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Short communication

A simple tool for the assessment of water quality in polluted lagoon systems: A case study for Küçükçekmece Lagoon, Turkey

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ABSTRACT

Lagoon systems have particular ecological, morphological and hydrodynamic characteristics and act like transitional zones between inland and open waters. The aim of this study is to develop a Lagoon Water Quality Index (L-WQI) for environmental control of polluted lagoon systems by focusing on primary problems such as increasing stress on aquatic biota, eutrophication and organic pollution. The indicators used in L-WQI are dissolved oxygen saturation, total nitrogen to total phosphorus ratio, nitrate, orthophosphate, chlorophyll-a, chemical oxygen demand, pH, turbidity and electrical conductivity. L-WQI establishes a new normalization function for each variable and uses a modified version of the weighted aggregation method. L-WQI has been adapted to Küçükçekmece Lagoon, a highly polluted watershed located in western Istanbul. The results correlated with the observed water quality trends in this lagoon and highlighted the impact of pollution in its tributaries.

1. Introduction

Lagoons are ecotones that develop at the interface between coastal, terrestrial and marine ecosystems. On the world scale, lagoon systems comprise 13% of earth's coastline (Barnes, 1989). Each of these coastal areas is a unique, sensitive ecosystem, extremely valuable as a natural habitat for many life forms. Lagoons are also important to socio-economic structure in terms of providing opportunities for agriculture, aquaculture, tourism and recreational purposes. However the above-mentioned socio-economic advantages may become disadvantageous for the ecological environment if they are not managed and supervised with great care. Lagoons have limited water circulation to compensate for changes in water quality and are susceptible to anthropogenic pollution (Johnson et al., 2007). In lagoon systems water quality assessment is of vast importance in sustaining ecological characteristics.

Water quality in freshwater bodies is a complex issue with multiple aspects such as physical, chemical and biological processes and their interactions. In recent decades, various tools have been developed to assist water quality management including mathematical models, optimization approaches and integrated decision support systems (Huang and Xia, 2001). Along with the increasing use of these sophisticated tools, water quality indices are also being developed and used world-wide due to their simplicity, adaptability and easy-to-use nature (Kannel et al., 2007; Simoes et al., 2008). The popularity of the Water Quality Index (WQI) comes from its pragmatic structure; complex mathematical evaluations of huge quantities of water characterization data are transformed into a simple scale value. This value is easily comprehended by planners, managers and the general public (Giljanovic, 1999). Some notable implementations of WQI were by the US National Sanitary Foundation (NSF), Oregon Department of Environmental Quality, British Columbia Ministry of Environment, Canada Council of Ministers of Environment (CCME) and Environmental Protection Administration of China (Cude, 2001; Chen et al., 2006, Lumb et al., 2006). Methodologically, WQIs can be based on objective or subjective criteria. Objective WQIs make use of statistical analysis based on pre-defined threshold values set by administrative boards. Subjective WQIs are based on a parameter set, relative weights, normalization curves and aggregation algorithms (Abbasi, 2002). In recent studies, artificial neural networks and fuzzy logic have been adapted to WQIs (Khuan et al., 2002; Icaga, 2007; Nasiri et al., 2007). The common application areas of WQIs are surface waters, coastal areas or aquacultures contaminated by heavy metals and/or organic matter (Said et al., 2004; Jonnalagadda and Mhere, 2001; Liou et al., 2004; Atazadeh et al., 2007; Kaurish and Younos, 2007; Aguilera et al., 2001; Edet and Offiong, 2003).

This study develops a "Lagoon Water Quality Index" (L-WQI) to evaluate the quality of water in lagoons facing ecological problems

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such as eutrophication, organic pollution and increasing stress on aquatic biota. Küçükçekmece Lagoon was selected as the study area, showing typical characteristics of polluted lagoon systems. This lagoon once sheltered migratory birds and diverse flora and fauna. Today, however, it has vastly deteriorated as a result of extensive regional urbanization and industrialization.

2. Material and methods

2.1. The study area and sampling sites

Küçükçekmece Lagoon is located between 41°00′N and 28°45′E in the south-west of Istanbul. The lagoon's total drainage area is 340 km^2 and its surface area is approximately 15.22 km^2 with a maximum length of 7.5 km from north to south and 4 km from east to west. Maximum depth of the lagoon reaches 20 m near the Sea of Marmara shoreline. The three streams feeding the lagoon are Eşkinoz, Sazlidere and Nakkaşdere. The freshwater inflow to the lagoon was notably reduced after 1998 upon initiation of Sazlidere Dam. Currently, with an annual capacity of 85106 m^3, the dam is used for supplying potable water to Istanbul (Taner et al., 2007). The lagoon and the Sea of Marmara are connected by a channel which is 1.5 km in length. Thermal stratification of the lagoon is restricted to the summer period, whereas from November to May the lagoon shows a relatively homogenous profile. Küçükçekmece Lagoon is euthrophic and its algal blooms become explicit usually during early spring and late fall. The environmental degradation trend of the Küçükçekmece Watershed began in the 1990's as a result of rapid land-use transformations. The population of the area increased fivefold between the 1990s and 2000s. Currently, the majority of residents in the area are squatters with no access to adequate environmental infrastructure. A vast majority of industrial facilities in the region do not operate their wastewater treatment plants regularly.

During the development of L-WQI, water and sediment quality was monitored periodically (Üstün et al., 2005). Our monitoring program was carried out from November 2005 to March 2008 at nine sampling stations. Stations 10–13 are located in the lagoon; Stations E2 and E3 are located on Eşkinoz Stream; Station D3 is in Sazlidere Dam; and Stations D1 and D2 are located on Sazlidere Stream (Fig. 1). During monitoring studies: dissolved oxygen (DO), pH, electrical conductivity (EC) and salinity are measured *in situ* by using WTW Oxi 330i/set; chemical oxygen demand (COD) by the open reflux method; turbidity, orthophosphate, nitrate and chlorophyll-a by spectrophotometric methods (APHA, 1995). We also benefited from an additional set of data collected by the Turkish State Hydraulic Works (DSI) from sampling stations S1 (from May 1994 to December 1998), S2 (from February 1990 to October 1996), S3 (from February 1999 to December 2006), S4 (from February 1999 to October 2006) and S5 (from January 1990 to May 1994) on Sazlidere Dam (Fig. 1).

2.2. Index methodology

This study introduces a general framework for water quality indices consisting of five primary phases: determination of objectives, selection, normalization and aggregation of variables and validation (Fig. 2). The first phase is the determination of index objectives based on unique characteristics of the water body (e.g. lagoons, coastal waters, lakes). These objectives should be related to all living species' life sustainability and beneficial use for human beings. Water quality variables are then selected based on these pre-defined objectives as well as data availability and financial constraints. Subsequently, variables are normalized according to certain water quality standards and thresholds in parallel with index objectives. Then follows the aggregation phase where selected water quality parameters are aggregated to express the final water quality score in the most appropriate way. The first four phases of the above framework was given below for L-WQI, while the index validity was discussed in the results section.

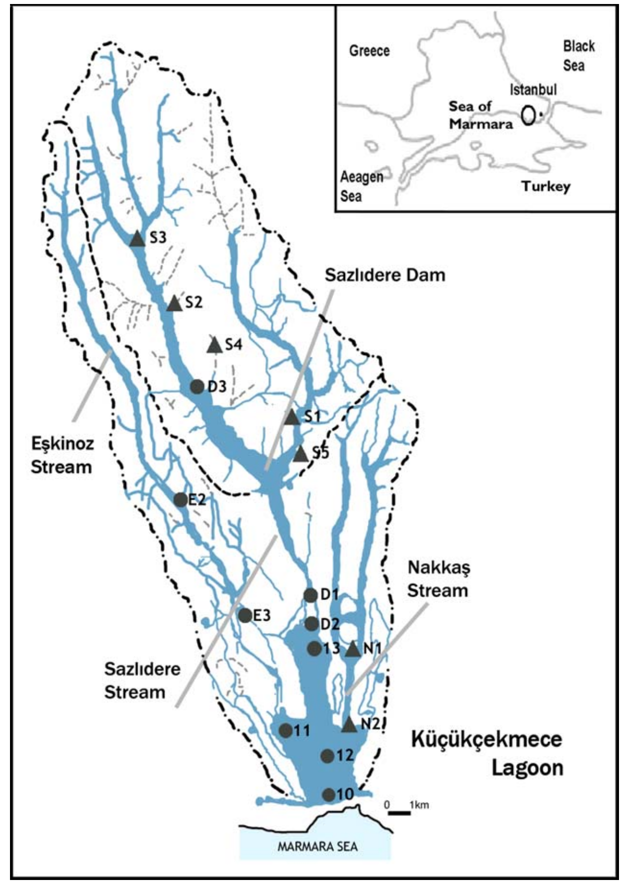

Fig. 1. Küçükçekmece Watershed and Water Quality Monitoring Stations. Our team's sampling stations on Eşkinoz Creek (Stations D1–D3), Sazlidere Creek (Station E2 and E3) and Kucukcekme Lagoon (Stations 10–13) are marked with ●. The additional data set of State Hydraulic Works' (DSI) on Sazlidere Dam (stations S1–S5) are marked with ▲.

2.2.1. Index objectives and variable selection

The objective of L-WQI is to evaluate critical stress on aquatic biota i.e. eutrophication and decreases in oxygen levels of ecosystems as a result of organic pollution by anthropogenic sources. To complete the evaluation, the following parameters were selected as water quality variables to be used in the index: dissolved oxygen (mg/L), DO (saturation ratio); temperature (°C); salinity (ppt); total nitrogen to total phosphorus ratio (TN:TP); orthophosphate, $O\text{-}PO_4$, (mg/L); nitrate, NO_3 (mg/L); chlorophyll-a, Chl-a, (μg/L); chemical oxygen demand, COD (mg/L); ph; turbidity (NTU); and electrical conductivity, EC, (mS/cm). DO is a basic indicator of aquatic stress in water bodies for L-WQI. DO is measured in terms of saturation ratio which is an attribute of in-stream temperature and salinity. COD is an effective indicator of organic pollution load especially in water bodies receiving excessive industrial discharges. TN:TP, Redfield Ratio, indicates the limiting nutrient in the environment for algal growth (Wetzel, 2001). Determination of the limiting nutrient is particularly vital for lagoon systems as they exhibit a transitional character between inland and marine waters. NO_3 and $O\text{-}PO_4$ are soluble and readily found forms of primary nutrient species in freshwaters. Chlorophyll-a, a vital pigment for photosynthesis, is present in most plants and algae. Nutri-

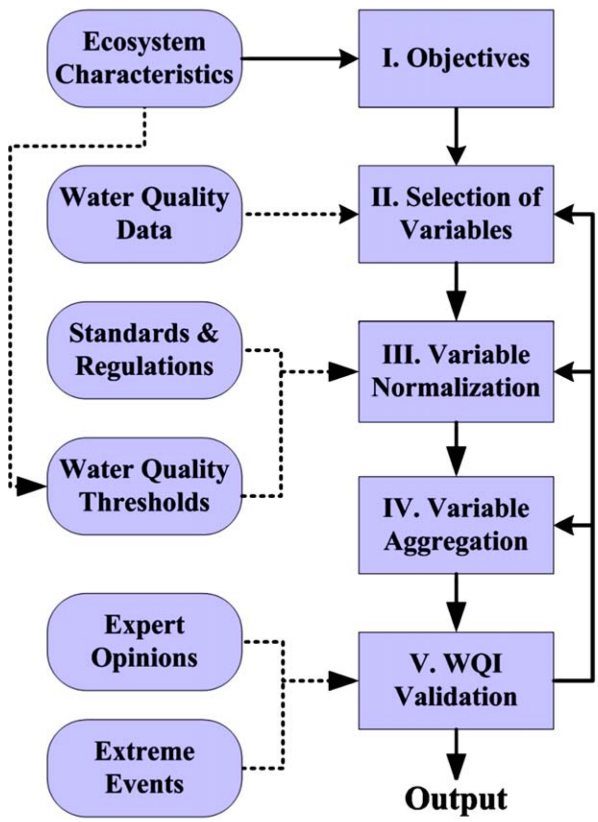

Fig. 2. General framework for water quality indices. The major five steps for developing a WQI.

ent concentrations and chlorophyll-a biomass may correlate in freshwater; however certain factors such as temperature, pH and toxicity may inhibit biomass growth despite excessive nutrient presence.

2.2.2. Variable normalization

In the variable normalization phase, four primary classes have been determined on a scale from 100 to 75 excellent quality, from 75 to 50 good quality, from 50 to 25 critical quality and from 25 to 0 very poor quality. In accordance with this evaluation scale, unique normalization curves were drawn for every L-WQI variable based on international standards and previously developed indices (UNECE, 1994; ANZECC, 2000; Debels et al., 2005) (Fig. 3). The normalized value of each variable was shown with an initial C (e.g. C_{DO}). dissolved oxygen (C_{DO}), chemical oxygen demand (C_{COD}), pH (C_{PH}), electrical conductivity(C_{EC}) and turbidity (C_{TRB}) were directly obtained from normalization curves while a sub-index was used for calculations determining a tropic state index score (C_{TS}). C_{TS} was calculated in two steps based on TN:TP, NO_3, O-PO_4 and chlorophyll-a. First, either C_{NO_3} or $C_{O\text{-}PO_4}$ was selected as the nutrient index score, C_N based on TN:TP ratio Eq. (1). Then, C_N and $C_{Chl\text{-}a}$ were compared and the lowest value was selected as C_{TS} Eq. (2).

$$C_N = \left\{ \begin{array}{l} \text{IF TN : TP } \geq 7.2,\ C_{NO_3} \\ \text{IF TN : TP } < 7.2,\ C_{O-PO_4} \end{array} \right\} \tag{1}$$

$$C_{TS} = \min(C_N, C_{chl\text{-}a}) \tag{2}$$

2.2.3. Variable aggregation

The normalized index scores were finally aggregated with the "weighted sum" formula Eq. (3). Other alternative methods for the aggregation such as the weighted and multiplicative sum, the harmonic mean and power sum function were not effective due to the absolute influence of "low scored" parameters. The power sum which eliminates the shortcomings of the other methods was found to be ineffective in representing small quantitative changes of water quality data. $WQI = \sum_{i=1}^{n} C_i P_i$ *****Weight factors (P_i) assigned to the parameters showed the relative significance of every index variable. The variable weights were 0.25 for DO; 0.24 for tropic state; 0.23 for COD; 0.10 for pH and 0.09 for turbidity and electrical conductivity Eq. (4).

$$\text{L} - \text{QWI} = \sum_{i=1}^{n} CiPi \tag{3}$$

$$\begin{aligned} \text{L} - \text{WQI} = {} & 0.25C_{DO} + 0.24C_{TS} + 0.23C_{COD} + 0.10C_{pH} \\ & + 0.09C_{EC} + 0.09C_{TRB} \end{aligned} \tag{4}$$

3. Results and discussion

3.1. Water Quality Assessment by raw data

The monitoring study in Küçükçekmece Watershed covered a period of 2.5 years and took place at four stations in the lagoon (Stations 10, 11, 12 and 13) and five stations in its tributaries (Station D1, D2, D3, E2 and E3) (Fig. 1). State Hydraulic Works (DSI)'s data covered 5 stations (S1 to S5) and restricted to the area of Sazlidere Dam but in a longer time frame of approximately 8 years. The results of the monitoring study showed persistent life threatening conditions in general with huge fluctuations (Table 1). These fluctuations can be attributed to local conditions and seasonal changes in agricultural and industrial activities within the watershed. DO concentrations in stations E2 and E3 were 2-3 mg/L on average, occasionally dropping below 1 mg/L, which is fatal for fish and other higher species. Severe conditions were also observed in other stations throughout the watershed, while stations from S1 to S5 located in the unpolluted upstream of Sazlidere had DO concentrations around saturation levels. COD measurements yielded extremely high results, around 300 to 500 mg/L on average and reaching above 2000 mg/L during extreme conditions. While such COD values are associated with industrial wastewater discharges rather than natural streams, the tributaries of Küçükçekmece function as a "discharge channel" for the factories and residential areas in the vicinity. The environmentally unacceptable conditions were also explicit for nutrient concentrations. For the lagoon, nutrient concentrations reached their peak at Station 10, yielding an average of 9.3 mg/L and 6.3 for NO_3^--N and O-PO_4 respectively, while stations 11, 12 and 13 also indicated euthrophic conditions. Even higher nutrient levels were seen at tributary stations with E2 on the extreme, having average concentrations of 16.1 mg/L for NO_3^--N and 18.5 mg/L for O-PO_4 (Table 1).

3.2. Water quality assessment by L-WQI

The L-WQI results supported the water quality assessments based on individual water quality variables. L-WQI scores of our monitoring stations for the entire monitoring period were found at "critical quality" on a majority of occasions between November 2005 and March 2008 (Fig. 4). The only exception was the D3 Sampling Station with an occasional water quality classification of "good quality". Sazlidere and Eşkinoz Streams were proven to be the primary pollutant sources of the lagoon with critical to very poor water quality. As a result, it was no surprise when the water

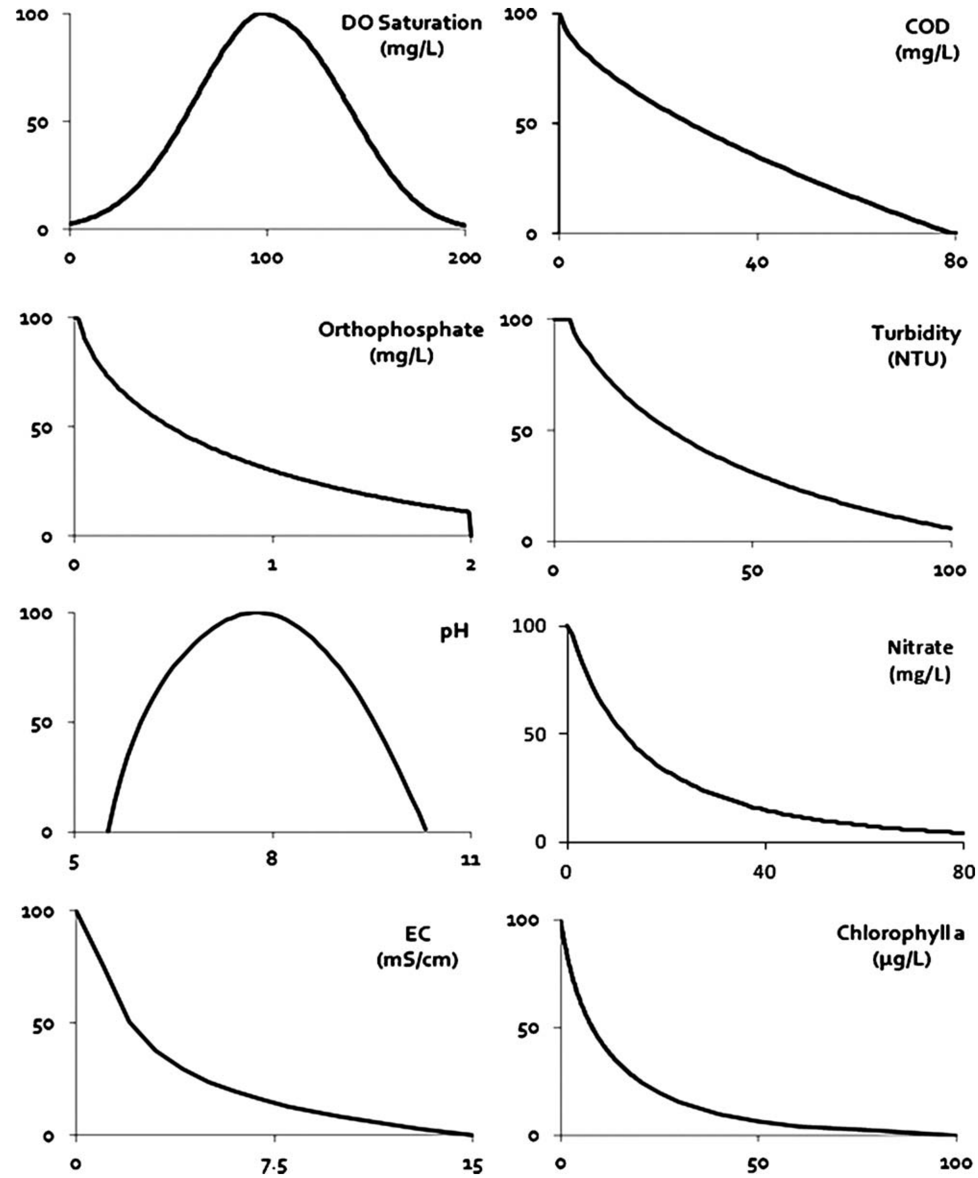

Fig. 3. Variable normalization curves for L-WQI. In each graph, the *x*-axis in each shows measurment values and the *y*-axis shows the normalized values.

at Stations D1 and D2 on Sazlidere Stream outlet was found to be seriously degraded. Water quality at Station 10 (located near the lagoon's connection channel) and Station 12 (in the center of the Lagoon) was slightly better than that of Stations 11 and 13 on the respective outlets of Sazlidere and Eşkinoz Stream. The WQI showed lower scores for all our stations during the algal blooming event at December 2005 (Fig. 4). However DSI's monitoring study yielded clearly higher L-WQI scores. As expected, samples from stations S1 to S5 were found to be mostly "good quality" due to the fact that they were all taken from locations on the unpolluted upstream part of Sazlidere. There were also notable differences in the dispersion of L-WQI scores between wet and dry seasons (Fig. 5). The average L-WQI scores of Stations from S1 to S5 from November to February (wet season) were 79, 79, 76, 79, 77 while March to October (dry season) L-QWI scores were slightly higher: 83, 85, 82, 82 and 83 respectively. This seasonal difference in water quality can be attributed to land-use patterns at the upstream part of Sazlidere Stream, i.e. the dominance of agricultural applications and washout of pesticides and fertilizers.

3.3. Validity of L-WQI

Indices are aggregate performance evaluation tools that do not have cause-effect structures as in mechanistic models. Up to now, no widely accepted formal procedures have been proposed for validating WQIs. On a pragmatic approach, it would be to argue that a WQI is valid with respect to its intention purpose, if the WQI score reflects water quality conditions. For the study of L-WQI, the index scores were found to reflect spatial changes (e.g. differences between tributaries and water quality changes in the Lagoon) and temporal changes (e.g. the wet season-dry season effect on water quality, seasonal algal blooms) as they were found to be temporarily parallel to the overall water quality trends throughout the study area.

For evaluating index performance, L-WQI scores at our monitoring stations were also compared with the Oregon WQI (O-WQI) (Cude, 2001) and the Arithmetic Coastal WQI (C-WQI) (Gupta et al., 2003). The O-WQI, which aids the assessment of water quality for general recreational uses (i.e. fishing and swimming) and calculated based on temperature (°C), dissolved oxygen (mg/L), bio-

Table 1
Water quality data for the sampling stations at Küçükçekmece Lagoon Watershed. *N* shows the number of samples collected. "A" is for annual averages, "D" is for dry Season (from March to October), "W" is for wet season (from November to February). The values show the mean ± standard error.

Station and *n*-value		DO (mg/L)	Temp. (°C)	EC (mS/cm)	COD (mg/L)	NO_3-N (mg/L)	O-PO_4 (mg/L)	TN:TP	Turbidity (NTU)	pH	Chlorophyll-a (μg/L)
D1 *n* = 16	A	5.16 ± 0.83	14.82 ± 1.92	3 ± 0.72	176 ± 47	7.88 ± 2.83	20.94 ± 2.49	1.96 ± 0.84	34.44 ± 6.19	7.66 ± 0.09	95.71 ± 27.34
	W	4.17 ± 0.93	10.8 + 1.21	1.7 ± 0.49	237 ± 78	11.19 ± 4.52	19.15 ± 3.50	3.09 ± 1.37	40.78 ± 9.18	7.51 ± 0.11	68.32 ± 25.38
	D	6.45 ± 1.41	19.99 ± 3.26	4.68 ± 1.31	96 ± 17	4.58 ± 0.56	23.03 ± 2.70	0.83 ± 0.17	26.29 ± 7.43	7.85 ± 0.1	127.67 ± 44.86
D2 *n* = 12	A	6.53 ± 0.99	16.59 ± 2.31	9.0 ± 1.87	162 ± 51	4.15 ± 0.61	11.26 ± 2.18	1.41 ± 0.70	20.92 ± 3.74	7.8 ± 0.13	64.25 ± 17.9
	W	7.11 ± 1.32	10.93 ± 1.81	5.92 ± 2.12	106 ± 27	3.76 ± 0.61	6.83 ± 2.05	0.52 ± 0.08	21.33 ± 4.98	7.78 ± 0.19	53.13 ± 25.58
	D	5.95 ± 1.56	22.25 ± 2.72	12.09 ± 2.67	217 ± 97	4.53 ± 0.98	15.7 ± 1.36	2.6 ± 1.05	20.5 ± 6.06	7.83 ± 0.2	77.6 ± 24.13
D3 *n* = 14	A	7.95 ± 1.00	14.36 ± 2.69	0.43 ± 0.04	110 ± 25	5.79 ± 1.00	1.18 + 0.40	27 ± 4.9	37.93 ± 20.9	8.01 ± 0.12	19.34 ± 10.16
	W	8.17 ± 1.28	9.33 ± 1.17	0.47 ± 0.03	179 ± 29	9.6 ± 3.84	0.9 ± 0.40	3.68 ± 1.99	51.5 ± 33.74	8.11 ± 0.15	22.81 ± 14.91
	D	7.68 ± 1.63	21.08 ± 4.57	0.38 ± 0.07	84 ± 15	1.97 ± 1.26	1.52 ± 0.64	14 ± 3.27	19.83 ± 8.1	7.89 ± 0.18	13.8 ± 8.1
E2 *n* = 14	A	4.24 ± 0.73	13.96 ± 1.43	1.55 ± 0.13	597 ± 162	16.06 ± 2.20	18.51 ± 4.14	14.51 ± 7.74	386.36 ± 234	7.72 ± 0.05	13.23 ± 2.64
	W	4.75 ± 0.91	12.68 ± 1.14	1.63 ± 0.17	371 ± 73	15.67 ± 2.68	14.05 ± 2.94	8 ± 3.76	110.33 ± 32	7.78 ± 0.06	12.13 ± 3.2
	D	3.31 ± 1.24	16.26 ± 3.44	1.4 ± 0.19	1005 ± 394	16.68 ± 3.87	25.2 ± 7.53	30.79 ± 15.9	883.2 ± 631	7.61 ± 0.08	15.2 ± 5
E3 *n* = 14	A	2.71 ± 0.52	16.36 ± 1.88	2.17 ± 1.04	386 ± 84	12.19 ± 3.03	19.11 ± 4.04	9.28 ± 5.08	87.64 ± 14.3	7.68 ± 0.07	12.7 ± 5.15
	W	3.37 ± 3.37	12.57 ± 12.57	1.15 ± 1.15	283 ± 283	13.67 ± 3.67	10.61 ± 0.6	2.01 ± 2.01	92 ± 25.4	7.68 ± 0.1	16.72 ± 8.78
	D	2.06 ± 0.59	20.14 ± 3.16	3.19 ± 2.07	488 ± 147	10.93 ± 1.51	26.2 ± 5.25	16.55 ± 2.01	83.29 ± 27.06	7.68 ± 0.11	8 ± 4.33
10 *n* = 13	A	7.29 ± 1.12	13.43 ± 2.00	15.56 ± 0.80	1034 ± 143	9.27 ± 3.18	6.38 ± 1.73	1.57 ± 6.91	15.77 ± 4.96	8.02 ± 0.11	146.79 ± 62.48
	W	6.94 ± 1.63	10.42 ± 1.42	16.27 ± 0.85	1461 ± 291	16.37 ± 5.31	8.69 ± 3.67	1 ± 1.15	20.83 ± 10.24	7.83 ± 0.19	201.47 ± 120.98
	D	7.59 ± 1.66	16.01 ± 3.32	14.95 ± 1.32	667 ± 138	5.72 ± 2.14	4.73 ± 0.75	2.02 ± 0.3	11.43 ± 3.08	8.19 ± 0.09	92.11 ± 33.9
11 *n* = 13	A	5.39 ± 0.72	12.76 ± 1.40	12.14 ± 1.60	602 ± 250	7.89 ± 2.49	5.95 ± 0.95	1.08 ± 0.48	21.69 ± 3.58	7.77 ± 0.12	61.66 ± 36.93
	W	5.89 ± 0.90	11.55 ± 0.93	13.13 ± 1.97	726 ± 362	8.83 ± 3.15	7 ± 1.26	0.63 ± 0.14	25.38 ± 3.45	7.65 ± 0.16	95.93 ± 57.97
	D	4.61 ± 1.22	14.7 ± 3.35	10.56 ± 2.84	403 ± 307	6.57 ± 4.02	4.38 ± 0.26	2.88 ± 0.3	15.8 ± 7.25	7.97 ± 0.18	6.82 ± 2.11
12 *n* = 14	A	7.92 ± 0.99	13.33 ± 1.79	15.64 ± 0.75	738 ± 296	6 ± 1.78	4.8 ± 0.44	1.13 ± 0.39	15.5 ± 4.55	8.03 ± 0.13	122.28 ± 48.11
	W	7.43 ± 1.15	11.13 ± 1.24	16.32 ± 0.72	795 ± 539	7.47 ± 2.65	5.6 ± 0.54	0.79 ± 0.19	14 ± 5.43	7.87 ± 0.17	128.63 ± 65.9
	D	8.41 ± 1.69	15.53 ± 3.05	14.96 ± 1.33	680 ± 331	4.95 ± 2.19	4.13 ± 0.44	1.46 ± 0.50	17 ± 7.52	8.18 ± 0.2	114.88 ± 71.34
13 *n* = 14	A	7.02 ± 1.03	13.72 ± 1.90	14.41 ± 1.24	436 ± 112	6.27 ± 2.02	4.77 ± 0.63	0.66 ± 0.28	19.79 ± 6.33	7.89 ± 0.16	101.3 ± 58.46
	W	6.05 ± 1.12	10.73 ± 1.44	14.9 ± 1.48	348 ± 114	9.36 ± 4.19	4.23 ± 1.05	0.37 ± 0.17	27.33 ± 13.86	7.93 ± 0.26	168.53 ± 126.02
	D	7.76 ± 1.62	15.96 ± .2.99	14.04 ± 1.94	503 ± 180	4.34 ± 1.46	5.09 ± 0.68	0.84 ± 0.33	14.13 ± 4.06	7.86 ± 0.22	43.69 ± 11.6
S1 *n* = 54	A	9.77 ± 0.22	13.65 ± 0.98	0.57 ± 0.03	15 ± 0.85	2.08 ± 0.24	0.5 ± 0.05	11.21 ± 1.75	36.78 ± 3.17	7.87 ± 0.05	n/a
	W	11.15 + 0.22	6.6 ± 0.67	0.63 ± 0.06	17 ± 1.58	3.2 ± 0.42	0.43 ± 0.07	10.32 ± 1.95	41.13 ± 6.39	8.07 ± 0.08	n/a
	D	9.16 + 0.23	16.76 ± 0.99	0.55 ± 0.03	14 ± 0.98	1.59 ± 0.25	0.53 ± 0.07	11.6 ± 2.4	34.85 ± 3.61	7.79 ± 0.06	n/a
S2 *n* = 34	A	10.09 ± 0.25	12.94 ± 1.16	0.6 ± 0.03	13 ± 0.76	1.69 ± 0.27	0.41 ± 0.06	8.12 ± 1.3	26.97 ± 2.39	7.93 ± 0.07	n/a
	W	11.22 ± 0.27	7.5 ± 1.02	0.61 ± 0.06	13 ± 1.42	2.87 ± 0.46	0.31 ± 0.07	7.4 ± 1.1	34.67 ± 4.77	8.12 ± 8.12	n/a
	D	9.48 ± 0.27	15.91 ± 1.33	0.6 ± 0.03	12 ± 0.89	1.04 ± 0.24	0.44 ± 0.08	8.6 ± 1.8	22.77 ± 2.24	7.82 ± 0.09	n/a
S3 *n* = 27	A	8.42 ± 0.36	12.26 ± 1.35	0.7 ± 0.01	11 ± 0.89	2.4 ± 0.44	0.66 ± 0.11	7.86 ± 1.9	31.63 ± 5.48	7.25 ± 0.06	n/a
	W	8.94 ± 0.64	4.82 ± 0.88	0.63 ± 0.02	12 ± 1.92	3.42 ± 0.91	0.69 ± 0.21	9.26 ± 3.62	39.09 ± 11.18	7.25 ± 0.11	n/a
	D	8.07 ± 0.41	17.38 ± 0.83	0.75 ± 0.02	9 ± 3.52	1.7 ± 0.33	0.63 ± 0.13	6.9 ± 2.1	26.5 ± 5.12	7.24 ± 0.07	n/a
S4 *n* = 18	A	8.58 ± 0.51	11.44 ± 1.47	0.75 ± 0.08	10 ± 2.24	1.12 ± 0.37	2.22 ± 0.92	4.79 ± 2	32.28 ± 5.37	7.29 ± 0.09	n/a
	W	9.62 ± 1.03	5 ± 0.77	0.7 ± 0.08	12 ± 1.59	1.84 ± 1.01	1.34 ± 0.68	2.72 ± 0.79	39.33 ± 12.79	7.23 ± 0.22	n/a
	D	8.06 ± 0.53	14.67 ± 1.42	0.77 ± 0.02	9 ± 3.28	0.75 ± 0.24	2.66 ± 1.34	5.83 ± 2.97	28.75 ± 5.12	7.33 ± 0.09	n/a
S5 *n* = 28	A	9.89 ± 0.30	13.9 ± 1.37	0.53 ± 0.04	13 ± 1.77	1.61 ± 0.22	0.34 ± 0.05	14.74 ± 4.06	39.68 ± 8.03	7.99 ± 0.07	n/a
	W	11.38 ± 0.38	6 ± 1.05	0.56 ± 0.04	17 ± 1.04	2.83 ± 0.43	0.18 ± 0.03	29.49 ± 12.9	39.43 ± 6.7	8.16 ± 0.12	n/a
	D	9.4 ± 0.32	16.53 ± 1.37	0.51 ± 0.02	11 ± 1.97	1.2 ± 0.19	0.39 ± 0.06	9.82 ± 2.91	39.76 ± 10.57	7.93 ± 0.09	n/a

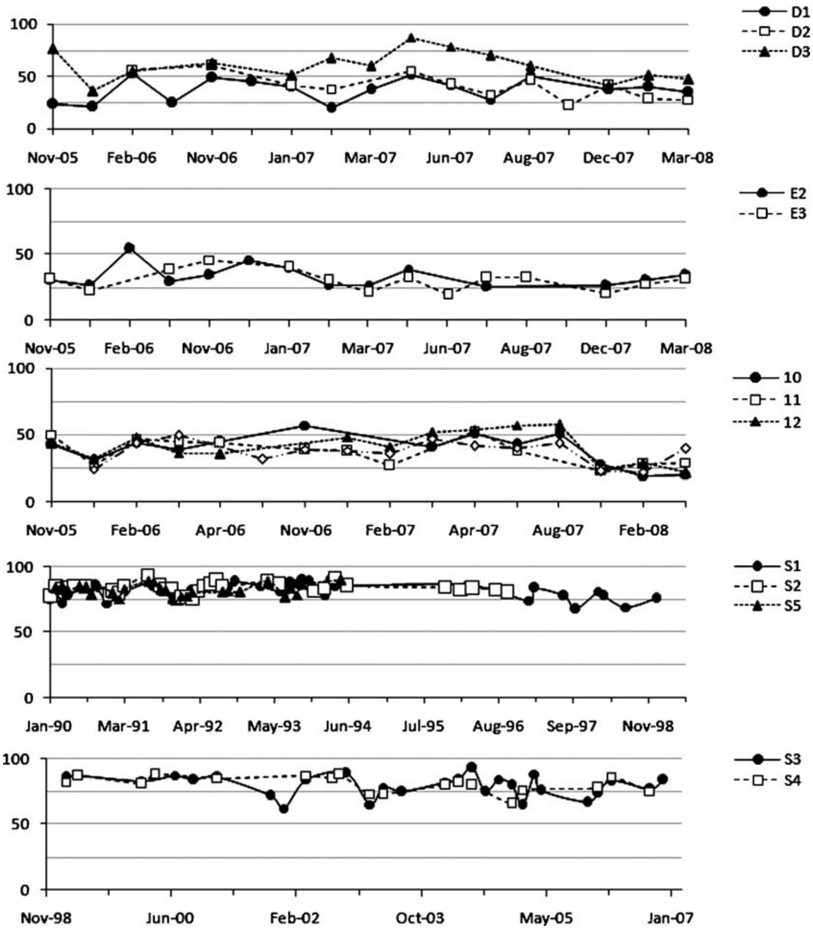

Fig. 4. Monthly trends of L-WQI scores for Water Quality Monitoring Stations at Küçükçekmece Watershed. Gridlines represent critical L-WQI values, 25, 50 and 75 respectively.

chemical oxygen demand (mg/L), pH, total nitrogen (mg/L), total phosphorus (mg/L), total solids (mg/l) and feacal coliform (#/mL) was found insensitive to spatial and temporal changes with an average standard error of 0.28 (Fig. 6). On the other hand C-WQI, based on coastal water quality standards and an expression of dissolved oxygen (mg/L), pH, biochemical oxygen demand (mg/L), temperature (°C), total suspended solids (mg/L) and turbidity (NTU) was highly correlated with L-WQI (Table 2), but yielded notably higher scores at all stations (Fig. 6). The comparison of the three indices showed that both L-WQI and C-WQI can be effectively used for polluted coastal lagoons, while O-WQI is not suitable. C-WQI's tendency to give higher scores is a disadvantage compared to L-WQI, especially for expressing temporal variability in polluted systems.

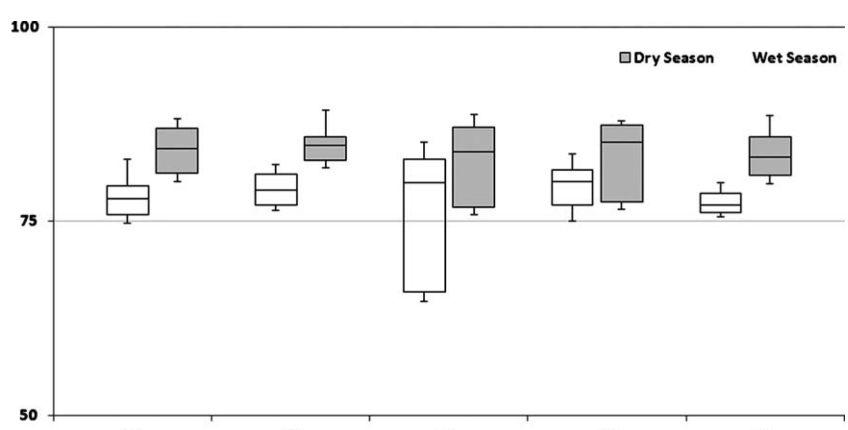

Fig. 5. Seasonal comparison of L-WQI scores for Water Quality Monitoring Stations from S1 to S5. Dry season is from March to October, wet season is from November to February. The Box-and-whisker diagram depicts the 10th percentile, lower quartile (25th percentile), the median, the upper quartile (75th percentile) and the 90th percentile of the WQI scores respectively.

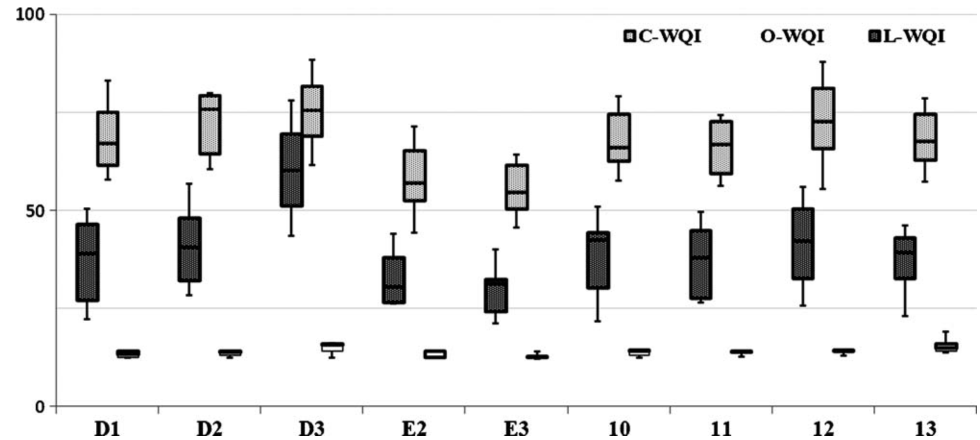

Fig. 6. Comparison of Lagoon Water Quality Index (L-WQI), Coastal Water Quality Index (C-WQI) and Oregon Water Quality Index (O-WQI) for Kucukcekmece Lagoon. The Box-and-whisker diagram depicts the 10th percentile, lower quartile (25th percentile), the median, the upper quartile (75th percentile) and the 90th percentile of the WQI scores respectively.

Table 2
Correlation matrix for L-WQI, C-WQI and O-WQI at stations D3, E3 and 12. IN1 is for L-WQI, IN2 is for C-WQI and IN3 is for O-WQI.

IN1_D3	IN2_D3	IN3_D3	IN1_E3	IN2_E3	IN3_E3	IN1_12	IN2_12	IN3_12	
1	0.8016	−0.2563	0.1685	0.1866	0.1191	0.7007	0.7706	0.3647	IN1_D3
	1	−0.031	0.141	0.2706	0.3909	0.48	0.7736	0.2042	IN2_D3
		1	−0.1386	0.0369	0.3393	−0.3981	−0.3016	−0.016	IN3_D3
			1	0.722	0.5644	0.4555	0.3608	0.392	IN1_E3
				1	0.6382	0.5384	0.3835	0.4467	IN2_E3
					1	−0.0562	0.1719	0.0988	IN3_E3
						1	0.7908	0.5199	IN1_12
							1	0.3852	IN2_12
								1	IN3_12

4. Conclusions

- WQIs are simple assessment tools in contrast to today's computer based decision support systems. The use of WQIs has advantages for government agencies and institutions where regular water quality data is scarce and financial budgets are limited. Furthermore indices are ideal for sharing information with the general public and decision-makers who do not have the adequate background to interpret complicated water quality outputs.
- Lagoon systems necessitate specially developed water quality assessment tools. WQIs used as water quality assessment tools in lagoons should take their sensitive ecology and unique transitional character between inland and saline waters into consideration. The key indicators for this purpose are a primary emphasis on dissolved oxygen levels, the dominant shifts in nutrient compounds and organic pollution loads.
- The Lagoon Water Quality Index (L-WQI) developed in this study has been applied in the Küçükçekmece Watershed, one of the most problematic regions of Istanbul in terms of environmental degradation. Despite limited data availability, L-WQI performed satisfactorily in revealing both spatial and temporal water quality trends in the study area.
- For lagoon systems in general, the proposed L-WQI can be further enhanced by introducing new water quality variables (e.g. those related to toxicity) and can be tested and used as a simple decision support tool for urbanized and polluted lagoon systems in particular.

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References

Abbasi, S.A., 2002. Water Quality Indices, State of the Art Report No:INCOH/SAR-25/2002. INCOH, National Institute of Hydrology, Roorke.

Aguilera, P.A., Castro, H., Rescia, A., Schmitz, M.F., 2001. Methodological development of an index of coastal water quality: application in a tourist area. Environ. Manage. 27 (2), 295–301.

ANZECC, 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. National Water Quality Management Strategy, Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

A.P.H.A., 1995. Standard Methods for The Examination of Water and Wastewater, 19th ed. American Public Health Association, Washington.

Atazadeh, I., Sharifi, M., Kelly, M.G., 2007. Evaluation of the trophic diatom index for assessing water quality in River Gharasou, Western Iran. Hydrobiologia 589, 165–173.

Barnes, R.S.K., 1989. The Lagoons of Britain: an overview and conservation appraisal. Biol. Conserv. 49, 295–313.

Chen, C.H., Liu, W.L., Leu, H.L., 2006. Sustainable water quality management framework and a strategy planning system for a River Basin. Environ. Manage. 38, 952–973.

Cude, C.G., 2001. Oregon Water Quality Index: a tool for evaluating water quality management effectiveness. J. Am. Water Resour. Assoc. 37 (1), 125–137.

Debels, P., Figueroa, R., Urrutia, R., Barra, R., Niell, X., 2005. Evaluation of water quality in the Chillán River (Central Chile) using physicochemical parameters and a modified Water Quality Index. Environ. Monit. Assess. 110, 301–322.

Edet, A.E., Offiong, O.E., 2003. Evaluation of water quality pollution indices for heavy metal contamination monitoring. A study case from Akpabuyo – Odukpani area, Lower Cross River Basin (southeastern Nigeria). Geo. J. 57, 295–302.

Giljanovic, N.S., 1999. Water quality evaluation by index in Dalmatia. Water Res. 33 (16), 3423–3440.

Gupta, A.K., Gupta, S.K., Patil, R.S., 2003. A comparison of water quality indices for coastal water. J. Environ. Sci. Health A 38, 2711–2725.

Huang, G.H., Xia, J., 2001. Barriers to sustainable water-quality management. J. Environ. Manage. 61, 1–23.

Icaga, Y., 2007. Fuzzy evaluation of water quality classification. Ecol. Indic. 7, 710–718.

Johnson, D.E., Bartlett, J., Nash, L.A., 2007. Coastal lagoon habitat re-creation potential in Hampshire, England. Mar. Policy 31, 599–606.

Jonnalagadda, S.B., Mhere, G., 2001. Water quality of the Odzi river in the eastern highlands of Zimbabwe. Water Res. 35, 2371–2376.

Kannel, P.R., Lee, S., Lee, Y.S., Kanel, S.R., Khan, S.P., 2007. Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. Environ. Monit. Assess. 132, 93–110.

Kaurish, F.W., Younos, T., 2007. Developing a standardized Water Quality Index for evaluating surface water quality. J. Am. Water Resour. Assoc. 43 (2), 533–545.
Khuan, L.Y., Hamzah, N., Jailani, R., 2002. Prediction of Water Quality Index (WQI) based on artificial neural networks (ANN). Student Conference on Research and Development, Shah Alam, Malaysia, pp. 157–161.
Liou, S., Lo, S., Wang, S.A., 2004. Generalized Water Quality Index for Taiwan. Environ. Monit. Assess. 96, 35–52.
Lumb, A., Halliwell, D., Sharma, T., 2006. Application of CCME Water Quality Index to Monitor Water Quality: a case of the Mackenzie River Basin. Canada. Environ. Monit. Assess. 113, 411–429.
Nasiri, F., Maqsood, I., Huang, G., Fuller, N., 2007. Water Quality Index: a fuzzy river-pollution decision support expert system. J. Water Resour. Plng. Mgmt. 133 (2), 95–105.
Said, A., Stevens, D.K., Sehlke, G., 2004. An innovative index for evaluating water quality in streams. Environ. Manage. 34 (3), 406–414.
Simoes, F.S., Moreira, A.B., Bisinoti, M.C., Gimenez, S.M.N., Yabe, M.J.S., 2008. Water Quality Index as a simple indicator of aquaculture effects on aquatic bodies. Ecol. Indic. 8 (5), 476–484.
Taner, M.Ü., Üstün, B., Şenduran, C., 2007. Perspectives of development a Watershed Sustainability Index. In: Proceedings of the 3rd International Conference on Environmental Science and Technology, Houston, TX.
UNECE, 1994. Standard statistical classification of surface freshwater quality for the maintenance of aquatic life. In: Readings in International Environment Statistics. United Nations Economic Commission for Europe, United Nations, New York and Geneva.
Üstün, B., Ince, N., Cansever, G., Ülger, E., Agcıoglu, B., Sapçı, Z., Demirel, S., Taner, M.Ü., et al., 2005. The Development of Environmental Management Model in Küçükçekmece Basin. Joint Research and Development Project (GSRT-TUBITAK 102A011).
Wetzel, R.G., 2001. Limnology, 2nd ed. Saunders College Publishing, New York.