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The implications of climate change driven depletion of Lake Kinneret water levels: the compelling case for climate change-triggered precipitation impact on Lake Kinneret's low water levels☆

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ABSTRACT

The dramatic drop in water levels in the Kinneret Lake (Sea of Galilee) during the past years is evaluated. Recently published measurements of temperature, precipitation and other hydrological data support the position that climate change is driving the contraction of this iconic water resource. The article presents a range of evidence confirming long-term shifts in the hydrological dynamics of the watershed and details the associated ecological implications. In response to these trends, Israel's government has decided to build a desalination plant along the Northern Mediterranean shoreline that will provide water to replenish the depleted water levels in lake. Given the likelihood of continued global warming expediting increased evaporation and reduced precipitation, such climate adaptation policies constitute prudent public policy.

1. Introduction

Few water bodies in the world are as celebrated as the Kinneret Lake – the iconic "Sea of Galilee" which offered the backdrop to many of the evangelical activities chronicled in the Gospels. A productive fishery, central recreational destination and long a source of spiritual inspiration, the Kinneret is also the lowest freshwater lake in the world, lying more than 215 m below sea level (Orni and Efrat, 1973). Historically, annual recharge of the Kinneret averaged roughly 850 million cubic meters (mcm) of water – 520 mcm of the flow came from the Jordan River – (Goldsmid, 1971) about 30% of which was lost to evaporation (Whitman, 1988). When a national Water Carrier was completed in 1964, the Kinneret served as the country's national reservoir, providing over half of Israel's water (Shoham and Sarig, 1995).

During the past decade, rainfall in the watershed has dropped significantly (Ziv et al., 2012) and water levels in the Kinneret Lake have dropped significantly. As a result, Israel's Water Authority has largely discontinued pumping water out of the lake for domestic or agricultural use (Tal, 2016). Even so, in 2018, measurements show the Kinneret to be at historically low level (Gomes-Hochberg, 2018). Fig. 1 reflects the trends over the past decade in the lake's water levels. A minimum "red-line" established by hydrologists in the 1960s, is a precautionary water level reflecting the minimum safe level for extraction in the lake (Tal, 2002; Markel, 2014; Bismuth, 2016). For the past two years, the lake has fallen below that level. (A maximum red-line level, based on the distance between existing buildings and the shoreline and concerns about financial compensation, was established in 1969 after record rains led to the flooding of the riparian town of Tiberias. When this line is exceeded, water is to be released into the Jordan River.).

Every morning at 7:30 the lake level is measured. Fig. 1 presents a composite of the daily measurements reflecting the inter annual fluctuations in lake levels.

The most recent monthly report published by Israeli government's Hydrological Service describes the dire situation of the lake in somewhat technical terms:

> *"The level of the Kinneret dropped during the month of October by 19 cm and stood as of November 1, 2018 at the level of −214.62 m (below sea level AT), 162 cm. below the minimum "red line" and the lowest it has been for this period since 2001. (The level today is near the nadir that was recorded in November 2001, a level of −214.87 m.) Relative to*

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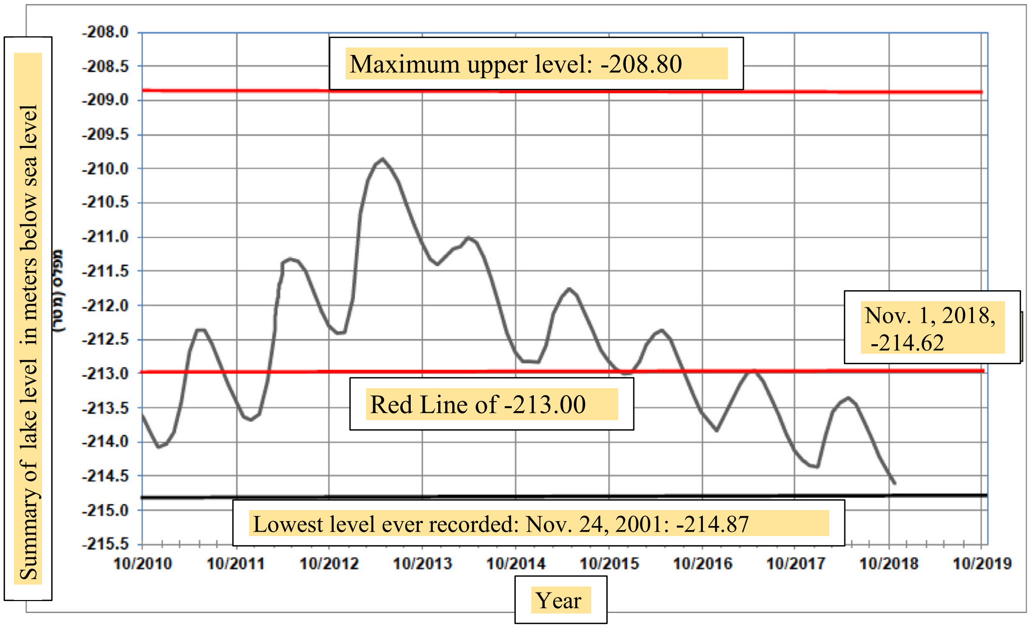

Fig. 1. Drop Kinneret lake water levels by year. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)
(Source: Israel Hydrological Service, 2018)

the maximum redline a (level of 208.80 m) the water line today lacks 5.82 m (or a total volume of roughly 950 million cubic meters (mcm).

The end of the lake's role as a national reservoir emerges as well from Fig. 2, which reflects the annual trends in available water for extraction. The graph shows the amount of water that could be pumped in a given year without drawing water levels below the red line. Since 2014, the lake literally has had no water to give, with additional pumping exacerbating the environmental risks.

The Israeli government water authorities report this bad news laconically:

"The level of the Kinneret dropped during the month of October by 19 cm and stood as of November 1, 2018 at the level of −214.62 m (below sea level AT), 162 cm. below the minimum "red line" and the lowest it has been for this period since 2001. (The level today is near the nadir that was recorded in November 2001, a level of −214.87 m.) Relative to the maximum redline a (level of 208.80 m) the water line today lacks 5.82 m (or a total volume of roughly 950 million cubic meters (mcm)."

The full scope of the ecological and social disasters associated with the mismanagement and disappearance of other lakes, such as the Aral Sea (Micklin, 2010; Graham et al., 2017) or Lake Chad (Akanni, 2018) are only now being understood. Assessing the reasons for the drop in Kinneret water levels and their ramifications, therefore constitutes a critical question for water managers, ecologists and millions of people with a concern for the country's only fresh water lake.

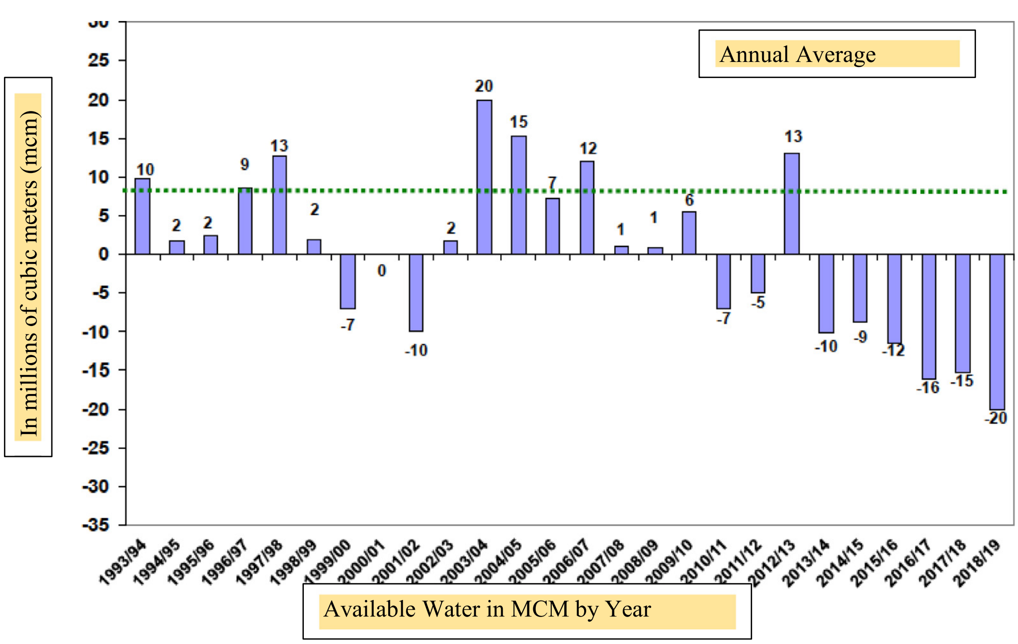

Fig. 2. Kinneret lake water volume availability.
(Source: Israel Hydrological Service, 2018)

In this article, we review the environmental implications of the drop in precipitation and the drawdown of Lake Kinneret. Our analysis confirms that climate change indeed appears to be driving the negative trends and there is little basis to assume that the present depletion of water levels in the Kinneret will change. The Israeli government's decision to direct the water produced a major desalination plant is designed to allow the lake to continue to function ecologically and to maintain its water.

2. Environmental impacts of the Kinneret drawndown

The environmental meaning of the precipitous retreat in water levels should not be understated. This is particularly apparent in the littoral zone, or the Kinneret's shallow, transitional environment a critical area for both terrestrial and aquatic organisms, which naturally exhibits high species diversity, biomass and fish abundance.

This shoreline habitat and the native biota are negatively affected by recent years of drawdown in lake levels, and the resulting reduction in the proportion of the rocky littoral areas. For instance, as lake levels drop the stony substrate that is so important for fish spawning is reduced affecting the reproduction of several species (Gasith and Gafny, 1990; Gasith et al., 2000). Dense, forest-like invasive species (e.g., *Acacia saligna*, *Parksonia aculate* and even *Washingtonia* palms) become established on the sandy shores at the expense of the natural reed (*Phragmites australis*) population (Zohary and Gasith, 2014).

Due to regulatory interventions in the watershed to reduce the sewage discharges, nonpoint source runoff and phase out of fish ponds, pollution levels for many parameters in the Kinneret have improved. The nutrient dynamics in the lake have changed: Today the lake's ecosystem has shifted from one of phosphorus to nitrogen limitation (Gophen, 2018). Salinity, however, has gotten worse.

Evidence of Fig. 3 shows the steady increase in salinity levels in the lake which as present hydrological models predict, corresponds to the reduction in precipitation (Gvirtzman et al., 1997; Rimmer et al., 1999). Salinity is measured as chloride ions at a depth of 0–15 m below the lake's surface. Present elevated salinity and the projected concentrations affect agricultural and human uses negatively (Rimmer and Nishri, 2014. As these trends continue, the aquatic ecosystem may also be disturbed.

During the 1990s, cyanobacteria began to replace the algal dominance of Peridinium in the Kinneret (Zohary et al., 2014). Researchers attribute this increases in the lake's cyanobacteria population, inter alia, to the rise in salinity levels. Indeed, a review by Israel's leading experts about cyanobacteria attributes the recent success of these unwelcome "blue-green" organisms to several causes that are directly associated with climate change: water column temperature, reductions in wind and the reduced precipitation around the lake. The rise in the alkalinity, pH, and salinity of the lake is a factor, but probably of lesser importance (Hadas et al., 2015).

3. Evidence of climate change

As mentioned, the Kinneret waterline retreat has taken place during a period when Israel's precipitation patterns appear to be changing. A team of leading Israeli climatologists evaluated rainfall regimes and the same 40-year trends across Israel between 1975 and 2010, and concluded that that a 3.3% drop in rainfall per decade had occurred in the northern Galilee region where the Kinneret watershed is located (Ziv et al., 2012). Since the study was published, Israel has faced five consecutive years of drought, making claims of a shift in rainfall patterns even more compelling. The prevailing view among Israeli government experts and academic water researchers is that diminishing rainfall along with increased evaporation have reduced annual flow into the lake. The dramatic drop in average annual precipitation in the watershed is typically attributed to climate change (Givati and Rosenfeld, 2007; Markel, 2014; Gophen, 2019).

For much of its early history, Israel had an unfortunate proclivity for "over pumping" its surface and ground water resources to provide water to agricultural consumers (Israel State Comptroller, 1990). During these years, when the Kinneret levels were low, it was water extractions

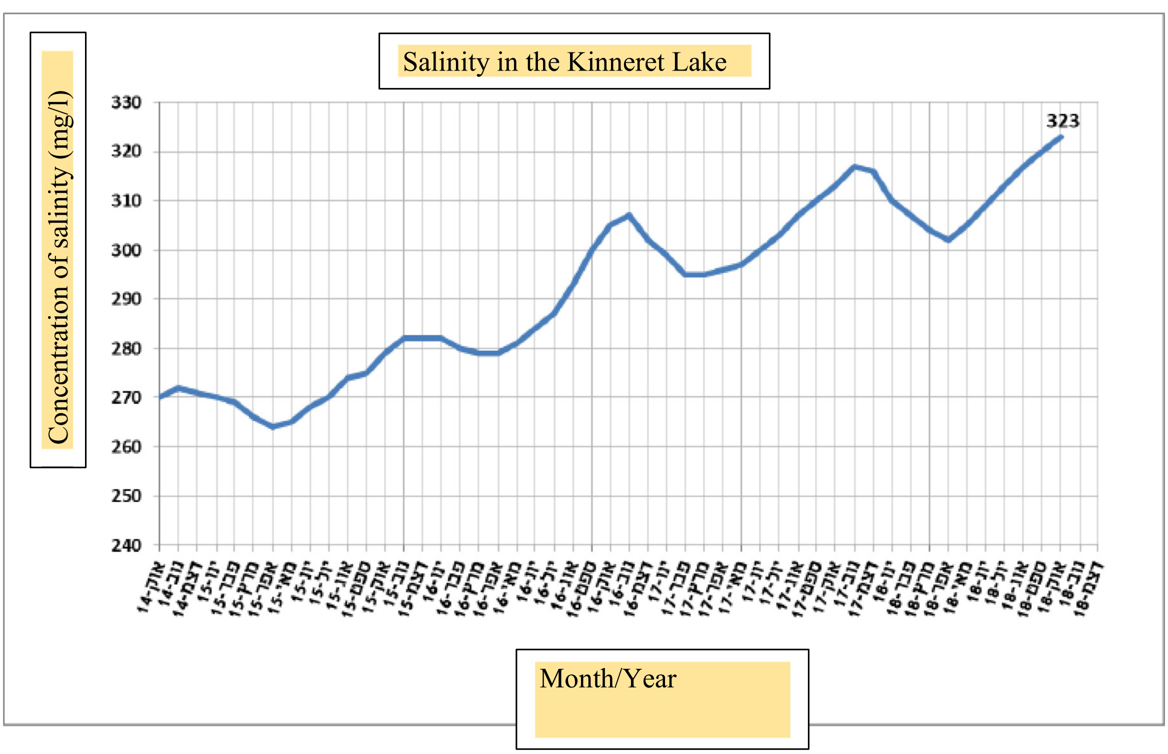

Fig. 3. Kinneret lake salinity: Oct. 2014–Dec. 2018.
(Source: Israel Hydrological Service, 2018)

authorized by Israel's water authorities that usually constituted the proximate cause. If this water management policy had persisted, desalinated replenishment of the Kinneret, an expensive climate adaptation policy, would not be a particularly cost-effective alternative. Rather, reduction of water allocations to farmers or enforcement of existing water restrictions would constitute a more prudent policy than constructing a costly desal facility. This is particularly true as the plant has been unpopular with environmental advocates due to concerns over a range of impacts on the coastal environment (Tal, 2018). Today, however, profligate, agricultural water supply no longer appears to be the reason for the lake's depletion.

The flow in Israel's streams and rivers is predominantly supplied by rainfall. Fig. 4 shows composite annual rainfall in northern watersheds across Israel, using a baseline that relies on the average perennial precipitation measured since 1985–1986. The graph reflects the reduced precipitation in the Galilee around the Kinneret River Basin. While there are anomalous years where high levels are recorded, the general downward trend is clear.

Similarly, rain and snowmelt during the spring from the Golan Heights deliver most of the flow to Lake Kinneret's tributaries, the most important of which is the upper Jordan River. Fig. 5 contains the most recent water quantity data for these streams. While annual rainfall fluctuates, a generally reduced flow has been measured across the watershed over the past decade, especially in the Jordan River, where volume has dropped by over 50% since 2004.

Regulation of water in Israel is as stringent and monitored as anywhere in the world. Any water extraction and utilization requires a permit. Precise measurements of the different sources utilizing water within the Kinneret water basin go back over 40 years. A comprehensive report in 2014 by Israel's Water Authority detailed water extraction within the Kinneret watershed by myriad sources (agricultural and municipal) and demonstrated clearly that removal of water within the Kinneret basin since 1975 has either stayed constant or dropped over the previous forty years (Sapir and Sagui, 2014). Fig. 6 shows the removal of water by different water users in the watershed. Fig. 7 shows the same forty years trends according to removal by geographic region.

Removal of water involves not only extraction but utilization of any water that would naturally flow into the lake from all sources. The graph confirms that the primary use of water has always been for domestic purposes, with agricultural wells being a secondary water consumer in the basin. During past decades, total annual water removal averaged around 180 mcm, while in peak years, during the 1980s and 1990s, total annual capture would often be as high as 210 mcm. In short, Fig. 6 reflects intensive government monitoring in the Kinneret drainage basin and confirms that the amount of water captured has decreased in recent years.

Indeed, discussions with water managers responsible for region confirm that during the four years since these data were collected and analyzed, water removal from the Kinneret watershed has been further reduced: Allocations to farmers have been cut back; Fish ponds, for example, which used to consume significant quantities of water, have essentially been phased out of operation (Markel et al., 2014); Artesian wells, such as that at Horshat Tal, in fact, release water into the watershed and do not constitute a net drain on lake inflow. Similarly, the Shamir well which became operational in 2011, is located upstream, in the foothills of the Golan Heights. It yields 7 mcm a year, from an aquifer which never contributed to Kinneret flow historically. Of this amount, 2 million are released into the Jordan River tributaries and eventually reach Lake Kinneret (Doron Markel, personal communication, 2019).

It would follow that given the drop in supply to different water consumers in the Kinneret watershed, water inflow into the Kinneret lake *should have* increased or at least remained stable. Yet, measurements at the Kinneret, as shown in Fig. 8, indicate that despite occasional high rainfall years, the general trend of inflow into the Kinneret, as demarked by the black line, has decreased. Reduced rainfall constitutes the obvious, proximate cause.

Because of the dramatic fluctuations in daily evaporation rates, the precise amount of water evaporating from the Kinneret is unknown (Assouline and Mahrer, 1993). Yet increased evaporation as a result of rising temperatures and its contribution to surface water depletion has been demonstrated in other lakes that are shrinking (Sereda et al., 2011; Roderick et al., 2014).

In the past, Kinneret evaporation was generally estimated to be 240 mcm/year, but it fluctuates significantly according to wind conditions. Accordingly, evaporation was not included in the calculations involving the Kinneret's water line, even though it is clear that due to increase in temperature (roughly 0.4 °C/decade during the critical summer months) evaporation has increased over the past decades. Fig. 9 shows the steady increase in temperatures as measured in Kibbutz Masada, an agricultural community containing the closest weather station to the lake. Accordingly, the contribution of climate change to falling Kinneret Lake water levels goes beyond than that associated only with reduced rainfall.

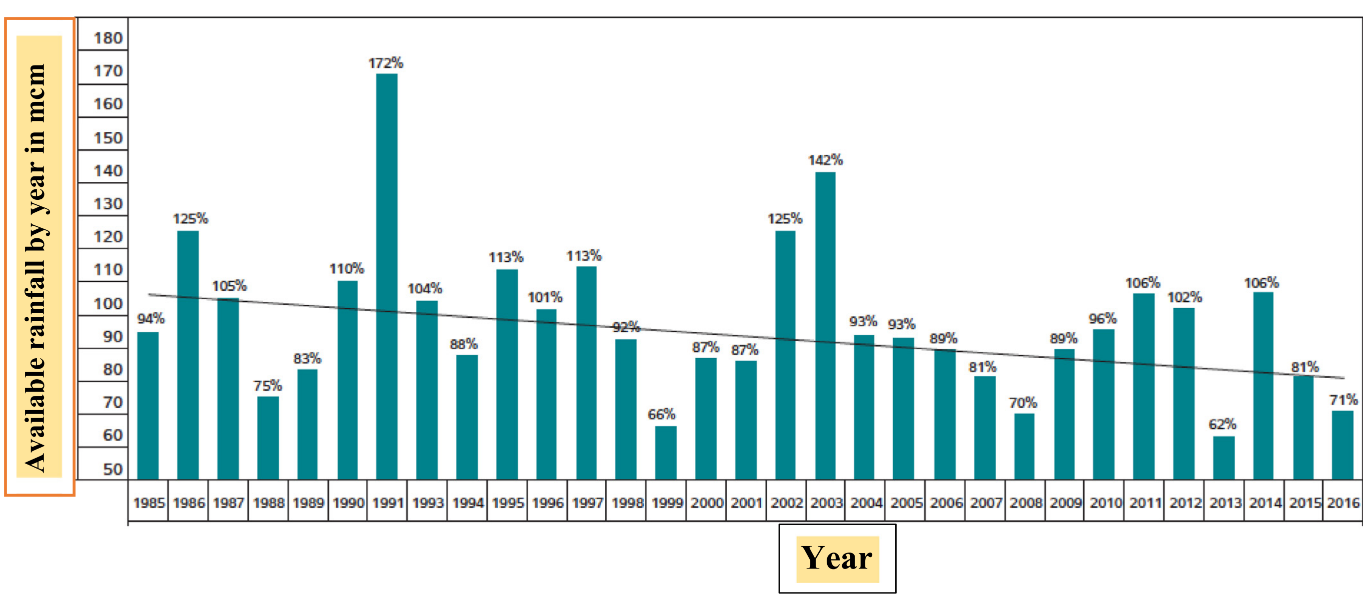

Fig. 4. Annual rainfall quantities in Israel relative to the annual average: 1985–2016, (Givati and Tal, 2017).

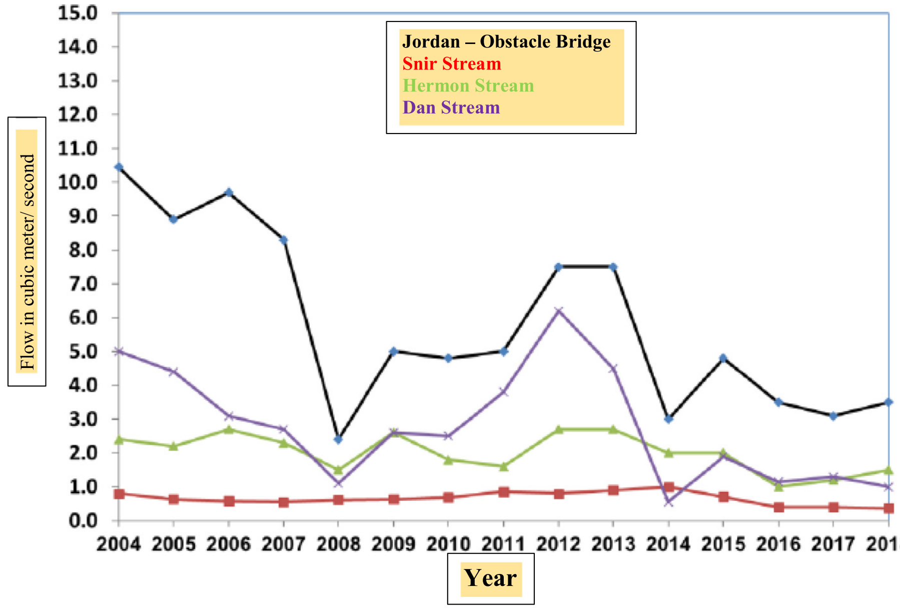

Fig. 5. Flow in 4 Kinneret tributaries: 2004–2018.
(Source: Israel Hydrological Service, 2018)

4. Conclusion: a climate change adaptation strategy for the Kinneret

Israel's government has decided that the new hydrological reality in the Galilee requires heroic measures. Despite the objections of the local communities who expressed environmental concerns, in December 2018, work began on a new desalination plant on the country's northern Mediterranean coastline (Rinat, 2018). The 1 billion dollar plant (Gorodiski, 2018) is expected to produce 100–200 mcm per year,

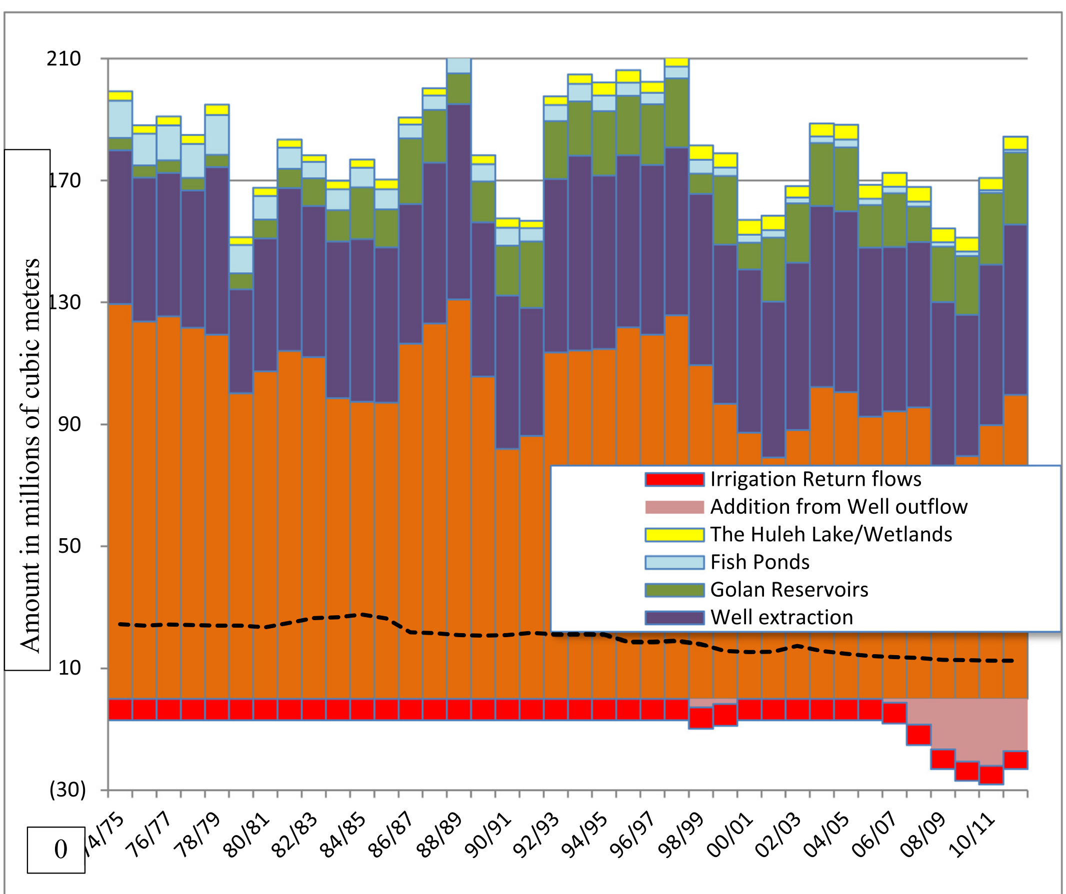

Fig. 6. Water capture in Kinneret basin by source, by hydrological year.
(Source, Israel Water Authority, 2018)

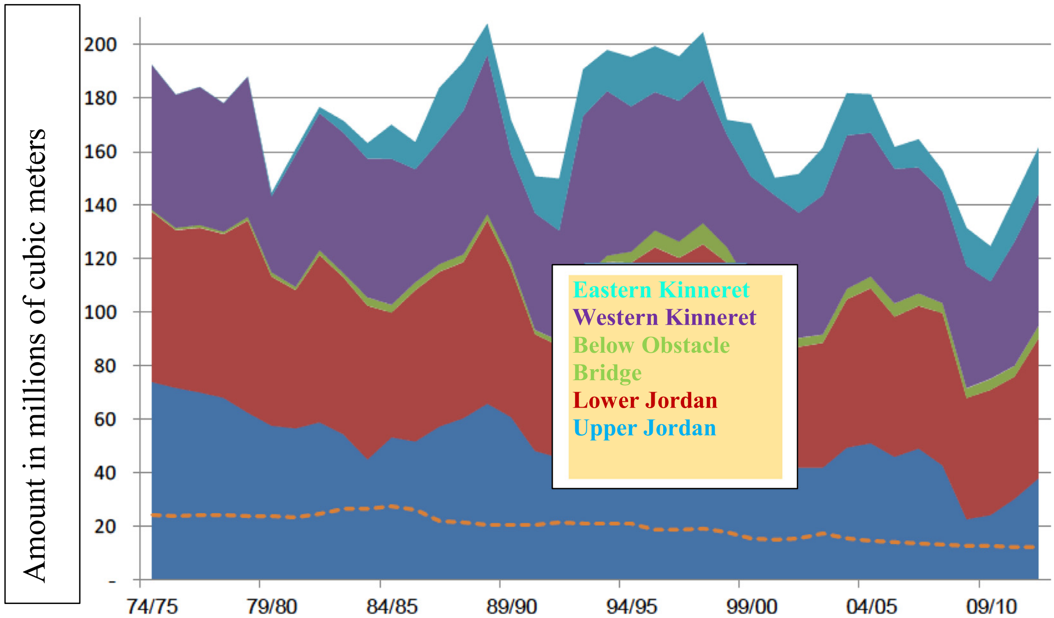

Fig. 7. Water capture in Kinneret basin by geographic region by hydrological year.
(Source: Sapir and Sagui, 2014)

which will be delivered by pipelines to Lake Kinneret in order to raise water levels by almost a meter per year.

Israel's Minister of Water and Energy, recently described the project as a climate adaptation measure – given his ministry's assumption that over time, rainfall will continue to shrink in the Galilee (Steinitz, 2018). Israel's new national water strategy aspires to reestablish the Kinneret as a back-up national reservoir, given the vulnerability of the country's desalinated domestic water supply in such a geopolitically turbulent region. Maintaining historic water levels in the lake is also critical for the country's water security, because the pumping system for the National Water Carrier becomes inoperable once water levels fall below 215 m below sea level.

The fresh source of water should allow the lake to retain its natural ecological cycles and ensure reasonable water quality. As a unique spiritual and recreational resource, the value of the Sea of Galilee is difficult to quantify. All the same, the centrality of the lake to the booming Galilee tourist industry – which attracts roughly 1.4 million international visitors a year with estimated associated revenues of almost 2 billion dollars (Raz-Chaimovich, 2017) offers a compelling economic rationale for preserving the integrity of the lake.

The preponderance of the hydrological evidence indicates that climate-related reductions in rainfall and rising average temperatures are driving water depletion in Lake Kinneret. Present trends suggest that intervention is necessary if the physical dimensions and ecological integrity of this critical water resource are to be preserved. Assuming that the carbon footprint can be minimized through renewable energy supplies, replenishing depleted water levels through sea desalination

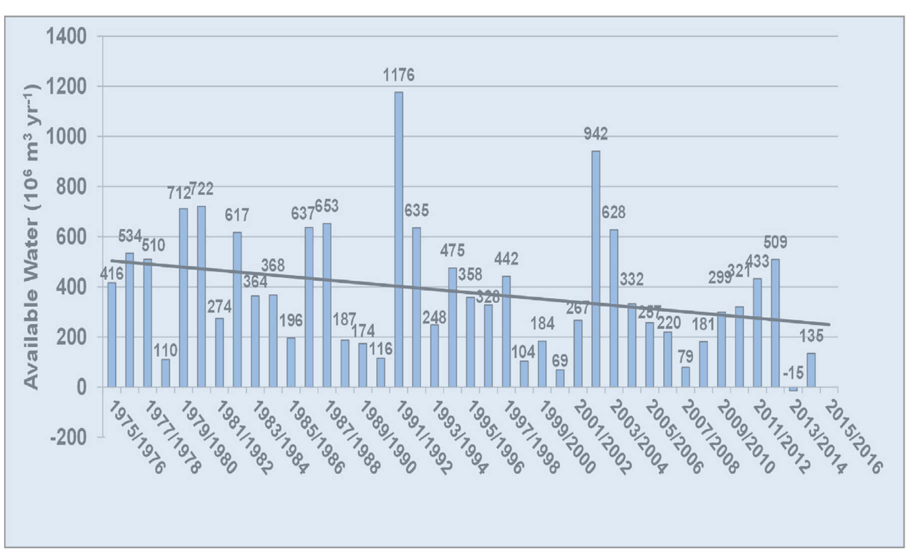

Fig. 8. Drop in inflow to the Kinneret Lake: 1975–2016.
(Source, Markel, Israel Water Authority)

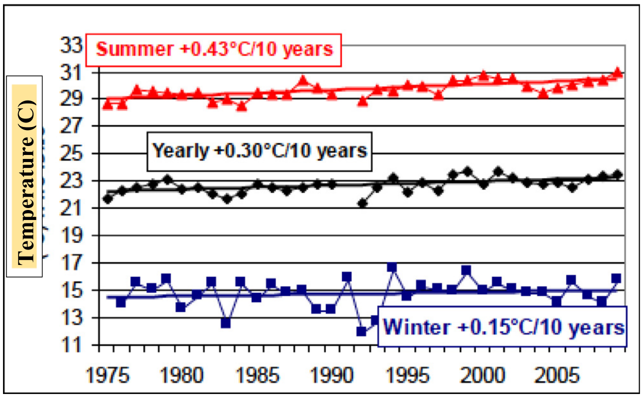

Fig. 9. Increase in average temperatures in Kinneret Basin (Masada Weather Station) 1975–2010.
(Source: Ziv et al., 2011)

constitutes a prudent policy response to climate-related impacts on lakes and streams.

References

Akanni, A., 2018. Decision Management tools for trans-boundary water management in Lake Chad Basin. J. Water Resour. Ocean Sci. 7 (3), 49–54. https://doi.org/10.11648/j.wros.20180703.14.

Assouline, S., Mahrer, Y., 1993. Evaporation from Lake Kinneret: 1. Eddy correlation system measurements and energy budget estimates. Water Resour. Res. 29, 901–910. https://doi.org/10.1029/92WR02432.

Bismuth, C., 2016. Water resources, cooperation and power asymmetries in the water management of the Lower Jordan Valley: the situation today and the path that has led there. In: Hüttl, R., Bens, O., Bismuth, C., Hoechstetter, S. (Eds.), Society - Water - Technology. Water Resources Development and Management. Springer, Cham.

Gasith, A., Gafny, S., 1990. Effects of water level fluctuation on the structure nad function of the littoral zone. In: Tilzer, M.M., Serruya, C. (Eds.), Large Lakes, Ecological Structure and Function. Springer, Berlin, pp. 156–171.

Gasith, A., Gafny, S., Goren, M., 2000. Response of the fish assemblage of rocky habitats to lake fluctuations: possible effect of varying habitat choice. Arch. Hydrobiol. 55, 317–331.

Givati, A., Rosenfeld, D., 2007. Possible impacts of anthropogenic aerosols on water resources of the Jordan river and the Sea of Galilee. Water Resour. Res. 43. https://doi.org/10.1029/2006wr005771.

Givati, A., Tal, A., 2017. The hydrological situation in the Kinneret Basin, observed and projected trends on the basis of hydro-climatic models, (in Hebrew). Ecol. Environ. 8 (4), 12–19.

Goldsmid, Y., 1971. Water quality management of the Israel national water system. Developments in Water Quality Research. Ann Arbor Science Publishers, Ann Arbor Michigan, pp. 1–12.

Gomes-Hochberg, C., 2018. Five-year drought brings Israeli water bodies to historically low levels. Jerusalem Post (August 26, 2018).

Gophen, M., 2018. The impact of available nitrogen deficiency on long term changes in the Lake Kinneret ecosystem. Ecological Research in the Lake Kinneret and Hula Valley (Israel) Ecosystems. Scientific Research Publishing, pp. 128–140.

Gophen, M., 2019. Climate change and water loss in the Kinneret drainage basin. Land Use Policy 80, 424–429.

Gorodiski, S., 2018. The water authority approved establishment of a desalination plant in the Western Galilee. The Marker (January 21, 2018). https://www.globes.co.il/news/article.aspx?did=1001220453.

Graham, N.A., Pueppke, S.G., Uderbayev, T., 2017. The current status and future of Central Asia's fish and fisheries: confronting a wicked problem. Water 9 (9), 701. https://doi.org/10.3390/w9090701.

Gvirtzman, H., Garven, G., Gvirtzman, G., 1997. Hydrogeological modeling of the saline hot springs at the Sea of Galilee, Israel. Water Resour. Res. 33, 913–926.

Hadas, O., Kaplan, A., Sukenik, A., 2015. Long-term changes in cyanobacteria populations in Lake Kinneret (Sea of Galilee), Israel: an eco-physiological outlook. Lifestyles 5 (1), 418–431. https://doi.org/10.3390/life5010418.

Israel Hydrological Service, 2018. The monthly hydrological situation: surface water in Main drainage areas and groundwater levels in the National System ((in Hebrew) November 1, 2018).

Israel State Comptroller, 1990. Report on the Administration of Israel's Water Economy. 53. State Comptroller, Jerusalem (Hebrew).

Markel, D., 2014. Monitoring and management of Lake Kinneret (Sea of Galilee) – preserving Israel's major surface water resource. *Enviro Geo*. Chim. Acta 1, 411–420.

Markel, D., Shamir, U., Green, P., 2014. Operational management of Lake Kinneret and its watershed. In: Zohary, T., Sukenik, Berman, T.A., Nishry, A. (Eds.), Lake Kinneret. Ecology and Management. Springer, Dordrecht, pp. 541–560.

Micklin, P., 2010. The past, present, and future Aral Sea. Lakes Reserv. Res. Manag. 15, 193–213.

Orni, E., Efrat, E., 1973. Geography of Israel. Israel Universities Press, Jerusalem, p. 444 (p. 156).

Raz-Chaimovich, M., 2017. The Ministry of Tourism believes that incoming tourism contributed NIS 20 billion to the Israeli economy. Globes (December 27, 2017). https://en.globes.co.il/en/article-record-36m-tourists-visit-israel-in-2017-1001217309.

Rimmer, A., Nishri, A., 2014. Salinity. In: Zohary, T., Sukenik, Berman, T.A., Nishry, A. (Eds.), Lake Kinneret. Ecology and Management. Springer, Dordrecht, pp. 113–131.

Rimmer, A., Hurwitz, S., Gvirtzman, H., 1999. Spatial and temporal characteristics of saline springs: Sea of Galilee, Israel. Ground Water 37, 663–673.

Rinat, Z., 2018. New Pipeline Will Bring Desalinated Water to Israel's Only Freshwater Lake, Haaretz. (December 2, 2018). https://www.haaretz.com/israel-news/.premium-israel-s-national-water-carrier-to-bring-desalinated-water-to-lake-kinneret-1.6702557.

Roderick, M.L., Sun, F., Lim, W.H., Farquhar, G.D., 2014. A general framework for understanding the response of the water cycle to global warming over land and ocean. Hydrol. Earth Syst. Sci. 18, 1575–1589.

Sapir, G., Sagui, A., 2014. Estimating the quantity of water removed from the Kinneret by human usages in the watershed. (in Hebrew). Internal Government Report. Israel Water Authority, Tel Aviv (copy available with Israel Water Authority or author).

Sereda, J., Bogard, M., Hudson, J., Helps, D., Dessouki, T., 2011. Climate warming and the onset of salinization: rapid changes in the limnology of two northern plains lakes. Limnologica 41 (1), 1–9.

Shoham, Y., Sarig, O., 1995. The National Water Carrier. in Hebrew. Mekorot, Sappir, p. 9.

Steinitz, Y., 2018. Israel minister of water and energy. Presentation at Ecopeace Conference, Dead Sea, Jordan, November 12, 2018.

Tal, A., 2002. Pollution in a Promised Land – An Environmental History of Israel. University of California Press, Berkeley.

Tal, A., 2016. Has technology trumped adaptive management? A review of Israel's idiosyncratic hydrological history. Glob. Environ. 9, 484–515.

Tal, A., 2018. Addressing desalination's carbon footprint: the Israeli experience. WaterSA 10. https://doi.org/10.3390/w10020197.

Whitman, J., 1988. The Environment in Israel. Ministry of Interior, Jerusalem, p. 136.

Ziv, B., Saaroni, H., Apert, P., 2011. Temperature, heat-stress and rainfall fluctuations and trends in Israel during the last 30 years: is it an evidence for climatic change? Climatological-synoptic Study, Report Submitted to the Israel Ministry of Environmental Protection (In Hebrew)

Ziv, B., Saaroni, H., Pargament, r., Harpaz, T., Alpert, P., 2012. Trends in rainfall regime over Israel, 1975–2010, and their relationship to large-scale variability. Reg. Environ. Chang. https://doi.org/10.1007/s10113-013-0414-x.

Zohary, T., Gasith, A., 2014. The littoral zone. In: Zohary, T., Sukenik, A., Berman, T., Nishri, A. (Eds.), Lake Kinneret, Ecology and Management. Springer, Dordrecht, pp. 517–534.

Zohary, T., Sukenik, A., Berman, T., 2014. Peridinium gatunense. In: Zohary, T., Sukenik, Berman, T.A., Nishry, A. (Eds.), Lake Kinneret. Ecology and Management. Springer, Dordrecht, pp. 191–212.