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RESEARCH

Comparative evaluation of spatiotemporal variations of surface water quality using water quality indices and GIS

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Abstract
There is a need for a comprehensive comparative analysis of spatiotemporal variations in surface water quality, particularly in regions facing multiple pollution sources. While previous research has explored the use of individual water quality indices (WQIs), there is limited understanding of how different WQIs perform in assessing water quality dynamics in complex environmental settings. The objective of this study is to evaluate the effectiveness of three WQIs (Canadian Council of Ministers of the Environment (CCME), National Sanitation Foundation (NSF) and System for Evaluation of the Quality of rivers (SEQ-Eau) and a national water quality regulation in assessing water quality dynamics. The pilot study area is the Acısu Creek in Antalya City of Turkey, where agricultural practices and discharge of treated wastewater effluents impair the water quality. A year-long intensive monitoring study was conducted includig on-site measurements, analysis of numerous physicochemical and bacteriological parameters. The CCME and SEQ-Eau indices classified water quality as excellent/good at the upstream, gradually deteriorating to very poor downstream, showing a strong correlation. However, the NSF index displayed less accuracy in evaluating water quality for certain monitoring stations/sessions due to eclipsing and rigidity problems. The regulatory approach, which categorized water quality as either moderate or good for different sampling sessions/stations, was also found less accurate. The novelty of this study lies in its holistic approach to identify methodological considerations that influence the performance of WQIs. Incorporating statistical analysis, artificial intelligence or multi-criteria decision-making methods into WQIs is recommended for enhanced surface water quality assessment and management strategies.

Keywords CCME · Monitoring study · NSF · SEQ-Eau · Water quality index · Water quality regulation

Introduction

Increasing water demand globally, driven by agricultural, industrial activities, population growth, urbanization, and climate change, intensifies pressure on water resources (Kummu et al. 2016). About half of the global population faces severe water scarcity at least part of the year, with some regions experiencing year-round shortages (IPCC 2023) and as of 2022, 2.2 billion people were without access to safely managed drinking water (UN 2024). Pollution from fertilizers, pesticides, and wastewater further exacerbates water quality issues. In lower-income countries, inadequate wastewater treatment primarily contributes to poor ambient water quality, while in higher-income countries, agricultural runoff is the main concern. Evaluating water body status and sustainable water management are crucial to meet growing water demand and protect ecosystems. However, there is a lack of water quality data especially in many low- and lower-middle-income countries as ambient water quality data are not consistently gathered (UN 2023). This poses a risk to over 3 billion people, as their freshwater ecosystems may fall below acceptable standards (UNEP 2021).

Aquatic system monitoring programs are crucial for sustainable water quality management, yet complexities arise when handling vast amounts of data from numerous monitoring stations for many water quality parameters (Almeida et al. 2007). In many cases, water practitioners face difficulty

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to comprehend the monitoring results of a single water status/class due to the large amount of data obtained from monitoring studies which usually requires the need for advanced knowledge and expertise for evaluation (Zotou et al. 2020). However, water quality indices (WQIs) simplify interpretation by condensing data into a single value, aiding decision-making and assessing pollution impacts (Poonam et al. 2013). WQIs utilize diverse physicochemical, bacteriological, and metallic trace element data to generate final index values through subindices. WQIs are widely used globally for water quality assessment (Maansi Jindal and Wats 2021; Lopes et al. 2021; Uddin et al. 2021; Gupta and Gupta 2021; Al Falal et al. 2024). Moreover, WQIs are used to determine spatiotemporal variations in water quality (Noori et al. 2019), to analyze changes in water quality trends (Sun et al. 2016) and to compare water quality at different locations or geographical areas (Sun et al. 2016). Integration of WQIs with remote sensing and GIS enhances modeling (Mohammed et al. 2023, 2024; Muneer et al. 2021; Sattar et al. 2024).

WQIs can be categorized into four groups: general, specific, statistical, and planning/decision-making indices. General WQIs assess overall water quality, disregarding specific use designations, while specific WQIs target particular water uses (Abbasi and Abbasi 2012). Examples of general WQIs include the National Sanitation Foundation (NSF) (Brown et al. 1970), British Columbia WQI (Zandbergen and Hall 1998), Oregon WQI (Dunnette 1979), Overall Index of Pollution (OIP) (Sargaonkar and Deshpande 2003), River Pollution Index (Liou et al. 2004), Universal WQI (U-WQI) (Boyacioglu 2007), Canadian Council of Ministers of the Environment (CCME) WQI (CCME 2001a, b) and System for Evaluation of the Quality of rivers (SEQ-Eau) (SEQ-EAU 2003; SEEE 2008). The Aquatic Toxicity Index is an example of specific WQIs to evaluate the health of aquatic ecosystems (Wepener et al. 1992). The statistical WQIs apply statistical techniques, such as factor analysis and principal component analysis, to evaluate data instead of expert opinions and they identify the significance of important parameters in water quality assessment (Poonam et al. 2013). Harkin's Index (Harkin 1974), Beta Function Index (Schaeffer and Janardan 1977), Mixed Aggregation Function (Liou et al. 2004), WQI based on multivariate techniques (Qian et al. 2007; Coletti et al. 2010) are some examples for the statistical WQIs. Starting with the study of Kung et al. (1992) artificial intelligence techniques were applied to develop WQIs often in conjunction with the statistical methods (Mahmood and Batool 2020; Elsayed et al. 2021a), spectral indices and multivariate modeling (Gad et al. 2020, 2022; Elsayed et al. 2021b). Planning/decision-making indices cover a wide range of applications including the impacts of ecoregional, hydrological and limnological factors, watershed quality and pollution assessment, irrigation water quality, reclaimed water for irrigation, drinking water adequacy, protection of stream corridor integrity and water quality buffers to control diffuse pollution (Abbasi and Abbasi 2012).

National regulations and regional water quality directives are commonly developed and applied to set environmental objectives, guide monitoring, and propose pollution control measures, such as The European Water Framework Directive (WFD) (EC 2000). However, national regulations or directives lack standardized methods for water quality classification, leading to compatibility issues (Trikoilidou et al. 2017; Zotou et al. 2020). Due to the involvement of different national and international agencies in water quality assessment globally, different indicator parameters are considered as water quality criteria for different beneficial uses of water, which complicates the comparison of final water status (Mogane et al. 2023). Additionally, water practitioners and researchers face difficulty to choose the best approach, national/international regulations, or alternative tools/methods, for the evaluation and classification of water quality (Gupta and Gupta 2021; Lukhabi et al. 2023). While previous research has explored the use of individual WQIs (Hamlat et al. 2017) or focused on specific geographic areas (Sener et al. 2017; Gikas et al. 2023), there is limited understanding of how different WQIs perform in assessing water quality dynamics in complex environmental settings (Syeed et al. 2023). Consequenly, there is a need for comparative studies of water quality classification using different methods and tools to test their accuracy and reliability (Chidiac et al. 2023). Therefore, this study aims to evaluate the effectiveness of three internationally well-known and mostly applied WQIs (CCME, NSF and SEQ-Eau) and a national water quality regulation in assessing water quality dynamics using the capabilities of the GIS, and to highlight the importance of methodological considerations in WQIs (parameter selection, sub-index calculation, and aggregation methods) which can significantly impact the accuracy of water quality assessments. The novelty of this study lies in its comprehensive comparative analysis of spatiotemporal variations in surface water quality using different WQIs and a national water quality regulation to provide a robust assessment of water quality dynamics. The study area of Acısu Creek in Antalya, Turkey, presents a good case study due to its specific environmental challenges. By conducting an intensive monitoring study involving on-site measurements and analysis of numerous physicochemical and bacteriological parameters, this research offers a comprehensive understanding of water quality in a region facing multiple sources of pollution (Muhammetoglu et al. 2022a). The comparison of WQIs allows for an in-depth evaluation of their strengths and limitations in assessing water quality, providing valuable insights for future research and water management practices.

Materials and methods

Study area

The pilot study area (PSA) of the Acısu Creek is about 40 km away from Antalya city center and it is located between *Aksu* and *Koprucay* Streams, in the south of Turkey, between the northern latitudes of 36°48'-37°9' and the eastern longitudes of 30°57'-31°12' (Muhammetoglu 2022b). The creek is within the Antalya River Basin and discharges to the Mediterranean Sea. The location of the PSA in Turkey and in Antalya province is depicted in Fig. 1 with the districts of Antalya. The whole length of the Acısu Creek is approximately 40 km and the total basin area is 37,818 ha. Approximately 71% of the basin consists of agricultural areas (26,710 ha) and 21% is covered by forests (7891 ha). In the northern part of the basin, the majority of the area is used or covered by forests and agricultural lands (Fig. 2a). Intense agricultural activities are carried out in the Acısu Creek Basin which is also an important tourism destination for local and international tourists.

The Mediterranean climate is dominant in the PSA, with high precipitation in winter and high evaporation rates in summer. The mean annual air temperature, total annual precipitation, and surface evaporation rates were 19 °C, 782 mm/year, and 1392.5 mm, respectively, for the year 2021. The land elevations in the basin range from sea level to 1464 m above sea level where the elevation increases towards the northern part of the basin. The study area is located in the Antalya Neogene basin, encompassing Miocene and Pliocene basins. Geological units include the Miocene Karpuzçay Formation and Quaternary alluvial deposits. Erosion surfaces dating back to the Late Pliocene-Early Pleistocene are the oldest features, with elevations of about 100–120 m. Karpuzçay is the dominant formation, characterized by deltaic features and consisting of sandstone, mudstone, and siltstones. Rivers incise the terrain, forming steep valleys and wide delta plains. The Kızılot delta plain is formed by alluvium from Karpuzçay and Acısu Creek. The region features salty-alkaline areas and wetlands. A lagoon has formed behind the coastal barrier at the mouth of Acısu Creek. Wind transport inland has formed dunes reaching 5–10 m in elevation (Ozcelik 2017).

Between October 2020 and September 2021, the average flow rates at the upstream and downstream sections of the Acısu Creek were reported as 0.05 and 6.32 m^3/s, respectively (Muhammetoglu 2022b). The upstream section of the creek has an average water depth of 0.15 m, while the midstream ranges from 1.2 to 2.7 m, with a maximum depth of 2.7 m. Downstream depths range from 1.0 to 2.5 m, with urban settlements and tourism concentrated in this area. Three wastewater treatment plants (WWTPs) discharge directly into the creek near the coast. These discharges, along with agricultural activities, are major sources of both point and diffuse pollution, leading to water quality deterioration. Excessive irrigation and reduced summer precipitation often lead to stagnation or drying of the upstream section (Muhammetoglu 2022b).

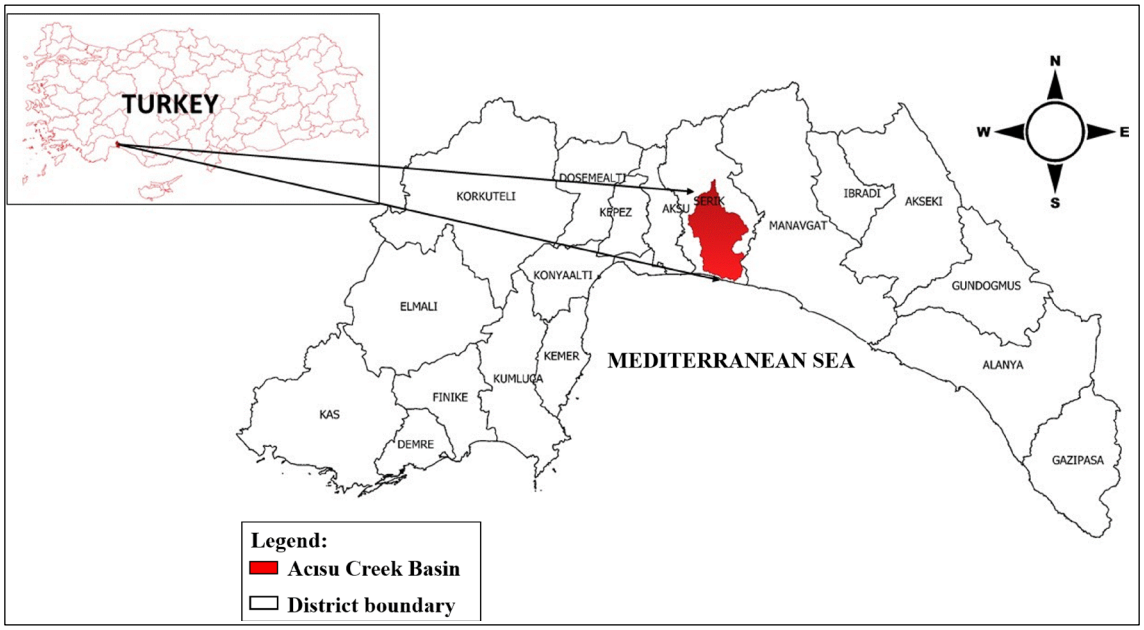
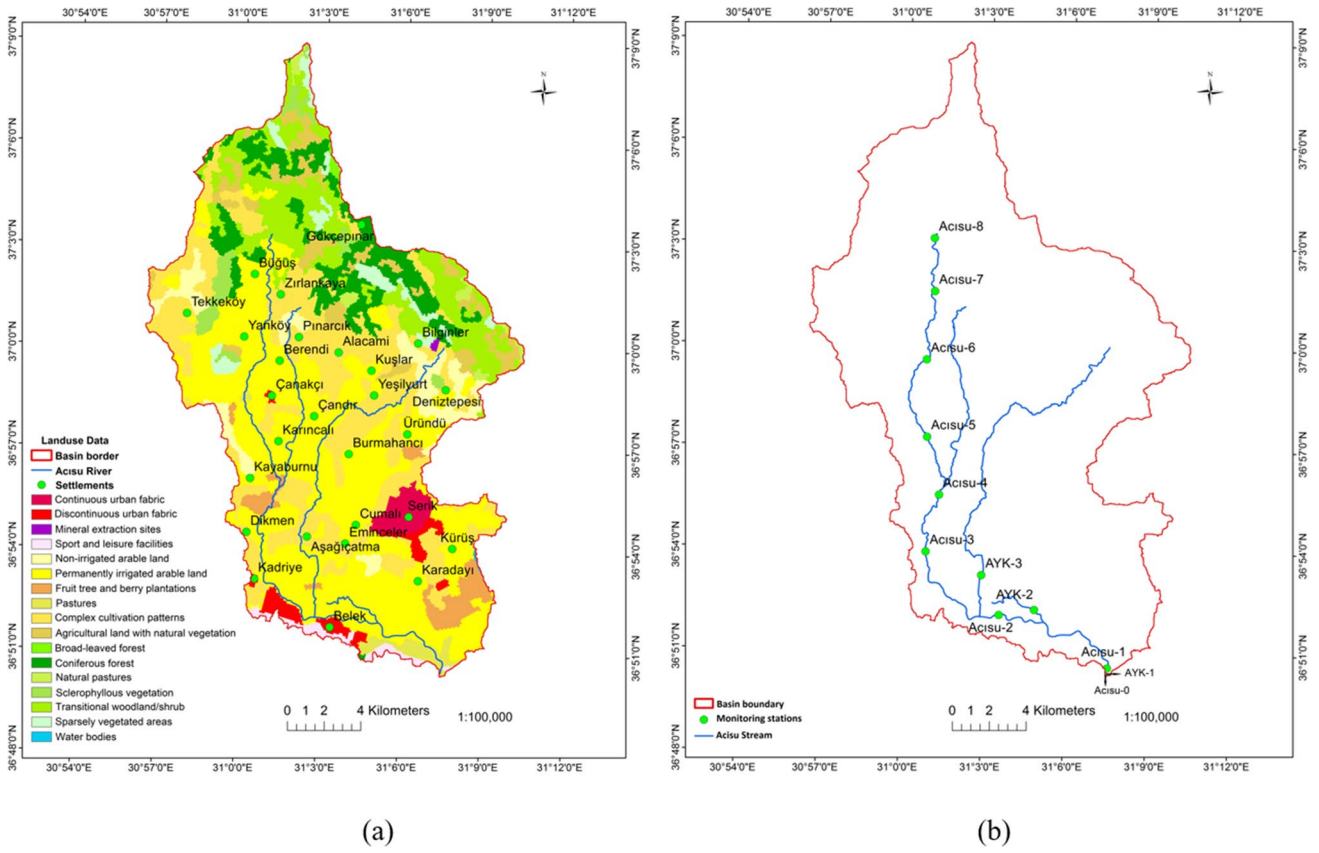


Fig. 1 Location of the study area in Turkey, Antalya province, and the districts



(a) (b)

Fig. 2 **a** Land-use and land cover in the Acısu Creek Basin and (**b**) locations of water quality monitoring stations

Water quality monitoring study

The monthly water quality monitoring study of the Acısu Creek was carried out at 12 sampling and monitoring stations (nine stations on the mainstem, and three stations on the tributaries (YK), see Fig. 2b) from September 2020 to September 2021. The coordinates of all monitoring stations are given in Table S1 in the Supplementary Material. The locations of the monitoring stations were selected considering several criteria such as geographical coverage, hydrological conditions, land use/cover, topography and geology, accessibility, hydrological connectivity and regulatory requirements to have a good representation of the spatial variability of water quality in the PSA.

Sampling of water was carried out in accordance with the national and international standards (ISO 5667-6 1990; ISO 5667-2 1991; ISO 5667-3 1994). Composite water samples (approx. 10 L) representing the entire width and water column were manually collected at each monitoring station and 2.5 L of this sample was transferred to polypropylene containers in the field and stored in cooled transport bags. For bacteriological analysis, 100 mL amber-colored glass bottles, previously sterilized, were submerged directly in the water at the mid-section of the creek. In stations without direct water access, samples were collected using a water sampling device and filled into sterilized bottles. A small volume (2 mL) was acidified with concentrated hydrochloric acid and stored under pH = 2 conditions. Measurements of dissolved oxygen (DO) concentration and percent saturation, pH, temperature, salinity, electrical conductivity (EC) and chlorophyll-a were carried out at the field using a multiparametric measurement probe (YSI EXO2). The color parameter was measured as true color at different wavelengths (436, 525, and 620 nm) using UV/VIS spectrophotometer (ISO 7887 2011). The analyses of suspended solids (SS), total alkalinity, bicarbonate, chemical oxygen demand (COD), and 5-day biochemical oxygen demand (BOD_5) were conducted according to the standard methods (APHA 1998). Anion (nitrite, nitrate, phosphate, sulfate, fluoride, bromide and chloride) and cation (ammonium, calcium, magnesium, potassium, lithium and sodium) groups were analyzed by an ion chromatography system (Thermo Scientific Dionex ICS-3000 Reagent-Free Ion Ion Chromatography). The device comprises Dionex IonPac AS18 anion exchange and CS12A cation exchange columns, along with CSRS 300 cation suppressor and 300 anion suppressor conductivity detector. Total organic carbon (TOC) and total nitrogen (TN) parameters were analyzed simultaneously with a

TOC/TN analyzer (HACH IL550 TOC/TN) according to the high-temperature catalytic combustion method. Total phosphorus (TP) was determined spectrophotometrically using the ascorbic acid method and persulfate digestion (APHA 1998). Total coliform, fecal coliform (FC), Escherichia coli (E.coli), and fecal streptococcus analyzes were conducted by membrane filtration method (APHA 1998; Myers and Sylvester 1997). Total dissolved solids (TDS) values were computed from EC values using the basic relationship of TDS (mg/L) = EC (µS/cm)*0.65. Quality control and quality assurance standards were met by regular calibration of instruments and equipment, use of certified reference materials and standard solutions, adherence to standard operating procedures for sample collection, preservation, storage, and analysis, including quality control samples in each batch. Instruments were maintained per manufacturer guidelines, lab personnel were trained in proper techniques and procedures, and data validation procedures were implemented to review for outliers, inconsistencies, and errors, documenting and investigating any deviations from expected results.

Regulatory approach for water quality classification

The classification of inland surface water bodies in Turkey is primarily determined by physicochemical parameters and follows the guidelines outlined in the Turkish Surface Water Quality Regulation (SWQR). This regulation encompasses rivers, lakes, as well as coastal and transitional waters (SWQR 2021). The determination of the overall physicochemical water quality class is based on the lowest class assigned to any of the parameters. There are three distinct quality classes: Class-I (indicated by a blue color, representing very good quality), Class-II (indicated by a green color, representing good quality), and Class-III (indicated by a yellow color, representing moderate quality). The water quality criteria of inland surface water resources are presented in Table S2 for general chemical and physicochemical parameters. Similar to the European WFD technique, the attained water quality class is further evaluated by additional quality components of biological, hydro-morphological, and chemical groups (for specific contaminants).

Water Quality Indices (WQIs)

In this study, the CCME, the NSF, and the SEQ-Eau WQIs were used for the comparative assessment of spatiotemporal water quality variations at the Acısu Creek. The CCME index is based on a formula developed by the British Columbia Ministry of Environment and modified by Alberta Environment (CCME 2001a, b). This index is one of the most widely used indices for assessing water quality (Tyagi et al. 2013; Sutadian et al. 2016; Regmi et al. 2017; van den Doel et al. 2023). The advantages of the index could be listed as; easy to calculate, tolerance to missing data, compatibility with different legal requirements and different water uses, and flexibility in the selection of input parameters and objectives (Terrado et al. 2010; Abbasi and Abbasi 2012; Tyagi et al. 2013). The index contains 3 factors: scope (F_1), frequency (F_2), and amplitude (F_3). Scope (F_1) refers to the number of variables that do not meet water quality goals. Frequency (F_2) corresponds to the percentage of individual tests that do not meet objectives (failed tests) whereas amplitude (F_3) represents the amount by which failed test values do not meet their objectives (CCME 2001a, b; Terrado et al. 2010; Hu et al. 2022). The CCME index value is calculated using the formula given in Eq. (1) where the divider 1.732 normalizes the resultant values to a range between 0 and 100. Water quality is classified according to the final index value into one of the following categories: 0–44 poor, 45–64 marginal, 65–79 fair, 80–94 good, 95–100 excellent (CCME 2001a, b). For the application of CCME WQI to the Acısu Creek, 27 water quality parameters were selected. Table 1 presents the selected water quality parameters with their target values (objectives) to sustain a good level of water quality for the protection of the ecosystem and the beneficial uses (suitable for water supply, irrigation water and aquaculture production) according to the relevant Turkish regulations and standards (SWQR 2021; WPCR 2004; RDWQ 2019) and international Blue Flag water quality criteria for microbiological parameters.

$$\text{CCME-WQI} = 100 - \left(\frac{\sqrt{F1^2 + F2^2 + F3^2}}{1.732} \right) \quad (1)$$

The NSF index, developed by the National Sanitation Foundation in 1970, is one of the most widely applied WQIs in the literature and was proposed to compare the water quality of various water sources (Brown et al. 1970; Sutadian et al. 2016). Summarizing data in a single index value in an objective, rapid and reproducible manner, comparison of water quality for different areas, and identifying changes in water quality are the reported advantages of the NSF index (Tyagi et al. 2013). The calculation steps of the NSF index are summarized in detail in Fig. 3. In this study, NSF-WQI online calculator (WRC 2023) was used for the determination of the sub-index values. The website is open-access and provides a water quality report to the user. This report also includes the NSF index value, the number of parameters considered in the calculation, and the weighting factors assigned to these parameters. Water quality is classified according to the final NSF index value into one of the following categories: 0–25 very bad, 26–50 bad, 51–70 medium, 71–90 good, and 91–100 excellent (Brown et al. 1970).

Table 1 The target values (objectives) of the selected water quality parameters for the CCME

Parameter	Target value	Parameter	Target value
pH	6.0–9.0[a]	DO_{sat} (%)	70[b]
Color 436 nm (m^{-1})	3[a]	TSS (mg/L)	5[b]
Color 525 nm (m^{-1})	2.4[a]	TDS (mg/L)	1500[b]
Color 620 nm (m^{-1})	1.7[a]	TOC (mg/L)	4[c]
EC (µS/cm)	1000[a]	Cl^- (mg/L)	250[c]
DO (mg/L)	6[a]	Br^- (mg/L)	46[a]
COD (mg/L)	50[a]	Na^+ (mg/L)	200[c]
BOD_5 (mg/L)	8[a]	NO_2^- (mg/L)	0.5[c]
NH_4-N (mg/L)	1[a]	SO_4^{2-} (mg/L)	250[c]
NO_3-N (mg/L)	10[a]	FC (cfu/100 mL)	100[d]
TN (mg/L)	11.5[a]	FS (cfu/100 mL)	100[d]
PO_4-P (mg/L)	0.16[a]	TC (cfu/100 mL)	500[d]
TP (mg/L)	0.2[a]	*E-coli* (cfu/100 mL)	100[d]
F^- (µg/L)	1500[a]		

[a]SWQR 2021; [b]WPCR 2004; [c]RDWQ 2019; [d]Blue Flag 2019

The SEQ-Eau, developed by the French watershed agencies (SEEE 2008), is a tool to evaluate the physicochemical and microbiological quality of surface/groundwater and also identifies the parameters that cause deterioration in water quality. There are four steps to apply this index and in the first one, the alteration types and parameters are selected. In the second step, the weighted index of the analyzed parameters (IPpa) is determined for each monitoring station. The IPpa is obtained by considering the importance of the analyzed parameters on the deterioration of water quality, where the weight values usually range from 0 to 100. The weighted index for the analyzed parameter is calculated as shown in Eq. (2). In the third step, the weighted index for each alteration is determined by averaging the values of the weighted indices of the parameters that characterize the selected alteration. In the final step, the overall quality index is determined by selecting the lowest index value obtained from all considered alterations (Table 2). In this study, SEQ-Eau index values were calculated by the SEQ-Eau calculator which was developed by the authors using the Python programming language.

$$IP_{pa} = I_i + \left[\left(I_s - I_i\right)/\left(b_s - b_i\right)\right] * \left(b_s - p_a\right) \quad (2)$$

where $IP_{p.a.}$: weighted index for the parameter analyzed, I_i: lower index, I_s: upper index, b_i: lower limit, b_s: upper limit; and p_a: analyzed parameter value. Water quality is classified into five categories as follows: 0–20 very poor, 20–40 poor, 40–60 average, 60–80 good, 80–100 excellent.

The water quality classes obtained for the Acısu Creek from both the regulatory approach and the applied WQIs were presented by the GIS maps to show the spatiotemporal variations of water quality. Additionally, correlation analysis was conducted to find similarities and differences between the assessment results obtained from the WQIs and the regulatory approach.

Results and discusssion

Water quality assessment according to the regulatory approach

Initially the water quality assessment results according to the relevant Turkish regulation, based on only general physicochemical water quality parameters, is presented as an example of a regulatory approach. To give brief background information about the water quality at the PSA, a statistical summary of the monitored water quality parameters is presented in Table S3 (in the Supplementary Material) for the upstream (Acısu-6) and downstream (Acısu-0) monitoring stations. Acısu-6 was chosen as the upstream station as the two stations upstream of Acısu-6 (Acısu-7 and Acısu-8) were frequently dry or stagnant during sampling sessions. Due to point and diffuse pollution sources, the water quality was gradually impaired in the downstream direction. Significant increases in EC and the main ions were caused by the mixing of creek water and seawater at the point of stream discharge into the Mediterranean Sea. The concentrations of nutrients (NH_4-N, NO_3-N, TN, PO_4-P, and TP) and indicators of organic pollution (COD, BOD_5, and TOC) were much higher at downstream in comparison to upstream sites. Additionally, the effluent discharges from three municipal WWTPs, located at the downstream section of the basin,

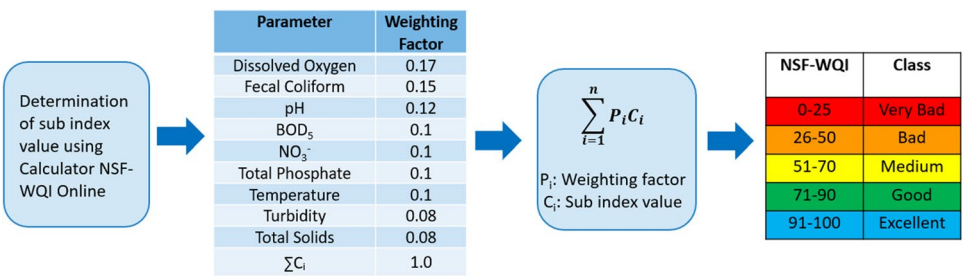


Fig. 3 Calculation steps of the NSF

Table 2 Classification of surface water quality according to the SEQ-Eau index (SEEE 2008)

Quality class		Excellent	Good	Average	Poor	Very poor
Index values		100 – 80	80 – 60	60 – 40	40 – 20	20 – 0
Alteration No:1 - Temperature						
Temperature	°C	0–20	20–25	25–30	30–35	35–40
Alteration No:2 - Acidification						
pH		6.5–8.5		8.5–9.2	3-6.5 or 9.2–10	
Alteration No:3 - Organic and oxidizable substances						
BOD_5	mg O_2/L	0.5–3	3–5	5–10	10–25	25–1000
COD	mg O_2/L	1.5–30	30–35	35–40	40–80	80–2000
DO	mg/L	7–10	5–7	3–7	1–3	0–1
NH_4^+	mg/L	0–0.1	0.1–0.5	0.5–2	2–8	8–50
Alteration No:4 - Phosphorus						
PO_4^{3-}	mg/L	0–0.2	0.2–0.5	0.5-1	1–5	5–20
TP	mg/L	0–0.1	0.1–0.3	0.3–0.5	0.5-3	3–25
Alteration No: 5 - Mineralization						
EC at 20 °C	µs/cm	100–750	750–1300	1300–2700	2700–3000	3000–7000
Alteration No:6 - Suspended Particles						
SS	mg/L	< 50	50–200	200–1000	1000–2000	2000–10,000
Turbidity	NTU	< 15	15–35	35–70	70–100	> 100
Alteration No:7 - Nitrate						
NO_3^-	mg/L	< 10	10–25	25–50	> 50	
Alteration No:8 - Microorganisms						
Fecal coliform	cfu/100 ml	0–20	20–2000	2000–20,000	20,000–50,000	> 50,000

adversely affected the bacteriological quality in the Acısu Creek.

According to the regulatory approach, initially, the water quality classes were determined for each monitoring session/station using the monthly measurement/analysis results of the physicochemical parameters (color measurements at three different wavelengths, pH, EC, COD, BOD_5, NH_4-N, NO_3-N, TN, PO_4-P, TP, F^-) according to the Turkish SWQR. The resultant water quality classes of the Acısu Creek are presented in Table 3 for all stations and sessions for the monitoring period between September 2020 to October 2021.

The monitoring results show the spatiotemporal variation of water quality for the investigated physicochemical parameters. As a result, water quality was classified as good for three monitoring stations, namely Acısu-3, Acısu-4, and Acısu-5, for all monitoring sessions, which are located in the mid-section of the creek. Additionally, the water quality class was moderate for two mainstem stations (Acısu-0 and Acısu-1) and two tributaries (YK-1 and YK-2) located at the downstream section of the Acısu Creek for all monitoring sessions. Two upstream monitoring stations (Acısu-8 and Acısu-7) were mostly dry during the monitoring period due to reduced precipitation and the water quality class was either good or moderate. The water quality of the YK-3 tributary showed a significant temporal variation as this sampling station was under the effect of drainage water from the agricultural lands and its quality was subject to frequent changes. The water quality of the remaining monitoring stations (Acısu-2 and Acısu-6) was either good or moderate depending on the monitoring sessions. Very good (Class I) water quality was not achieved at any monitoring station or session. The yearly average water quality classes of the Acısu Creek were also determined according to the Turkish SWQR using the yearly average values of the monitored parameters, as presented in Table 4 and Fig. 4a.

The resultant water quality class was moderate for four mainstem monitoring stations (Acısu-0, Acısu-1, Acısu-2, and Acısu-7) and two tributaries (YK-1 and YK-2) where the water quality was classified as good for the remaining stations.

The parameters that cause impairment of the water quality at the tributaries (YK-1 and YK-2) were EC, BOD_5, NH_4-N, PO_4-P, TP, and DO. The water quality of the downstream monitoring stations (Acısu-0 and Acısu-1) was impaired due to increased concentrations of PO_4-P and TP and very high values of EC due to mixing with seawater. The water quality was classified as very good for only color and fluoride parameters for all monitoring sessions. In general, the downstream section of the Acısu Creek, which extends from Acısu-2 till the discharge point to the Mediterranean Sea at Acısu-0, exhibited the lowest water quality for all monitoring sessions which causes an adverse impact on the coastal water quality as well. The discharges of the three municipal WWTPs were also effective in the deterioration of the water quality at the downstream monitoring station Acısu-0.

Table 3 Water quality classes (II: good, III: moderate) of the Acısu Creek for each monitoring session/station according to the Turkish SWQR

Station	Sep/20	Oct /20	Dec/20	Jan/21	Feb/21	Mar/21	Apr/21	May/21	Jul/21	Aug/21	Sep/21	Oct/21
Acısu-8	dry	dry	dry	II	III	II	II	dry	dry	dry	dry	dry
Acısu-7	dry	dry	dry	II	III	II	II	dry	dry	dry	dry	dry
Acısu-6	III	II	stagnant	II	II	III	stagnant	II	stagnant	II	II	stagnant
Acısu-5	II	II	II	II	II	II	II	II	II	II	II	II
Acısu-4	II	II	II	II	II	II	II	II	II	II	II	II
Acısu-3	II	II	II	II	II	II	II	II	II	II	II	II
YK-3	II	II	III	II	II	III	II	III	II	II	II	II
Acısu-2	II	III	III	II	II	II	II	II	II	III	III	stagnant
YK-2	III	III	III	III	III	III	stagnant	III	III	stagnant	III	stagnant
Acısu-1	III	III	III	III	III	III	III	III	III	III	III	III
YK-1	dry	III	III	stagnant	III	III	stagnant	stagnant	stagnant	III	III	stagnant
Acısu-0	III	III	III	III	III	III	III	III	III	III	III	III

Results of the applied WQIs

In the CCME WQI application, 27 water quality parameters were selected and the water quality criteria specified for Class II-good level was considered in determining the target values, in line with the goal of achieving good water status in surface water resources (RDWQ 2019; SWQR 2021; WPCR 2004). The CCME index values were calculated using the monitoring data of 12 monitoring sessions and the results are presented on the GIS map (Fig. 4b). Table S4 (in the Supplementary Material) presents the number of failed parameters, failed test numbers, F1, F2, F3, the final index results, and water quality class. The CCME index results revealed that the water quality was excellent at the upstream station (Acısu-8) and it was gradually degraded to a very poor class towards the downstream point (Acısu-0). The degradation of water quality at Acısu-1, Acısu-0 monitoring stations and the two tributaries (YK-1 and YK-2) were due to exceedance of the target values for many parameters including EC, TSS, TDS, DO_{sat}, major ions, nutrients (NH_4-N, TN, PO_4-P, TP), indicators of organic pollution (BOD_5, COD, TOC) and bacteriological parameters. The water quality was impaired at the YK-1 tributary due to drainage flow from agricultural lands whereas the other tributary, YK-2, receives the wastewater discharges of a municipal WWTP and diffuse pollution sources from the agricultural lands. The water quality was classified as good for two mainstem stations (Acısu-7 and Acısu-6) at the upstream and fair for the mid-section of the creek. The total test numbers were the lowest (107 tests) for the upstream monitoring stations (Acısu-8 and Acısu-7) as they were dry at most of the monitoring sessions. The downstream stations (Acısu-1 and Acısu-0) showed the worst water quality which failed to comply with the target values of the highest number of parameters (21 and 19 parameters, respectively, out of 27 total parameters) and failed tests (136 and 129 tests, out of 312 and 316 tests, respectively). The impairment of the water quality downstream is mainly due to diffuse sources of pollution from the upstream agricultural fields, the discharge of treated wastewater effluents, and the mixing of stream water with seawater.

Table 4 The yearly average water quality values and classes (blue: very good, green: good, yellow: moderate) of the Acısu Creek

Station	Color (nm/m)			pH	EC (µS/cm)	DO (mg/L)	COD (mg/L)	BOD_5 (mg/L)	NH_4^+-N (mg/L)	NO_3-N (mg/L)	TN (mg/L)	PO_4^--P (mg/L)	TP (mg/L)	F (µg/L)	Yearly average class
	436	525	620												
Acısu-8	0.006	0.006	0.007	8.40	486	10.18	4.47	2.79	0.024	0.173	0.243	0.003	0.163	37.2	II
Acısu-7	0.012	0.011	0.012	8.40	542	10.41	7.00	2.65	0.012	3.414	3.819	0.004	0.280	78.9	III
Acısu-6	0.022	0.017	0.016	8.28	517	9.02	10.54	5.87	0.043	2.229	2.621	0.011	0.043	170.6	II
Acısu-5	0.028	0.021	0.019	8.37	502	9.53	9.26	5.09	0.024	1.705	1.938	0.029	0.074	177.0	II
Acısu-4	0.054	0.047	0.043	8.33	506	8.94	11.15	4.25	0.041	1.997	2.329	0.035	0.073	185.8	II
Acısu-3	0.053	0.044	0.041	8.30	489	8.99	9.54	4.25	0.063	1.290	1.600	0.033	0.069	183.3	II
YK-3	0.033	0.025	0.030	8.31	500	10.68	12.75	4.43	0.186	1.829	2.279	0.052	0.104	179.0	II
Acısu-2	0.034	0.028	0.025	8.32	1113	8.35	9.68	4.12	0.040	1.273	1.887	0.034	0.081	170.4	III
YK-2	0.039	0.027	0.024	7.94	858	3.04	16.46	9.62	3.682	2.195	7.078	0.947	1.500	232.8	III
Acısu-1	0.032	0.026	0.023	8.17	5570	7.42	28.02	7.14	0.827	1.984	4.039	0.214	0.215	664.7	III
YK-1	0.040	0.028	0.025	8.36	3164	8.53	36.08	9.57	1.732	1.041	3.376	0.041	0.112	327.5	III
Acısu-0	0.032	0.026	0.024	8.21	9237	7.68	32.91	7.31	0.724	1.928	3.516	0.180	0.208	534.6	III

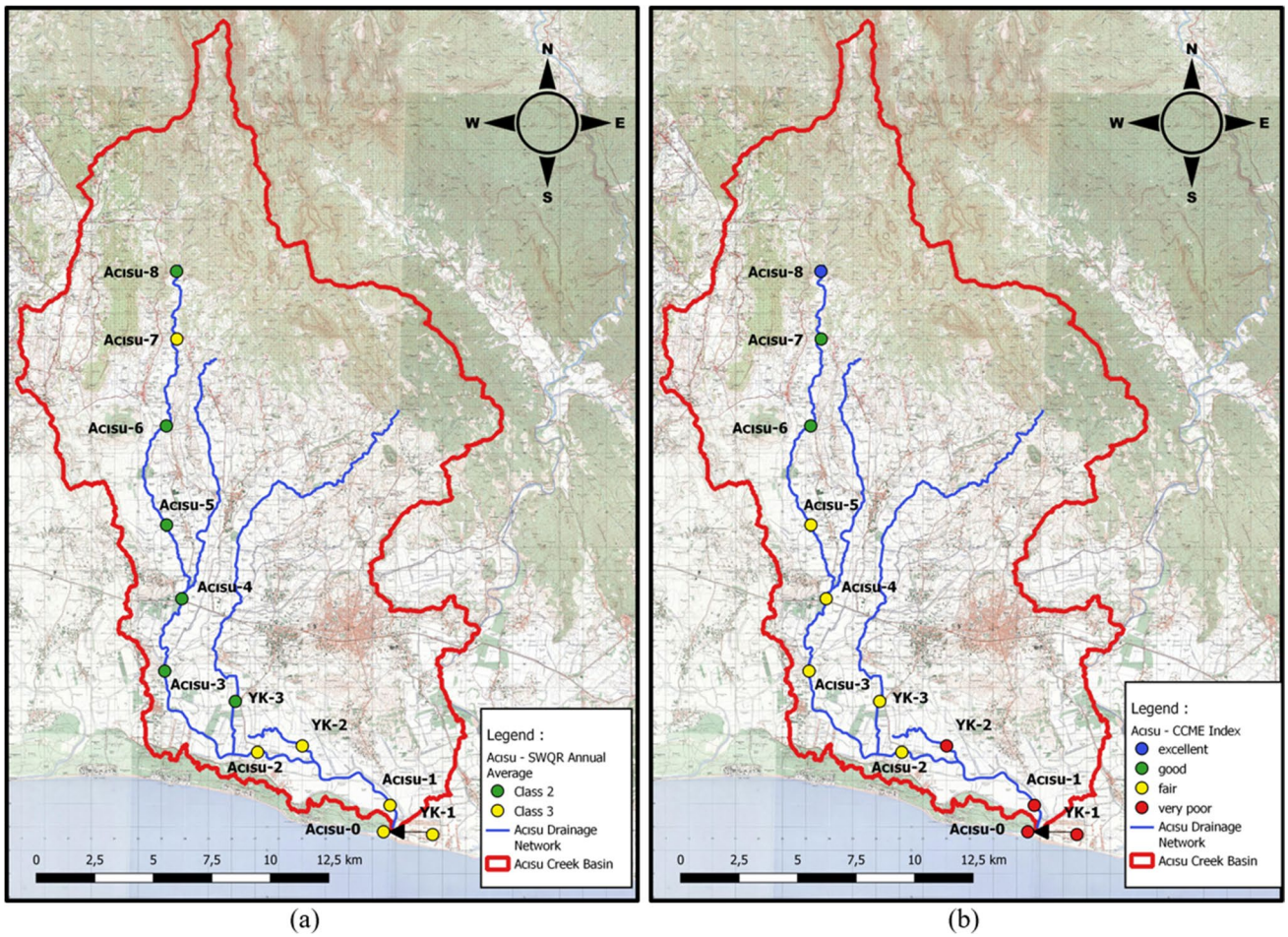


Fig. 4 Water quality classes of the Acısu Creek monitoring stations according to (a) the Turkish SWQR as the regulatory approach, and (b) the CCME index

In the NSF index, nine water quality parameters (DO, FC, pH, BOD_5, NO_3^-, PO_4-P, temperature variation, turbidity, and total solids) are used to determine the water quality class and these parameters were all included in the NSF WQI application for the Acısu Creek. The NSF index results obtained for each monitoring session and station are presented in Table 5. For the 1st monitoring session in Sep 2020, the water quality class was good at all monitoring stations, and a good water quality class was determined for the upstream monitoring stations (Acısu-8 and Acısu-7) for all monitoring sessions. The water quality was gradually impaired at the mid-section of the Acısu Creek (starting from Acısu-6 and flowing downstream till the tributary YK-2) and exhibited both medium and good water quality classes during the whole monitoring period. The tributary, YK-2, exhibited the worst water quality among all monitoring stations and it was the only monitoring station where the water quality was classified as bad. This tributary also deteriorated the water quality at the downstream stations (Acısu-1 and Acısu-0) and the water quality class was mostly medium. The water quality class of the YK-1 tributary, which was either stagnant or dry during half of the monitoring sessions, was also medium and it was also effective to impair the water quality at the Acısu-0 monitoring station. The water quality was mostly impaired due to comparatively low sub-index values of FC, BOD_5, nitrate, and total solids. The NSF index could clearly indicate the worst quality for the tributary YK-2 but it was not accurate to show the impairment of the water quality at the downstream section of the Acısu Creek. Among all monitoring sessions, the lowest NSF index scores and the worst water quality classes were obtained for the winter monitoring session in January 2021 and the resultant GIS map for this session is presented in Fig. 5a.

Eight alteration groups containing 13 water quality parameters were considered for the SEQ-Eau index application to the Acısu Creek. The SEQ-Eau index results obtained for each monitoring session and station are presented in

Table 5 The NSF index values and water quality classes (G: good, M: medium, B: bad) for the Acısu Creek for 12 monitoring sessions

Station	Sep/20	Oct /20	Dec/20	Jan/21	Feb/21	Mar/21	Apr/21	May/21	Jul/21	Aug/21	Sep/21	Oct/21
Acısu-8	dry	dry	dry	87-G	82-G	89-G	83-G	dry	dry	dry	dry	dry
Acısu-7	dry	dry	dry	75-G	81-G	84-G	74-G	dry	dry	dry	dry	dry
Acısu-6	82-G	74-G	stagnant	73-G	81-G	67-M	stagnant	71-G	stagnant	73-G	74-G	stagnant
Acısu-5	86-G	72-G	77-G	65-M	77-G	83-G	80-G	70-M	70-M	66-M	68-M	74-G
Acısu-4	86-G	71-G	69-M	66-M	75-G	78-G	68-M	67-M	72-G	67-M	66-M	73-G
Acısu-3	82-G	68-M	71-G	66-M	67-M	79-G	70-M	74-G	72-G	68-M	67-M	70-M
YK-3	84-G	75-G	71-G	68-M	75-G	76-G	69-M	67-M	69-M	72-G	67-M	75-G
Acısu-2	83-G	71-G	77-G	64-M	66-M	81-G	72-G	74-G	69-M	66-M	64-M	stagnant
YK-2	72-G	46-B	47-B	43-B	43-B	62-M	stagnant	50-B	51-M	stagnant	46-B	stagnant
Acısu-1	78-G	69-M	70-M	60-M	65-M	78-G	71-G	65-M	67-M	63-M	63-M	60-M
YK-1	dry	69-M	63-M	stagnant	63-M	75-G	stagnant	stagnant	stagnant	69-M	65-M	stagnant
Acısu-0	77-G	64-M	69-M	59-M	61-M	78-G	79-G	70-M	67-M	64-M	65-M	63-M

Table 6. Excellent water quality was observed only for a few monitoring stations and sessions whereas the mid-section of the Acısu Creek (starting from Acısu-6 and flowing downstream till the tributary YK-2) exhibited both medium and good water quality classes during the whole monitoring period. For the tributary YK-2, the water quality was mostly

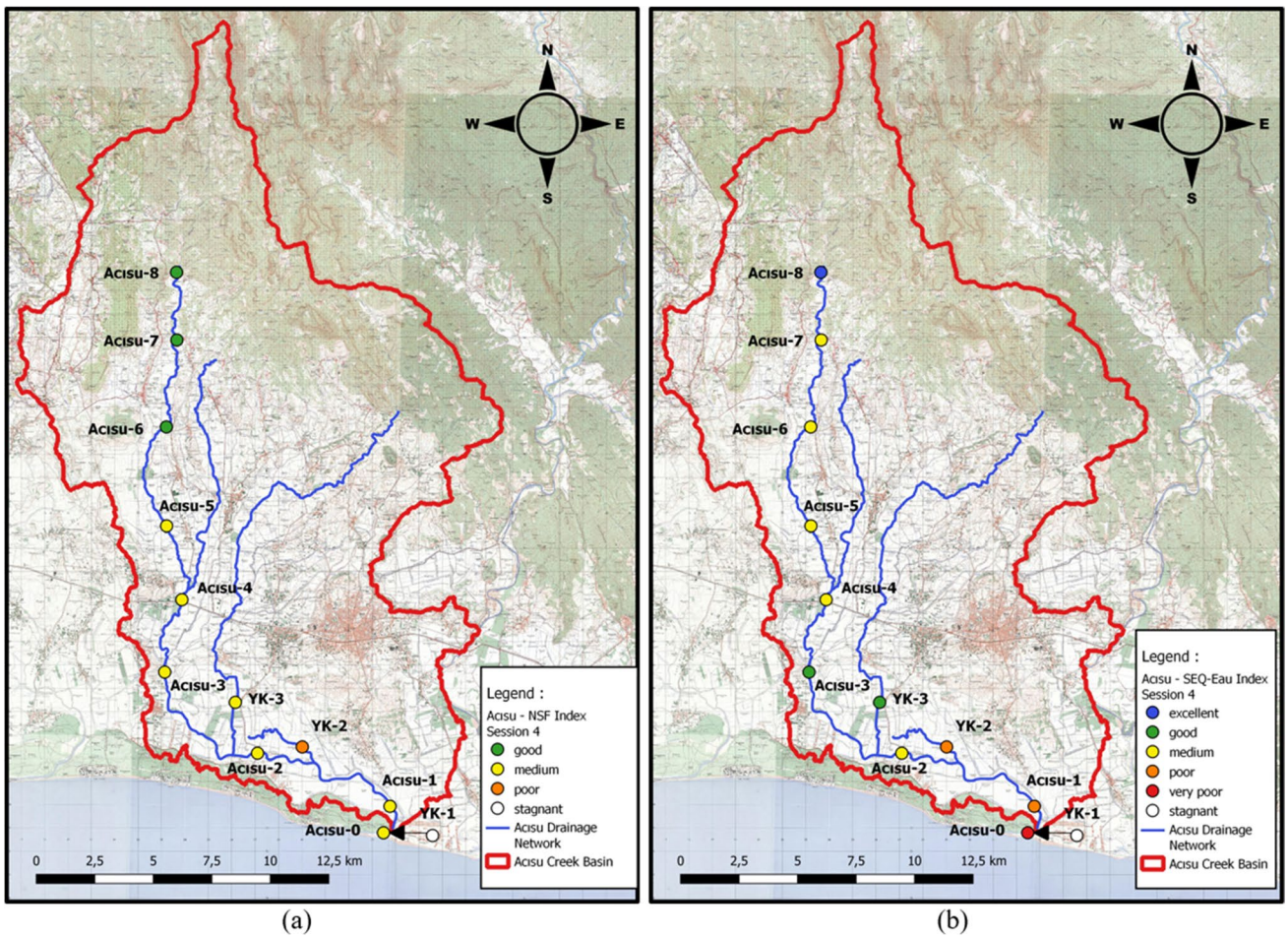


Fig. 5 Water quality classes of the Acısu Creek monitoring stations according to (**a**) the NSF index, (**b**) the SEQ-Eau index

Table 6 The SEQ-Eau index values and water quality classes (E: excellent, G: good, A: average, P: poor, V: very poor) for the Acısu Creek

Station	Sep/20	Oct /20	Dec/20	Jan/21	Feb/21	Mar/21	Apr/21	May/21	Jul/21	Aug/21	Sep/21	Oct/21
Acısu-8	dry	dry	dry	82-E	69-G	81-E	59-A	dry	dry	dry	dry	dry
Acısu-7	dry	dry	dry	60-A	67-G	78-G	80-G	dry	dry	dry	dry	dry
Acısu-6	73-G	78-G	stagnant	57-A	70-G	67-G	stagnant	67-G	stagnant	70-G	75-G	stagnant
Acısu-5	81-E	79-G	79-G	56-A	57-A	75-G	81-E	69-G	60-G	58-A	58-A	78-G
Acısu-4	81-E	59-A	64-G	60-A	56-A	79-G	72-G	68-G	66-G	56-A	54-A	74-G
Acısu-3	80-E	73-G	71-G	65-G	58-A	81-E	75-G	77-G	63-G	64-G	61-G	74-G
YK-3	73-G	60-A	76-G	62-G	70-G	71-G	60-A	64-G	67-G	65-G	61-G	78-G
Acısu-2	73-G	52-A	49-A	58-A	54-A	81-E	80-G	65-G	56-A	49-A	58-A	stagnant
YK-2	43-A	29-P	18-V	36-P	35-P	39-P	stagnant	28-P	49-A	stagnant	26-P	stagnant
Acısu-1	11-V	7-V	0-V	35-P	44-A	0-V	1-V	3-V	8-V	2-V	14-V	6-V
YK-1	dry	45-A	13-V	stagnant	69-G	49-A	stagnant	stagnant	stagnant	0-V	47-A	stagnant
Acısu-0	0-V	0-V	0-V	17-V	35-P	0-V	0-V	0-V	3-V	0-V	8-V	0-V

classified as poor due to *Alteration No:4 Phosphorus* which contains PO_4^{3-} and TP. The SEQ-Eau index considers the lowest sub-index value from all alterations for the classification of water quality. As an example, the sub-index values of *Alteration No:5 Mineralization* were very low and the water quality was classified as very poor for all monitoring sessions due to very high EC values at the two downstream monitoring stations (Acısu-1 and Acısu-0).

Among all monitoring sessions, the lowest SEQ-Eau index scores and the worst water quality classes were obtained for the winter monitoring session in January 2021 for all monitoring stations, and the resultant GIS map for this session is presented in Fig. 5b.

Comparison of the applied WQI results and the regulatory approach

The comparison of the annual average WQI values of the NSF, CCME, SEQ-Eau indices and the regulatory approach are presented in Fig. 6. According to the SEQ-Eau index methodology, the lowest sub-index value obtained from all alterations is considered to determine the resultant index result. Therefore, the lowest WQI values were obtained by the SEQ-Eau index, and the alteration which gave the lowest sub-index value was *Alteration No:5 Mineralization* which contains the EC parameter. In general, all the applied WQIs were consistent to evaluate the best state of the water quality

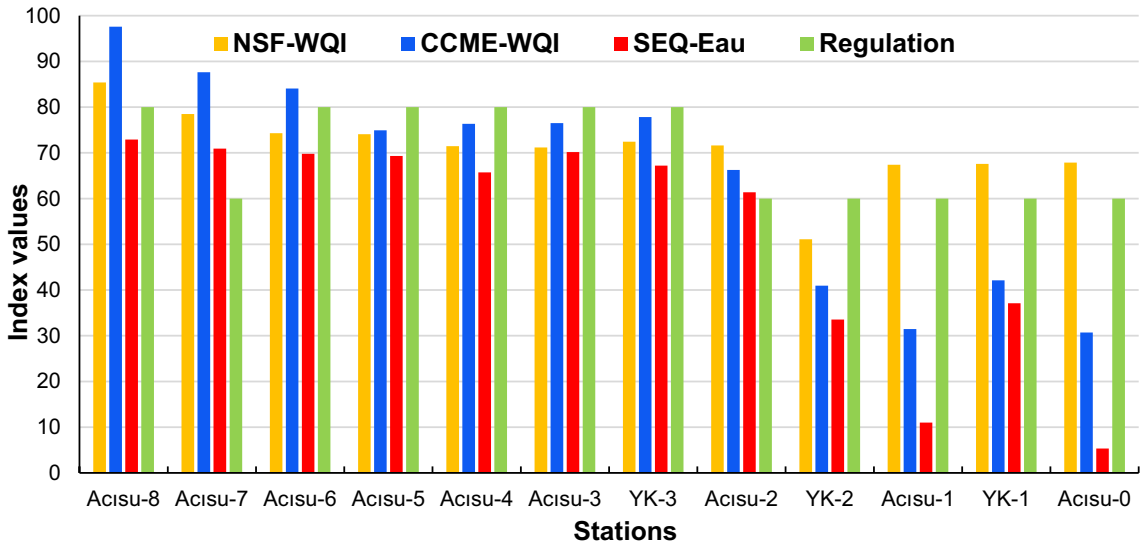


Fig. 6 Comparison of WQI results according to the annual average index values and the evaluation results of the Turkish regulation for the Acısu Creek

at the upstream monitoring stations (Acısu-8 and Acısu-7) and the worst state of water quality at the downstream section of the Acısu Creek including two tributaries (YK-2 and YK-1) and two mainstem monitoring stations (Acısu-1 and Acısu-0). The good quality class of the upstream water was gradually impaired to medium quality class at the mid-section of the Acısu Creek. With the influence of the YK-2 tributary, the downstream water quality was evaluated to be bad/poor and even very poor. The temporal variation of the water quality was clearly shown by the NSF and the SEQ-Eau indices, as these WQIs could be applied for each monitoring session. As the CCME index requires to use at least four sessions of water quality monitoring results, this index is not suitable for the evaluation of short-term temporal variations of water quality. It was interesting to observe that nearly equal or very close yearly average index values were obtained from the three WQIs for the mid-section of the Acısu Creek, which covers the monitoring stations of Acısu-6, Acısu-5, Acısu-4, Acısu-3, Acısu-2, and YK-3 tributary. The water quality of the Acısu Creek was noticeably impaired by the influence of the tributary YK-2 that carries the effluents from a municipal WWTP and the diffuse pollution from the upstream agricultural lands. However, the NSF index was not successful to show the distinct impairment of the water quality at the downstream monitoring stations (mainly Acısu-0 and Acısu-1) because there are only nine fixed water quality parameters in the NSF index and they were not enough to present water quality variations due to mineralization and bacteriological pollution. The water quality evaluation results of the regulatory approach were included in Fig. 6 with the representative values of 80 for good (II) and 60 for moderate (III) water quality classes. The regulatory approach was not accurate and could not represent the spatial water quality variation.

In general, there were differences between the applied three WQI results and the final water quality classes for some of the monitoring stations and sessions due to the involvement of different water quality parameters in the WQIs and the differences in their calculation methodologies. At the PSA, the downstream water quality was highly impaired by the point discharges of three municipal WWTP effluents, diffuse pollution of TN, TP, and total solids from the upstream agricultural lands, and the mixing of stream water with the seawater that caused high increases in EC values and major ions. In this study, the NSF index, which is one of the most widely applied general WQI in the literature, was not accurate to evaluate the water quality variations for the PSA for some monitoring sessions/stations. Therefore, water practitioners and researchers need to choose the most appropriate WQI considering the spatiotemporal variations of water quality in their research area. Another important aspect is to include the essential water quality parameters in the WQIs with acceptable water quality criteria as target values. In this respect, the CCME index is very advantageous as the users are free to choose any number of water quality parameters and their target water quality criteria according to their needs.

For a better presentation of the similarities and differences between the three WQIs and the regulatory assessment results, the correlation values are given in Table S5. As a result, the lowest correlation (0.48) was between the regulation assessment and the NSF index results, while the correlation between the NSF and the CCME index results was comparatively high (0.75). The highest correlation was achieved for the SEQ-Eau and CCME index results with a correlation value of 0.95, which is very close to the best correlation value of 1. This very high correlation value reveals that the SEQ-Eau and CCME indices gave very close/consistent results and these indices were successful for accurate spatiotemporal evaluation of the water quality for the PSA by including a large number of water quality parameters. Additionally, the NSF index had relatively low correlation values with the other index results and was not able to respond well to the spatiotemporal variations of the water quality due to limited number of parameters involved.

Discussion

WQIs provide several benefits such as estimation of critical water quality parameters, resource/fund allocation, comparison of water quality at different locations & geographical areas, enforcement of standards, trend analysis, public information, and scientific research. Therefore, the use of WQIs is common worldwide and they have been widely applied and showed a significant development over the past several decades (Mogane et al. 2023). To date, more than 35 WQIs were developed for surface water quality evaluation globally (Abbasi and Abbasi 2012) and they were applied in many countries so far. Although WQI applications cover different types of surface water bodies, such as lakes, rivers, and estuaries, more than 80% of the WQI applications were for rivers, and in about half of the studies the CCME and the NSF indices were applied (Uddin et al. 2021).

The majority of WQIs consist of four steps: parameter selection, parameter sub-index determination, parameter weight determination, and aggregation of the sub-indices to compute the overall WQI. Most of the WQIs in the literature employed 8 to 11 water quality parameters where the most commonly included parameters in the WQIs are temperature, turbidity, pH, suspended solids, TDS, FC, DO, BOD, and ammonium-N. Some WQIs offer flexibility in parameter selection such as the CCME, whereas in some WQIs, such as the NSF, the users can only consider the fixed parameters of the WQI. In some circumstances, the conventional WQIs, which do not consider biological parameters,

heavy metals, or toxic organic material, may falsely ignore the major factors for the ecological deterioration of river ecosystems. Therefore, expert knowledge and experience are important for parameter selection and also the use of statistical analysis (correlation, principal component, cluster, or discriminant) is helpful to choose the critical/important water quality parameters (Chidiac et al. 2023; Mogane et al. 2023). The second stage of sub-index calculation and the third state of parameter weighting are crucial components of the WQI methodology and they have a direct effect on the final WQI result. However, some WQIs may omit these stages, such as the CCME. The weights used for the same parameters vary significantly between the WQIs and the use of advanced methods, such as the Analytical Hierarchical Process, is recommended to determine the significance of the parameters and reduce uncertainty. In general, the differences between the WQI results are primarily due to the selection of different water quality parameters, differences in the number of selected parameters, assigned weights to the parameters and the aggregation formulas to compute WQI results. Another important aspect of the use of WQIs is the general problems of ambiguity, eclipsing, rigidity, and uncertainty (Gupta and Gupta 2021; Syeed et al. 2023). The eclipsing effect is commonly reported as the main drawback of the many WQIs. Due to the eclipsing effect, one or more parameters that have values above permissible limits could be masked if the rest of the parameters are within the limits. The use of a minimum operator index aggregation function or automated aggregation function is recommended to minimize the eclipsing effect. Additionally, the aggregation function is shown as a major source of uncertainty, and the use of multiplicative aggregation function and statistical approaches are recommended to mitigate uncertainty in the selection and weighing process of parameters.

In the presented case study of the Acısu Creek, three WQIs were utilized, each employing different parameters, calculation methods, and parameter weights. This comparative analysis revealed the strengths and weaknesses of each index. The NSF index was not accurate for the evaluation of the water quality at the PSA for some monitoring stations/sessions due to eclipsing and rigidity issues while the CCME index demonstrated flexibility and efficiency in spatiotemporal evaluations. The SEQ-Eau index, commonly used in France, Morocco, Cameroon, and Algeria (Nyamsi et al. 2017; El Madani et al. 2019; El Hmaidi et al. 2022) also showed promising performance in assessing water quality variations. Overall, both the CCME and SEQ-Eau WQIs exhibited good efficiency and accuracy in evaluating water quality. To compare the findings of the presented research, three recent studies from the literature were taken into account, which examine the effectiveness of various WQIs across diverse geographical locations. In the study of Hamlat et al. (2017), ten WQIs were employed to evaluate trends of water quality in the Tafna basin in Algeria, and the researchers stated significant variations in results, with CCME and British Columbia WQI providing the most accurate assessments. Similarly, in the study of Gikas et al. (2023) the applicability of four WQIs were investigated to evaluate status of small rivers in Northern Greece. This study revealed the significant differences in quality classification among methodologies where CCME demonstrated superior capability in assesing spatiotemporal variations in river water quality. In the third study, WQI adaptations for monitoring water quality in Africa were compared and the researchers identified CCME as one of the most suitable indices and highlighted biases towards physicochemical parameters and recommended improvements, such as incorporating biological metrics and employing less subjective statistical methods (Lukhabi et al. 2023). Despite variations in geographical settings, all studies underscore the importance of tailoring WQIs to reflect the unique conditions of water bodies, emphasizing the need for adaptable methodologies to support effective environmental management globally.

This study serves as a notable example of comparative research on WQIs for water practitioners and researchers, offering insights into the spatiotemporal variations in surface water quality, the performance of different WQIs and evidence-based information to support their efforts in monitoring, protecting, and managing water resources effectively. The practical implications include improved assessment methods, informed decision-making, methodological guidance and capacity building to conduct comprehensive evaluation of water quality and implement effective management strategies.

Conclusions

Developing a tailored WQI for a water body, considering its unique conditions like geography, hydrology, discharge rate, and pollution sources, is crucial for accurately reflecting water quality and guiding environmental planners to design and implement effective pollution abatement strategies. While the previous research has explored the use of individual WQIs or focused on specific geographic areas, there is limited understanding of how different WQIs perform in assessing water quality dynamics in complex environmental settings. Therefore, this study evaluated the accuracy and reliability of the three internationally well-known and commonly applied WQIs (NSF, CCME, and SEQ-Eau) and a regulatory approach for assessing water quality dynamics using the capabilities of the GIS, and highlighted the importance of WQI methodologies for parameter selection, sub-index calculation, and aggregation methods. The pilot study area (PSA) of the Acısu Creek offered a good case study for comprehensive understanding and assessment of

spatiotemporal variations of water quality in basins facing multiple sources of pollution. Consequently, the novelty of this study lies in its comprehensive comparative analysis of spatiotemporal variations in surface water quality using different WQIs and a national water quality regulation to provide a robust assessment of water quality dynamics. Although, the selected WQIs employed different numbers of water quality parameters, sub-index calculation and aggregation methods, the results of the two WQIs (CCME and the SEQ-Eau) showed a very high correlation and they were efficient and adequate to evaluate the spatiotemporal variations of the water quality at the PSA. The third WQI, NSF, was not accurate for the evaluation of the water quality at the PSA for some monitoring stations/sessions due to the eclipsing and rigidity problems. The presentation of the index results through GIS maps improved the interpretation of the results and provided a good visualization. Selecting the most appropriate WQI for spatiotemporal evaluation poses a challenge for both water practitioners and researchers. However, this study offers valuable insights for future investigations as follows: (i) the process of selecting the optimal WQI entails considering factors such as the specific water quality characteristics of the site, data availability, and the researcher's expertise, (ii) maintaining flexibility in choosing water quality parameters and their target values enhances the spatiotemporal assessment, accommodating different water use designations, (iii) it is crucial to assess and quantify the uncertainty associated with WQIs for any given application, (iv) utilizing multiple WQIs facilitates comparison and aids in determining the most representative water quality evaluation. For future work, statistical analysis, multi-criteria decision-making methods, artificial intelligence, and fuzzy rules can be incorporated into the WQIs to overcome the general problems of eclipsing, rigidity, and uncertainty.

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Author contributions The authors confirm contribution to the paper as follows: study conception and design by A.M.; data collection: S.T.D. and A.U.; analysis and interpretation of results: all authors; draft manuscript preparation: A.U. and A.M. All authors reviewed the results and approved the final version of the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethical approval Not applicable.

Consent to participate/publish Not applicable.

Competing interests The authors declare no competing interests.

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References

Abbasi T, Abbasi SA (2012) Water quality indices. Elsevier, Amsterdam

Al Falal ANA, Fadaly EA, Elsayed S, Gad M (2024) Monitoring and assessment of surface water quality using physicochemical parameters and indexical approaches in El Manzala Lake, Egypt. Int J Environ Stud Res 3(1):1–11

Almeida CA, Quintar S, Gonzalez P, Mallea MA (2007) Influence of urbanization and tourist activities on the water quality of the Potrero De Los Funes River (San Luis-Argentina). Environ Monit Assess 133:459–465

APHA (1998) Standard Methods for the Examination of Water and Wastewater. 20th edition. American Public Health Association, Washington, DC

Blue Flag (2019) Blue Flag beach criteria and explanatory notes 2019, 43 pages

Boyacioglu H (2007) Development of a water quality index based on a European classification scheme. Water SA 33(1):101–106. https://doi.org/10.4314/wsa.v33i1.47882

Brown RM, Mc Clelland NI, Deininger RA, Tozer RG (1970) A water quality index – do we dare? Water Sew Works 117(10):339–343

CCME (2001a) Canadian Council of Ministers of the Environment, Canadian water quality guidelines for the protection of aquatic life: CCME water quality index 1.0. User's Manual. In: Canadian environmental quality guidelines, Winnipeg

CCME (2001b) Canadian water quality guidelines for the protection of aquatic life: CCME water quality index 1.0. Technical report. In: Canadian environmental quality guidelines, Winnipeg

Chidiac S, El Najjar P, Ouaini N, El Rayess Y, El Azzi D (2023) A comprehensive review of water quality indices (WQIs): history, models, attempts and perspectives. Rev Environ Sci Biotechnol 22(2):349–395. https://doi.org/10.1007/s11157-023-09650-7

Coletti C, Testezlaf R, Riberion TAP, de Souza RTG, Pereira DA (2010) Water quality index using multi-variate factorial analysis. Rev Bras Eng Agr Amb 14(5):517–522

Dunnette DA (1979) A geographically variable water quality index used in Oregon. J Water Pollut Control Fed 51(1):53–61

EC (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000, Establishing a framework for Community action in the field of water policy, OJ L 327, 22.12.2000, pp 1–73

El Hmaidi A, Talhaoui A, Manssouri I, Jaddi H, Ben Daoud M, Kasse Z, El Ouali A, Essahlaoui A (2022) Assessment of the physicochemical water quality of the Moulouya River, Morocco, using the SEQ Eau index. Environ Monit Assess 194(1):37. https://doi.org/10.1007/s10661-021-09636-4

El Madani FZ, Lahlou K, Idrissi N, Elallaoui N, Ben Abbou M, Merzouki M, Chetouani A, Taleb M, Rais Z (2019) Identification of the quality of surface waters in the city of Fez by the SEQGIS approach and analysis of variance. Moroccan J Chem 7(4):673–682

Elsayed S, Ibrahim H, Hussein H, Elsherbiny O, Elmetwalli AH, Moghanm FS, Ghoneim AM, Danish S, Datta R, Gad M (2021a) Assessment of water quality in Lake Qaroun using ground-based remote sensing data and artificial neural networks. Water 13:3094. https://doi.org/10.3390/w13213094

Elsayed S, Gad M, Farouk M, Saleh AH, Hussein H, Elmetwalli AH, Elsherbiny O, Moghanm FS, Moustapha ME, Taher MA, Eid EM, El-Safa MM (2021b) Using optimized two and three-band spectral indices and multivariate models to assess some water quality indicators of Qaroun Lake in Egypt. Sustainability 13:10408. https://doi.org/10.3390/su131810408

Gad M, Elsayed S, Moghanm FS, Almarshadi MH, Alshammari AS, Khedher KM, Eid EM, Hussein H (2020) Combining water quality indices and multivariate modeling to assess surface water quality in the Northern Nile Delta. Egypt Water 12:2142. https://doi.org/10.3390/w12082142

Gad M, Saleh AH, Hussein H, Farouk M, Elsayed S (2022) Appraisal of surface water quality of Nile River using water quality indices, spectral signature and multivariate modeling. Water 14:1131. https://doi.org/10.3390/w14071131

Gikas GD, Lergios D, Tsihrintzis VA (2023) Comparative assessment of the application of four water quality indices (WQIs) in three ephemeral rivers in Greece. Water 15:1443. https://doi.org/10.3390/w15081443

Gupta S, Gupta SK (2021) A critical review on water quality index tool: Genesis, evolution and future direction. Ecol Inf 63:101299. https://doi.org/10.1016/j.ecoinf.2021.101299

Hamlat A, Guidoum A, Koulala I (2017) Status and trends of water quality in the Tafna catchment: a comparative study using water quality indices. J Water Reuse Desalin 072:228–245. https://doi.org/10.2166/wrd.2016.155

Harkin RD (1974) An objective water quality index. J Water Pollut Control Fed 46(5):588–591

Hu L, Chen L, Li Q, Zouc K, Li J, Ye H (2022) Water quality analysis using the CCME-WQI method with time series analysis in a water supply reservoir. Water Supp 22(7). https://doi.org/10.2166/ws.2022.245

IPCC (2023) Summary for Policymakers. H. Lee and J. Romero (eds.), Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, IPCC

ISO 5667-2 (1991) Water quality - - Sampling - - Part 2: Guidance on sampling techniques. International Organization for Standardization

ISO 5667-3 (1994) Water quality - - Sampling - - Part 3: Guidance on the preservation and handling of samples. International Organization for Standardization

ISO 5667-6 (1990) Water quality - - Sampling - - Part 6: Guidance on sampling of rivers and streams. International Organization for Standardization

ISO 7887 (2011) Water quality - - Examination and determination of colour. International Organization for Standardization

Kummu M, Guillaume JHA, De Moel H, Eisner S, Flörke M, Porkka M, Siebert S, Veldkamp TIE, Ward PJ (2016) The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. Sci Rep 6:38495. https://doi.org/10.1038/srep38495

Kung H, Ying L, Liu YC (1992) A complementary tool to water quality index: fuzzy clustering analysis. Water Resour Bull 28(3):525–533

Liou SM, Lo SL, Wang SH (2004) A generalized water quality index for Taiwan. Environ Monit Assess 96:35–52. https://doi.org/10.1023/B:EMAS.0000031715.83752.a1

Lopes OF, de Jesus RM, de Sousa LF, Rocha FA, da Silva DM, Amorim AF, da Silva VH, Navoni JA (2021) Comparison between water quality indices in watersheds of the Southern Bahia (Brazil) with different land use. Environ Sci Pollut Res Int 28:12944–12959

Lukhabi DK, Mensah PK, Asare NK, Pulumuka-Kamanga T, Ouma KO (2023) Adapted water quality indices: Limitations and potential for water quality monitoring in Africa. Water 15(9). https://doi.org/10.3390/w15091736

Maansi Jindal R, Wats M (2021) Evaluation of surface water quality using water quality indices (WQIs) in Lake Sukhna, Chandigarh, India. Appl Water Sci 12(2). https://doi.org/10.1007/s13201-021-01534-x

Mahmood K, Batool R (2020) Comparison of stochastic and traditional water quality indices for mapping groundwater quality zones. Environ Earth Sci 79:405. https://doi.org/10.1007/s12665-020-09148-3

Mogane LK, Masebe T, Msagati TAM, Ncube E (2023) A comprehensive review of water quality indices for lotic and lentic ecosystems. Environ Monit Assess 195:8. https://doi.org/10.1007/s10661-023-11512-2

Mohammed OM, Sayl KN, Sulaiman SO, Mahmood NS, Allawi MF, Al-Ansari N (2023) Geoinformatics-based approach for aquifer recharge zone identification in the western desert of Iraq, Int J GEOMATE 25(110):220–234. ISSN: 2186–2982 (P), 2186–2990 (O), Japan. https://doi.org/10.21660/2023.110.3448

Mohammed SS, Sayl KN, Kamei AH (2024) Modeling of spatially distributed soil moisture in the Iraqi Western Desert, AIP Conf. Proc. 3009:030058. https://doi.org/10.1063/5.0190545

Muhammetoglu A (2022b) River Water Quality Assessment and Management Using Deterministic Modelling, Water Quality Indices and Statistical Analysis, Project Final Report, TUBITAK Project No:119Y267. Akdeniz University, Antalya

Muhammetoglu A, Akdegirmen O, Dugan ST, Orhan P, Kocer MAT, Muhammetoglu H (2022a) Assessment of pressures and impacts on water quality of a small Mediterranean stream using an integrated approach. Desalin Water Treat 260:241–252. https://doi.org/10.5004/dwt.2022.28606

Muneer AS, Sayl KN, Kamal AH (2021) Modeling of spatially distributed infiltration in the Iraqi Western Desert. Appl Geomat 13:46–479. https://doi.org/10.1007/s12518-021-00363-6

Myers DN, Sylvester MA (1997) Fecal Indicator Bacteria. In: D.N. Myers and F. D. Wilde (eds) Biological Indicators, USGS TWRI Book 9, Chapter A7, 1–38

Noori R, Berndtsson R, Hosseinzadeh M, Adamowski JF, Abyaneh MR (2019) A critical review on the application of the National Sanitation Foundation Water Quality Index. Environ Pollut 244:575–587. https://doi.org/10.1016/j.envpol.2018.10.076

Nyamsi TNL, Zébazé TSH, Foto MS, Onana FM, Tchakonté S, Yémélé TC, Gah-Muti SY, Njiné T (2017) Characterization of a Physicochemical Water Quality Reference Status for the Centre-South Forest Region of Cameroon. Int J Sci Res 6(11):397–405. https://doi.org/10.21275/ART20177749

Ozcelik M (2017) Importance of Shoreline for the Belek Coast (Antalya, Turkey). Geol Bull Turk 60:331–346. https://doi.org/10.25288/tjb.325395. (in Turkish)

Poonam T, Tanushree B, Sukalyan C (2013) Water quality indices-important tools for water quality assessment: a review. Int J Adv Chem 1(1):15–28

Qian Y, Migliaccio KW, Wan Y, Li Y (2007) Surface water quality evaluation using multivariate methods and a new water quality index in the Indian River Lagoon, Florida, Water Resour Res 43(8). https://doi.org/10.1029/2006WR005716

RDWQ (2019) Regulation on Quality and Treatment for Drinking Water Supply, Ministry of Environment and Forestry, Official Gazette No: 30823, Date: 06 July 2019

Regmi RK, Mishra BK, Masago Y, Luo P, Toyozumi-Kojima A, Jalilov S (2017) Applying a water quality index model to assess the water quality of the major rivers in the Kathmandu Valley, Nepal. Environ Monit Assess 189:382

Sargaonkar A, Deshpande V (2003) Development of an overall index of pollution for surface water based on a general classification scheme in Indian context. Environ Monit Assess 89:43–67. https://doi.org/10.1023/A:1025886025137

Sattar B, Sayl K, Rashid R (2024) Modeling of spatially distributed sedimentation in Houram Dam H-3, AIP Conf. Proc. 3009:030125. https://doi.org/10.1063/5.0190480

Schaeffer DJ, Janardan KG (1977) Communicating environmental information to the public a new water quality index. J Environ Educ 8(4):18–26

SEEE (2008) Secrétariat d'État auprès du ministère de l'Énergie des Mines, de l'Eau et de l'Environnement), fiche sur le nouveau système d'évaluation de la qualité des eaux, Maroc, 5 p., [en ligne]

Sener S, Sener E, Davraz A (2017) Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey). Sci Total Environ 584–585:131–144. https://doi.org/10.1016/j.scitotenv.2017.01.102

SEQ-EAU (2003) Système d'évaluation de la Qualité de l'Eau des cours d'eau. Rapport d'étude des Agences de l'Eau. Rapport de présentation SEQ-EAU Version2

Sun W, Xia C, Xu M, Guo J, Sun G (2016) Application of modified water quality indices as indicators to assess the spatial and temporal trends of water quality in the Dongjiang River. Ecol Indic 66:306–312

Sutadian AD, Muttil N, Yilmaz AG, Perera BJC (2016) Development of river water quality indices-A review. Environ Monit Assess 188(1):58

SWQR (2021) Update on Surface Water Quality Management Regulation, Ministry of Agriculture and Forestry, Official Gazette No: 31513, Date: 16 June 2021

Syeed MMM, Hossain MS, Karim MR, Uddin MF, Hasan M, Khan RH (2023) Surface water quality profiling using the water quality index, pollution index and statistical methods: A critical review, Environ Sustain Ind 18. https://doi.org/10.1016/j.indic.2023.100247

Terrado M, Barcelo D, Tauler R, Borrell E, Campos SD (2010) Surface-water-quality indices for the analysis of data generated by automated sampling networks. Trends Anal Chem 29(1):40–52

Trikoilidou E, Samiotis G, Tsikritzis L, Kevrekidis T, Amanatidou E (2017) Evaluation of water quality indices adequacy in characterizing the physico-chemical water quality of lakes. Environ Process 4:35–46. https://doi.org/10.1007/s40710-017-0218-y

Tyagi S, Sharma B, Sing P, Dobhal R (2013) Water Quality Assessment in terms of Water Quality Index. Am J Water Resour 1(3):34–38. https://doi.org/10.12691/ajwr-1-3-3

Uddin GM, Nash S, Olbert AI (2021) A review of water quality index models and their use for assessing surface water quality. Ecol Indic 122:107218

UN (2023) The United Nations World Water Development Report 2023: Partnerships and cooperation for water. UNESCO, Paris. https://unesdoc.unesco.org/ark:/48223/pf0000384655. Accessed 10 June 2024

UN (2024) Water for prosperity and peace. Fatcs, Figures and Action Examples. The United Nations World Water Development report 2024, Prepared by WWAP, Engin Koncagül. Richard Connor and Valentina Abete, UNESCO

UNEP (2021) United Nations Environment Programme, Progress on Ambient Water Quality: Tracking SDG 6 Series-Global Indicator 6.3.2 Updates and Acceleration Needs. UNEP, Nairobi

Van den Doel A, van Kollenburg GH, van Remmen TDN, de Jonge JA, Postma GJ, Tinnevelt GH, Stroomberg GJ, Buydens LMC, Jansen JJ (2023) Calculating required purification effort to turn source water into drinking water using an adapted CCME water quality index. Water Resour Res. https://doi.org/10.1029/2020WR027925

Wepener V, Euler N, Van Vuren JHJ, Du Preez HH, Köhler A (1992) The development of an aquatic toxicity index as a tool in the operational management of water quality in the Olifants River (Kruger National Park). Koedoe 35(2):1–9

WPCR (2004) Water Pollution Control Regulation, Ministry of Agriculture and Forestry, Official Gazette No: 25687 Date: 31 December 2004

WRC (2023) Water Research Center. KnowYourH2O. https://www.knowyourh2o.com/outdoor-3/water-quality-index-calculator-for-surface-water. Accessed 10 June 2024

Zandbergen PA, Hall KJ (1998) Analysis of the British Columbia water quality index for watershed managers: a case study of two small watersheds. Water Qual Res J Can 33(4):519–549

Zotou I, Tsihrintzis VI, Gikas GD (2020) Water quality evaluation of a lacustrine water body in the Mediterranean based on different water quality index (WQI) methodologies. J Environ Sci Heal A 1532–4117. https://doi.org/10.1080/10934529.2019.1710956

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