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Agriculture, diversions, and drought shrinking Galilee Sea

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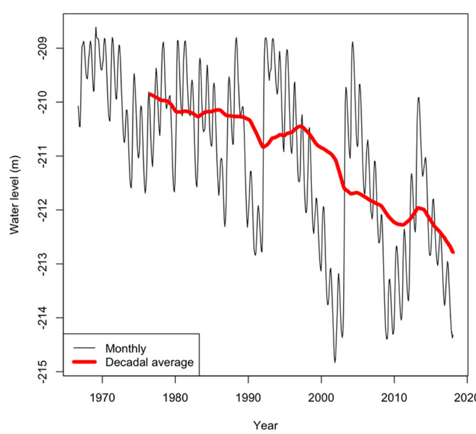
HIGHLIGHTS

- Lakes are disappearing on all inhabited continents, due to numerous factors.
- The Sea of Galilee, of religious significance to billions worldwide, is shrinking.
- Past work mistakenly implicated drought with the Sea's shrinkage.
- In fact, agriculture and flow diversion are primary causes of lake shrinkage.

GRAPHICAL ABSTRACT



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ABSTRACT

In water-limited regions worldwide, climate change and population growth threaten to desiccate lakes. As these lakes disappear, water managers have often implicated climate change-induced decreases in precipitation and higher temperature-driven evaporative demand—factors out of their control, while simultaneously constructing dams and drilling new wells into aquifers to permit agricultural expansion. One such shrinking lake is the Sea of Galilee (Lake Kinneret), whose decadal mean level has reached a record low, which has sparked heated debate regarding the causes of this shrinkage. However, the relative importance of climatic change, agricultural consumption, and increases in Lebanese water consumption, remain unknown. Here we show that the level of the Sea of Galilee would be stable, even in the face of decreasing precipitation in the Golan Heights. Climatic factors alone are inadequate to explain the record shrinkage of the Sea of Galilee. We found no decreasing trends in inflow from the headwaters of the Upper Jordan River located primarily in Lebanon. Rather, the decrease in discharge of the Upper Jordan River corresponded to a period of expanding irrigated agriculture, doubling of groundwater pumping rates within the basin, and increasing of the area of standing and impounded waters. While rising temperatures in the basin are statistically significant and may increase evapotranspiration, these temperature changes are too small to explain the magnitude of observed streamflow decreases. The results demonstrate that restoring the level of the Sea of Galilee will require reductions in groundwater pumping, surface water diversions, and water consumption by irrigated agriculture.

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1. Introduction

In water-limited regions worldwide environmental and ecosystem demands are simultaneously threatened by climate change and in competition with human water requirements to satisfy urban, agricultural, and industrial demands of a growing global population (Vorosmarty et al., 2000; Vorosmarty et al., 2010). Impacts of agricultural water consumption on environmental flows are exacerbated by rising evaporative demand due to higher temperatures and in certain regions—including the already water starved Middle East—lower precipitation due to changing rainfall patterns as the Earth system warms (Waha et al., 2017). While technological advances such as desalinization have somewhat ameliorated water scarcity in certain locations (Shannon et al., 2008; Elimelech and Phillip, 2011; Ziolkowska, 2016), the impacts of water consumption in arid lands worldwide remains dire as demonstrated by the demise of the Aral Sea and Lake Chad and decades of sustained rapid retreat of the Dead Sea (Micklin, 1988; Vitousek et al., 1997; Coe and Foley, 2001; Micklin, 2007; AghaKouchak et al., 2015; Hillel et al., 2015) among a growing list of other desiccating lakes (Liu et al., 2013).

To date, drivers implicated in the desiccation of lakes within Earth's six inhabited continents, which might be referred to as the Aral Sea syndrome, have included agricultural water consumption, urban water requirements, mining, construction of dams, and climatic changes (Liu et al., 2013; Fazel et al., 2017). In North American lakes suffering from this syndrome including the Great Salt Lake, Owens Lake, and Walker Lake, the primary causes were non-climatic (Wurtsbaugh et al., 2017). Similarly, in attempting to distinguish between human and climatic impacts in Iran's Lake Urmia watershed, Fazel et al. (2017) observed that headwater flow regimes were unaltered while proximal to the lake significant land-use changes occurred over time, consistent with a non-climatic driver impacting lake levels. In contrast, in semi-arid northern China a combination of climatic and agricultural impacts were implicated in the desiccation of over 100 lakes, though covariance of temperature and precipitation may challenge attempts to statistically infer the relative importance of these factors (Liu et al., 2013). Other research has suggested that climatic warming impacts on large lakes have not yet been observed (Beeton, 2002).

In past cases where lakes have desiccated, negative consequences have been widespread, including creation of natural hazards, impaired environmental quality, and economic impacts. The Dead Sea perhaps holds the unfortunate distinction of serving as the preeminent case study of the unanticipated impacts of a declining sea level on hydrogeologic natural hazards; specifically, with this sea's rapid retreat, swarms of sinkholes formed (Arkin and Gilat, 2000; Yechieli et al., 2006; Gutiérrez et al., 2014; Kottmeier et al., 2016), swallowing roads, vehicles, caravans, groves of date palms, and unlucky people, while forcing authorities to fence off large tracts of land considered high risk for sink holes. The incision of wadis draining into the Dead Sea has created micro canyons that threaten the stability of roads and affects the ecosystem of the alluvial fans (Bowman et al., 2010). In addition to explicit natural hazards, lake desiccation is well known to impact environmental quality, as in the case of the Aral Sea, wherein dried salt from the bottom of the sea was transported in large dust storms, damaged agricultural areas, and caused respiratory problems (Micklin, 1988). Desiccation of a large inland sea also removes its modulating influence on the climate (Micklin, 2007). From an economic perspective, lakes can be economic engines, promoting revenue from tourism, recreation, and fisheries (Wurtsbaugh et al., 2017). Finally, in the presence of saline groundwater or brines, decreases in lake head can enhance the hydraulic gradient and consequent discharge of saline groundwater into a freshwater lake, thereby jeopardizing the safety of a historical source of drinking water (Rimmer et al., 1999).

However, the impacts of groundwater pumping on surface water flows are less straightforward. Historically, groundwater and surface water were not believed to interact (Phillips et al., 2011). Indeed, there is a physical basis for groundwater being isolated from surface water in the presence of low permeability rock—an aquiclude. In addition to this physical basis, there is an economic motive to assume that groundwater and surface water systems are isolated. Assuming that these systems are isolated would allow for liberal exploitation of subsurface water, with no fear of impacting the quality or quantity of surface water bodies. However, contamination of shallow wells by methane accessed by wells as much as two kilometers below the surface (Osborn et al., 2011) as well as groundwater pumping that has reduced flow in rivers or converted perennial rivers to ephemeral (Zume and Tarhule, 2008; Kustu et al., 2010; Phillips et al., 2011) demonstrate the critical importance of considering the impacts of subsurface extraction on surface water. Consequently, a mechanistic understanding of groundwater-surface water interactions is a critical prerequisite to sustainably managing surface water resources potentially impacted by subsurface water extraction. Methods to model streamflow depletion caused by groundwater pumping have included both analytically derived models for idealized scenarios (Cuthbert, 2014), depletion apportionment equations (Zipper Samuel et al., 2018), and physically based distributed numerical methods that couple representation of surface and subsurface hydrologic processes (Ferguson and Maxwell, 2012).

One such case study of global change impacts on environmental flows is the Sea of Galilee (Fig. 1), whose level has entered a sustained decline that is unprecedented in modern recorded history (Fig. 2). In the absence of an examination of the water balance, currently local water managers attribute this decline to climatic effects. This claim that observed lake declines can be attributed to climate—even in the presence of extensive agricultural water use—is not uncommon and is similar to claims regarding Lake Abert (Moore, 2016), Lake Poopo (Satgé et al., 2017), and Lake Urmia (AghaKouchak et al., 2015), before formal investigations were undertaken. However, the relative impacts of natural climatic variability, anthropogenic climate change, and agricultural water use remain unknown. Furthermore, any impacts on flows in the Upper Jordan River (UJR) due to water consumption changes in Lebanon remain undetermined.

The Sea of Galilee has considerable importance from numerous perspectives and consequently government has vested interest in its conservation. This Sea has biblical significance such that it and its environs are visited by one million Christian pilgrims annually (Zvulun, 2016). Historically, the Sea has been an important water source, with the National Water Carrier transporting freshwater from it to the drier central and southern regions. It supports a commercial fishery in addition to a unique aquatic ecosystem. Geopolitically, a 50–55 MCM yr^{-1} transfer of high quality drinking water to the Kingdom of Jordan is required from the Sea of Galilee as part of the 1994 Israel-Jordan peace treaty, though recently transfers have increased in association with the flight of Syrian refugees to Jordan. Israel is considered to be a leader in the realm of water management, whether it be in the agricultural or desalinization sectors—maintaining this position will require preserving the Sea of Galilee. Consequently, the State of Israel—through the Water Authority (Ministry of Energy), Ministry of Agriculture, Ministry for the Protection of the Environment, the Nature Reserves Authority, Ministry of Tourism, and Ministry of Foreign Affairs—has a vested interest in and responsibility for the future of this lake.

Therefore, the goal of this study was to improve understanding of global change impacts on the level of the Sea of Galilee. In pursuit of this goal we tested the working hypothesis of the Israel Water Authority—that the current low level of water in the Sea of Galilee is a consequence of several consecutive years of low rainfall (Givati and Rosenfeld, 2007; Markel, 2014; Markel et al., 2014)—along with a suite of alternative hypotheses: 1) Increased water consumption in the headwaters of the UJR primarily located in Lebanon has reduced downstream flows. 2) Rising temperatures due to climate change have increased evapotranspiration within the Jordan River valley. 3) Expansion of agriculture in the UJR watershed—including construction of