Management of natural lake water resources: problems and solutions

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Introduction

Scientifically (ecologically) based management of water resources could be presented as a sequence of steps which reflect inherent multidisciplinary character of this challenging scientific task (Fig. 1).

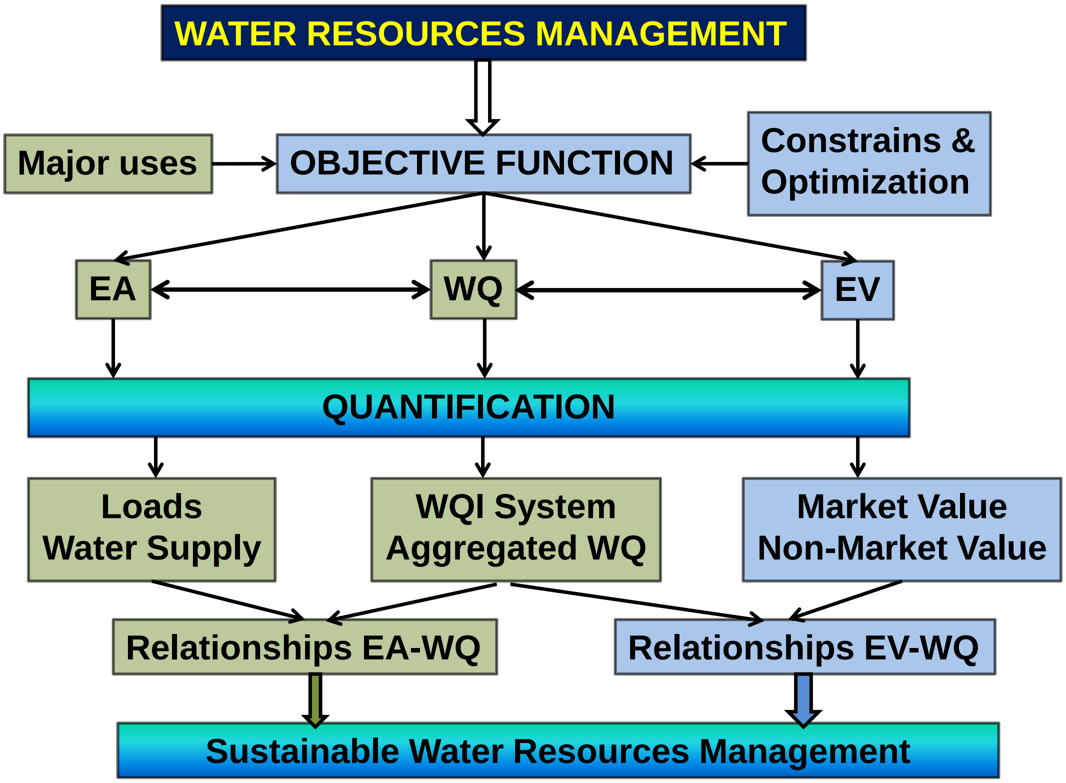

Figure 1. Simplified scheme of sustainable water resources management. Compartments in green have been achieved in the Lake Kinneret case study; the compartments in blue are yet to be achieved. See text for designations.

We define "management" as the ability to carry out a direct measurable action aimed at causing beneficial, predictable and measurable changes in the aquatic ecosystem function. Methodologically, the task of management can be described as optimization of an objective function Q (Fig. 1) of the economic activities (EA) such as anthropogenic activities in the lake watershed and intensity of water resources uses, water quality (WQ), and economic effectiveness of the management (costs versus benefits, CB):

$$Q = f\,(EA; WQ; CB) \qquad (1)$$

Quantification of various parameters in eq. 1 (EA, WQ, CB) and establishment of the relationships between them should be a central task for establishing of ecologically based

water resource management strategy (Jorgensen and Vollenweider 1989; Groffman et al. 2006). Solution of this multidisciplinary task requires tight cooperation between water resource managers and scientists from different fields: ecology, mathematical modeling and environmental economy. The lack of this cooperation results in incorrect formulation of the management task, misuse of existing terminology and forms conceptual gaps between several partners in management.

In this study, we assumed that the water resources management should be “sustainable”, i.e., aimed at the utilization of water resources that allows conservation of their quality within assessed desirable (permissible) ranges (Parparov et al., 2006). Here, we summarize our experience in water quality quantification and establishment of its relationships with some major economic activities using subtropical Lake Kinneret (Israel) as a case study.

Description of the Lake Kinneret social-ecological system

Table 1: Characteristics of Lake Kinneret and its watershed (Serruya 1978).

Watershed		Lake Kinneret	
Surface area, km^2	2730	Surface area, km^2	160-170
Water inflow, km^3 yr^{-1}	0.3-1.5	Volume, km^3	3.3-4.2
TP load, g m^{-2} yr^{-1}	0.4-1.6	Water supply, km^3 yr^{-1}	0.2-0.6
TN load, g m^{-2} yr^{-1}	3.1-12.5	Total phosphorus (TP), mg L^{-1}	0.02
Population	255,000	Total nitrogen (TN), mg L^{-1}	0.60
		Fish yield, t yr^{-1}	2000
		Main uses: Domestic water supply, Fisheries, Recreation	

Lake Kinneret, the largest fresh water body in the Middle East, is a subtropical lake located at about -210 m altitude, i.e. below mean sea level, (Fig. 2). It has a surface area of approximately 167 km^2 and a watershed of 2730 km^2 (Table 1). The main inflow is via the Jordan River contributing about 70% of the total inflows from tributaries, while the main outflow is through pumping to Israel's National Water Carrier. The lake is meso-eutrophic with a mean annual primary production of 650 g C m^{-2} (Berman et al., 1995; Yacobi, 2006). A prominent biological feature of the lake has been the spring bloom of the dinoflagellate *Peridinium gatunense*, though since 1994, the lake has exhibited uncharacteristic developments in the phytoplankton assemblage, including blooms of a potentially toxic, N_2-fixing cyanobacteria, and lack of the spring Peridinium bloom (Zohary, 2004). Further details on the basic limnology of Lake Kinneret can be found in Serruya (1978).

The main uses of the lake (Table 1) have been for drinking and irrigation supply (30% of total national demand). A portion of the lake's water is used to replenish the aquifers along the Mediterranean coast. The most critical management issues facing the Lake Kinneret resource managers are the progressively increasing portion of cyanobacteria in algal biomass (Zohary, 2004) and increase of water salinity above the acceptable level of 245 mg Cl L^{-1}. **One of the main objectives of management of the lake water resources is the conservation of the lake ecosystem in order to ensure continued acceptable WQ and quantity at affordable costs (Wetzel, 2001).**

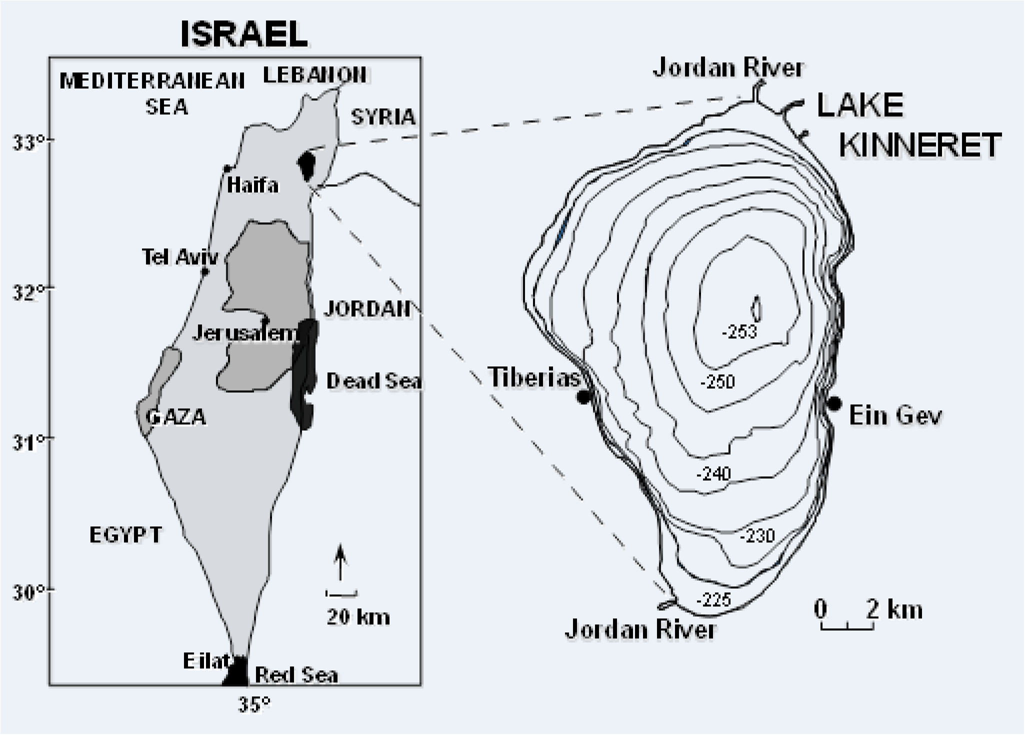

Figure 2. Lake Kinneret and its location in Israel

The ecological monitoring system in Lake Kinneret is one of the most detailed in the world. An extensive long-term database (running from 1969) includes data for more than 100 hydrological, meteorological and limnological variables collected weekly and fortnightly at five stations (Markel and Shamir, 2002).

Economic activities affecting quality of lake water resources

In this study we assumed that the nutrient loads reaching the lake represent the economic activities in the watershed and that lake level is a proxy for the amount of water pumped from the lake. We linked nutrient loads and water level to lake water quality and therefore, in essence, we were associating between the economic activities in the lake and its watershed and lake WQ.

The nitrogen and phosphorus loads (N & P loads, g m^{-2} yr^{-1}) were calculated as a product of the Jordan River water discharge and the concentration of the nutrient total forms. It was assumed that water discharge from the Jordan River comprised 70% of the entire discharge (Gal et al. 2009) and represented a similar portion of the total watershed load into the lake.

Within the investigated period, the N loads P loads varied between 2.5 to 20.6 g m^{-2} yr^{-1}, and from 0.15 to 0.80 g m^{-2} yr^{-1}, respectively. Annual dynamics of the nutrient loads into the lake showed similar features for both N and P (Fig. 3a) resulting in a strong positive correlation between the N and P loads (R^2 = 0.78). The largest values of the N and P loads were detected during extremely high water discharges in 1992 and 2004.

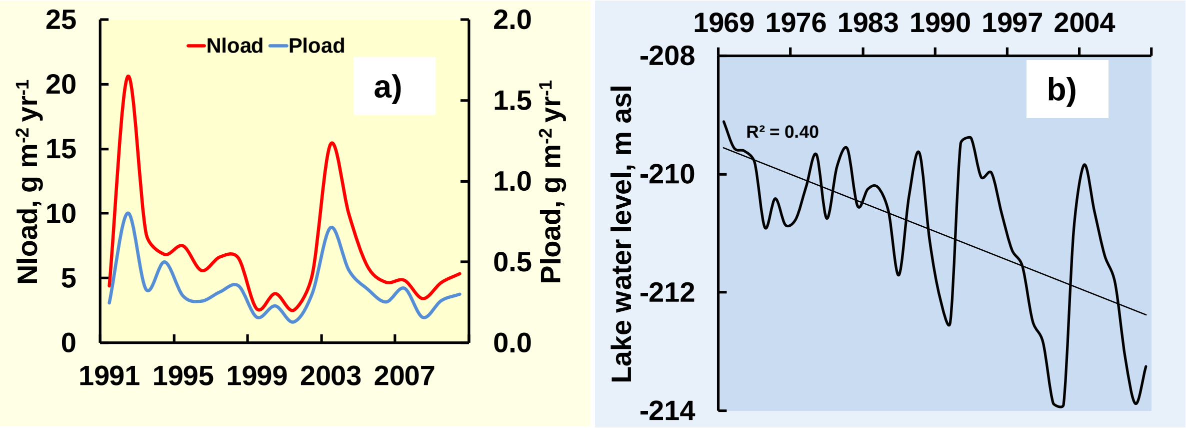

Figure 3. Dynamics of annual average values of the nutrient loads (a) and the lake water level (b) in Lake Kinneret in 1991-2010.

Over the course of the period of the study, the mean annual lake level varied from -209.4 to -213.9 m asl mainly due to climatic conditions. The amplitude of lake level fluctuations during the 1991-2010 period was larger than the amplitude observed during the period of 1969-1983 with an overall trend of water level lowering (Fig. 3b).

Economic valuation of Lake Kinneret water resources

Cost and benefit analysis is apparently obvious and natural way to compare the profits and benefits associated with management of the Lake Kinneret water resources. The problem is in economic (i. e., money) valuation of the mentioned costs and benefits. Understanding of the vital importance of water for human beings, is accompanied with absence of water prices, or if water is priced, the price often does not reflect its real value to society. For instance, the price of water withdrawn from Lake Kinneret comprises only a few percent of Israel financial budget (Kislev, 2010). Obviously, economic valuation of water resources of Lake Kinneret is not complete: it represents only indefinite part of its market value, while non-market value, associated with the environmental ecosystem services, remained unknown.

The importance of economic valuation of management of the natural water resources was mentioned in the European Union Framework directive (WFD, 2000). Recently, the state-of the art in this intensely developing field of science was described in the WFD Technical Guidelines (Brouwer et al., 2009), however most of the publications concern the eutrophication problem solely.

The economic valuation of water resources should allow supplementing of the objective function of management with this conceptually important variable, accounting for which should lead to essential transformation of the criteria of management (O’Riordan, 1999).

Quantification of water quality

Water quality (WQ) is a term used to describe the condition of a water body with reference to human needs or values and is therefore likely to have elements of subjectivity related to perceptions and biases of the observer (CWA, 2002). Quality is not absolute; the terms “good” or “poor” water quality have meaning only in relation to the use of water and the assessment of the user. Investigations of the eutrophication phenomenon, particularly those stimulated by escalation of eutrophication in the 1960s and 1970s, resulted in quantification of the trophic classification system (Vollenweider, 1976; Carlson, 1977; Parparov et al., 2010). WQ has been considered as a synonym of the trophic status (e.g., Burns et al., 2005; Carvalho et al., 2009; Giordani et al., 2009). Further progress in

WQ assessment is associated with implementation of optimization approaches (Müller et al., 1998; Wetzel, 2001) in order to **establish the natural resource sustainable management policies contributing conservation of aquatic ecosystems within some desired reference condition** (Jorgensen & Vollenweider, 1989; Gilbert, 1996; WFD, 2000; Fischer et al., 2009).

Parparov et al. (2006) suggested the following principles for quantification of WQ and its implementation in lake management:

1. A system of water quality indices (WQI) and their acceptable ranges should be devised and quantified by an expert panel consisting of all partners in lake management.
2. The WQIs and their driving processes must be suitable for mathematical modeling.
3. The WQIs and the model together should serve as a self-organizing tool for lake management.
4. The WQI must be dynamic and sensitive to changes in ecosystem functioning.

Our approach to water quality assessment in Lake Kinneret which included the establishment of a system of water quality indices (WQI) and their permissible ranges was based on quantitative modifications of the expert panel method (Brown et al., 1970; Parparov and Hambright, 1996; Parparov et al., 2006; Bharti and Katyal, 2011) and was described in detail in Hambright et al. (2000). In fact, WQ quantification represents establishment of a consequence quantitative relationship aiming at creation of direct relationship between water quality and economic activities. These steps are illustrated for the chloride concentration (Cl), an index of water salinity (Fig. 4).

We suggested that the water resources of Lake Kinneret would be managed in order to maintain water quality within the range of a “reference” state (1969-1992), because at that period, lake water quality was acceptable for all uses, especially for drinking water supply. The expert panel chose the set of 10 water quality indices and constructed rating curves for each variable. For Lake Kinneret, it was decided to distinguish between two ecologically different periods: Winter-Spring (January-June) and Summer-Autumn (July-December).

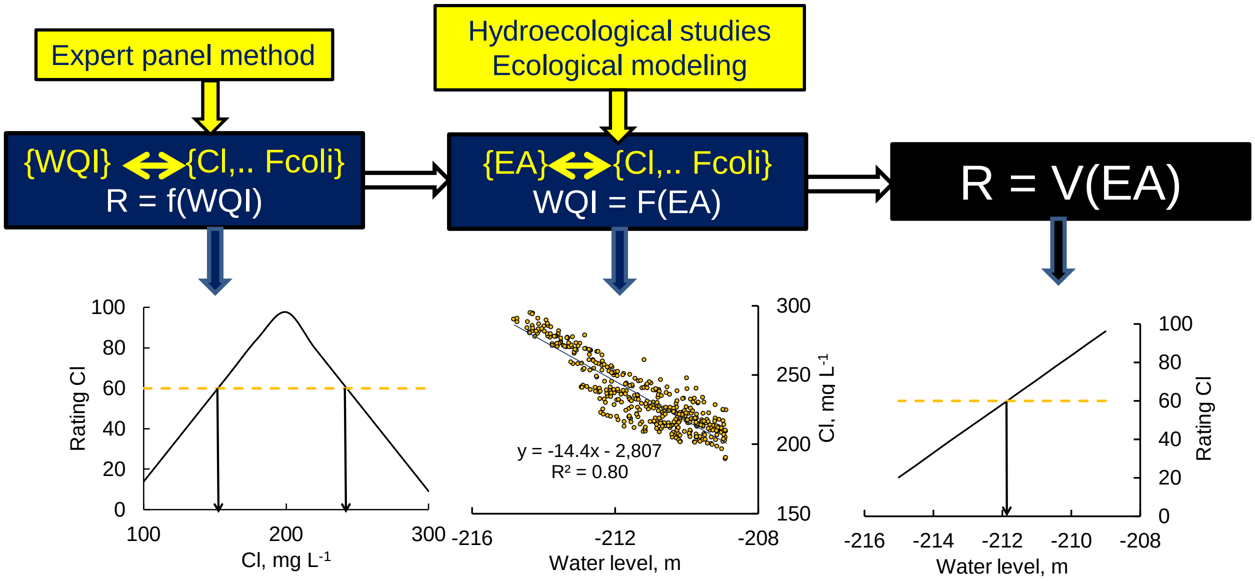

Figure 4. The steps of WQ quantification using Cl as example. **A**) The rating curve R = f (WQI) representing the relationship between concentration of Cl and its rating value, R, which ranged 10-100 established by expert panel (Delphi method).The arrows indicate permissible range for Cl (60≤R≤100). **B**) WQI = F(EA): the relationship between water quality (Cl) and economic activity (EA, here, water level). For this step, we applied statistical analyses of the existing database (presented in Figure as regression of Cl vs Water Level) combined with ecological modeling (Gal et al., 2009; Parparov and Gal, 2012). **C**) Direct relationship between economic activity (Water Level) and Water Quality (Rating of Cl) obtained combining R = f(WQI) and WQI = F(EA).

Permissible ranges for the separate WQI were defined as the range of 60≤R≤100. The WQ system, established for Lake Kinneret, includes a total of 10 indices (Table 2) and provides a means for identifying the major water resource uses and environmental threats associated with them:

- *drinking water supply,* given by indices of total suspended solids (TSS) and turbidity (TU);
- *eutrophication*: given by indices such as the total phosphorus (TP) and total nitrogen (TN), primary production (PP), chlorophyll (Chl)and percentage of cyanobacteria (%Cyano) in the total algal biomass ;
- *organic pollution*: represented by an index of the number of coliform bacteria(Fcoli);
- *food supply for fishes*: the zooplankton biomass (ZB) index;
- *increase in salinity* above accepted drinking water supply standards: chloride (Cl) concentration index.

The established WQ system is used

- as a common language for the partners in management;
- as a target in water quality monitoring;
- as an output of the ecological model;
- as a target of the lake water resources management.

Aggregated WQ (Composite Water Quality Index (CWQI)) was calculated as a weighted sum of rating values for the entire set of the WQ indices. The weighting procedure used variable weights inversely proportional to the separate rating values, thus providing extra weight to indices with lower rating values (Parparov and Hambright, 2007):

$$CWQI = \Sigma(R_i \bullet (R_0 - R_i)/\Sigma(R_0 - R_k)) \quad (5),$$

where summation should include ratings of all ‘i’ and ‘k’ WQ indices from 1 to 10. In our calculations, we applied $R_0 = 100$.

Table 2. Acceptable winter-spring and summer-autumn ranges ($100 \geq \text{Rating} \geq 60$) for selected water quality indices for conservation of L. Kinneret water quality.

Index	Winter-Spring	Summer-Autumn
Chloride, mg L^{-1} (Cl)	152-242	153-245
Total suspended solids, mg L^{-1} (TSS)	0.8-8.3	0.3-4.9
Turbidity, NTU (Tu)	1.4-5.3	0.8-3.6
Total phosphorus, µg L^{-1} (TP)	7.5-36.7	4.0-27.3
Total nitrogen, mg L^{-1} (TN)	0.38-1.20	0.25-0.98
Chlorophyll, µg L^{-1} (Chl)	4.7-37.7	1.0-10.0
Primary production, g C m^{-2} d^{-1} (PP)	1.13-3.17	0.71-2.32
Cyanobacteria, % total algae biomass (%Cyano)	0-5.1	1-12.3
Biomass of Zooplankton, g m^{-3} (ZB)	0.46-3.03	0.55-5.38
Fecal coliforms, No. 100 mL^{-1} (Fcoli)	0-200	0-1000

The above-described system provides a direct correspondence between permissible ranges for WQ indices and permissible ranges for economic activities (EA):

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$$\{WQI_{LOW} < WQI < WQI_{HIGH}\} \leftrightarrow \{EA_{LOW} < EA < EA_{HIGH}\} \qquad (6),$$

where subscripts LOW and HIGH represent the lower and upper permissible values, respectively and '↔' infers correspondence. **Eqn. (6) provides the limits of management based on criteria of conservation of water quality. When supplemented with the requirements for socio-economic optimization, this expression may be considered as an *operational definition of "sustainable management*".**

There was a clear tendency of deterioration in the Lake Kinneret WQ during the period from 1991 to 2010 (Fig. 5). Within this period, the decrease in the CWQI values was driven by high concentrations of chloride (caused by progressive water level lowering) and increased concentrations of cyanobacteria in algal biomass.

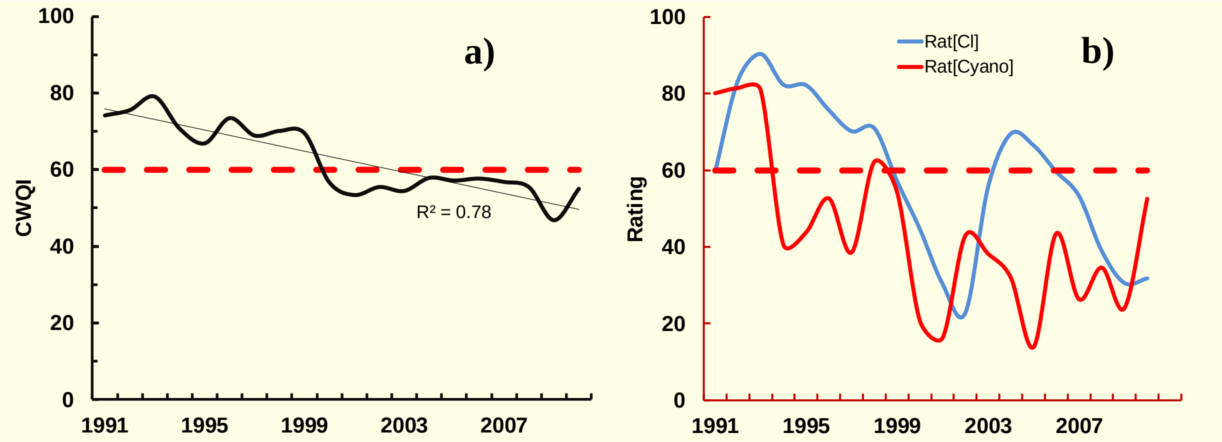

Figure 5. Dynamics of aggregated water quality (CWQI, a)) and ratings of Cl and Cyano (b) in Lake Kinneret during 2001-2010. The solid straight line represents a linear trend of the CWQI dynamics, and horizontal dashed line indicates lower boundary of acceptable water quality (CWQI = 60).

Brief description of the ecosystem model, DYCD

The impact of a number of management scenarios on the Lake Kinneret ecosystem was evaluated based on 20 year simulations using the ecosystem model DYRESM-CAEDYM (DYCD, Gal et al., 2009). It is a process-based model that incorporates the important physical processes taking place in a lake leading to changes in temperature and salinity with time and depth and has been applied to Lake Kinneret for a number of years (Bruce et al. 2006, Gal et al. 2003)). The ecosystem model consists of the Computational Aquatic Ecosystem Dynamics Model (CAEDYM) coupled to the one-dimensional physical model: Dynamic Reservoir Model (DYRESM) (Fig. 6). CAEDYM uses a series of ordinary differential equations to describe changes in concentrations of nutrients, detritus, dissolved oxygen, bacteria, phytoplankton and zooplankton as a function of environmental forcing and ecological interactions for each Lagrangian layer represented by DYRESM. Due to the fast run-time of the model and its accuracy over time, DYCD is well suited for long-term simulations and for examining multi-annual variability. Input required for model simulations include forcing data (inflows, withdrawals and meteorological conditions), initial physical, chemical and biological conditions, and a series of user defined parameters.

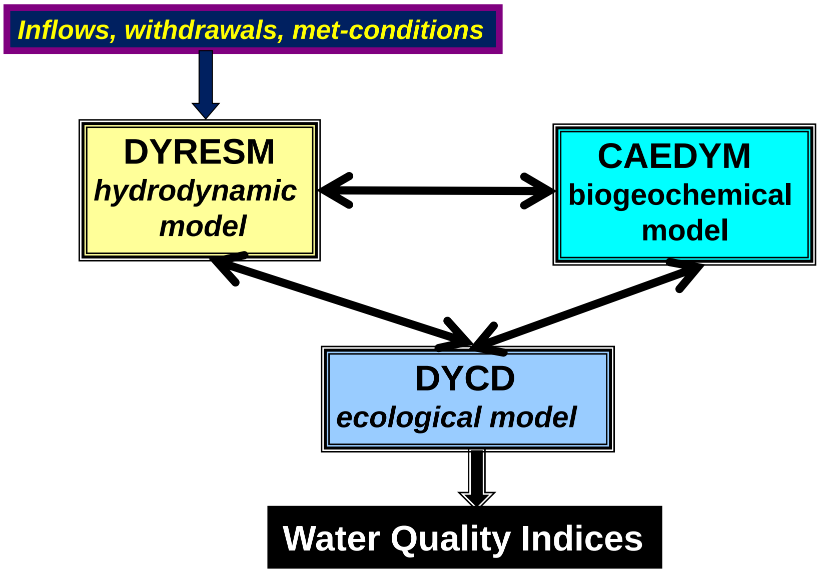

Figure 6 . Scheme of the DYCD ecological model

Simulation runs

In order to assess the relationships between the selected EA (nutrient loads and water level) and lake WQ, we conducted a series of simulations and examined the output in the form of the individual WQI or the CWQI:

- Nutrient loading into the lake was varied over a wide range (from 0.01 to 10 of the baseline loads) by multiplying the concentrations of N, P or N and P in tandem in the inflows. During the loading simulations lake level was held constant between years thus there was seasonal variation but no interannual variability. Initial and final lake level for these simulations was –210 m.
- Lake level was varied between -208.0 and -216.0 m (WL scenario, hereafter). Under the WL scenario, the nutrient loads were unaltered within the base line values (with a multiplication factor value ≈ 1).

The 20 yr. simulations input data were constructed based on real data collected during the year 2000. The mean annual values of the last 3 years of the simulations were used for the establishing of the relationships between CWQI and major EA. This was done in order to ensure use of results from quasi-steady state conditions.

Relationships between the economic activities and water quality

Relationships obtained from the monitoring data

In most publications concerning WQ assessment, the main function of WQ monitoring is indicating changes in water quality (Cude et al., 2001; Burns et al.,2005). However, the quantified WQ is an argument of the objective function of management (eqn. 1), and therefore the aggregated WQ (e. g., CWQI) should be a target of management, rather than only an indicator of change, (Parparov and Hambright, 2007). Moreover, determining the correspondence between permissible ranges for water quality indices and permissible ranges for economic activities makes quantified water quality an important tool of management.

Traditionally, the relationships between ecosystem variables and different environmental effects reveal from statistical analysis of the monitoring data. For Lake Kinneret, water level appeared to be the best correlator with several WQI among considered economic activities (Table 3).

Table 3. Square correlation coefficients between water quality (as ratings of Chloride and %Cyano and aggregated water quality, CWQI) and major Economic Acivities: Nutrient Loads and Water Level

Economic Activities	Rating[Cl]	Rating[%Cyano]	CWQI
Nitrogen Load	0.22*	0.26*	0.08
Phosphorus Load	0.18	0.19	0.04
Water Level	0.88**	0.33**	0.38**

The relationship between the lake water level and CWQI establishes a direct relationship between WQ and EA, which allowed estimating of permissible range for the lake water level (Fig. 7).

The data shown in Table 2, represent combined effect of the separate economic activities: loads and water level, acting together with each other. The net effects of the individual EA could be revealed only under assumptions about constancy of other EA, due to modeling simulations.

Relationships obtained from the simulation runs

Results of all water level scenarios were combined in order to determine a quantitative relationship between lake level and aggregated WQ (CWQI) and, thus, providing a means for estimating the critical value for water level lowering (CWQI≤60; Fig. 7). The modeling results are in a good correspondence with those obtained from the lake-based data thus providing similar estimates of the permissible range for lake level: WL≥-213.5 m and WL≥-212.5 m, respectively.

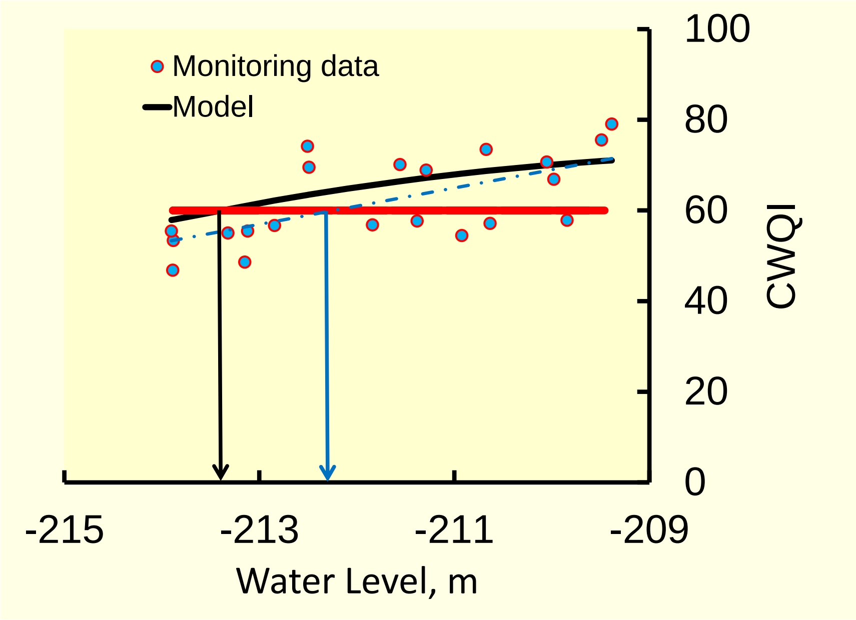

Figure 7. The relationship between annual average aggregated water quality (as CWQI) and lake water level. The results are based on simulation results (solid line) and monitoring data (blue dots). The dashed line represents linear regression obtained from lake based data. The arrows indicate the threshold water level value (corresponding to CWQI=60), based on model output (-213.5 m, solid arrow) and monitoring data (-212.5 m, dashed arrow)

Therefore, the observed statistically significant relationship between the water level and WQI (especially, CWQI), obtained despite "noisy masking" by the loads, could be interpreted as an indirect evidence of relatively higher Lake Kinneret ecosystem sensitivity to its water level changes.

Simulation results allowed us to establish the direct relationships between nutrient loads and the aggregated WQ in the form of a "polygon" of permissible ranges of the nutrient loads (Fig. 8) allowing conservation of the lake WQ (Parparov & Gal, 2012). The polygon of the permissible ranges establishes the correspondence between the combined effect of the nutrient loads and the aggregated water quality: the N&P load values inside of the polygon correspond to the loads which should allow sustaining of acceptable WQ conditions(CWQI>60) . The load values outside of the polygon are potentially dangerous for the lake water quality.

Combining of these results with the estimate of the permissible range for the lake water level (WL>-213.5 m) allowed us to outline the sustainable water resources management policy (Table 3), based on a single ecological criterion: conservation of water quality.

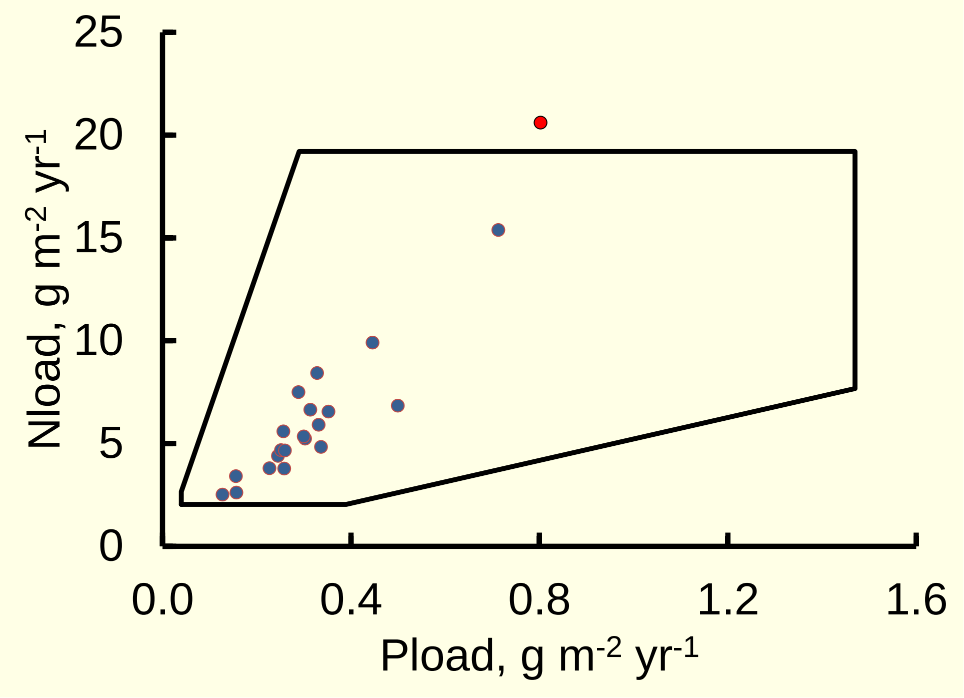

Figure 8. Polygon of permissible values of Nload and Pload, plotted as graphic solution of the inequities CWQI = f(Nload, Pload and N/Pload) obtained from the results of simulation runs under assumption of stability of lake water level (~-210 m). The load values within the polygon should allow maintaining of lake water quality within its permissible range (60<CWQI<100), while the loads outside of the polygon can deteriorate water quality. The circles within the polygon represent nutrient loads obtained from lake based data for the period from 1991 to 2010.

It should be emphasized that Fig. 8 shares the results obtained with various independent methods: a Delphi expert panel, ecological monitoring of the lake and its watershed and ecological modeling. It is important to note that the nutrient loads obtained from the monitoring database for the period from 1991 to 2010, are well within the N&P polygon obtained from the simulation runs (besides one extreme point). Good correspondence between lake based data and the output of the combined independent methods indicates a successful implementation of the ecological model DYCD for solution of the tasks of sustainable water resources management, and should be considered as important, though indirect, model validation.

Table 3. Outline of sustainable management policy representing the limits of economic activities that will allow water quality conservation for the Lake Kinneret case study. I – permissible ranges for the nutrient loads were estimated based on the assumption that the N&P loads affect lake water quality independently of each other; II - 2-dimensional area (polygon) of permissible values of the N&P loads accounting for their combined effect on water quality

Economic Activity	Permissible ranges	
	I	II
Nload, g m^{-2} yr^{-1}	2.04<Nload<19.2	
Pload, g m^{-2} yr^{-1}	0.04<Pload<1.47	
Water Level, m	WL>-213.5	WL>-213.5

Concluding remarks

What has been already done?

In this study, we suggested a methodological framework for sustainable water resources management based on hydroecological criteria and aimed at conservation of the meso-eutrophic Lake Kinneret ecosystem at a predefined reference state. The suggested methodological framework includes ecological monitoring, quantified system of WQ indices, and an ecosystem model.

Hydroecological monitoring of Lake Kinneret includes systematic determinations of more than 100 variables in the lake and watershed. This unique database was earlier implemented for calibration of DYCD (Gal et al., 2009). Implementation of the quantified system of WQ indices allowed us to utilize only a subset of the monitored variables, 10 in total , in order to provide a “water quality monitoring”. Combining of the quantified WQ system and the ecological model provided a means for establishing and verifying the quantitative relationships between WQ and major EA, with the data obtained from ongoing lake monitoring (e.g. Fig. 7). This allowed us to establish a direct correspondence between permissible ranges for WQ and permissible ranges for the EA and thus to outline a “sustainable management policy” for Lake Kinneret water resources (Fig. 8 and Table 3).

It should be noted that for Lake Kinneret all three components required for the assessment of the methodological framework were available (ecological monitoring, WQ system and ecological model).

What has not been done yet?

Our approach to assessment of the sustainable management policy was based on a single, hydroecological criterion: the necessity to conserve lake ecosystem within pre-defined conditions representing a desirable, reference state. **However, in reality, the target of the sustainable management policy should be a social-ecological system and not an aquatic ecosystem per se. Therefore, water resources management should be based on multi-criteria (Eqn. 1); it should also account for the economic aspects (costs and benefits for society) of the problem**(O’Riordan, 1999; Costanza et al., 2002; Walker et al., 2002; Derissen et al., 2011).

Once established, will this combined hydrological-ecological criterion be sufficient for the effective water resources management? The damages associated with water over-supply during drought periods are multiple: loss of the lake water potential, deterioration of the lake water quality for drinking water supply and recreation. However, the benefits are also obvious: uninterrupted domestic water supply and water for irrigation: without water supply these uses of the social-ecological system of Lake Kinneret would be significantly damaged.

Cost and benefit analysis is obvious and a natural way to compare the management options of natural waterbody resources. The problem is in the economic (i. e., money) valuation of those costs and benefits. Understanding the vital importance of water for human well-being is accompanied with existence of water prices which do not necessarily reflect its real social value. Obviously, existing economic valuation of the Lake Kinneret water resources is not complete: it represents an indefinite part of its market value, while non-market value, associated with the environmental ecosystem services, remains totally unknown.

Establishment of the quantitative relationships between EA, WQ and total economic value of water resources is a challenging scientific problem. Its solution will be a conceptually important step towards scientifically based -water resources management.

Implementation of water resources management based on combined hydrological, ecological and economic criteria is a challenging scientific problem which will contribute significant modification of the developed methodological framework:

- **A quantified system of WQ indices should be revised in view of suitability for carrying out economic valuation surveys based on preference and contingent valuation methods;**
- **The DYCD ecological model should be transformed to an ecological-economic model;**
- **The total economic value of the social-ecological system of Lake Kinneret should be assessed and its relationships with major management activities should be estimated in interaction with the Monitoring and Ecological-Economic Model despite the challenges involved.**

Finding solutions to these tasks should allow establishment of new, advanced, methodological framework. We understand how challenging this task is: to our knowledge such a task has not been solved for any natural waterbody to date.

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