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Indices of water quality for sustainable management and conservation of an arid region lake, Lake Kinneret (Sea of Galilee), Israel

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ABSTRACT

1. Economic development in arid regions is closely linked to efficient use of limited water resources. As such, management and conservation of these water resources requires concurrent optimization of the interrelationships between supply quantity and resource quality.
2. Multiple uses of water resources generate conflicting needs within management, with different uses requiring objective characterization of quality for different management scenarios and goals.
3. A sound management programme needs close interactions between water policy makers, managers, users, engineers and limnologists, and thus needs a common language that can transcend the boundaries of the individual fields.
4. This paper describes a system of water quality indices and standards designed for conservation and sustainable management of Lake Kinneret (Sea of Galilee), Israel, based on observed variability in various chemical and biological parameters during a 25-year period (1969–1992). Such a system can form a common language which can then be used as a tool for optimal management.
5. This system of water quality indices (a) includes both traditional limnological parameters (plant nutrients, chlorophyll, primary production) and engineering parameters (coliform bacteria, turbidity), (b) is acceptable to all parties involved in lake management, and (c) is easily adaptable to different management scenarios and to management-induced changes in ecosystem functioning.
6. Analysis of variability in these water quality parameters in Lake Kinneret during 1994–1999 when the lake was showing signs of destabilization highlights the usefulness and limitations of this system.

KEY WORDS: expert panel; Lake Kinneret; sustainable management; water quality

INTRODUCTION

The need for proper management and conservation of natural aquatic ecosystems has long been recognized, especially in cases where the ecosystem serves as a source of fresh water (e.g. see Cooke *et al*., 1993). A specific problem emerges with respect to lakes in arid regions, where water resources are principal limiting factors for economic development. Here, domestic and agricultural consumption

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generally predominate over other water uses and water managers usually increase supply by increasing the 'turnover rate' of the supply source. In practice, the water turnover rate of a lake is increased (residence time is reduced) by boosting outflows to augment consumption needs. Because inflows to these lakes are restrained by climatological conditions and cannot be simultaneously increased, enhanced outflows generally lead to greater seasonal and annual fluctuations in lake water levels and long-term reductions in mean lake water levels. Associated with these lake morphological changes is the potential subsequent deterioration of water quality supplied, together with associated changes in ecosystem flora and fauna (Micklin, 1988; Parparov, 1990; Aladin and Williams, 1993). Kira (1993) suggests that changes in lake morphometry caused by excessive water discharge are among the most important factors leading to cultural eutrophication. Hence the possibility of an inverse relationship between the quantity of water supplied from a given resource (e.g. a lake) and the quality of water in that resource suggests the need for well-defined management directed toward optimizing water use in arid regions. This requires both quantity and quality of water (i.e. use and conservation of a water resource) to be maximized concurrently (Hillel, 1994).

The meaning of management, as well as its objectives, differs widely depending on the type and use of the resource and on the point of view of the managers (Cooke *et al.*, 1993; Straskraba *et al.*, 1993). Statements about the necessity of 'optimal', 'rational' or 'sustainable' use of water resources frequently offer no definition of these terms. Moreover, 'water quality', the primary concept of interest by which management success is often judged, is typically poorly defined (Boon and Howell, 1997b). Because a sound lake management programme requires close interactions between water policy-makers, managers, users, engineers and limnologists, a common language that can transcend the boundaries of the individual fields is needed. It is proposed that a system of water quality indices form that common language that can then be used as a tool for optimal management.

The concept of a water quality index has existed for many years (e.g. Horton, 1965; Inhaber, 1975). However, within the last two decades there has been a surge in the development and application of water quality indices worldwide both for specific water resources (e.g. Chesapeake Bay, USA: Hennessey, 1994; Lake Sapanca, Turkey: Baykal *et al.*, 1996) and for regional water resources (e.g. Louisiana, USA: Burden *et al.*, 1985; South Africa: O'Keeffe *et al.*, 1987; Mexico: Jimenez-Cisneros, 1996; Scotland: Boon *et al.*, 1997; Ukraine: Romanenko *et al.*, 1999; Dalmatian County, Croatia: Stambuk-Giljanovic, 1999). The primary objectives of such projects are water quality assessment and specification of permissible ranges for various water quality parameters that express important relationships and are comprehensible without professional knowledge (Håkanson and Peters, 1995). A variety of approaches have been developed, leading to various systems of water quality based on normalization to existing water quality standards (Melloul and Collin, 1998; Stambuk-Giljanovic, 1999), common hydroecological considerations (Schindler, 1987; Cairns *et al.*, 1993) or existing systems of trophic classification (OECD, 1982). A common feature of these efforts is a direct or indirect admission that neither the system of water quality indices nor their permissible ranges can be derived from strict scientific considerations. Rather, this information should be formulated with the assistance of a panel of water quality experts (though often a single individual is used). Here, the authors have chosen to use the DELPHI method as described by Brown *et al.* (1970) and Smith (1987, 1990).

Lake Kinneret (Sea of Galilee), Israel, has served as the principal storage and supply reservoir for Israel's National Water Carrier since 1964. In addition, the lake also serves important recreational and commercial interests. Although long-term monitoring (1969 to present) has revealed occasional events that may have had immediate and short-term negative impacts on water quality, no serious deviations from 'natural' background variability adversely affecting long-term water quality occurred prior to 1994 (Berman *et al.*, 1992, 1995). Since 1994, however, changes in various biological parameters (e.g. increased occurrence and abundances of cyanobacteria: Berman *et al.*, 1998; Pollingher *et al.*, 1998) have revived both public and scientific awareness that water quality problems in Lake Kinneret could arise.

To date, water quality in Lake Kinneret has been defined subjectively according to various limnological, hydrological and engineering paradigms (e.g. Serruya *et al*., 1969, 1979; Berman, 1972; Shamir *et al*., 1985; Assouline, 1993), but growing demand and a changing regional political atmosphere dictate the need for precise definitions (Parparov and Hambright, 1996a). An effective water resource management programme based on precise and formal definitions of management criteria and water quality was proposed for Lake Kinneret (Parparov and Hambright, 1996b). Key elements of this programme would include (1) identification and prioritization of different lake uses, (2) definitions of management goals and criteria, (3) definitions of indices and standards of water quality, (4) constant evaluation and adjustment of the management programme, (5) mathematical modelling as a self-organizing tool, especially with regards to designing limnological investigations directed toward lake management, and (6) a quantifiable economic analysis.

This paper describes a system of water quality indices for Lake Kinneret based on observed variability in various chemical and biological parameters during a 25-year period (1969–1992). The usefulness and limitations of this system are demonstrated by analysing unusual variability in the same parameters during 1994–1999 when the lake was showing signs of destabilization.

General description of Lake Kinneret

Lake Kinneret (the largest freshwater body in the Middle East) is a warm-monomictic lake located at about −210 m altitude (i.e. below mean sea level) in the northern part of the Dead Sea Rift Valley (part of the Afro-Syrian Rift Series). The limnology of the lake is well documented (Serruya, 1978). The lake is 22 km long and 12 km at maximum width; maximum and mean depths are 42 and 24 m, respectively, and the surface area is 170 km^2. The lake is amictic during most of summer and autumn, with surface temperatures approaching 30°C (Hambright *et al*., 1994). The hypolimnion is anoxic. The main inflow (60–70% of the total) is from the Jordan River, while the main outflow is Israel's National Water Carrier, supplying *ca* one-third of the country's freshwater needs. The water level of the lake depends on climatic inputs and withdrawal for water supply (Serruya, 1978).

Lake Kinneret is meso-eutrophic with a mean annual primary production of 650 g C m^{-2} (Berman *et al*., 1995). Secchi depths vary from 0.7 to 5.5 m and turbidity from 0.7 to 22 NTU (nephelometric turbidity units) (A. Parparov, unpublished). A prominent biological feature of the lake has been the spring bloom of the dinoflagellate *Peridinium gatunense* (Pollingher, 1978; Berman *et al*., 1992), though since 1994, the lake has exhibited uncharacteristic developments in the phytoplankton assemblage (Berman *et al*., 1998), including the first-ever bloom of potentially toxic, N_2-fixing cyanobacteria (Pollingher *et al*., 1998). Further detail on the basic ecology of Lake Kinneret can be found in Serruya (1978) and Hart *et al*. (2000).

Lake Kinneret plays a unique socio-economic role in Israel. It supplies nearly 50% of all drinking water in the country (Eckstein *et al*., 1994; Berman, 1998), serves as a vacation and recreation centre for hundreds of thousands of visitors annually, and generates nearly US$5 million annually in the form of commercial fish harvests (Ben-Tuvia *et al*., 1992). Perhaps more importantly, though more difficult to quantify, the conservation of Lake Kinneret for future generations is a matter of national prestige. Furthermore, in view of the developing Middle East Peace Process, there is no doubt that in the future there will be more importance paid to Lake Kinneret as a regional water supply source.

Use and management of Lake Kinneret

Several aspects of use and management of Lake Kinneret water have been previously discussed (Rodhe, 1969; Berman, 1972, 1985; Serruya, 1985; Shamir *et al*., 1985). The primary use of the lake's watershed is agriculture, including pond-based aquaculture although tourism and recreation are increasingly important. Present management aims for Lake Kinneret are directed at prevention of water quality deterioration. There are four foci of management that have direct impacts on lake water quality — water level fluctuations, salinity reduction, catchment basin development and fisheries regulation.

Water levels

Since the construction of a regulatory dam in 1932 at the lake's southern outflow, water levels have been manipulated to regulate the discharge volume. Throughout the period of British Mandate in Palestine and until 1986 water levels in the lake were maintained within arbitrary, but legislated limits. The maximum level was set at -208.9 m altitude and the minimum at -212 m. In 1986, following several years of successive drought, the lower limit was changed to -213 m to increase the lake's storage potential. Increasing demand and recent years of drought resulted in a lowering of the lake level a further 30 cm in summer 1999 to -213.3 m.

Salinity

Prior to 1964, the lake waters were characterized by relatively high salinities (up to 400 mg chloride litre^{-1}) caused by the inflows from several groups of thermo-mineral springs and seepage rich in sodium and chloride around the shores and on the lake bottom. The high salinity was problematic, resulting in damage to irrigated crops and salinization of soils and underground aquifers (Hillel, 1994). The situation was improved by the construction of a salt water channel which diverts some major saline springs at the north-west coast of the lake and removes about 70000 t of chloride annually. Consequently the chloride content fell from 370 mg litre^{-1} in 1965–1966 to 204–221 mg litre^{-1} in 1980–1985 (Smith *et al.*, 1989). Nevertheless, because the present chloride concentrations are close to the upper permissible limit for drinking water and because of the continuing problem of soil and underground aquifer salinization further reduction of lake water salinity is desirable (Waldman and Shevah, 1984; Serruya, 1985). Estimations are that a further twofold reduction of salinity is possible, though the ecological consequences of salinity changes in the lake remain a critical issue.

Catchment basin

In the late 1950s, a large natural wetland (Lake Hula) in the northern catchment of Lake Kinneret was drained in order to eradicate malaria, increase arable farmland and reduce evaporative losses of fresh water. Though this endeavour increased the national water budget by 28×10^6 m^3 year^{-1}, the agricultural benefits were less extensive than planned, and ecological and environmental problems appeared in large areas of the drained wetland. These included rapid soil deterioration by decomposition, wind and water erosion, soil subsidence and nitrate build-up, uncontrollable underground fires, dust storms, increased nitrate loading downstream to Lake Kinneret, and the loss of species (119 locally, 37 nationally, see Dimentman *et al.*, 1992; Zohary and Hambright, 1999). To remedy this situation, a rehabilitation project (the Hula Project) was initiated in 1994, creating *ca* 90 km of regulatory channels and a small, shallow lake (Lake Agmon) which now serves as the focus for developing eco-tourism, as well as for storage and reuse of agricultural waste waters (Hambright, 1998; Hambright and Zohary, 1999). Because most of the inflowing water to Lake Kinneret travels through the Hula Valley, this region is a major source of nutrient and other pollutant loads.

Fisheries

Conflicts between fisheries management and water supply management are well-known (e.g. see Wagner and Ogelsby, 1984). Fisheries managers strive for highly productive 'green' waters while water supply managers aim for unproductive 'clear' waters. There are 28 species of fish in Lake Kinneret, 15 of which are exploited commercially. Formal fishery regulations exist mainly for maximization of yield, though water quality concerns (via cascading food web effects) have been considered (Gophen *et al*., 1983). Nevertheless, enforcement is underfunded and generally ineffective and there is constant pressure from commercial fishermen to enhance stocks through supplemental stocking of native and exotic species. Overharvest led to the complete collapse of the Kinneret bleak fishery in 1993 (Hambright and Shapiro, 1997), which has still not recovered (J. Shapiro, Israel Fisheries Department, personal communication). Fisheries management is a major forcing function in lake trophic dynamics, thus affecting water quality. As Israel increasingly relies on Lake Kinneret as its source for high quality fresh water, there will be a need to re-evaluate the role of commercial fisheries in the lake.

METHODS

Definition of water quality indices

Our approach to designing a system of water quality indices is based on the expert panel method, whereby a group of experts representing all phases of lake management are asked independently to express their opinions regarding various water quality-related issues. This approach has been widely used in developing water resource management programmes in other countries, including New Zealand, Great Britain, South Africa, and the USA (Burden *et al*., 1985; Fusilier, 1985; House and Ellis, 1987; O'Keeffe *et al*., 1987; Smith, 1987, 1990; Boon *et al*., 1997). Here the results as derived from an expert panel consisting of scientists and engineers from the Kinneret Limnological Laboratory and the Mekorot Water Company will be presented. The panel was asked their opinions about several issues pertaining to Lake Kinneret and its watershed.

The object of management (*sensu* Parparov and Hambright, 1996b) was defined as Lake Kinneret and its watershed. Although there are many uses for Lake Kinneret water (see above), the panel was asked to limit their considerations to only one primary use — conservation of the natural ecosystem (for a discussion on conservation as a resource 'use', see Boon and Howell, 1997a). The rationale for this limitation was based on the consideration that historically, lake water quality has been acceptable for all uses, especially for drinking water supply. Thus, it was assumed that the water resources of Lake Kinneret would be managed in order to maintain water quality within the range of the current steady state, which was defined based on variability recorded during the period 1969–1992. Adoption of this management scenario requires realization of long-term policies to conserve the present lake ecosystem and to prevent deterioration of the lake's water quality.

The panel was asked to select appropriate parameters that in their opinion could be used as indices of water quality. Rating curves were built according to the descriptors shown in Table 1. To assist the panel in choosing parameters and determining appropriate ratings for the chosen uses, frequency distributions, means and standard deviations of all routinely monitored physical, chemical and biological parameters in

Table 1. Descriptors for the range of rating values (R) (modified from Smith, 1990)

$100 > R \geq 80$	Excellent: eminently usable for all purposes
$80 > R \geq 60$	Good: suitable for all uses
$60 > R \geq 40$	Intermediate: main use and/or some uses may be jeopardized[a]
$40 > R \geq 20$	Bad: unsuitable for main and/or several uses[b]
$20 > R \geq 0$	Very bad: totally unsuitable for main and/or many uses

[a] For example, high turbidity during the *Peridinium* bloom period requires treatment by sedimentation or filtration before water is suitable for human consumption.
[b] For example, dissolved oxygen below 1 mg litre^{-1} is unsuitable for human consumption, but suitable for irrigation.

Lake Kinneret during the period 1969–1992 were provided from the Kinneret Limnological Laboratory database. The panel was asked to choose a set of parameters (10 or fewer, to reduce complexity of analyses and to facilitate application of a mathematical model in future) most indicative of lake water quality from the data set provided. The panel then constructed rating curves according to Table 1 for each parameter, spanning the entire range of values observed in the lake. They were instructed to restrict the 'acceptable ranges' for the separate water quality indices within a range of 60–100, (i.e. the ratings must indicate good–excellent in order to be acceptable). All panel responses regarding ratings for various levels of each parameter were then averaged for each index and integrative rating curves were formulated.

To demonstrate the usefulness of this approach, water quality was then examined in the lake for the period 1994–1999.

RESULTS

The final panel responses regarding choice of parameters to be used in the indexing system were tallied yielding 10 parameters (Table 2). The panel unanimously agreed that the acceptable ranges for toxic substances (e.g. heavy metals, pesticides, herbicides, etc.) should correspond to established standards for drinking water. Hence these parameters are not considered further in the present demonstration. Moreover, the panel stressed that their list of 10 parameters be considered tentative, as future studies may require changes in the parameter list.

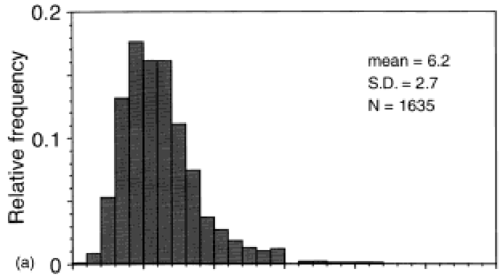
Given the prescribed primary use (conservation), the average rating curves corresponded closely with the observed frequency distributions for each parameter (Figure 1). Because of the drastic seasonal differences in many parameters in Lake Kinneret, the final water quality index system is sub-divided into winter–spring and summer–autumn periods (Table 3, Figure 2). The use of rating values as opposed to absolute values for each parameter allows easy comparison across seasons (Figure 3).

It is evident from these figures that changes in lake water quality have been quite drastic since 1994. There were two notable periods of unacceptable water quality in Lake Kinneret when the variability in water quality parameters fell outside the acceptable ranges — (1) 1994–1995 and (2) 1998 (see Figure 3). The first of these two periods was characterized by exceptional algal blooms. The *Peridinium* blooms in

Table 2. Mean, standard deviation (S.D.), and number (N) of observations for the 10 panel-selected water quality parameters in Lake Kinneret

Parameter	Winter–spring			Summer–autumn		
	Mean	S.D.	N	Mean	S.D.	N
Chloride (mg litre^{-1})	221	15.4	4840	228	14.3	4535
Total suspended solids (mg litre^{-1})	4.5	4.7	1515	2.7	2.1	1497
Turbidity (NTU)	2.9	2.8	513	2.2	1.0	559
Total phosphorus (μg litre^{-1})	24	16	6201	16	8	5614
Total nitrogen (μg litre^{-1})	0.83	0.35	6211	0.58	0.29	5581
Chlorophyll (μg litre^{-1})	21.8	30.8	1746	6.2	2.7	1635
Primary production (g C m^{-2} d^{-1})	1.9	1.0	198	1.4	0.6	176
Cyanobacteria (% total biomass)	2.5	4.9	424	13.5	17.0	420
Zooplankton (g m^{-2})	31.4	25.2	1796	21.1	15.1	1765
Faecal coliforms[a] (no. 100 ml^{-1})	837	4503	452	135	397	465

Data are for the winter–spring (January–June) and summer–autumn (July–December) periods.
[a] Based on hydrological periods October–March and April–September.



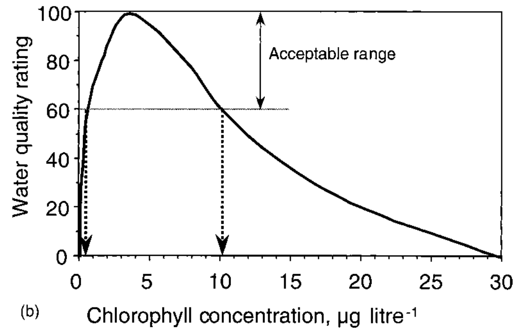


Figure 1. (a) Frequency distribution of summer–autumn (July–December) chlorophyll concentrations in Lake Kinneret at Station A from weekly or biweekly measurements during 1969–1992. (b) Water quality rating curve for chlorophyll for conservation of Lake Kinneret water quality.

Table 3. Acceptable winter–spring and summer–autumn ranges ($100 > R > 60$) for selected water quality parameters for conservation of Lake Kinneret water quality

Parameter	Winter–spring	Summer–autumn
Chloride (mg litre^{-1})	184–244	184–246
Total suspended solids (mg litre^{-1})	1.0–7.1	0.6–4.1
Turbidity (NTU)	1.2–4.9	0.7–3.0
Total phosphorus (µg litre^{-1})	9–38	5–28
Total nitrogen (mg litre^{-1})	0.3–1.2	0.2–0.9
Chlorophyll (µg litre^{-1})	5.5–40.5	1.5–10.1
Primary production (g C m^{-2} day^{-1})	1.1–3.2	0.7–2.2
Cyanobacteria (% total biomass)	0–3.7	1–10.8
Zooplankton (g m^{-2})	13–52	7–37
Faecal coliforms[a] (no. 100 ml^{-1})	0–1000	0–500

[a] Based on hydrological periods October–March and April–September.

spring 1994 and 1995 were the largest ever recorded, the *Aphanizomenon* bloom in autumn 1994 was the first of its kind ever recorded, and the *Microcystis* bloom in winter 1995 was the first noted in 20 years (Berman *et al*., 1998). Monthly mean values for nine of the 10 indices exceeded the acceptable range at least once during this period. Although most parameters returned to acceptable limits by mid to late 1995, the percentage of cyanobacteria repeatedly exceeded the acceptable limit throughout the 6-year period.

The second major period of unacceptable water quality coincided with the spring 1998 *Peridinium* bloom. Although the *Peridinium* bloom season is usually characterized by relatively higher values for most water quality parameters compared with the summer–autumn period, in 1998 total suspended solids, turbidity, total phosphorus, and chlorophyll exceeded the acceptable limits for water quality.

There were also other occasions when only a few parameters varied outside the acceptable ranges. For example, faecal coliform bacteria exceeded acceptable limits every year during the winter rain season, except during the drought year 1999. Also during this year, chloride concentrations increased beyond the acceptable limits. Zooplankton biomass exceeded the acceptable limits several times during 1996–1999.

Overall, the average (with equal weighting) water quality rating for Lake Kinneret has been in the acceptable range throughout the 6-year period, except for 4 months — October 1994, and April 1995, 1997, and 1998 (Figure 4), indicating relatively good water quality. However, the frequency of occurrence of 'unacceptable' levels of the individual indices during this period suggests that water quality in Lake Kinneret has been lower than in the previous 25 years. These changes may also signal destabilization of the lake ecosystem and increased sensitivity of the lake to external disturbances.

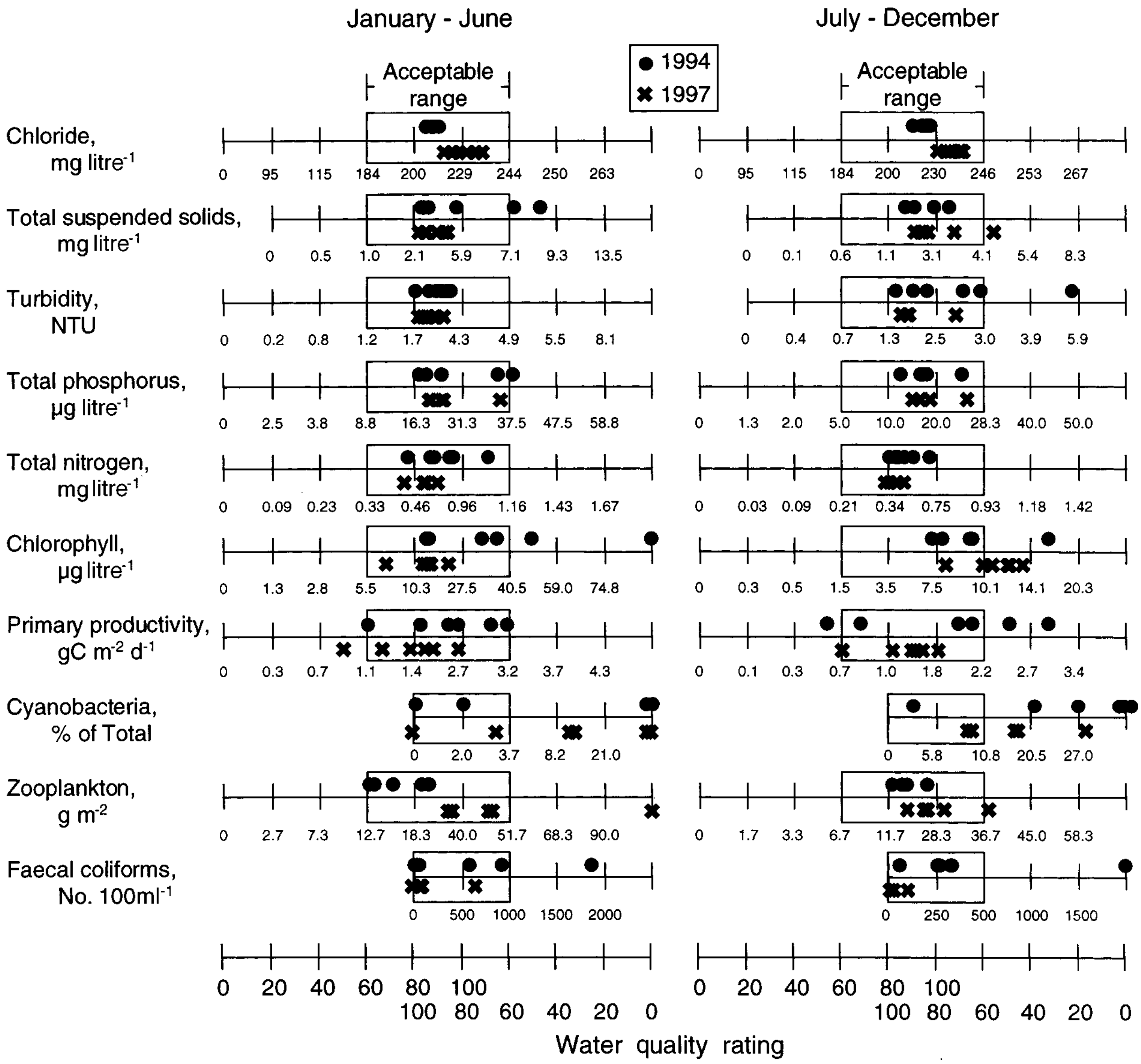


Figure 2. Monthly water quality ratings for Lake Kinneret in 1994 and 1997.

DISCUSSION

Defining water quality in natural or man-made water bodies is a difficult task (Boon and Howell, 1997a,b). Previous attempts to define standards of water quality for natural systems have relied on expert opinion, either singly or by panel, to define ranges of acceptable water quality for a given system (e.g. Burden *et al.*, 1985; Fusilier, 1985; Smith, 1987, 1990). However, as water uses and quality criteria and physical, chemical and biological dynamics are variable across systems, so too should be water quality definitions. Therefore, any given lake is likely to require a unique set of water quality definitions. For Lake Kinneret, a relatively simple system of water quality indices designed for addressing a single goal (conservation and sustainable management) has been designed and based on opinions of a narrow panel.

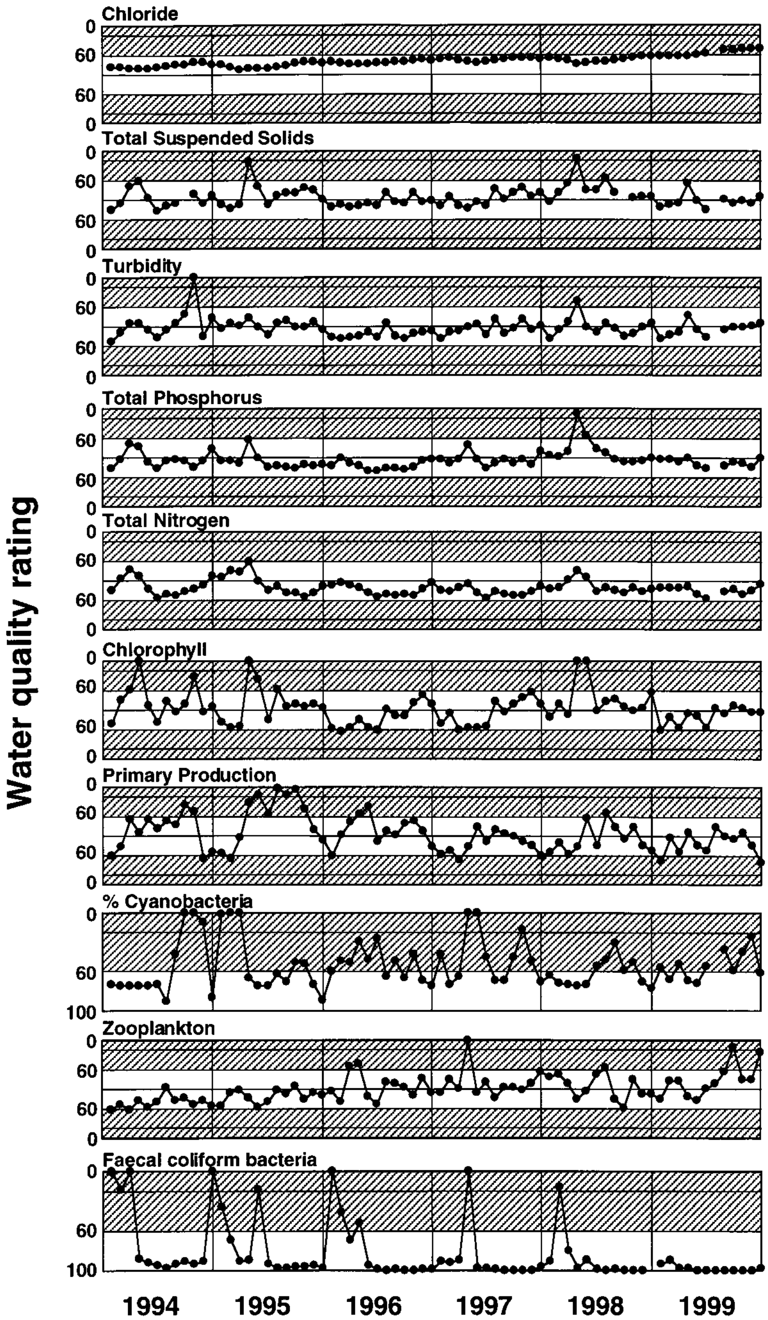


Figure 3. Trends in monthly water quality ratings for Lake Kinneret during 1994–1999.

Obviously, more goals will require panels of greater breadth of expertise. Nevertheless, even the present definitions have formed the basis for a common language for all concerned with the management of Lake Kinneret and have thus been officially adopted for use to evaluate lake water quality (Berman, 1998).

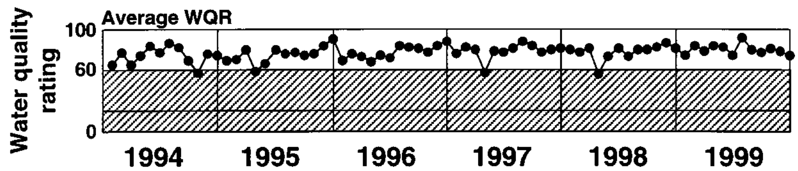


Figure 4. Average water quality ratings for Lake Kinneret during 1994–1999.

A few points should be noted regarding the system of water quality indices for Lake Kinneret. First, even though increased variability in water quality parameters may indicate ecosystem destabilization and a decline in water quality in recent years, the mean water quality index indicates that water quality in Lake Kinneret has remained in relatively good condition. Nevertheless, concern for future water quality is warranted. The increased use of Lake Kinneret water and recent drought conditions (1990–1991, 1998–1999) have led to a current situation of relatively high salinity (mean value for chloride in December 1999 was 260 mg litre^{-1}). Further increases in salinity will lead to unacceptable levels of chloride and thus jeopardize some uses of Lake Kinneret water. For example, many crops are salt sensitive and high salinity water cannot be used for irrigation (Hillel, 1994). There were more cyanobacteria in the lake in recent years, though there is no clear indication of immediate negative effects (Berman *et al.*, 1998). The increased incidence of cyanobacteria coupled with high chlorophyll and primary production also implies a potential increase in the rate of eutrophication of Lake Kinneret.

The approach to defining a system of water quality indices outlined here may appear arbitrary with the selection of parameters and their acceptable limits influenced heavily by the composition of the panel. However, it is precisely this apparent flaw that provides strength to the approach. It could be argued that a strict definition of acceptable ranges of various parameters derived from statistical descriptions of past variability is more objective than subjective derivations of a panel of experts. For example, the inter-quartile (25–75th percentile) range of variability during 1969–1992 could be used to define 'acceptable' water quality in Lake Kinneret. However, this approach is less objective than it might seem. For example, the choice of parameters, as well as the choice of which statistical descriptors (e.g. inter-quartile range) to use are entirely subjective. This is simply an extreme form of the expert panel method where the opinion of a single statistician ('expert') is used to determine which parameters (and their variability descriptors) are best indicative of water quality, rather than the collective opinion of a multidisciplinary panel. Nevertheless, in defining water quality parameter ranges for ecosystem conservation, a high overlap between statistical and expert panel ranges was expected, except in situations where the historical variability is known to have been affected by some external factor (e.g. management). Such a case highlights an important advantage in the expert panel method — a flexible system that can be modified as experience is accumulated.

Statistical descriptions of water quality parameters in Lake Kinneret for the period 1969–1992 are static; water quality ratings by a panel are not. They can be updated as knowledge and understanding accumulate. For example, the acceptable range of zooplankton biomass encompasses the 10th and 90th percentile range of the period 1969–1992. However, the variability in zooplankton biomass during 1969–1992 has been influenced negatively by inappropriate fisheries management (e.g. Gophen *et al.*, 1990; Hambright and Shapiro, 1997). Therefore, it is conceivable that in the future the expert panel will modify the acceptable ranges of zooplankton biomass for Lake Kinneret to better reflect 'natural' levels that were characteristic of the 1970s before zooplankton biomass in the lake began to decline.

Many water resources experts have asked: why do we need a system of water quality indices? The answer becomes clear if one considers the present situation. Today, there is no quantifiable or qualifiable system which defines water quality in most of the world's lakes, including Lake Kinneret. Yet even since the early years of the Kinneret Limnological Laboratory, the prospect of deteriorating water quality with increasing development and nutrient inputs from the watershed has been a major concern (Berman, 1972). Clearly, most would agree that increasing nutrient inputs to the lake would lead to undesirable changes in water quality such as increased primary production and algal biomass (i.e. classic symptoms of 'cultural eutrophication'). However, the same questions always surface: how much of an increase in these parameters constitutes a decline in water quality? By what magnitude would water quality decline given increases in nutrient loading? Only with a well-defined system of water quality indices and standards can quantitative answers to these questions be attempted.

A system of water quality indices does not supply answers to all management questions. Rather, such a system can serve as a diagnostic tool for quantifying changes that may occur in the lake. Of course, Lake Kinneret is a complex ecosystem. With the present lack of an ecological model, future variation in the various water quality parameters or the potential responses of these parameters to management actions cannot be reliably predicted. However, even without a quantitative model in hand, a system of water quality indices permits lake managers readily to quantify the state of lake water quality at any given time and provides a common language between all members of society concerned with lake water quality. For example, recently Zohary and Hambright (1994) concluded that lowering the minimum lake water level to -214 m might lead to water quality deterioration. Intense public debate ensued, in part due to a lack of quantification of 'water quality deterioration'. A system of water quality indices could have averted much of this controversy. Consider the following fictitious scenario: Suppose it was concluded that for every metre of lake level reduction, algal abundance (indicated by chlorophyll) increases by 40%. Hence a drop in mean lake level by 1 m would result in a change from mean summer chlorophyll concentrations from 6.2 to 8.7 μg litre^{-1}. Although this value may provide useful information to limnologists and perhaps even to engineers, it is less likely that an increase of 3 μg chlorophyll litre^{-1} carries any meaning to policy makers within the government. On the other hand, a decline in the water quality rating from 90 to 68 (Figure 1) would indicate to all parties concerned that the predicted rise in chlorophyll in response to lowering the lake water level by 1 m would mean a drop in water quality (from 'excellent' to 'good'). A 2 m decrease in lake level would yield a rating of 'bad' water quality. Although this is a fictitious example, it demonstrates the basic usefulness of the index system in providing a common language by which all sectors of water resources management can communicate more effectively.

Although the years since 1994 have been marked with major changes in Lake Kinneret, in general the lake has demonstrated remarkable resilience during the past 30 years to increasing demands as both the regional and national populations have increased and development in the lake's catchment has boomed (Berman *et al*., 1992, 1995). The natural 'buffering capacity' of the lake has minimized many of the impacts brought on by these increasing demands. Nevertheless, recent events (e.g. greater incidence of cyanobacterial blooms, collapse of the Kinneret bleak fishery) indicate that this buffering capacity may have been exceeded. Moreover, these events warn that the time has come for devising, adopting and implementing a scientifically-based, optimal management programme.

Of course, defining water uses, quality criteria and indices is only the beginning. The development of a mathematical/ecological model (currently being carried out), in which the system of indices described above is the primary output, should lead to more rational management strategies in the future.

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