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Climate and anthropogenic contributions to the desiccation of the second largest saline lake in the twentieth century

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ABSTRACT

Urmia Lake, once the second largest saline lake in the world, is on the verge of complete desiccation. It has been suggested that the desiccation is caused by intensified human activities, especially irrigation, and prolonged droughts in the lake basin, but there is a lack of quantitative analysis to attribute the observed water level decline to natural and anthropogenic causes. In this study, we use remote sensing data, ground observations, and a hydrological model with human impact assessment capabilities (HiGW-MAT) to investigate the natural and human-induced changes in the hydrology of Urmia Lake basin from 1980 to 2010. Based on the analysis of remote sensing data, we find a ∼98% and ∼180% increase in agricultural lands and urban areas, respectively, from 1987 through 2016, with a corresponding shrinkage in lake area by ∼86%. Further, we use model results to examine the changes in terrestrial water storage (TWS) over the basin including the lake. Results indicate that TWS declined over the lake region and the lake lost water at a faster rate than the watershed did. Comparison of river inflow to the lake from two simulations—one with and the other without human activities—suggests that human water management activities caused a reduction in streamflow of ∼1.74 km^3/year from 1995 to 2010, which accounts for ∼86% of the total depletion in lake volume during the same period. It is also found that irrigation water requirement almost tripled, causing high withdrawals from rivers. These results demonstrate that the on-going depletion of Urmia Lake is not solely due to prolonged droughts but also due to direct anthropogenic alterations which caused significant changes in land use, streamflow, and water storage within the basin. This study provides important insights on the natural and human-induced changes in the hydrology of Urmia Lake and highlights the need for a high resolution regional scale modeling approach for better understanding potential future changes toward restoring the lake and putting forth a course of action to stop further desiccation and avoid a major environmental catastrophe.

1. Introduction

There are increasing evidences from ground- and satellite-based observations that human land-water management activities have profoundly impacted the natural pattern of water flows and storages over large scales (Carpenter et al., 2011; Halpern et al., 2008; Meybeck, 2003; Newbold et al., 2016; Nilsson et al., 2005; Vitousek et al., 1997; Vörösmarty et al., 2010). These evidences clearly indicate that, today, more than 40% of the natural landscape has been heavily modified (Foley et al., 2005; Ramankutty et al., 2008), most of the large river systems around the world remain largely fragmented (Dynesius and Nilsson, 1994; Gleick, 2003; Nilsson et al., 2005), groundwater storage in the world's largest aquifer systems are declining at an alarming rate (Long et al., 2013; Pokhrel et al., 2015, 2012b; Rodell et al., 2009; Scanlon et al., 2012; Wada et al., 2010), and some of the largest inland water bodies are fast disappearing (AghaKouchak et al., 2015; Micklin, 2010, 1988; Pokhrel et al., 2017). Climate change and variability is inarguably an important driver of these changes (Donohue et al., 2011, 2010; Irmak et al., 2012; Liu and McVicar, 2012; McVicar et al., 2012; Milly and Dunne, 2016, 2011; Scheff and Frierson, 2014; Wild, 2014; Willett et al., 2008), but there is a growing consensus that human activities now rival natural climatic factors and hence are the major drivers of the observed changes in many regions (Carpenter et al., 2011; Rockström et al., 2009; Sanderson et al., 2002; Steffen et al., 2007; Wisser et al., 2010).

Flow regulation by dams and water use for irrigation are amongst many human water management activities that cause significant alterations in natural flow regimes through changes in the magnitude, duration, timing, and rate of flow (Döll et al., 2009;

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Haddeland et al., 2014; Lorenz et al., 2014; Lytle and Poff, 2004; Poff et al., 1997; Pokhrel et al., 2017; Veldkamp et al., 2017; Wurtsbaugh et al., 2017). In river basins that drain to a terminal inland water body (e.g., a lake or sea), such alterations in flow regimes not only affect the downstream hydrological and ecological systems but also impact the long-term water balance of the terminal water body. One of the prominent examples of such human-induced alterations in the water balance of an inland sea is of the Aral Sea in Eurasia (Stone, 2015; Wurtsbaugh et al., 2017), where a net loss of ~1000 km^3 (~92% of sea volume) of water was observed in a four decade period (Micklin, 1988; Pokhrel et al., 2017) which has been attributed to large-scale river diversion and an increase in consumptive water use for irrigation within the drainage basins (AghaKouchak et al., 2015; Micklin, 2010, 1988; Pokhrel et al., 2017; Tan et al., 2017). As the desiccation of the Aral Sea remains to be "one of the very greatest ecological problems" of the twentieth century (Micklin, 1988), water levels in many other inland water bodies around the world are in a persistent decline (Anda et al., 1998; Carrera-Hernandez, 2017; Coe et al., 2009; FAO, 2011; Gross, 2017; Li et al., 2007; Macías and Lind, 1990; Swenson and Wahr, 2009; Wurtsbaugh et al., 2017). One of such endangered system is the Urmia Lake in Iran which is at an imminent risk of falling victim to the same syndrome that desiccated the Aral Sea (AghaKouchak et al., 2015).

There is a growing body of literature contributing to the ever-growing debate on the shrinkage of the Urmia Lake and its ultimate fate, suggesting that the observed depletion of the lake can be attributed to various climatic and anthropogenic factors (Abbaspour and Nazaridoust, 2007; AghaKouchak et al., 2015; Arkian et al., 2016; Delavar et al., 2007; Delju et al., 2013; Fathian et al., 2014; Hassanzadeh et al., 2012; Madani, 2014; Zeinoddini et al., 2015). While some studies have considered the impacts of growing human land-water management activities (AghaKouchak et al., 2015; Alizade et al., 2018; Hassanzadeh et al., 2012; Shadkam et al., 2016; Zeinoddini et al., 2015), most others have focused only on the climatic factors, particularly precipitation and temperature (Arkian et al., 2016; Delavar et al., 2007; Delju et al., 2013; Fathian et al., 2014), hence leaving a gap in the thorough understanding of the combined effects of climatic and human factors. Arkian et al. (2016) investigated the climate data from four meteorological stations in the lake basin for 1965–2010 period and found a correlation of 0.69 between the changes in precipitation and lake level. This correlation was found to be even higher during the period of 1990–2005. A similar study conducted by Delju et al. (2013) showed that mean precipitation decreased by 9.2% and average maximum temperature increased by 0.8 °C from 1964 to 2005. Likewise, using water budget, multiple regression, and artificial neural networks approaches on a monthly scale, Delavar et al. (2007) concluded that the decrease in precipitation had larger effects on Urmia Lake's water level variation than the decrease in input discharge. Fathian et al. (2014) studied the trends in the time series of hydro-climatic variables of Urmia Lake basin for the period of 1960–2007 and suggested that lake depletion can be connected to both the temperature increase in the basin and the over-exploitation of the water resources.

Some other studies have examined the impacts of anthropogenic factors on the depletion of Urmia Lake, which are not considered in the aforementioned studies that focused on the climatic factors. For example, Hassanzadeh et al. (2012) simulated the basin hydrology using a system dynamics model and suggested that the changes in inflows due to climate change and surface water exploitation, construction of four dams in the upstream watersheds, and reduced precipitation are responsible for 65%, 25%, and 10% of the total desiccation of the lake, respectively. Abbaspour and Nazaridoust (2007) also highlighted the importance of river discharge to the lake's water balance using a hydrodynamic model. Likewise, Alizade et al., (2018) investigated the water budget of the lake and concluded that anthropogenic factors contributed to ~80% of lake volume decline, whereas Shadkam et al. (2016) showed climate change as the main contributor to the depletion, suggesting that anthropogenic factors such as irrigation withdrawal played a relatively minor role.

The aforementioned studies have provided crucial insights on the ongoing changes in the water balance of Urmia Lake and its basin, but river flow, which accounts for the majority of water input to the terminal lake, has not yet been thoroughly investigated. Previous studies such as AghaKouchak et al. (2015) have emphasized the need for direct water budget assessment and quantification of the anthropogenic influence on the water cycle, rather than relying on the attribution to prolonged droughts and climate change. To fill this gap, here we provide a comprehensive analysis of the combined effects of climatic and anthropogenic factors on the water balance of Urmia Lake, with a particular focus on the changes in water use within the basin and the resulting impacts on the river inflow to the lake. Specifically, this study presents how climate change and anthropogenic exploitation of land and water resources in the watershed contributed to the desiccation of Urmia Lake over the modeling period of 1980–2010. It contributes to the debate on the anthropogenic impact on Urmia Lake watershed by interpreting the scale of impact from medium resolution land use land cover (LULC) maps and a global Land Surface Model (LSM) which accounts for human water management activities. The results from the LSM provide a comparative study of Urmia Lake basin with and without human activities. The specific objectives are to (1) investigate the changes in meteorological conditions and its impact on the lake; (2) map the changes in land use patterns due to expanding agricultural activities within the watershed; (3) assess the changes in terrestrial water storage (TWS) within the basin and its impact on the shrinkage of the lake; and (4) examine how the increase in irrigation water requirement affected the inflow to the lake. These objectives provide the structural sub-headings used in the following Methods, Results and Discussions sections.

2. Study site, data, and model

2.1. Study site

Urmia Lake, located in northwestern Iran, is one of the largest hypersaline lakes in the world. Until it began rapidly desiccating in the late 20th century (Ghaheri et al., 1999) it was the world's second largest hypersaline lake (Alizade et al., 2017) and the 20th largest lake by area (Emdadi et al., 2016). Several aspects of Urmia Lake such as chemistry and morphology are analogous to that of the Great Salt Lake in the United States and the Dead Sea in the Middle East (Alizade et al., 2017). The lake surface area varied between 5200 and 6000 km^2 during the last few decades of the 20th century (Tourian et al., 2015). Based on the precipitation data from 1973 to 2011, the average annual mean precipitation over the basin is 352 mm/year (Farajzadeh et al., 2014) and the air temperature usually ranges between 0 and −20 °C in winter, and up to 40 °C in summer (Eimanifar and Mohebbi, 2007). The lake has the maximum and average depth of 16 m and 5 m, respectively (Alesheikh et al., 2004). The drainage basin, with a total area of ~52,000 km^2, is home to several metropolitan cities in Iran such as Tabriz, Urmia, and Miandoab (Alipour, 2006). The basin drains into the lake through thirteen main rivers (Alipour, 2006; Ghaheri et al., 1999). More than three dozen dams have been built on these river systems to divert water for agricultural and other uses within the basin; the Alavian, Mahabad, Nahand and