running, 2007) the ECMWF data delivers better time series in terms of compatibility with other hydrological data (Lorenz et al., 2014). Therefore, in this study we use the monthly $0.75^\circ \times 0.75^\circ$ data sets of the ECMWF data.

2.3. Groundwater data

In this study, we use in situ groundwater observations of 19 piezometric stations of the Iranian Water-resource Research Center (WRC) over the Urmia basin (Fig. 1). The observations of different stations cover different time periods, but all the 19 stations provide observation for the time period of 2003–2011. Apart from two stations of Salmas and Oshnavieh that show peculiar behavior after 2008 containing ~8 m of sudden change in groundwater level, we use all the other stations for our analysis.