Journal of Great Lakes Research 42 (2016) 942–952

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

Impacts of climate change and water resources development on the declining inflow into Iran's Urmia Lake

Somayeh Shadkam [a,c,*], Fulco Ludwig [a], Pieter van Oel [b], Çağla Kirmit [a], Pavel Kabat [a,c]

[a] Water Systems and Global Change, Wageningen University and Research, PO Box 47, 6700 AA Wageningen, The Netherlands
[b] Water Resources Management group, Wageningen University and Research, Wageningen, The Netherlands
[c] The International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

ARTICLE INFO

Article history:
Received 14 November 2015
Accepted 6 June 2016

Communicated by Barry Lesht

Index words:
Urmia Lake
Hypersaline lake
Water resources development
Reservoirs
Irrigation
Climate change and variability

ABSTRACT

Urmia Lake, the world's second largest hypersaline lake, has decreased in size over recent decades primarily because inflow has diminished. This has caused serious socio-environmental consequences similar to those of the Aral Sea disaster. By using the variable infiltration capacity (VIC) model, this study estimates the relative contributions of climate change and water resources development, which includes the construction of reservoirs and expansion of irrigated areas, to changes in Urmia Lake inflow over the period 1960–2010. The model results show that decreases in inflow generally follow observed decreases in precipitation, although the variability in inflow is more pronounced than the variability in precipitation. The results also suggest that water use for irrigation has increased pressure on the basin's water availability and has caused flows to decrease by as much as 40% during dry years. On the other hand, the presence of reservoirs positively contributed to water availability during relatively dry years and did not significantly reduce lake inflow. By accelerating irrigation expansion in the basin, reservoirs have, however indirectly, contributed to inflow reduction. Our results show that annual inflow to Urmia Lake has dropped by 48% over the study period. About three fifths of this change was caused by climate change and about two fifths was caused by water resource development. The results of this study show that, to prevent further desiccation of Urmia Lake, it will be necessary both to develop national plans to reduce irrigation water use and to develop international plans to address climate change.

Introduction

Climate change[1] significantly influences the natural hydrological cycle which can contribute to water scarcity (Haddeland et al., 2014; IPCC, 2014). To safeguard water and food supplies for growing population, humans construct reservoirs, extract water for irrigation, and modify land use. These actions have been associated with an increasing number of drying lakes in arid and semi-arid areas (IPCC, 2014). However, only a limited number of studies have assessed the role of climate change and water resources development, individually and combined, on the desiccation of lakes. This knowledge gap hampers our ability to develop adequate and effective adaptation strategies to rehabilitate and preserve endangered lakes. Among all vulnerable lakes, the saline and hypersaline lakes need particular attention due to their highly vulnerable ecosystems and the irreversible socio-environmental impacts of their desiccation. Here, we evaluate the impact of climate change and water resources development on the desiccation of the world's second largest permanent hypersaline lake, Urmia Lake (Karbassi et al., 2010).

Urmia Lake basin is located in the northwest of Iran and has been seriously affected by both climate change and water resources development (Farokhnia, 2015; Fathian et al., 2014; Hassanzadeh et al., 2012). The Urmia Lake basin is an important agricultural region with a population of around 6 million people. The lake's water level and surface area have sharply declined over the last two decades (Kakahaji et al., 2013). This has caused an environmental disaster from increased salinity and has had negative effects on ecosystems, agriculture, livelihoods, and health (Karbassi et al., 2010). An outcome similar to that observed in the Aral Sea is likely for this lake (AghaKouchak et al., 2015; Badescu and Schuiling, 2010). The Aral Sea has dried up over the past several decades and affected the surrounding communities with windblown salt storms (Micklin, 1988). Moreover, the population around Urmia Lake is much larger than around the Aral Sea, and thus more people are at risk (UNEP, 2012).

A number of recent papers have discussed reasons for the shrinkage of Urmia Lake and the possible environmental consequences. Delju et al. (2013) showed how a decrease in precipitation combined with an increase in temperature in the basin has caused the most severe drought in the last 40 years. Other studies have assessed the observed

* Corresponding author at: The International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.
E-mail address: shadkam@iiasa.ac.at (S. Shadkam).

[1] In this study, climate change is defined as follows: "A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity" IPCC Fourth Assessment Report 2007: Climate Change: Synthesis Report.

http://dx.doi.org/10.1016/j.jglr.2016.07.033
0380-1330/

precipitation over the basin and have confirmed the decreasing trend (Farokhnia and Morid, 2014; Hassanzadeh et al., 2012; Katiraei et al., 2006; Rezaei Banafsheh et al., 2010). A recent investigation showed that Urmia Lake only receives a relatively small amount of groundwater discharge (up to 3%), so it is very sensitive to the surface inflow fluctuations (Hashemi, 2011; ULRP, 2015). Hassanzadeh et al. (2012) demonstrated that the decline in surface inflow has been the dominant reason for lake shrinkage. They showed that, in total, 65% of the decline in lake water levels and volumes had been caused by changes in inflow, which was due to surface water use and climate change. Fathian et al. (2014) showed the correlation between inflow reduction and climate variability (precipitation and temperature). They also estimated that inflow to the lake is more sensitive to temperature than to precipitation. On the other hand, AghaKouchak et al. (2015) suggested that human water use has been the most influential factor on the lake desiccation. Although the studies mentioned indicated different factors to be the major contributor to the declining inflow, they all agree that a combination of climate change and water resources development has caused the observed decline. However, the relative contributions of these two drivers has not been quantified so far, and it is therefore not clear to what extent climate change and water resources development have contributed to the declining inflow. The aim of this paper is to quantify the relative contributions of climate change and water resources development to the declining inflow into Urmia Lake over the last 50 years.

Study area

The Urmia Lake basin area is around 51,000 km^2, of which the lake formerly covered approximately 5000 km^2. Urmia Lake's water level started to decrease sharply from 1995 (Fig. 1). Because the lake is shallow (Djamali et al., 2008), the surface area of the lake also shrunk rapidly (see Fig. 1 in Shadkam et al., 2016).

There are 17 permanent rivers and 12 seasonal rivers which terminate at Urmia Lake (Fig. 2). The basin can be divided into six main subbasins: west, southwest, south, east, north, and northeast. The average annual precipitation in the basin is between 300 and 400 mm. The mean annual air temperatures vary from 6.8 to 14.8 °C (Iran Ministry of Energy, 2014a; Karbassi et al., 2010).

The basin has an arid to semi-arid climate; this means that agriculture in the basin is highly dependent on irrigation. There are ~510,000 ha of irrigated land in the basin with 33 modern and traditional irrigation networks. The reported irrigation efficiency is quite low: 37% for farming and 45% for gardening (Iran Ministry of Energy, 2014b). To support agricultural growth, the area under irrigation around the lake has increased over seven times during the last 15 years (Iran Ministry of Energy, 2014b). These land cover changes along with climate change put extra pressure on the basin's water resources and have caused a dramatic decline in the inflow to the lake (Hashemi, 2011).

Forty-one small and large reservoirs have been built in the basin since 1970 (Fig. 2), storing around 2000 × 10^6 m^3 water (Iran Ministry of Energy, 2013) (Fig. 3). Information about heights, operating purpose, storage capacities, and surface area of all reservoirs were provided by the Iranian Ministry of Energy, Deputy of Water and Wastewater, Macro Planning Bureau (Iran Ministry of Energy, 2013). Of the 511,926 ha of irrigated lands in the basin, 356,420 ha (70%) are farms and 155,506 ha (30%) gardens. Information on land use, irrigation pattern, and cropping calendar was provided by the Urmia Lake Restoration Program.

Method

Data management

To assess the precipitation trend during the study period, we used precipitation data from 146 rain gauges distributed over the basin (Fig. 2). Data-quality control and homogenization of precipitation time series have been done by applying the method described in Vicente Serrano et al. (2010) as reported by the Iran Ministry of Energy, 2014c. This method comprises three steps. The first step filled the data gaps using auxiliary information obtained from Iran Meteorological Organization and nearby observatories. The second step identified the records that differed noticeably from values recorded in neighboring stations and replaced anomalous and questionable ones. The third step verified the homogeneity of the data series to avoid the presence of spurious data in the final data set. Observed annual inflow into the lake for the period 1960–2010 was obtained from 18 hydrometric stations located near the outlets of all important tributaries to the Lake (Fig. 2).

Hydrological model

To separate impacts of climate change and water resources development, we used the variable infiltration capacity (VIC) model, including reservoir and irrigation modules. The VIC model is a grid-based soil–vegetation–atmosphere transfer schemes model (Liang et al., 1994; Nijssen et al., 1997; Nijssen et al., 2001b). The input data are daily precipitation, maximum and minimum temperature, and wind speed. Each grid cell is divided into multiple vegetation types and into multiple soil layers. Historical vegetation data were obtained from the SAGE database at the University of Wisconsin–Madison (available online at http://www.sage.wisc.edu/). Evapotranspiration is calculated using the Penman–Monteith equation. The simulated surface streamflow and base flow, combined referred as inflow in this paper, are routed from each grid cell to the basin as described by Lohmann et al. (1998a, 1998b). The VIC model, like most land surface models, does not consider deep groundwater withdrawals (Haddeland et al., 2007), which therefore are not taken into account in this study. The model has been widely used for streamflow studies globally (Nijssen et al., 2001a; Van Vliet et al., 2013) and for major river basins, as well as for other basins of the world in Europe, the US, and China (Hurkmans et al., 2008; Van Vliet et al., 2012; Wu et al., 2007; Xie et al., 2007a). The results of these studies have shown that the model has been able to reproduce the water cycle well.

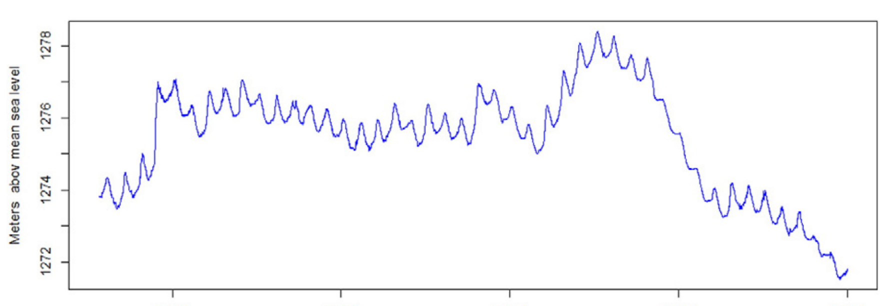

Fig. 1. Urmia Water level for the period 1965–2010 (data provided by Urmia Lake Restoration Program).