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TRENDS IN AQUATIC ECOLOGY II

Development and application of a sustainability index for a lake ecosystem

Gideon Gal · Tamar Zohary

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Abstract We modify an existing water quality index of Lake Kinneret to better match the objective of sustaining the ecosystem over time. The Kinneret Sustainability Index (KSI) provides a quantitative indication of how similar the current ecosystem is in relation to a reference state that managers are striving to achieve and sustain once accomplished. As Lake Kinneret is the only freshwater lake in Israel, it is vital to sustain the lake ecosystem over time. The KSI provides lake managers with a means for assessing the state of the lake. The KSI is based on nine ecosystem variables and provides information on each variable and the combined index. We present examples of application of the KSI to lake management and conduct a sensitivity analysis of the underlying assumptions demonstrating its robustness to the assumptions. While the index presented here is specific to Lake Kinneret, it is a general approach that can be readily applied to lakes worldwide and can assist, for example, in achievement of the required *good status* for European lakes.

Keywords Lake ecosystem management · Reference conditions · Lake Kinneret · Sensitivity analysis

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G. Gal (✉) · T. Zohary
Kinneret Limnological Laboratory, Israel Oceanographic and Limnological Research, P.O. Box 447, 14950 Migdal, Israel
e-mail: gal@ocean.org.il

Introduction

Lake ecosystems provide a wide range of ecosystem services vital to society (Millennium Ecosystem Assessment, 2005), and as a result, there is a need for management that will allow sustaining ecosystems and ecosystem services over time. Sustaining ecosystems over time, in order to maintain the provision of services, is not, however, trivial (Cooke et al., 2005). For example, one of the key services provided by lakes is the supply of water for drinking, thus maintaining water quality at drinking level standards is of prime importance. Anthropogenic activities have, however, induced modifications to lake ecosystem characteristics; lake water quality has been affected by discharges of pollutants and biological components have been subject to human influence through water abstraction, commercial fish harvesting, and the introduction of alien species (Borja et al., 2012). The increasing anthropogenic activities further hinder sustainability of the ecosystems over time.

Water quality is a term used to describe the ecological status or condition of a water resource, usually with reference to human needs or values. The term water quality is therefore likely to have elements of subjectivity related to perceptions and biases of the users of the resource. While the concept of categorizing water based on the degree of pollution has its roots in the mid-nineteenth century, major progress only occurred following Horton's work (1965). Progress in water quality assessment has been associated with the establishment of sustainable management policies based on conservation within desired reference conditions (Smith, 1990; Wetzel, 2001). This was the first development of numerical indices to assess water quality and induced development of alternative approaches (Lumb et al., 2011). The use of the trophic level index is a common approach for assessing water quality when the trophic state is a management objective. It is also possible to define ecological indicators as measurable characteristics of the structure, composition, or function of ecological systems (Niemi & McDonald, 2004). Another approach is the development and application of a water quality index (WQI; Cude, 2001).

Environmental indicators, such as WQIs, are an attempt to distil information overload, isolate key aspects of the environmental condition, and assist managers in determining appropriate actions (Niemeijer, 2002). A WQI is a single number that reflects the water quality by integrating information of a range of ecosystem variables (indicators) such as dissolved oxygen, chlorophyll, nitrogen, phosphorus, and water clarity. It further provides a simple means for visualizing and communicating this information. A WQI, therefore, provides an integrated assessment index (Lee et al., 2014) on the state of a water body for different possible uses, such as drinking water supply (Rickwood & Carr, 2009), recreation (Cude, 2001), or multiple uses (Smith, 1990). It provides the decision maker, manager, or scientist, with an overview of the state of the ecosystem and the basic knowledge to decide whether, or not, there is a need to explore deeper. WQIs are becoming increasingly common due to the rapid raise in the amount of available data and information (van Puijenbroek et al., 2014; Kılkış, 2016). Furthermore, they are viewed as an accepted means for conveying the condition of ecosystems to decision makers and the public at the state, national, and international level (Liou et al., 2004; Rickwood & Carr, 2007; Carr & Rickwood, 2008). Reducing complex information, however, from multiple ecosystem elements to a single value remains a substantial challenge.

Observed changes of ecosystem variables over time can be compared to a predefined reference period. This is similar to the approach mandated by the EU WFD (WFD, 2000; Wacker et al., 2002; Parparov et al., 2010). A reference period is a period of time selected to represent a stable and/or desired state of the ecosystem. The reference period is used to define the permissible (i.e., desired) ranges of values for each variable. The permissible range can vary according to the stated use of the index. In this study, the key use of the index is to promote ecosystem sustainability, i.e., maintaining historical conditions over time, in relation to a predefined reference state of the lake ecosystem. Therefore, the permissible ranges will emulate the ranges observed during the reference period and defined as the desired state of the ecosystem.

While selection of the reference period and ecosystem variables used to characterize the lake are subjective, they should represent the key ecological processes and key elements of the ecological system. The variables should represent the main biochemical cycles, primary producer and consumer populations, and key energy fluxes into the system. Once the variables are selected, and their permissible ranges defined, the values, e.g., concentrations, of all variables, need to be transformed to a common scale referred to hereafter as index values. The index values can then be merged into a single quantitative index that represents the state of the ecosystem.

Lake Kinneret is the only freshwater lake in Israel. It provides 25–30% of the country's drinking water and as such is comprehensively managed and monitored (Sukenik et al., 2014). In addition, the lake provides a range of ecosystem services such as fishing, recreational activity, and cultural and religious experiences. There is a need, therefore, to sustain the lake ecosystem over time. The Israel Water Authority, the body charged with managing the lake, recognized this need for sustainability. Their long-term plan for water resources in Israel states two prime management objectives for the lake: maintaining water quality of the lake as a source for drinking water and sustaining the lake ecosystem into the future (IWA, 2012). Thus, there is a need for an index that will provide the Water Authority with a means for assessing the state of the lake in order to correctly manage it given these two objectives while providing the required services. In an attempt to address this need, Hambright et al. (2000) developed a WQI for the lake based on the Delphi method. The WQI they developed consisted of 11 parameters including chloride, TSS, turbidity, total phosphorus, total nitrogen, chlorophyll, primary productivity, cyanobacteria as a percentage of total algal biomass, zooplankton biomass, fecal coliforms, and BOD_5 (Hambright et al., 2000; Parparov et al., 2006, 2013). From these 11 indices, a composite WQI (CWQI) was developed (Parparov & Hambright, 2007) and proved to be an efficient tool for testing the impact of management scenarios on the ecosystem (Gal et al., 2009; Parparov et al., 2010; Gilboa et al., 2014). Nevertheless, the composite index suffered from several shortcomings, stemming from the lack of a clear definition of management objectives by the resource managers. As a result, the parameters included both drinking water quality parameters and ecological parameters and did not entirely address either of the two objectives defined by the Water Authority.

The overall objective of this study was, therefore, to update and modify the existing Lake Kinneret WQI System in order to create an index that would address one of the prime objectives, namely sustaining the ecosystem. This implies that a separate index addressing the management of the lake as a source of drinking water should be developed separately. Within the context of the objective of sustaining the lake ecosystem, we assume ecosystem sustainability to be the preservation of the ecosystem, as close as possible to a reference state, over time. Thus, we assume a narrow definition and do not consider the linkage between sustainability and sustainable development and the connection made between social sustainability, economic sustainability, and environmental sustainability (Singh et al., 2009; Moldan et al., 2012). Within the limits of our definition, we developed and applied a Lake Kinneret ecosystem Sustainability Index (KSI) that focuses on ecosystem variables and maintaining their values within predefined limits. We use the KSI in order to examine long-term changes that have occurred within the lake ecosystem and evaluate sustainability based on the similarity of the ecosystem to a predefined reference state. Finally, we evaluate the impact of management measures, namely changes to lake level and nutrient loading, on the ecosystem. While the modified index is specific to Lake Kinneret, the underlying assumptions, variables, and the form of application are generic and can be used to develop similar indices for other freshwater lakes around the world. The use of similar indices for European lakes would, for example, assist in the ability to determine lake status in-line with the needs defined by the Water Framework Directive (2000).

Methods

The construction of a quantitative index representing the state of the ecosystem and the deviation from the reference period requires several steps. These steps include the selection of the variables, selection of the reference period, definition of a permissible range for each of the variables, transformation of the values of the variables to index values, and calculation of a combined index of all variables.

In order to select the variables and reference period, we adopted the expert panel approach as suggested by the Delphi method (Okoli & Pawlowski, 2004 and references therein). This included open discussions with experts on the ecology of Lake Kinneret and voting to determine the variables, the reference period and the acceptable range of values for each parameter. The results of the steps taken to construct the index, especially the selection of the variables and reference period, will clearly vary according to the stated objective of the index and main use of the ecosystem. Therefore, we defined the main objective of the index as the need to achieve and sustain an ecosystem with characteristics similar to the relatively stable and predictable ecosystem observed in the past (Zohary et al., 2014a, b; Parparov et al., 2015).

Selection of ecosystem variables

Data for this study were extracted from the Lake Kinneret monitoring program, conducted since 1969 on a routine basis (Sukenik et al., 2014). This program includes tens of physical, chemical, and biological variables sampled at various depths and stations around the lake. Measurements of the variables examined were conducted on water samples collected, weekly or fortnightly, at Station A, a centrally located station, from 4 to 10 discrete depths between 0 and 10 m. Exceptions were the Secchi depth that was measured from a boat at the time of sampling, and primary productivity that was expressed per unit area and based on the depth-integrated volumetric values between 0 and 15 m. Samples were analyzed using standard methodology, based on protocols described in Zohary et al. (2014a). Data for each variable were averaged to create mean monthly values representing the upper layer of the lake. The basis for all further calculations were those monthly mean values.

Selection of the ecosystem variables for the index is not trivial as there are many possible variables that can be chosen. In order to assist in the selection process, criteria based on limnological characteristics were defined and included the following: an indicator of water transparency, indicators of the main nutrient cycles (nitrogen and phosphorus), representation of primary producers that were present during the reference period or are currently key populations in the lake, and a representative from a higher trophic level. The ecosystem variables to be used for computing the sustainability index were selected by an expert panel consisting of limnologists familiar with the Lake Kinneret ecosystem.

Selection of the reference period

We assume that the probability of ecological sustainability increases the closer the current situation is to a reference point or state (Wefering et al., 2000). Thus, a relatively stable and predictable ecosystem with limited anthropogenic impacts was key characteristics identified for selection of the reference period. Quantitative definition of stability is however rare (though see Parparov et al., 2015; Parparov & Gal, 2016). We therefore visually inspected the long-term (45 years) time-series of the selected variables, to search for a period matching the required characteristics. In addition, we accounted also for periods of time that are considered stable by scientists familiar with the ecosystem (Berman et al., 1995; Zohary et al., 2014b; Parparov et al., 2015). Another consideration in the choice of the reference period was the use of the same reference period as the one utilized for the previous WQI system developed for the lake (Hambright et al., 2000). This would allow comparison between the current index and the original index. The expert panel merged these considerations to select the reference period.

Definition of the permissible ranges

We employed the approach taken by the US EPA and others (Gibson, 2000; Dodds et al., 2006), in which limits are defined statistically based on a range of percentiles. This approach provides a solution for the issue of non-normal distributed data over time, thus minimizing the need for various types of data transformations. In order to select the best range of percentiles that would define the permissible ranges for each variable, we evaluated the use of several ranges that included: 5th–95th percentiles, 10th–90th percentiles, 20th–80th percentiles, and 25th–75th percentiles. The ranges evaluated were based on the values of the variables during the reference period. Following preliminary testing of the impact of the various ranges of percentiles, we selected to use the range of 10th–90th percentiles (see Sensitivity analysis below for more details). The significance of this range is that only values falling within this range are deemed acceptable. Furthermore, it implies that over time, on average, 20% of the values will be below, or exceed, the permissible range. We assume that the 10th–90th percentile range signifies natural variability in the system. Use of a wider range of values would lead to acceptance of extreme values observed during the reference period, while use of a narrower range of percentiles would result in an excessively large number of values beyond the permissible limits.

Transformation of variables values to index values

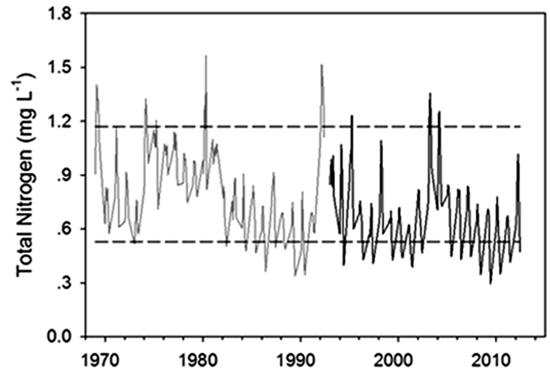
In order to construct a quantitative index of the state of the ecosystem based on numerous variables, it was essential that we standardize all variable values to a common scale. A standardized scale allows merging the variables into a single index and also conducting direct comparisons between variables. We standardized the lake values of each variable by transforming the values to a ranking value (R) ranging between 10 and 100, where a value of 60 delineates between permissible ($R \geq 60$) and non-permissible values, whereas the lower the value (below 60) the further the ecosystem is from the desired sustainable state. A ranking value of 100 is considered optimal. Values of

$R = 60$ are equivalent to the 10th and 90th percentiles of the variable during the reference period (Fig. 1A). For lack of a better objective criteria, the median value of a variable during the reference period was set at $R = 100$ (Fig. 1B, C). Using linear piecewise approximation, we calculated the remaining ranking (R) values for the entire range of variable values down to $R = 10$ (Fig. 1C, D). Note that in most cases every rating value corresponds to two values of the variable in question (Fig. 1C).

Calculation of a combined sustainability index

The calculation of the Lake Kinneret Sustainability Index (KSI) was similar to the method used to calculate the Lake Kinneret CWQI (Parparov & Hambright, 2007). The index is a weighted average of the ranking values of all the variables included in the index. Each variable, i, is allocated a relative weight (A). The weight (A) is proportional to the deviation of the ranking of i (R_i) from the maximum

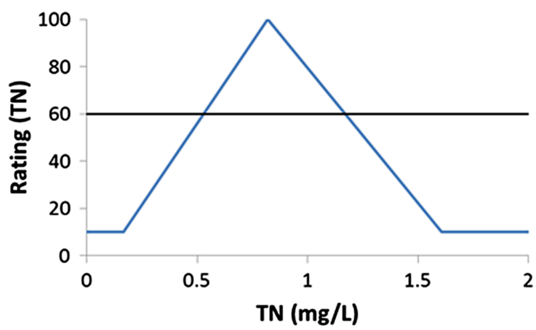
A



B

Variable	Total Nitrogen	
	Ranking	Concentration (mg L^{-1})
10th percentile	60	0.53
Median	100	0.82
90th percentile	60	1.17

C



D

R(TN)=10	If TN<0.17 or TN>1.61
R(TN)=137.93*TN-13.1	If 0.17<TN≤0.82
R(TN)=-114.26*TN+193.71	If 0.82<TN≤1.61

Fig. 1 An example of the process for calculating the ranking values for measured values of a variable included in the KSI: total nitrogen, TN, during winter–spring (Jan–Jun). **A** The long-term record of TN concentrations from Lake Kinneret, for Jan–Jun of each year, including the 10th and 90th percentiles calculated based on the reference period (*horizontal dashed lines*) only. The 10th and 90th lines represent the range of values deemed acceptable and thus $R \geq 60$. The median value for the period is defined to correspond to $R = 100$. The median and acceptable range of values are shown in table (**B**) and then plotted as rating values (R) as a function of the concentration of TN (**C**). Finally, the actual rating value, R, for a given concentration of TN is computed according to one of three possible equations (**D**)

ranking possible (R=100). The calculation is as follows:

$$A_i = 0.01 \ast (100 - R_i), \quad (1)$$

$$A = \sum_{1}^{i=n} A_i, \quad (2)$$

where A is the sum of weights applied to the index and n is the total number of variables

$$\mathrm{KSI} = \sum \frac{A_i}{A} \ast R_i. \quad (3)$$

The mean monthly rating values were used to calculate semi-annual averages for winter–spring (Jan–Jun) and summer–fall (Jul–Dec). Mean annual values were calculated as an average of the two seasonal values.

KSI ranges between a minimum score of 10 (poor sustainability) and a maximum of 100 (excellent sustainability). KSI values >60 are considered "acceptable."

Sensitivity analysis

The KSI values are an outcome of not only the state of the lake but also of the various decisions made while constructing the index. In order to evaluate the impact of the selected reference period, the range of percentiles, and the variables used, we conducted a sensitivity analysis (SA) of the KSI in which we varied those three definitions. For the reference period, we tested three different periods that included 1969–1980, 1969–1985, and 1969–1995. Two ranges of percentiles, in addition to the range used, were tested and included 5–95 and 20–80%. We further examined the sensitivity of the results to the variables by removing one variable at a time.

The SA was a one-by-one analysis in which we changed one of the three definitions each time. In total, there were 14 different options in addition to the calculated KSI. We compared all 14 results of the SA to the calculated KSI, for the period 1993–2012, in order to determine whether our decisions impacted the observed trends and overall values.

Application of the Lake Kinneret Sustainability Index (KSI)

As perturbations in the ecosystem have been linked to seasonal and inter-annual changes in lake level (Rachamim et al., 2010; Zohary & Ostrovsky, 2011; Gal et al., 2013), we examined the link between low KSI values and inter-annual changes in lake water level. Specifically, we calculated the net change in lake level between Novembers of each consecutive year. We selected November because lake level is at its annual minimum in November or December as it is prior to major rainfall and inflow events and following the long, hot dry summer. Additionally, we examined the linkage between low KSI values and past changes to lake levels with a lag of 1–2 years. The rationale behind this is the observed impact of large rapid changes in lake level on fish and zooplankton populations 1–2 years after the changes actually occurred (Ostrovsky & Walline, 2000; Gal & Anderson, 2010; Gal et al., 2013). We further examined whether a linkage exists between KSI values and nutrient loading. This was conducted as changes to nutrient loading is a driving force often identified as the major reason for changes in the ecosystem, especially phytoplankton populations.

Results

Ecosystem variables selection

The expert panel selected nine variables that represent the main biochemical cycles (total N, total P), chlorophyll, primary productivity, key primary producer populations (cyanobacteria, *Peridinium*), a representative of higher trophic levels (predatory zooplankton) and water clarity parameters (Secchi depth, total suspended solids; Table 1). The dinoflagellate *Peridinium gatunense* was the dominant species in the lake until 1995 often accounting for over 95% of the phytoplankton biomass in the lake and with regular and predictable spring blooms (Zohary, 2004). Cyanobacteria were a negligible to minor component of the phytoplankton through to the mid-1990s but have since become increasingly abundant (Zohary et al., 2014b). Justification to the choice of other parameters is given in Table 1.

Selection of the reference period

A reference period should be a sufficiently long period of time in which there were no obvious perturbations or large changes to the ecosystem, and for which there is a record of data. Analysis of the long-term dataset between 1969 and 2012 highlights a number of trends

Table 1 List of ecosystem variables selected for the Lake Kinneret Sustainability Index (KSI)

Ecosystem variables	Brief description of the ecological variables[a]
Secchi depth (*S*)	Due to simplicity and low cost, Secchi depth is used widely as an indicator of lake water quality. Together with TN, TP and chlorophyll *a* it is often used as a measure of lake trophic status
Total suspended solids (TSSs)	TSS is a measure of the concentration of suspended particulate matter in the water (biotic plus abiotic) and indicator of cycling of suspended matter
Total nitrogen (TN) Total phosphorus (TP)	TN and TP concentrations are indicative of the level of nutrient enrichment, and are the main parameters used for assessing the trophic status of aquatic systems
Chlorophyll *a* (Chl *a*) Primary production (PP)	Chlorophyll *a* and primary production are key ecosystem variables, being measures of the structure (biomass) and functioning (production) of the primary producers
Cyanobacteria biomass (Cyano)	Cyanobacteria have become an important component of the phytoplankton since the mid-1990s. Increased cyanobacterial blooms are characteristic of lake eutrophication. Cyanobacterial toxins are detrimental to drinking water quality and impact recreational use
Peridinium gatunense biomass (Perid)	The dinoflagellate *Peridinium gatunense* was the dominant phytoplankton species in the lake up until 1995 and its spring bloom was highly predictable. Changes in abundance of this dinoflagellate led to disruption of the food web and indicated ecosystem destabilization
Predatory zooplankton (Zoop)	Zooplankton represents food sources for the fish community and reflects the role of invertebrates in ecosystem functioning

A brief description of the importance of each variable is included. Terms in brackets indicate code used in the KSI

and significant changes that have occurred in the lake (Online Resource 1). Over the entire period, there was only limited variability in the inter-annual TSS and Secchi depth. The stability in TSS suggests that there is an equilibrium in cycling of suspended matter in the lake despite the observed changes to the phytoplankton species composition. And indeed, the most notable changes over time occurred to the phytoplankton community and chlorophyll concentration. The changes occurred mainly since the mid-1990s and included increased chlorophyll concentrations, increased biomass of cyanobacteria, and a decline in *Peridinium* biomass (Parparov et al., 2015). The changes in cyanobacteria and *Peridinium* concentrations were accompanied by a marked increase in inter-annual variability in phytoplankton biomass, most notable during the winter–spring season (Zohary et al., 2014b). Due to the above changes that occurred since the mid-1990s we selected the 1969–1992 as the reference period for the KSI. This is further supported by the overlap in the reference period used for the original Lake Kinneret CWQI, thus allowing a comparison between the two approaches.

Definition of the permissible ranges

Based on the selection of the 10th–90th percentiles as delimiters of the acceptable limits, we defined the permissible ranges for each variable (Table 2). In addition, using linear piecewise approximation, we outlined the equations transforming the observed data from the lake (e.g., concentrations) to rating values (Online Resources 2, 3). Based on the equations, we defined the entire range of observed values to correspond to rating values ranging between $R = 10$ and 100 and from $R = 100$ to 10 for both seasons (Fig. 2). In two cases the transformations and rating curves were modified to better match our understanding of the ecosystem. For cyanobacteria, the permissible lower limit was set to 0, thus indicating that an ecosystem without cyanobacteria is preferred by lake managers, though cyanobacteria did exist, albeit marginally, in the lake during the reference state. Though cyanobacteria are often naturally found in minimally impacted lakes, the presence of cyanobacteria in Lake Kinneret represents a clear indication of change in the ecosystem and the shift from the *Peridinium*-dominated ecosystem leading to a destabilization of the ecosystem (Parparov & Gal, 2016). For *Peridinium*, we used a different percentile to define the upper limit. In this case, we used the 99th percentile as the indicator of the upper acceptable limit, instead of the 90th percentile.

A consequence of using the 10th and 90th percentiles for the reference period as the limits of acceptable conditions ($R = 60$) was that during the reference period 10% of the values were higher than

Table 2 List of Kinneret Sustainability Index (KSI) variables, their median values during the reference period and permissible ranges for winter–spring (Jan–Jun) and summer–fall (Jul–Dec)

Ecosystem variables	Units	Winter–spring		Summer–fall	
		Median	Range	Median	Range
S	m	3.13	1.9–4.1	3.32	2.4–4.2
TSS	mg l^{-1}	3.75	2.1–7.7	2.50	1.5–3.8
TN	mg l^{-1}	0.80	0.5–1.1	0.52	0.3–0.8
TP	mg l^{-1}	0.02	0.02–0.03	0.02	0.01–0.02
Chl *a*	μg l^{-1}	16.40	7.7–37.6	7.20	4.9–10.4
PP	g C m^{-2} day^{-1}	1.93	0.8–3.0	1.38	0.7–2.1
Cyano	mg l^{-1}	0.04	0.0–0.2	0.11	0.0–0.7
Perid	mg l^{-1}	5.79	0.4–30.8	0.35	0.1–1.5
Zoop	Ind. l^{-1}	18.63	7.0–40.1	18.75	9.2–37.3

Abbreviations of variable names as in Table 1

the upper permissible limit and 10% were lower than the lower permissible limit. The changes to the ecosystem since the mid-1990s have led, however, to a larger than expected number of cases in which the limits were exceeded. Although the recorded values of post-reference period for most of the variables fall within the expected 20% exceedance of the limits ($R < 60$), three of the variables greatly exceeded the expected discrepancy: *Peridinium*, cyanobacteria and chlorophyll (Fig. 3). *Peridinium* was expected to exceed limits by only 11% as the upper limit was defined by the 99th percentile, while in reality some 55% of the cases *Peridinium* had rating values of $R < 60$, a factor of five more cases than expected. Cyanobacteria with an expected discrepancy of 10% had $R < 60$ in 43% of the cases. Chlorophyll had rating values below 60 in 37% of the cases instead of just 20%.

Calculation of the Lake Kinneret Sustainability Index (KSI)

Plots of the KSI calculated for the two semi-annual seasons and the merging into annual values clearly highlight the state of the lake ecosystem in relation to the desired conditions and emphasize the variables that are most problematic (Fig. 4). In the plots, the font size is dynamic and increases as the variable value decreases especially below 50. In addition, background colors have a traffic light ranking with green $R > 60$ (acceptable), yellow 50–60 (unacceptable), and red $R < 50$ (highly unacceptable). As an example, we calculated and plotted the rating values for the nine variables during the two semi-annual periods in 2012. The plots demonstrate the highly unacceptable rating values for several variables (in red) and the overall rating value observed during the two seasons in 2012 and for the entire year (the number at the center of each chart). During winter–spring, high cyanobacteria concentrations greatly exceeding upper acceptable limits resulted in an extremely low KSI rating value of 13. During the summer–fall, cyanobacteria, chlorophyll, and primary productivity, all exceeded upper permissible values for a period of 5 months (Jul–Nov 2012) resulting in rating values between 22 and 34. During the period Aug–Dec 2012, *Peridinium* had very low concentrations, below the lower acceptable concentrations, resulting in a very low rating value of 33. Four of the variables, TN, TP, TSS, and zooplankton exhibited high rating values for the entire year. The low rating values of the remaining variables resulted, however, in extremely low annual rating values for the various variables and for the overall KSI thus indicating the system was far from the conditions observed during the reference period.

We calculated the mean annual KSI values for the entire period of the study with emphasis on the post-reference period (1993–2012). During the reference period (1969–1992), annual KSI values were low (defined here as being below the acceptable threshold of $R = 60$) in six cases which equates to 25% of the total number of years (Fig. 5).

In an attempt to identify the possible ecosystem drivers leading to the very low (<50) rating values, we examined a possible linkage to nutrient loading and water level. We found no clear relationship between nutrient loading and declining rating values (not shown). There was, however, a clear linkage between water level and KSI values ≤ 50. Lake level is defined

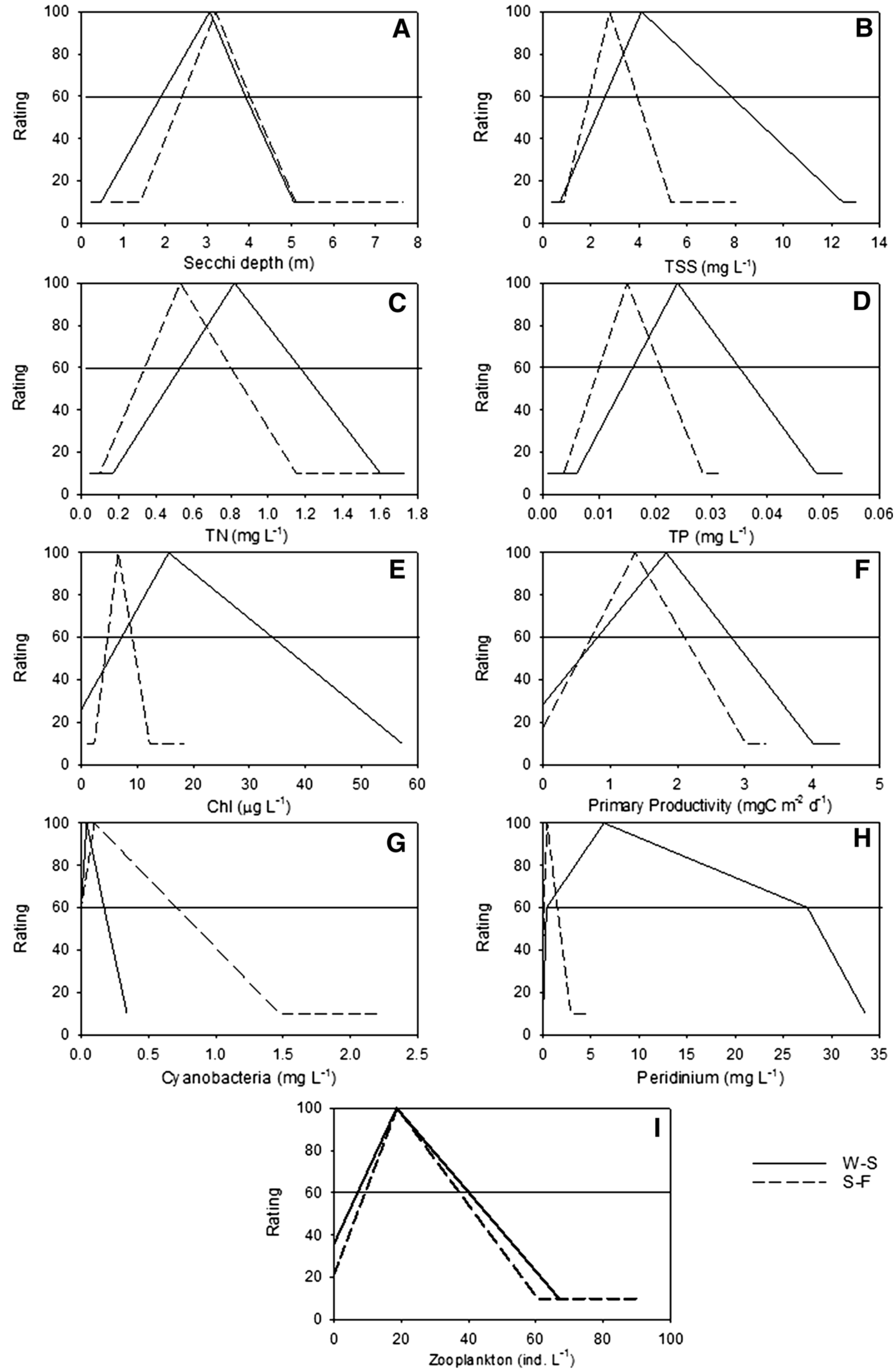


Fig. 2 Rating curves of the nine variables included in the KSI. There are two curves for each variable, representing the two seasons: winter–spring (W–S) and summer–fall (S–F). The curves represent the equations provided in Online Resources 2 and 3

by the balance between precipitation and inflows, on the one hand, and water extraction and evaporation, on the other. The major declines that occurred over the past two decades are a result of excessive extraction in relation to the relatively lower than normal inflow volumes in order to meet the country's needs. We

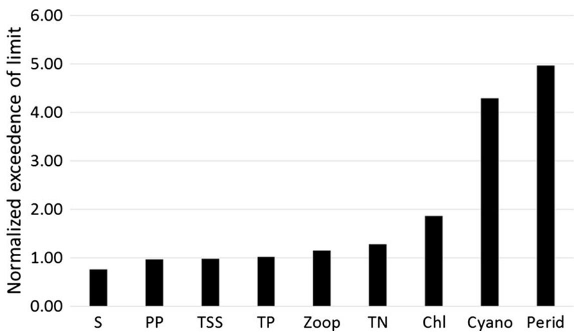


Fig. 3 The normalized exceedance of rating values (<60) for each of the index variables. The normalized value represents the percent of cases in which the rating values, for a given variable, were <60 in relation to the expected percent of cases. While for most variables, 20% of the cases are expected to be below 60 because of the use of the 10th–90th percentiles, cyanobacteria and *Peridinium* are expected to have a lower occurrence because of use of different ranges of percentiles, namely 0–90th and 10th–99th percentiles for cyanobacteria and *Peridinium*, respectively. A value of unity represents a match between the observed and expected number of cases with a rating value <60 while a value of 2, for example, indicates the occurrence of twice the number of expected cases

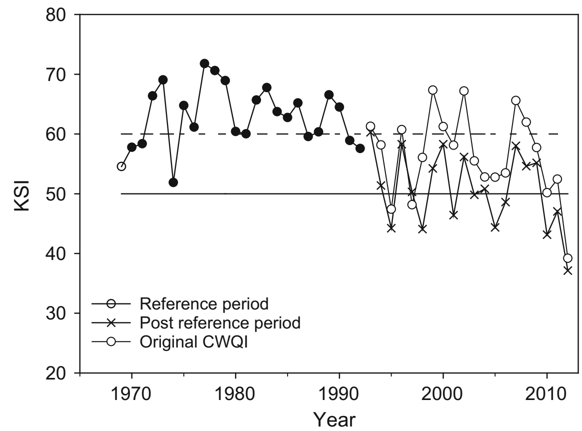


Fig. 5 The calculated annual mean KSI for the period 1969–2012. The values for the reference period and post-reference period are delineated. For sake of comparison, we have also included the Lake Kinneret CWQI values (Parparov et al., 2006) for the years following the reference period. *Dashed* and *solid horizontal lines* indicate KSI = 60 and 50, respectively

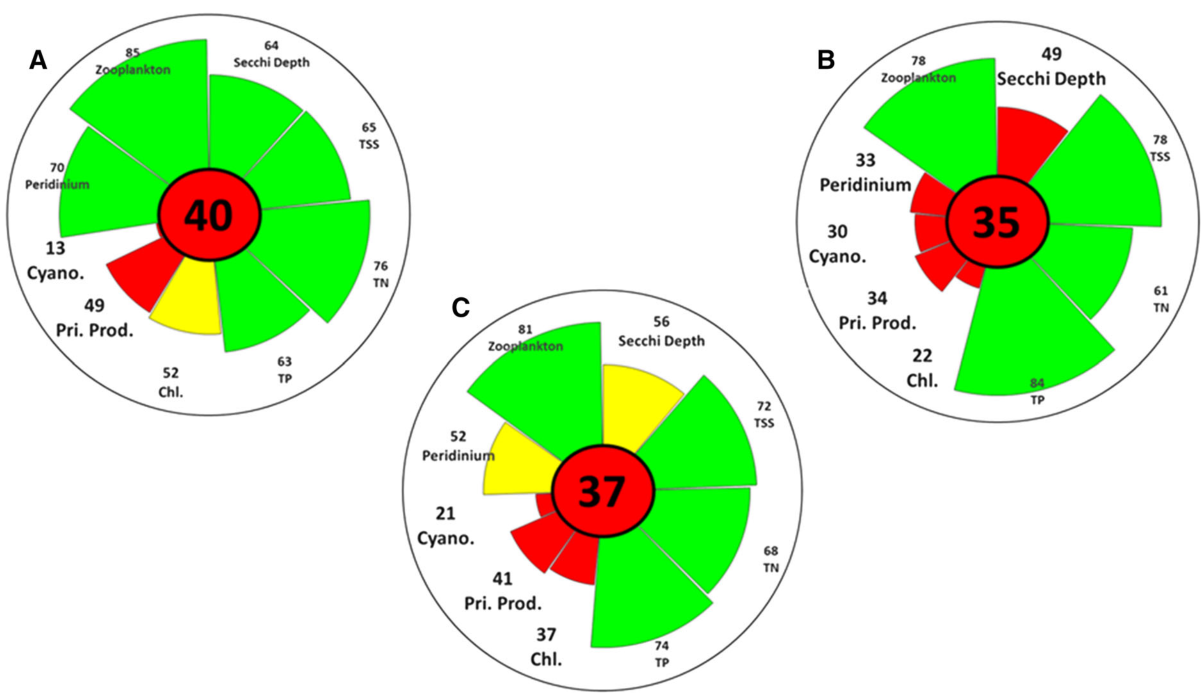


Fig. 4 Plots of the winter–spring (**A**), summer–fall (**B**) and annual (**C**) KSI values for 2012. The value in the *central circle* represents the overall semi-annual (**A**, **B**) or annual (**C**) KSI value where the surrounding *polygons* represent the rating for each of the nine variables consisting of the KSI. *Polygon* size is correlated to the ranking value. *Colors* are coded according to ranking value: *green* $R > 60$, *yellow* $60 \geq R \geq 50$, *red* $R < 50$

examined the net change in water level between November of consecutive years and with a 1 and 2 year lag in relation to the years with very low rating values. In seven of the eight cases, we found a recurring pattern of either large net changes in water level (>0.9 m) or two consecutive years of a net decline in water level within the 2-year lag (Fig. 6). There were two cases (1994, 2008) in which declines in water level exceeded 0.9 m but did not result in KSI <50 as expected (they were 51 and 55, respectively).

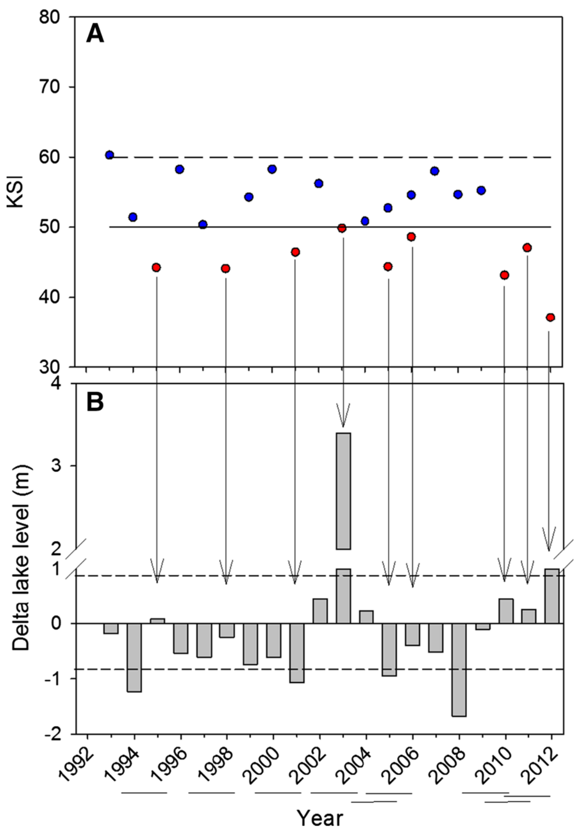


Fig. 6 Plot of **A** KSI and **B** the net annual change in lake level, for the post-reference period, 1993–2012. The KSI values represent annual values where the *dashed* and *solid horizontal lines* indicate KSI = 60 and 50, respectively. The annual change in water level was calculated based on the difference in water level between November of a given year and the level in November of the previous year. In the *lower panel* (**B**), *dashed horizontal lines* represent a net water level increase, or decrease, of 0.9 m (see text for explanation). In order to identify a relationship between KSI values ≤50 and changes in lake level we indicate the possible 2-year lag period between the change in lake level and observed KSI values of 50 or less. The relevant periods are indicated by the *horizontal lines* below the *X axis*. *Blue symbols* represent years with KSI values >50 and *red symbols* years with KSI values ≤50

We inspected the monthly rating values of the nine KSI variables during all semi-annual periods with values of KSI ≤50. Of the total 40 semi-annual periods between 1993 and 2012, 13 of them had KSI values of 50 or lower, 10 of which occurred since 2001. In addition, three of the five winter–spring periods with KSI ≤50 occurred during the years 2010–2012. During the summer–fall season there were a total of eight semi-annual periods in which the KSI values were below 50, five of which occurred during the eight year period between 2005 and 2012. Of the nine variables included in the KSI, three demonstrated a high occurrence of very low ($R < 50$) rating values (Fig. 7). During the period 1993–2012, cyanobacteria had a rating value ≤50 in 87% and 42% of the months in which the total KSI was ≤50, during W–S and S–F periods, respectively. Chlorophyll and *Peridinium* had rating values ≤50 in 67% and 60% of the months during the summer–fall periods, respectively.

Sensitivity analysis

We conducted a SA of key characteristics of the KSI calculations in order to evaluate the impact of our definitions of those characteristics on the KSI rating values. Specifically, we evaluated the impact of the period selected as the reference period, the range of percentiles used to determine the rating value of 60 for each variable, and the actual variables uses. The removal of each of the variables and recalculation of the KSI each time resulted in changes to the KSI value in relation to the base calculation (without changes). The differences were, however, small and they did not alter the observed trends and dynamics in the long-term annual KSI values (Fig. 8A). Removal of chlorophyll or cyanobacteria had the largest impact and led to an average improvement in the rating values by 8–9%, respectively, for the post-reference period. The KSI rating values increased without the cyanobacteria variable by up to 20% and up to 19% when chlorophyll was removed. This is not surprising given the high occurrence of low cyanobacteria index values during the periods in which the annual KSI values were low (Fig. 7). The maximum increase in rating values without cyanobacteria occurred during 2010, while without chlorophyll occurred during 2005. In both cases, this was due to the excessive concentrations during the winter–spring months of those years. Removing one of the remaining individual variables

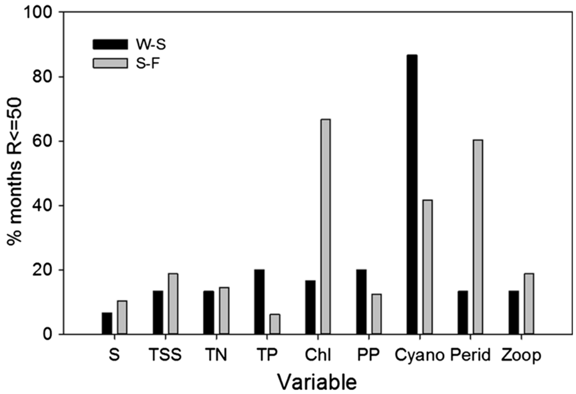


Fig. 7 The proportion (%) of cases during the post-reference period in which KSI variables had a rating value ≤50 out of the number of months in which the total KSI was ≤50. There were five winter–spring periods (a total of 30 months), and eight summer–fall periods (a total of 48 months) in which the total KSI was ≤50

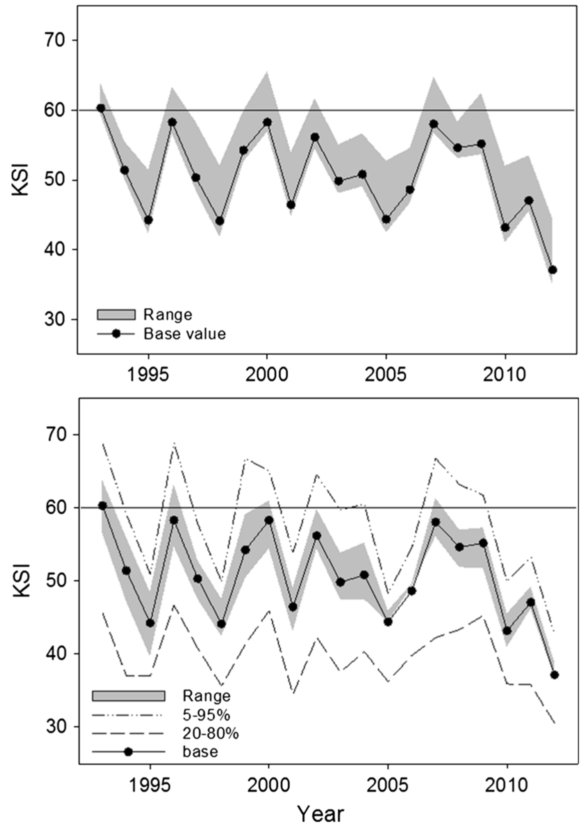


Fig. 8 KSI values for the period 1993–2012 based on the SA results. **A** The range of results, in *gray*, for each iteration in which one of the nine variables was removed. **B** The range of results, in *gray*, calculated based on the three different reference periods using the 10–90 percentiles and the results for two additional ranges of percentiles and the base reference period. In both *panels*, the base KSI is indicated by a *solid line* and the KSI = 60 threshold by the *horizontal line*

each time resulted in small differences with average differences of only 1–2%.

Selecting a different reference period for the KSI would have had little effect on the results of the KSI (Fig. 8B). Use of a different reference period would have resulted in only minor changes to the KSI values and no change in the long-term dynamics. As the reference period, we used, was identical to the period used for the original Lake Kinneret CWQI, the small differences reinforce our decision to use the same period.

Use of different ranges of percentiles to determine the values at which $R = 60$ had an impact on the KSI. Use of a wider range (5–95 percentile) resulted, as expected, in higher KSI values. This was because the 5–95 percentile range encompassed a wider range of extreme values observed during the reference period, thus broadening the range of values corresponding to $R \geq 60$. Nevertheless, the resulting trends and dynamics in the KSI, such as the drastic decrease in KSI rating values since 2007, were a near mirror image of the base KSI values. The use of the narrower range of percentiles (20–80) led to lower KSI values and moderately less inter-annual variability.

Discussion

The KSI was developed as part of the natural process of updating and modifying an existing index based on experience and new needs. The CWQI, developed for the lake during the late 1990s, suffered from several shortcomings but mainly from the fact that it included both drinking water quality variables and ecological variables and did not entirely address either of the two objectives defined by the Israel Water Authority (Hambright et al., 2000; Parparov & Hambright, 2007). The variables used in the KSI are variables that are collected routinely in lake monitoring programs and are often used to describe water quality or the state of the ecosystem in lakes. Their use in the KSI allows the managers, scientists, and the public to evaluate the state of the lake in relation to conditions that existed during the reference period and represent the ecosystem the managers wish to sustain over time.

The use of an index, such as the KSI, allows decision makers, mangers, and other stakeholders to both identify long-term trends and to evaluate the possible relationship between low index values and changes in lake level, nutrient loading, and other possible drivers. The KSI displayed a long-term trend of decline since the mid-1990s. During the post-reference period 1993–2012, a total of 20 years, only in one case was the KSI value *above* the threshold value of 60. Over the course of that 20-year period, a total of eight years (40%) had very low rating values (defined as KSI <50) of those, seven occurred since 2001. The increase in the number of low and very low rating values since the mid-1990s and especially during the current millennium clearly indicates a dramatic shift in the Lake Kinneret ecosystem sustainability since the mid-1990s. This is consistent with previous reports from the lake that identified significant changes in the lake ecosystem, especially at the lower trophic levels, including a shift from a stable *Peridinium*-dominated system to an unstable cyanobacteria-dominated system and large fluctuations in the zooplankton populations (Zohary, 2004; Roelke et al., 2007; Zohary et al., 2012). The changes have been identified as a shift between alternative states and a regime shift (Roelke et al., 2007; Gal & Anderson, 2010; Zohary et al., 2012). Parparov and colleagues (Parparov et al., 2015; Parparov & Gal, 2016) proposed an approach to quantifying stability of various ecological units in a lake ecosystem using Lake Kinneret as a case example. They show the decrease in stability in the lake over time especially since the early-mid 1990s.

Shifting from one index to another requires comparing the results of the two indices and ensuring that the patterns they highlight do not differ greatly. Calculating the original CWQI for the same period (Fig. 5) resulted in the same pattern of increase and decline of the KSI values with a small number of exceptions. The CWQI values, however, are consistently higher than the KSI values. It is interesting to note that the differences between the KSI and CWQI values are in some cases small (e.g., 1995 and 2012), while in other years the differences are large (e.g., 1999). These patterns stem from the variable, or variables, driving the index values in a specific year. In 1995 and 2012, the KSI values were very low in both cases and driven by multiple variables over the course of the year. Most of the variables with the low values overlap with the variables used to calculate the CWQI, and thus, the similarity in values is expected. However, dissimilarities are a result of differences in variables and also a consequence of the differences in sensitivities to the various variables stem from the approach used to calculate rating equations. For example, the relatively large differences in 1999 stem from differences in the number of variables and the number cases, for each variable, in which the calculated index values were very low. Based on the CWQI calculations only cyanobacteria and *Peridinium* exhibited extremely low index values (<20) over the course of 1999, each on a single occasion. Whereas based on the KSI calculations, the same two variables had extremely low rating values three and two times each, respectively. In addition, two additional variables had extremely low rating values (chlorophyll and zooplankton).

We used the index to examine possible drivers affecting the ecosystem and associated with the low KSI values as an indication of the use of KSI as a management tool. Results indicated that there was no link between nitrogen and phosphorus loading and KSI values. There was however a relationship to changes in lake level (Fig. 6). While the sample size is too small to claim statistical significance, there is a clear pattern that needs to be considered by lake managers when debating management actions that may impact water level. The observed linkage between water level fluctuations and low KSI values is not surprising. Studies from Lake Kinneret have addressed the impact of water level fluctuations on the ecosystem. These fluctuations impact abiotic factors, such as increased levels of resuspension, suspended matter, and mineralization rates (Nishri et al., 1996; Håkanson et al., 2000). They also affect biotic processes, such as changes in suitable substrate for fish eggs and nesting, modification of the littoral zone, and fish–zooplankton trophic interactions (Gafny et al., 1992; Ostrovsky & Walline, 2000; Parparov & Hambright, 2007; Gal et al., 2009, 2013; Makler-Pick et al., 2011; Zohary & Ostrovsky, 2011; Parparov & Gal, 2012). Increasingly, studies are demonstrating the impact of water level fluctuations on various aspects of ecosystems processes in lakes around the world (Hofmann et al., 2008; Elliott & Defew, 2012; McLaughlin & Cohen, 2013; Mims & Olden, 2013; Callieri et al., 2014). There are, however, only a limited number of cases in which attempts have been made to determine, test, or suggest water level-specific management strategies (e.g., Gilboa et al., 2014; Yang et al., 2014; Jeppesen et al., 2015). Tools such as the KSI represent a means for determining the impact of water level management on an ecosystem based on historical data or coupled to a lake ecosystem model.

The results highlight the impact of cyanobacteria on KSI values and especially as a main factor in the observed low index values. Cyanobacteria had the highest occurrence of extreme low values ($R < 50$) and in nearly 90% of the months in which the KSI <50, cyanobacteria was also <50. Low cyanobacteria results were often echoed by low chlorophyll and *Peridinium* index values. All other variables had rating values <50 during less than 20% of the time. Secchi depth had the lowest frequency of very low rating values, occurring during only 7 and 10% of the months that had very low rating values, during winter–spring and summer–fall periods, respectively. The rare occurrence of very low KSI values of Secchi depth indicates stable Secchi depth values over the entire period despite the large variations observed in the phytoplankton community.

Construction of the KSI required incorporating available knowledge of the ecosystem in question. An example of this is the use of different percentile ranges for two of the variables, namely *Peridinium* and cyanobacteria. In relation to *Peridinium*, the rationale was the large *Peridinium* blooms that occurred after the end of the reference period (for more information the reader is referred to Parparov et al., 2015). The reason for these large blooms is still unclear and seem unrelated to changes in nutrient loadings. While these very large blooms serve as an indication of a change, our understanding is that Lake Kinneret with a *Peridinium* bloom, even if very large, is ecologically similar to the Lake Kinneret of the reference period, so it is a feature that should be preserved. Using a 90th percentile for *Peridinium* would result in a large number of years designated with R values <60, whereas our perception is that those years should result in high R scores. Similarity, for cyanobacteria, it was thought that an ecosystem without cyanobacteria is closer in characteristics and dynamics to the ecosystem that existed during the reference period, and thus, the lower limit should be 0 and not the 10th percentile.

Results of the SA in which we repeatedly calculated the KSI, each time without one of the variables, demonstrated the relative insensitivity to most variables, although it is more susceptible to cyanobacterial and chlorophyll *a* as a result of their annual and inter-annual dynamics. Use of other possible reference periods also did not impact the overall KSI values and trends.

One of the main benefits of an index, such as the KSI, is the expansion of the tools available to resource managers and decision makers. The use of the KSI, for example, allows mangers not only to determine the linkage between observed trends and driving factors, e.g., changes in water level, but also to hypothesize what management steps should be taken given the observed trends in index values and the reasons for those values. Furthermore, it allows testing of management strategies in combination with ecosystem models, such as demonstrated with the CWQI (Gilboa et al., 2014).

The approach upon which the KSI developed maintains the need for an index that should represent the key ecological processes and key elements of the ecological system. Furthermore, its components should include representative of the main biochemical cycles, primary producer and consumer populations, and key energy fluxes into the system. In addition, the index is not an absolute index but rather provides an indication of the state of the ecosystem in relation to some predefined, desired conditions. An alternative approach is the construction of an index based on absolute scales such as the trophic state of the lake (Carlson, 1977), or the biomass and structure of a specific taxonomic group of which phytoplankton is the most common (Padisak et al., 2006; Lugoli et al., 2012; Katsiapi et al., 2016). While there are pros and cons to both approaches, ultimately the approach used will depend on the objectives for developing the index and the availability of data.

The construction of the KSI was possible due to an available extensive database that relies on the long-term monitoring program that was initiated in 1969 (Sukenik et al., 2014). However, many lakes lack the existence of a long-term database, thus limiting the possibility of constructing an index based on historical data. Furthermore, the effectiveness of an index such as the KSI is based on relative and not absolute conditions. Thus, construction of an index similar to the KSI can be achieved, even when an extensive database is lacking, by adopting an approach similar to that used to determine “Good Ecological Status” by the EU Water Framework Directive (2000). According to this approach, the reference condition is defined as a system with only "a slight departure from the biological community which would be expected in conditions of minimal anthropogenic impact" (http://ec.europa.eu/environment/water/water-framework/info/intro_en.htm, accessed 12 February 2017). Defining a relatively pristine lake ecosystem is a non-trivial task that can be accomplished when information is available on lakes from the region and with similar characteristics. Under such conditions, it is likely that the index will require revisions over time; however, the process itself of selecting the variables, and their ranges, for the index is a valuable process as is testing it over time. It is likely that for most lake ecosystems, there will be several common variables and possibly a number of variables that will be selected based on the unique issues for the ecosystem in question.

Conclusions

The development of the KSI was a progression from the initial WQI developed for Lake Kinneret and a natural process following the progress in the concepts and tools used to manage the lake. We have included key core principles required for developing an indicator of sustainability (Liverman et al., 1988; Braat, 1991). Specifically, an index should include indicators that are representative of the system in question, scientifically based, and quantifiable. Furthermore, it should include reference values and be presented visually in a clear and concise fashion. The KSI provides lake managers and other stakeholders with a clear and quantitative picture of the state of the ecosystem in relation to a reference period defined as ecosystem characteristics and traits that should be sustained. The index provides an assessment at the semi-annual, annual and, multi-annual resolution in a clear graphical form. The selected graphical form addresses the need to convey information at various levels of complexity starting from the simplest (i.e., one number and color-coded) through to scaling of multiple variables. Although the reference ranges and variables used to construct the KSI are lake-specific, the approach we present is generic and can be applied to other lakes.

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