In Water-Limited Landscapes, an Anthropocene Exchange: Trading Lakes for Irrigated Agriculture

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Abstract Lakes—quintessential features of Earth’s surface prized from perspectives of water security, aquatic ecosystems, and recreation alike—are shrinking in water-limited regions of all of Earth’s inhabited continents. Here we assessed Landsat-derived long-term decrease in global lake area relative to historical lake extent aiming to determine the role of recent Anthropocene levels of irrigated agriculture in the global phenomenon of lake desiccation. As of 2015, 11% (1.8 · 106 km²) of global lake area has already been lost, primarily due to increased water consumption in support of irrigated agriculture in endorheic basins within water-limited regions. However, current levels of irrigated agriculture portend substantial additional shrinkage of global lakes before reaching new equilibria with present-day inflows, with an additional 60–130% increase in endorheic lake loss anticipated. The time required for shrinking lakes to attain new equilibria ranges from decades to centuries depending on lake hypsometry. Even a small decrease in lake area can portend lake transition from exorheic to endorheic and dramatic reductions in water quality. Thus, lake area changes severely underestimate the perilous condition of global lakes. The watershed area contributing to shrinking (endorheic and exorheic) lakes accounts for 18% of Earth’s land area, far too large for the irrigated agriculture therein to be transferred elsewhere in order to save these lakes, though continued developments in the efficiency of water consumption in agriculture and urban areas can save significant quantities of water. This suggests that global lake shrinkage may be a harbinger signaling mankind having exceeded Earth’s sustainable carrying capacity.

Plain Language Summary Today, a host of processes influence the terrestrial water balance. These processes drive the observed shrinkage of lakes in water-limited regions of all inhabited continents. Typically, lake shrinkage is attributed either to climate change or unsustainable increases in human water consumption. However, while drivers of lake desiccation have been explored for individual lakes, the causes of this phenomenon have not been explored at the global scale. We therefore propose a simple conceptual model in which lake area and agricultural area are exchangeable in closed basins. We find that this simple model accurately determines the role of agriculture in loss of endorheic lakes. This model demonstrates that irrigated agriculture is the primary driver of desiccation of global lakes.

1. Introduction

Lakes—key reservoirs of drinking water, aquatic habitats, and invaluable venues for recreation—historically have been in dynamic equilibrium with the watersheds that feed them (Rimmer et al., 2011). On an annual basis lake levels fluctuate in accordance with primary water balance drivers—inflows from the watershed during the wet season and water losses due to direct evaporation of lake water, human water extraction, and—in the case of exorheic lakes—discharge to rivers (Wine, Rimmer, & Laronne, 2019). The Anthropocene Epoch (Lewis & Maslin, 2015) has witnessed exceptional rates of shrinkage in lakes that rely on inflow from water-limited watersheds (Zhan et al., 2019). Still, a consequential debate—with crucial water management implications—has transpired between advocates of climatic versus anthropogenic explanations for lake shrinkage (Jaramillo & Destouni, 2015; Khazaei et al., 2019; Madani, 2014; Madani et al., 2016; Wine, Null, et al., 2019; Wine, 2019e; Wurtsbaugh et al., 2017), with important implications for aquatic ecosystems (Grimm et al., 1997) and human water security (Almada et al., 2017).

Indeed, sustainable management of global water resources in water-limited regions on Earth presents a Herculean challenge for water managers in the 21st century (Rodell et al., 2018). Already two thirds of the
global population—four billion people—experiences annual incidents of water scarcity (Mekonnen & Hoekstra, 2016). Of the water required to sustain humanity, the agriculture sector consumes over 90% (Döll, 2009; Hoekstra & Mekonnen, 2012; Scanlon et al., 2017; Siebert et al., 2010), with demand for agricultural products—and irrigated agricultural area—increasing along with the global population (Siebert et al., 2015; Tilman et al., 2011). Nevertheless, responsibility for the shrinkage of certain inland water bodies has been assigned by some to climatic effects, including in the cases of the Great Salt Lake, Utah (Meng, 2019), Lake Urmia, Iran (Arkian et al., 2018; Dalby & Moussavi, 2017; Fathian, 2019; Fathian et al., 2014; Fathian et al., 2016; Jalili et al., 2012; Nourani et al., 2018; Nazeri Tahroudi et al., 2019; Shadkam et al., 2016), lakes in northern China and Mongolia (Cai et al., 2016; Li et al., 2018; Liu et al., 2013; Tao et al., 2015; Zheng et al., 2016), Lake Kinneret, Israel (Givati & Rosenfeld, 2007; Givati et al., 2019; Givati & Rosenfeld, 2013; Gophen, 2019; Tal, 2019a; Tal, 2019b; Tal, 2019c), and the Caspian Sea (Chen et al., 2017).

Recently informing this pivotal debate have been a satellite-based approach to map surface water changes at a 30 m spatial resolution for the entire Landsat record of 1984–2015 (Pekel et al., 2016; Zou et al., 2018) and an effort to attribute trends in global freshwater availability on the basis of terrestrial water storage derived from GRACE (Gravity Recovery and Climate Experiment) since 2002 (Rodell et al., 2018; Tapley et al., 2019; Wang et al., 2018). Despite the advances derived from these projects, their reliance on satellite data necessarily limited the scope of their analyses to recent decades with satellite data availability. Furthermore, global models understate decadal-scale trends in terrestrial water storage (Scanlon et al., 2018). Consequently, such projects substantially underestimate total change in inland water bodies (Table 1), such as the Aral Sea, which was already shrinking rapidly in the 1960’s (Micklin, 1988; Micklin, 2007) or the Great Salt Lake basin, where most water resource development occurred prior to 1904 (Wine, Null, et al., 2019; Wurtsbaugh et al., 2017).

The Global Lakes and Wetlands Dataset (GLWD) provides “historic” lake footprints for 3067 of Earth’s major lakes that may represent their “maximum recorded extents” (Lehner & Döll, 2004). Comparing GLWD data to Global Surface Water (GSW) (Pekel et al., 2016) then indicates permanent lake area extent change through 2015, a more natural benchmark than the launch date of a particular satellite. Permanent lake areal extent change underestimates total loss of aquatic systems in the Anthropocene given that it does not account for loss of intermittent water bodies, ephemeral water bodies, or wetlands. In turn the HydroBASINS project (Lehner & Grill, 2013) provides a dataset that can be rapidly and recursively queried to accurately determine the catchment area of all global lakes, and consequently the area likely to drive any change in lake inflows. A recently improved global irrigated area map (Meier et al., 2018) indicates the degree to which observed lake extent changes might be driven by consumption of water by irrigated agriculture or conversely in a predictive sense—if the extent of irrigated agriculture may portend additional lake shrinkage. If the relationship between changes in lake and irrigated area could be quantified in endorheic basins of water-limited regions, then this might allow for first order attribution of the role of irrigated agriculture in driving observed lake shrinkage at a global scale. This would further facilitate predictions of what future wetted areas would be in lakes that are currently shrinking due to increases in irrigated agriculture in their contributing basins.

Our goal is to improve quantitative understanding of the role of irrigated agriculture in the observed desiccation of Earth’s inland waters. To advance this goal we first develop a conceptual model of the steady state
water balance equation for endorheic lakes and their watersheds, applicable at the timescale of decades to centuries. Next we determine the watershed of all of Earth’s large inland waters, the extent of irrigated agriculture in the basin of each, and the extent of inland water desiccation. We integrate the conceptual model, newly developed dataset, and past conclusions regarding drivers of lake shrinkage to attain first-order global prediction and attribution of lake shrinkage. Finally, we discuss the implications of our results and suggest future research directions.

2. Conceptual Model

In the water balance equation for a watershed under natural conditions, differences between precipitation ($P$) and outflows—streamflow ($Q$), baseline evaporation ($E$), and the negligible influence of irrigated agriculture $c \cdot IA_0 \cdot (PET - P)$—are balanced by change in watershed storage ($\Delta S_{WS}$):

$$\Delta S_{WS} = P - Q - E - cIA_0 \cdot (PET - P),$$

where $c$ is a coefficient describing the water requirement of a crop relative to evaporation excess, $IA_0$ is pre-Anthropocene irrigated area, and $PET$ is potential evaporation. Let us consider the water balance of an idealized endorheic lake with inflows of $Q$, in which pumping of water from the lake itself is small. Evaporation from the historic lake area ($LA_0$) can be estimated, as the product of evaporation excess and lake area, in which case:

$$\Delta S_{Lake} = Q - (PET - P) \cdot LA_0,$$

where $\Delta S_{Lake}$ is change in lake water storage and $PET$ is potential evaporation. Noting that in endorheic basins outflow from the endorheic basin forms the inflow of the terminal lake:

$$P - E - cIA_0 \cdot (PET - P) - \Delta S_{WS} = \Delta S_{Lake} + (PET - P) \cdot LA_0$$

However, this simplified model has become increasingly discredited (Abbott et al., 2019; Abbott et al., 2019; Wine & Davison, 2019; Zeitoun et al., 2019) in favor of one that considers hydrological processes relevant to the human domination that characterizes the Anthropocene. Such processes have triggered the expansion in the distribution of irrigated agriculture ($IA_1$). In cases where expansion of irrigated agriculture is substantial lakes are expected to reach a new equilibrium at a smaller area $LA_1$:

$$P - E - cIA_1 \cdot (PET - P) - \Delta S_{WS} = \Delta S_{Lake} + (PET - P) \cdot LA_1$$

However, while evidence has emerged of decreasing storage in endorheic basins in recent years (Wang, Lee, et al., 2018), changes in storage remain unknown over the multi-decadal period going back to the 1960s or earlier when inland waters began shrinking. Changes in $\Delta S_{WS}$ would occur in water-limited systems either due to:

- seasonal cycles in which precipitation and evaporative demand are out of phase,
- multi-annual climatic variability such as that driven by synoptic weather patterns,
- climate change, or
- long-term changes in the water balance, chiefly—to date—increasing human water consumption.

If we are interested in solving Eq. 4 at a multi-decadal to centurial time scale, seasonal and interannual climate variability are likely to exert a minimal influence on $\Delta S_{WS}$. In the context of shrinking lakes, there is a large body of evidence demonstrating that anthropogenic climate change remains a background condition to and not a primary driver of global lake shrinkage (AghaKouchak et al., 2015; Alborzi et al., 2018; Ashraf et al., 2017; Ashraf et al., 2018; Chaudhari et al., 2018; Fazel et al., 2017; Hassani et al., 2020; Khazaei et al., 2019; Madani et al., 2016; Micklin, 1988; Micklin, 2007; Moore, 2016; Morin et al., 2018; Rodell et al., 2018; Wine, Null, et al., 2019; Wine, Rimmer, & Laronne, 2019; Wine & Davison, 2019; Wurtsbaugh et al., 2017). Though not featured prominently here, those lakes influenced by enhanced glacial melt may present an exception to this generalization. Finally, in cases where human water consumption is limited to surface water and renewable shallow groundwater, long-term changes in $\Delta S_{WS}$ would be bounded and small relative to cumulative precipitation and evaporation over a multi-decadal period. Similarly, following an
increase in water consumption $\Delta S_{\text{Lake}}$ would decrease over time to become small relative to the other water balance terms as the lake approached a new dynamic equilibrium. Under such quasi-steady state conditions, the transition from natural to Anthropocene may be given as the difference between Eq. 3 and Eq. 4:

$$-c \cdot \Delta IA \cdot (PET - P) = (PET - P) \cdot \Delta LA$$

Eq. 5 can be further simplified if $c$ is reconceptualized as an exchange coefficient that accounts not only for irrigated crop characteristics, but also possible climatic differences between the lake and its watershed:

$$c = \frac{\Delta LA}{\Delta LA}.$$  

3. Methods

Global-scale analysis of lake shrinkage required determining both baseline lake area and lost area. We obtained baseline lake area both from the Global Lakes and Wetlands Database (GLWD) (Lehner & Döll, 2004) and from the existing analysis of global surface water (GSW) extent change from the beginning of the Landsat record (1984) through 2015 (Pekel et al., 2016). Given the global scale of the analysis and noting that most single projections are inappropriate for use at the global scale, geodesic areas of lakes were calculated for GLWD polygons in ArcGIS 10.6. We calculated the area of each pixel using a spherical approximation:

$$\text{CellArea} = \left( \frac{\pi}{180} \right) \left( r^2 \right) \left( \sin y - \sin \left( \frac{\text{Cell Height}}{180} \right) \right) \cdot \text{Cell Width},$$

where $r$ is the radius of Earth 6,378,000 m, $y$ is latitude in units of radians, and cell dimensions are expressed in degrees.

We calculate initial lake area from the GSW transitions dataset (Pekel et al., 2016) as the sum of pixels classified as permanent (water throughout entire period), lost permanent (initially with water but later no water), lost seasonal (seasonal alterations between water and no-water), and permanent to seasonal (permanent water in the mid-1980’s transitioning to seasonal water in 2015). For the purposes of this analysis we define initial lake area as the maximum value of that reported by GLWD and that computed from GSW. In surface water bodies that have undergone extensive desiccation prior to 1984, area estimates derived from GLWD emerge as significantly larger than those from GSW (Table 1). In those that have undergone minimal desiccation, maximum areas derived by these two methods are similar. Lake loss is estimated as the difference between initial lake area and areas classified by GSW as permanent in 2015. We determined the watershed area contributing to each inland water by recursively querying the HydroBASINS (Lehner & Grill, 2013) dataset using the arcpy site package in Python. Within each watershed we determined irrigated agricultural area from Meier et al. (2018), which takes advantage of objective remotely sensed normalized difference vegetation index imagery to address the known limitations of irrigated areas reported in national statistics (Thenkabail et al., 2009). In the case of Lake Chad whose former lake floor is now cultivated, those cultivated areas not captured by Meier et al. (2018) are estimated from dry season Landsat 8 NDVI imagery subject to a threshold of 0.45. Average lake depth estimates follow Messager et al. (2016).

On the basis of the concept of trading lakes for irrigated agriculture, we estimate latent lake loss—lake desiccation that has not yet been realized but will be realized when the lake reaches equilibrium with the decreased inflow - as a consequence of increased levels of irrigated agriculture in endorheic basins. According to this concept, in systems in which irrigated agricultural area ($-c \cdot \Delta LA$) exceeds lake area loss, we estimate latent lake loss as the difference between agricultural area ($-c \cdot \Delta IA$) and lake area loss. This loss is subject to the natural boundary that realized lake loss and latent lake loss cannot exceed initial lake area.

4. Results and Discussion

4.1. Testing the Concept of Trading Lakes for Irrigated Agriculture on Earth’s Terminal Lakes

Our analysis of the GLWD and the GSW data shows that of total global lake area shrinkage, over 60% of this lost lake area occurred in water-limited terminal lakes within endorheic basins (Figure 1B), which are...
particularly sensitive to overexploitation (Yapiyev et al., 2017). Generally, the 1:1-line separates between those inland waters whose shrinkage has been attributed to irrigated agriculture (i.e., below the line) versus those whose shrinkage has been attributed to other drivers. To test the hypothesis that global lake

![Figure 1](image-url). The relationship between lake area loss and agricultural expansion in water-limited systems. A) Global distribution of the wetness index = nondimensional precipitation/potential evapotranspiration (Harris et al., 2014). Superimposed (in gray) are the watershed areas of shrinking lakes in water-limited systems affected by irrigated agriculture. B) Lake shrinkage by area from historical baseline conditions (Lehner & Döll, 2004) through 2015 (Pekel et al., 2016). C) The non-dimensional quotient of irrigated agricultural area (Irr. Ag.) in a lake's watershed to lake area loss. Where irrigated agricultural area exceeds lake loss, the ratio is set to 100%. D) For terminal lakes, we estimate potential latent lake loss—water body shrinkage that has been incurred due to agricultural expansion, but not yet realized due to lake hypsometry, assuming a 1:1 exchange of irrigated agricultural area for lake area. The realized extent of latent lake loss is sensitive to the irrigated area-lake loss exchange coefficient.
shrinkage compensates for increased irrigation, we compare observed lake shrinkage and irrigated agricultural area (Figures 1C, 2) with past publications attributing drivers of lake shrinkage, aiming to determine the extent to which the lake-irrigated agriculture exchange coefficient converges toward an identifiable set of values for those inland waters with characteristics matching the assumptions of the conceptual framework. The rate at which a new equilibrium is realized depends on the hypsometry of the lake (Haghhighi et al., 2016). In a shallow lake a new dynamic equilibrium would be reattained quickly. For example, Mohammed and Tarboton (2012) suggest that the Great Salt Lake would require 15 years to reach new dynamic equilibrium, though this estimate is contingent on the magnitude of the perturbation. In contrast, a deeper water body may require time scales of decades as in the case of the Dead Sea to millennia for the Caspian Sea (Rodell et al., 2018) to attain such an equilibrium. To this end we consider those irrigation-impacted shallow inland waters whose shrinkage has been attributed (Table 2).

Among Earth’s terminal lakes this analysis identifies the Aral Sea as having experienced the most extensive areal shrinkage (Figure 2) “overwhelmingly” due to increases in agricultural area (Micklin, 1988; Micklin, 2007; Micklin, 2016), which have continued despite the Sea’s rapid shrinkage (Chen et al., 2018). Also in Asia, the shrinkage of Lake Urmia, Iran, has been contested, with claims of the importance of climatic factors discredited relative to overexploitation for irrigated agriculture (AghaKouchak et al., 2015; Alborzi et al., 2018; Chaudhari et al., 2018; Fazel et al., 2017; Ghale et al., 2018; Khazaee et al., 2019; Madani, 2014; Madani et al., 2016; Taravat et al., 2016; Tourian et al., 2015). In North America, agricultural water consumption is identified as the primary driver of shrinkage of the Great Salt Lake, Utah, though secondary factors include mineral production and municipal and industrial uses; reservoir evaporation impacts on the lake water balance exerted only a tertiary impact (Wurtsbaugh et al., 2017). Other terminal lakes have undergone less absolute shrinkage in areal extent. In North America, the shrinkage of Lake Abert, Oregon, has been attributed to water withdrawals to support irrigated agriculture (Moore, 2016). In South America, desiccation of Lake Poopo, Bolivia, has been ascribed to increased regional evapotranspiration from irrigated agriculture, in part associated with quinoa culture (Satgé et al., 2017; Zolá & Bengtsson, 2006). Taken together, inland water loss in the Aral Sea, Lake Urmia, the Great Salt Lake, Lake Abert, and Lake Poopo accounts for more than half of total inland water loss in terminal lakes on several of Earth’s continents. Moreover, their relatively shallow depths make them appropriate for determining if the concept of a lake-irrigated agriculture exchange coefficient results in an identifiable parameter space. The narrow range of values of this coefficient (1–2) suggests that, at the global scale, one unit of endorheic lake area loss is associated with 1–2 units of expansion in irrigated agricultural area in the lake’s basin (Table 2). Hence, we suggest that Eq. 6 can be used for global-scale first order attribution and prediction with respect to the role of irrigated agriculture in inland water loss in Earth’s water-limited regions.

4.2. Causes of Departure From Idealized Behavior

Despite the evidence that the exchange coefficient falls in a narrow range when the conceptual model’s assumptions are met, in a number of cases, representing a smaller proportion of terminal lake area loss, coefficients outside the range of 1–2 are observed. In certain cases, this departure is consistent with endorheic basin behaviors that violated model assumptions. In the case of Lake Chad, west-central Africa, both climatic drivers and irrigation projects have been implicated in its shrinkage (Coe & Foley, 2001; Dai, 2010; Gao et al., 2011; Maharana et al., 2018). While global-warming-induced increases in air temperatures have been implicated in decreasing levels in the Caspian Sea (Chen et al., 2017), the high exchange coefficient of the Caspian Sea is consistent with the retreat of a deep sea as a consequence of irrigated agriculture (Rodell et al., 2018).
Similarly, we identify irrigated agriculture as a key driver in the Dead Sea’s shrinkage (Shentsis et al., 2019; Wine, Rimmer, & Laronne, 2019), though evaporation pools south of the Sea play a secondary role. The ratio of present evaporation pond extent (181 km²) outside the historic extent of the Dead Sea and Southern Dead Sea—outside the historic extent of the Dead Sea and Southern Dead Sea—to permanent sea extent (GLWD, 817 km²) implies that inflow reductions account for 75–80% of the sea’s shrinkage compared to evaporation ponds (20–25%). Evaporation pond extents reference those observed in Landsat 8 imagery from October 2019. Out of basin transfers, including via Israel’s National Water Carrier (Morin et al., 2018), contribute to the Dead Sea’s negative water balance. The Dead Sea case study reveals three additional (albeit minor) shortcomings of our proposed model. First, removal of water from storage—groundwater over-extraction in the Dead Sea basin (Alfaro et al., 2017; Quba’a et al., 2018; Rosenthal et al., 2009; Tal, 2019a; Wine, 2019a; Wine, Rimmer, & Laronne, 2019)—at intermediate time scales may allow for increased agricultural productivity. Consequently, basin irrigation volumes in excess of flows to the Dead Sea under natural conditions would somewhat overestimate the maximum shrinkage that could occur. At the regional to global scales there is a growing understanding of the role of groundwater extraction in reducing streamflows (Condon & Maxwell, 2019; de Graaf et al., 2019; Wada et al., 2010) and contributing to lake shrinkage (Ashraf et al., 2017; Vaheddoost & Aksoy, 2018; Wine, 2019a). Second, springs that drain directly into the Dead Sea without the impact of distant groundwater overdraft would cause the model to slightly overestimate shrinkage. Third, the extent of maximum shrinkage in hypersaline lakes may be limited by the brine water activity’s equilibrium value with relative humidity. According to this constraint, the Dead Sea’s stage may be limited to dropping by an additional ~100 m (Zilberman et al., 2017), which at a rate of 1.2 m yr⁻¹ (Lensky et al., 2005), corresponds to approximately eight decades of further shrinkage, assuming agricultural water consumption in the Jordan River basin remains unabated. This calculation neglects effects of lake hypsometry.

In Lake Hulun, China, we observe a high exchange coefficient, which disputes recent studies focusing on climatic drivers (Cai et al., 2016; Liu et al., 2013; Zheng et al., 2016). Securitization occurs when an issue is perceived as an existential threat justifying exceptional measures. One consequence of securitization is the development of a sanctioned discourse, a set of ideas that is considered either to reinforce the securitization or at a minimum not to threaten said securitization. In cases where water resources are securitized, if the domain of the resultant sanctioned discourse substantially limits scientific inquiry, including through restrictions on funding or data access, then hydrological process understanding may be impaired. Amid hints of securitization in China’s water resources (Biba, 2014) and with an understanding of how securitization may confound understanding of hydrologic processes in transboundary watersheds (Wine, 2019b; Wine, 2019d; Wine, 2019e; Wine, 2020), our framework provides a repeatable objective perspective on hydrologic processes in such a setting. A closer look at Hulun Lake reveals a limitation of our framework in that further lake shrinkage may have been averted via water transfer from the nearby Hailar River (Cai et al., 2016). Hence, there are a number of cases where a range of factors fall outside of the assumptions presented in our conceptual model—including but not limited to groundwater overdraft, interbasin transfers, and long-term persistence of climatic conditions.

Table 2

| Category | Inland water | Coefficient | Depth (m) | Attribution to irrigation | Continent |
|----------|--------------|-------------|-----------|--------------------------|-----------|
| Shallow  | Great Salt Lake | 1.4 | 3.5 | (Wurtsbaugh et al., 2017) | North America |
| Aral Sea  | 1.9 | 1.1 | (Micklin, 2007) | Western Asia |
| Lake Urmia | 1.3 | 0.4 | (AghaKouchak et al., 2015) | Asia |
| Lake Abert | 1.3 | 30.2 | (Moore, 2016) | North America |
| Lake Poopo | 1.0 | 1.5 | (Satgé et al., 2017) | South America |
| Deep     | Dead Sea     | 13.8 | 177.2 | (Morin et al., 2018; Shentsis et al., 2019; Wine, 2019b) | Western Asia |
| Caspian Sea | 10.8 | 200.5 | (Rodell et al., 2018) | Western Asia |

| **Note.** In deeper inland waters higher coefficients are currently observed. |
4.3. Attributing Global Endorheic Lake Shrinkage

The data suggest that this lake-irrigated agriculture tradeoff is subject to an exchange coefficient equal to the quotient of irrigated agricultural area and lake loss, which differs among water bodies: Aral Sea (1.9), Lake Urmia (1.3), Great Salt Lake (1.4), and Lake Poopo (1.0). The increase in evapotranspiration flux as a consequence of irrigated agricultural area within a lake’s watershed is very likely lower than evaporative flux from a lake because evaporation excess may be lower in the higher elevation, cooler watershed areas, crop coefficients of many crops are less than unity, and due to harvesting, growing season duration may be shortened.

Eq. 6 may be appropriate in determining the proportion of lake shrinkage caused by expansion of irrigated agriculture, subject to uncertainty regarding the exchange coefficient (Figure 3). Though the irrigated agriculture contribution to lake shrinkage decreases from 89% to 76% as the exchange coefficient increases from unity to two, the analysis nonetheless indicates clearly the primary role of irrigated agriculture in desiccating Earth’s endorheic lakes.

This concept might then be used to provide first-order predictions of latent lake shrinkage of terminal lakes—desiccation that has been incurred due to increases in irrigated agricultural area but not yet realized in deep water bodies that will require decades or centuries to reach a new equilibrium. Reaching a new equilibrium will bring about a 60–130% increase in loss of endorheic water bodies (Figure 1D, 4), of which incipient desiccation of the Caspian Sea accounts for half. This estimate may serve as a lower bound, as it neglects impacts of pending or future increases in irrigated agricultural area.

4.4. Trading Exorheic Lakes for Irrigated Agriculture: An Upper Bound on Agricultural Impacts

In exorheic lakes, inflows exceed lake evaporation, so expansion of irrigated agricultural areas indicates the maximum lake shrinkage that can be explained by this driver. However, due to this excess of water inflow in exorheic lakes, the simplified framework presented here is not able to project future lake shrinkage that may already have been incurred due to increasingly negative water balance in these lakes. Nonetheless, here we show that 16% of total global lake loss occurred in exorheic lakes draining water-limited watersheds (Figure 1B). Of total global lake loss in water-limited watersheds, including both endorheic and exorheic lakes, 74–86% can be explained by global increases in irrigated agriculture (Figure 1C). The watershed area contributing to shrinking lakes draining water-limited systems and impacted by irrigated agriculture accounts for 18% of Earth’s land area (Figure 1A).

4.5. Impacts of Lake Loss

The reduction of areal extent of global lakes understates the widespread broader impacts from physical, water quality, and aquatic ecosystem perspectives. Lake loss has triggered crippling natural hazards and impacted regional climate. For example, decreasing sea levels increase the hydraulic gradient in near-shore groundwater systems, driving groundwater flow toward the sea and triggering landslides and swarms of sinkholes in the karst hydrogeologic setting of the Dead Sea (Closson et al., 2010; Yechieli et al., 2006). With respect to surface hydrology, decreasing base level causes rapid channel incision.
and erosion (Bowman et al., 2010). Lake shrinkage diminishes the lake effect, dramatically changing regional climate as far as hundreds of kilometers downwind from the historical extent of large shrunken lakes, such as the Aral Sea (Small et al., 2001). These regional climatic changes drove creation of new desert areas that, in turn, serve as source areas for salt and dust storms (Indoitu et al., 2015; Micklin, 2016), which have been implicated in a range of negative impacts on human health (Micklin, 2007).

Lake shrinkage impacts the thermal structure of stratified lakes, as it is only the hypolimnion thickness that shrinks. Boundary mixing by internal waves increases internal nutrient loading (MacIntyre et al., 1999; Ostrovsky et al., 1996; Yeates & Imberger, 2003), with impacts similar to those of external nutrient enrichment and eutrophication (Moss, 2011). These impacts are further driven by the synergy of additional stressors—including rapidly rising global lake temperatures (O'Reilly et al., 2015), salinization (Paerl et al., 2011), and increased external nutrient loading (Carpenter et al., 1998). In extreme cases the hypolimnion shrinks to its complete elimination, turning meromictic, monomictic, or dimictic lakes into polymictic lakes. As a result, nutrients from the deeper layers are available to the biota in the shallow layers throughout the year, enhancing cyanobacterial blooms—as for example was the case with Lake Arancio in Sicily (Naselli-Flores, 2003). Toxic cyanobacterial blooms tend to become a recurring plague and increasingly threaten public health (Brooks et al., 2016).

Taking as an exemplar Israel's Lake Kinneret, a 6% reduction in surface area reduced lake volume by 24%, primarily due to over-extraction of water from the lake and its watershed (Wine, Rimmer, & Laronne, 2019). As the lake shrank, its water level initially dropped below the elevation of its outflow to the Lower Jordan River, converting it to a terminal lake while increasing residence time of lake water (Rimmer & Givati, 2014). Concurrently, the diminished outflow contributed to impoverished water quality in the Lower Jordan River (Hillel et al., 2015; Hillel et al., 2019). Furthermore, in parallel to the declining water levels, Lake Kinneret chloride concentrations increased from ~220 mg Cl\(^{-1}\) in the 1980s (Rimmer & Nishri, 2014) to over 320 mg Cl\(^{-1}\) in 2018. Thus, a 6% reduction in lake area understated the 100% reduction in water in the lake meeting the US EPA drinking water quality standard of 250 mg Cl\(^{-1}\) (Daley et al., 2009). As a consequence of this water quality degradation, the solute concentrations in Lake Kinneret have exceeded limits for irrigation of certain crops, thereby generating an incentive to capture high-quality freshwater before it reaches the lake, hence further reducing inflow volumes and exacerbating the problem.

As lakes shrink in size, their shorelines migrate offshore and their littoral zones are heavily impacted: they lose their macrophytic vegetation (Zohary & Ostrovsky, 2011) and their substrate becomes mainly smaller-sized particles (Hofmann et al., 2008). These changes translate to loss of habitats of high structural complexity that are utilized by fish and invertebrates (Gasith & Gafny, 1990; Glassic & Gaeta, 2019). As a result, sensitive species disappear, with marked loss to biodiversity while a few generalist invasive species are advantaged (Zohary & Gasith, 2014). The latter often become dominant, replacing the native keystone fauna and flora. The pelagic food web is often impacted via littoral-pelagic coupling processes, such as zooplanktivorous fish that depend on littoral resources for spawning, but then feed on zooplankton in the open water (Zohary & Ostrovsky, 2011).

In terminal lakes, declining water levels are usually accompanied by increasing salinity (Jeppesen et al., 2015). Changes in salinity have major impacts on community composition of the phytoplankton, zooplankton, macrophytes, zoobenthos, and fish. As salinity of freshwater increases, native species disappear whereas a few generalist more tolerant species prevail. An example is salinity-tolerant toxic golden algae that replace native flora in lakes with increasing salinity (Roelke et al., 2015). The changes then spiral up the food web, ultimately imperiling ecosystem services. In inland water bodies that have shrunken most drastically, the associated water quality implications have devastated aquatic ecosystems, as in the case of the Aral Sea (Aladin & Plotnikov, 1993), in which an order of magnitude increase in salinity decimated freshwater and brackish fish species along with the fishing industry (Hampton et al., 2018). Almost all native aquatic animals were extirpated from the Aral Sea due to rising salinity (Mirabullayev et al., 2004). While the Aral Sea disaster presents an extreme endmember with respect to ecological impacts of inland water body loss, even small areal shrinkage of lakes profoundly affects their ecological dynamics (Jeppesen et al., 2015).
4.6. Weighing in on the Global Change Versus Climate Change Debate

As global lakes continue to shrink, the debate continues over attributing this shrinkage to climatic change versus increased anthropogenic water consumption. Our results demonstrate that 74–86% of global lake shrinkage within water-limited basins can be explained by expansion of irrigated agriculture, thus relegating climatic factors, to date, to a background process relative to increases in human water consumption. While global warming is predicted to increase evaporation fluxes from Earth’s lakes at the multi-decadal time scale (Wang et al., 2018), realized and latent lake shrinkage will continue to have an opposing effect on the volume of water evaporated from lakes.

4.7. Plans to Save Lakes

Strategies to somewhat ameliorate the condition of desiccating lakes have been proposed, though under the pressure of entrenched interests and increasing water stress due to global population growth, the success of these proposals remains uncertain. The government of Israel has discussed the possibility of desalinating Mediterranean Sea water to increase freshwater availability in the basin of the shrinking Lake Kinneret, a solution with a heavy recurrent price tag, large cost in carbon emissions (Tal, 2018), and a range of environmental impacts (Elimelech & Phillip, 2011) that is complicated by the transboundary nature of the Jordan River basin (Wine, 2019a; Wine, 2019c; Wine, 2019e). In the Lake Urmia basin a 40% reduction in water consumption is recommended to partially refill the lake (Alborzi et al., 2018), though the socio-economic and political feasibility of choosing to allocate water to natural systems over humans at a large scale in the face of water scarcity remains unproven. Water transfer projects (Shumilova et al., 2018) could also be used to avert negative water balance in inland waters. Edwards and Null (2019) suggest water conservation markets as a possible solution to address the desiccation of the Great Salt Lake. Taking California’s Mono Lake as an example of a conservation success story, the effort involved sustained and organized commitment by a conservation organization, freedom of expression, a judicial process that assigned value to the continued existence of the lake, and action on the part of government (Williams, 2002).

4.8. Evaluating Technological Optimism

Burgeoning Tragedies of the Commons (Hardin, 1968) in water resource systems—including declines in aquifers and inland seas—have been observed in numerous regions of several of Earth’s continents by Rodell et al. (2018). In response, they optimistically suggest that “water-saving technologies and improved management and governance” in Israel “proves that a comprehensive water conservation strategy can work”. However, our study observes declines in both inland surface water bodies to which Israel is a riparian, including a receding Lake Kinneret (Wine, Rimmer, & Laronne, 2019) and a rapidly shrinking Dead Sea (Morin et al., 2018). Experience has demonstrated the limits of technological optimism as well as uncertainty that Israel’s experience is globally applicable. While drip irrigation has substantially improved productivity per unit water (Maisiri et al., 2005), widespread irrigation with gray water has salinized soils (Tal, 2016). Israel has focused on growing crops with a high value per unit water and import of virtual water—embedded in agricultural products—strategies that address issues of local water scarcity while exacerbating water scarcity in already highly water scarce regions of other parts of the globe (Fridman & Kissinger, 2018). Consequently, the technologies that Israel uses to manage water scarcity are by no means a silver bullet, nor have they been demonstrated to be applicable at the global scale.

Thus, despite advances in water technology, the degraded state of many of Earth’s common pool resources have led to suggestions that the only solution may be demographic (Anderson, 2019; Campbell et al., 2013; Crist et al., 2017; Ganivet, 2019; Potts, 2014; Ripple et al., 2017; Ripple et al., 2019; Tal, 2017; Warren, 2015; Warren, 2016; Wine, 2020). Nonetheless, the mainstream response to environmental degradation, as Earth struggles to support a growing population, remains solutions that improve efficiency in food production, consumption, and land use (Foley et al., 2011; Godfray et al., 2010; Lambin & Meyfroidt, 2011). These proposed solutions remain unproven at a global scale and require increasing global irrigated area (Mueller et al., 2012), the primary global driver of lake loss. Thus, our results suggest that the present level of the human population on Earth exceeds planetary bounds (Hoekstra & Wiedmann, 2014) with respect to the co-sustainability of human population and the aquatic ecosystems of water-limited regions.
5. Future Research Directions

Despite the progress presented herein, this research raises numerous unanswered questions:

- What are the water quality implications of global lake area declines?
- What are the implications for humanity of having fewer and smaller lakes?
- Which irrigated agricultural crops are primarily responsible for the observed lake shrinkage?
- To what extent are agricultural products that rely on irrigation consumed within the basins of lakes versus exported as virtual water out of the lake’s basin? (Alternatively, to what extent could Earth’s lakes be stabilized by reducing virtual water exports from their watersheds?)
- How will lakes’ areas evolve into the future as global population grows and other global change drivers develop?
- What is the relative role of withdrawal of lake water, river water, and groundwater in the global loss of lake area?
- What controls the variability among lake-irrigated agriculture exchange coefficients? To what extent is the value of this coefficient determined by fixed environmental considerations versus land management practices that may be subject to modification?
- What is Earth’s carrying capacity and that of its climatically distinct basins that would allow all lakes to exist intact alongside humanity?

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