Environ Monit Assess (2025) 197:699
https://doi.org/10.1007/s10661-025-14172-6

RESEARCH

# A comprehensive study of water quality in the Western Black Sea: Implementation of prospective human health risk assessment in Kastamonu, Turkey

**Arife Şimşek · Fikret Ustaoğlu · Ekrem Mutlu**

Received: 5 March 2025 / Accepted: 20 May 2025 / Published online: 30 May 2025


**Abstract** Water scarcity is becoming an increasing problem due to population growth and rapid urbanization. This study evaluates the water quality of Kirazlı Stream, located in the Kastamonu Province, in Turkey's Western Black Sea Region. To determine its suitability for regional use, samples were collected from 12 stations over 12 months between December 2021 and November 2022. A total of 24 physicochemical parameters were analyzed. Water quality classifications were assigned based on threshold values from the European Union (EU), World Health Organization (WHO), and Turkey's Surface Water Quality Regulation (TSWQR). The results revealed that Kirazlı Stream, categorized as Class I water quality, is suitable for use. The order of the mean values of cations were as follows: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ (39.14, 14.09, 12.45, and 5.95; mg/L), and order of anions: $SO_4^{2-} > Cl^- > NO_3^- > PO_4^{3-}$ (34.66, 7.48, 1.72, and 0.02; mg/L). Indices such as *WQI* (weighted arithmetic water quality index), *HEI*, *HPI*, and *ERI* indicated excellent to good water quality, whereas *SAR* and *Na%* indices supported its usability for irrigation purposes. However, the *MH* index suggested unsuitability for irrigation. Moreover, 25% of the sampling points met irrigation standards in terms of *KR*, while 75% did not. Potential health risks for both adults and children were below the threshold ($HI < 1$). Statistical approaches, including Spearman correlation, *PCA* and *HCA*, were employed to assess the physicochemical datasets representing water quality. This study is the first study conducted in the region to evaluate the water quality of the Kirazlı Stream and is an important reference for optimizing resource use and promoting sustainable water management.

**Keywords** Irrigation water · Kirazlı Stream · Magnesium hazard · *SAR* · Water quality · *WQI*

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s10661-025-14172-6.

A. Şimşek (✉)
Institute of Hemp Research, Ondokuz Mayıs University, 55139 Samsun, Turkey
e-mail: arife.simsek@omu.edu.tr

F. Ustaoğlu
Department of Biology, Giresun University, Gure Campus, 28200 Giresun, Turkey
e-mail: fikretustaoglu@hotmail.com

E. Mutlu
Faculty of Humanities and Social Sciences, Department of Geography, Kastamonu University, Kuzeykent Campus, 37000 Kastamonu, Turkey
e-mail: ekrem-mutlu@hotmail.com

## Introduction

Water is essential for the ongoing existence of life, making access to safe and accessible water a global priority (Dippong et al., 2023; Ben-tahar et al. 2025). Both human and natural activities have the potential to contaminate water. When polluted with various pathogens such as bacteria, fungi, and viruses, or toxic substances, and consumed in such a state, water can lead to diseases (Adesakin et al., 2020; Varol & Tokatli, 2023a, b). Water pollution and restricted use of water are caused by natural processes such as erosion, volcanic eruptions, and drought, as well as anthropogenic activities such as industrialization, agriculture, and mining (Dey et al., 2021; Nyantakyi et al., 2024).

Water scarcity influences more than 40% of the global population. Even though access to safe drinking water has improved worldwide over the past few decades, as stated by the Ministry of Agriculture and Forestry (2023), 80 countries still face water shortages. Approximately 844 million people cannot access to drinking water services, whereas over 2.1 billion individuals (more than 25% of the global population) are unable to access clean water. The growing global population and the increasing demand for high-quality water for domestic and economic activities further exacerbate water scarcity (Khatri & Tyagi, 2015; Perveen and Haque, 2023; Sabbagh et al., 2024; Ali et al., 2024). Simultaneously, the degradation of drinking water quality due to improper practices and usage necessitates a robust framework and management system to address challenges in the drinking water supply chain, from water catchment areas to consumers (Babu et al., 2024; Hasan et al., 2022; Nong et al., 2020).

Given the seasonal and spatial variability in water quality, regular monitoring is essential as assessing water composition can be challenging (Şimşek & Mutlu, 2023). Water quality can deteriorate due to improper treatment and the discharge of waste from domestic, agricultural, and industrial activities (Varol et al., 2011; Adimalla and Venkatayogi, 2018; Kükrer and Mutlu, 2019). As a result, assessing water quality analyzing physical, chemical, and biological parameters and ensuring continuous monitoring is critical to prevent quality degradation (Bakan et al., 2010; Cüce et al., 2022a; Şimşek et al., 2023; Üstün Odabaşı & Ceylan, 2023).

Since water bodies are vital for sustaining biotic life and serve as essential resources for domestic and agricultural purposes, it is crucial to determine their suitability for drinking and irrigation purposes. Many indices were developed in previous studies to determine water quality based on its natural, physical, and chemical properties (Şimşek et al., 2019; Ahmed et al., 2020; Tian et al., 2020; Gholami et al., 2022; Singh et al., 2023; Roy et al., 2024; Hossain Sadid et al., 2024; Sengupta et al., 2024). One such index is the water quality index (*WQI*), introduced by Horton (1965), which integrates and evaluates the combined effects of various water characteristics deemed significant for water quality (Howladar et al., 2021; Kangabam et al., 2017; Poursaeid et al., 2024; Tokatli et al., 2022; Ustaoğlu et al., 2020). The quality of irrigation water plays an equally significant role in preserving soil fertility (Çankaya et al., 2023). Various irrigation indices such as permeability index (*PI*), sodium adsorption ratio (*SAR*), magnesium hazard (*MH*), sodium percentage (*Na%*), and ecological risk index (*ERI*) can be utilized to analyze the quality of stream waters for irrigation purposes (Cüce et al., 2022a; Haq & Muhammad, 2023; Rehman et al., 2024). Moreover, health risk assessment techniques are commonly utilized to examine the health risks related with various pollutants in stream waters (Hoque et al., 2022; Pashaeifar et al., 2021; Zhang et al., 2020a). Multivariate statistical analyses, such as *HCA*, correlation coefficients, and *PCA*, are also employed to identify pollutant sources (Agyeman et al., 2022; Ben-tahar et al., 2025b).

Kirazlı Stream, located in Çatalzeytin, is in Kastamonu, the Turkish province with the most extensive coastline along the Black Sea, spanning approximately 170 km. Çatalzeytin, one of 6 districts of Kastamonu bordering the Black Sea, experiences a significant population increase during the summer months due to returning expatriates and tourists, despite its relatively small winter population (KPESR, 2023). The region is characterized by its natural coves and harbors, in addition to its diverse ecological features. There are natural beaches along the coastline, as well as diving areas and ports, whereas the steeply sloping shoreline hosts forests with rich plant diversity. The district also features fishing harbors that support local fishing activities. However, with no wastewater treatment facilities in place, untreated wastewater is directly discharged into the Black Sea (MLAP, 2018). The Kirazlı Waterfall and its surrounding biodiversity attract tourists, while local residents engage in agriculture (notably fruit farming), animal husbandry, and beekeeping. Fishing activities are also prevalent in coastal areas, with species like anchovy, bluefish, and rockfish being common. The region produces walnuts, apples, hazelnuts, and cornelian cherries, and Kirazlı Stream serves as an essential irrigation source.

In literature, there is no study examining the water quality of Kirazlı Stream. Therefore, comprehensive research is required to ascertain the usability of the streams's water for irrigation purposes. This study aims to: (1) evaluate the water quality of Kirazlı Stream by utilizing water quality indices, irrigation water indices, and metal pollution indices; (2) identify pollution sources that significantly impact the Stream's water quality statistically; and (3) evaluate non-carcinogenic health risks associated with its use. This study is also important as a reference for future studies as it is the most comprehensive water quality assessment study conducted in the region to date. By providing a detailed assessment adapted to the locality, it provides basic tools for water resource managers to develop effective management strategies, forward-looking prevention measures and cope with environmental challenges for water resources.

## Materials and methods

### Study area

Kirazlı Stream is located in the Black Sea region, passing through the Çatalzeytin District of Kastamonu Province (Fig. 1). Kastamonu province is a province with rich potential and diversity in terms of underground resources due to its geological structure. There are many metallic mines and industrial raw material deposits in the province and its immediate surroundings. The most important of these are copper-lead–zinc and quartzite deposits. Apart from this, manganese and mercury from metallic mines and clay, kaolin, quartz sand, graphite, cement raw materials, and phosphate formations from industrial raw material sources are found in the province. Çatalzeytin is situated 73 km away from Kastamonu city center. Çatalzeytin, with a surface area of 368 $km^2$, constitutes 2.8% of the total area of Kastamonu Province. The Black Sea climate characterized by year-round precipitation dominates this district. The flow regime of rivers in the area is regular and influenced by the seasonal distribution of rainfall. Agriculture in the district faces challenges due to fragmented and sloping terrain. Even though its potential for arable land is limited, fruit cultivation holds significant importance, and a wide range of fruit crops are grown. The most widely grown ones include walnuts, apples, plums, and hazelnuts. Çatalzeytin accounts for 100% of peach production, 77% of apricot production, 15% of fig production, and 8% of walnut production in Kastamonu Province. In terms of vegetables, green beans, table tomatoes, and green peppers are produced. In terms of animal husbandry, cattle and buffalo breeding are carried out. Despite the district's richness in forest resources, there has been a notable rise in concrete constructions in recent years, replacing traditional wooden structures. The district has a water potential of 77.78 $hm^3$/year. Its land use includes 10.277 ha of agricultural land, 21.149 haof forest, and 5.197 ha of non-agricultural land. As a coastal area, aquaculture activities are also conducted. Even though there is no Organized Industrial Zone (OIZ) in Çatalzeytin, there is a small industrial site with a capacity of 44 businesses, 21 of which are operational. Kirazlı Stream features a stony and gravelly riverbed surrounded by trees. However, the district lacks a municipal wastewater treatment facility, posing a threat of marine pollution.

### Water sampling and laboratory analysis

This study was carried out by analyzing water quality parameters collected monthly over 12 months from 12 stations located between 41°57′25″ North and 34°11′33″ East. The coordinates and detailed information on those points are provided in Supplementary Information (SI)−2 (Table S1). Sampling was started in December 2021 and finished in November 2022. Water samples were collected during the third week of each month using acid-cleaned 1000-mL glass bottles, at a depth of 50 cm. All samples were kept at + 4 °C until the analyses were performed at the laboratory. Twenty-four parameters were measured. On-site measurements of pH, water temperature (*WT*), dissolved oxygen (*DO*), and electrical conductivity (*EC*) were performed employing a YSI 556 MPS multiparameter device. Laboratory analyses included total suspended solids (*TSS*), chemical oxygen demand (*COD*), biological oxygen demand (*BOD*), total hardness (*TH*), total alkalinity (*TA*), nitrate ($NO_3^-$), phosphate ($PO_4^{3-}$), sulfate ($SO_4^{2-}$), chloride ($Cl^-$), calcium ($Ca^{2+}$), sodium ($Na^+$), magnesium ($Mg^{2+}$), and potassium

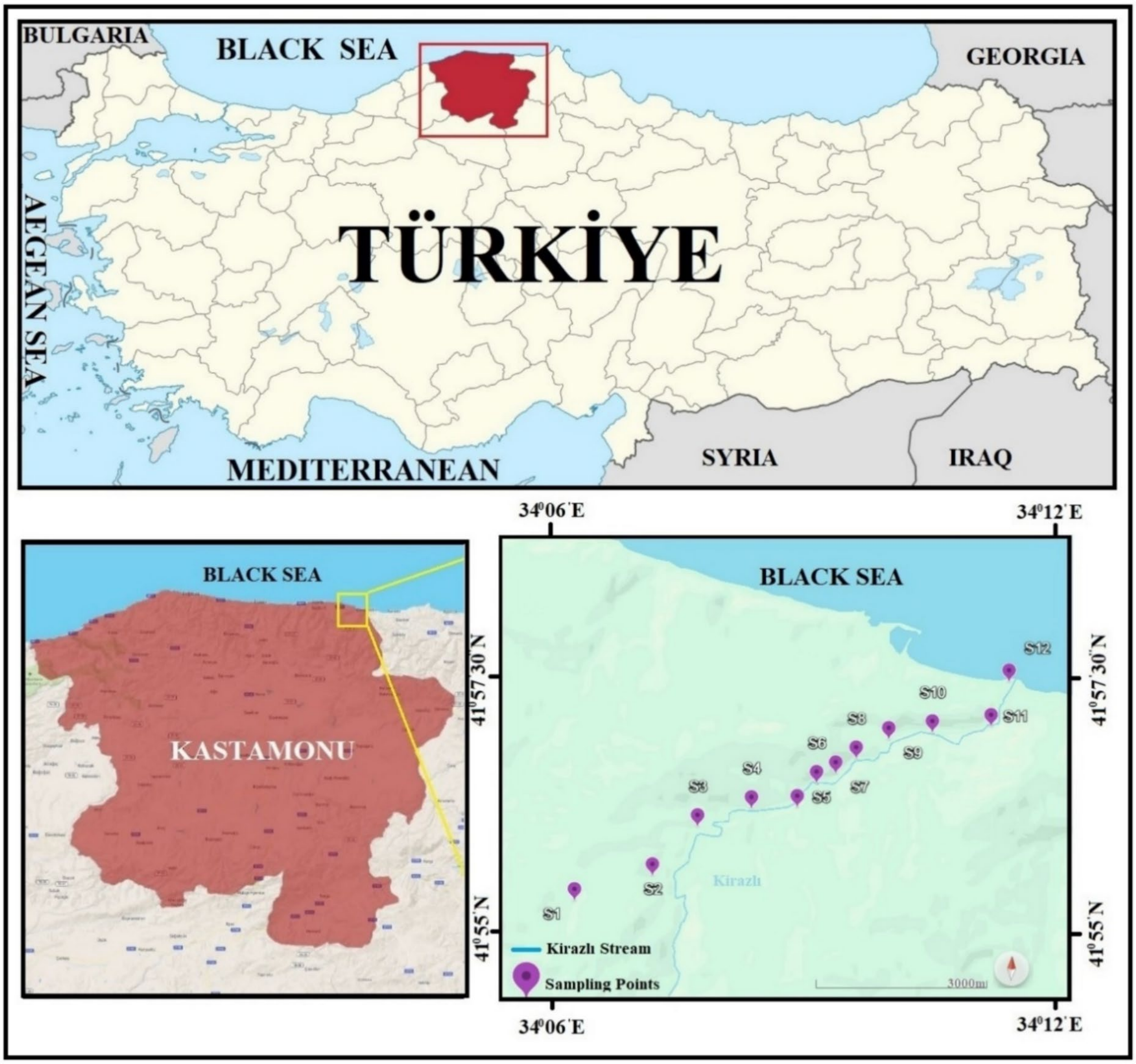


**Fig. 1** Study area showing Kirazlı Stream and sampling locations

($K^+$), all performed at the Central Research Laboratory of Kastamonu University, accredited by the Turkish Accreditation Agency (TURKAK), employing standard methods (APHA/AWWA/WEF, 2017). The accuracy of the samples was calculated using the ionic balance error (IBE) given in Eq. (1) to determine the analytical sensitivity between cations ($Mg^{2+}$, $Ca^{2+}$, $K^+$, and $Na^+$) and anions ($Cl^-$, $SO_4^{-2}$, $NO_3^-$, and $PO_4^{-3}$), and expressed as milliequivalents per liter (meq/L) for each sample (Boukich et al., 2024a; Li et al., 2021).

$$IBE = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} \times 100 \quad (1)$$

The ionic balance of the samples was less than 5%, representing the reliability of the analytical results.

Analyses of potentially toxic elements (PTEs) such as Fe, Cd, Pb, Cu, Zn, Ni, and Hg were carried out using ICP-OES (Spectro, SpectroBlue). Each metal was analyzed in triplicate, and the average value was taken for data analysis. Nitric acid solution (65% v/v) ($HNO_3$, Merck, Darmstadt, Germany) was provided to produce sample solutions and calibration standards. The validity of the test was assessed using UME CRM 1201 Spring Water, a certified reference material (CRM) obtained from Tubitak, Turkey. The CRM content was 100 mL of spring water, and the material was acidified to contain approximately 2% (w/v) $HNO_3$.

## Indexes for water quality assessment

Eight indices were employed to examine the water quality of Kirazlı Stream comprehensively. *WQI*, which measures the combined effects of each water parameter considered significant for water quality and facilitates integration, is useful for analyzing water quality from the aspects of potability and management implications (Basnet et al., 2024). In this study, 18 parameters (pH, *EC*, *BOD*, $Cl^-$, $SO_4^{2-}$, $NO_3^-$, $K^+$, $Mg^{2+}$, $Na^+$, $PO_4^{3-}$, *TH*, Fe, Pb, Cu, Cd, Hg, Ni, and Zn) were used in calculating the *WQI* to assess water quality for drinking purposes (Dimri et al., 2021). A weight ($W_i$) was determined for each parameter, considering its relative importance in affecting potable water quality, and the thresholds set by WHO (2011) were used. SI in Table S3 presents the relative weight ($wi$) values and the potable water standards established by WHO (2011). Some of the mostly used indices to assess general metal pollution in surface water resources are the ecological risk index (*ERI*), the heavy metal pollution index (*HPI*), and the heavy metal evaluation index (*HEI*) (Boukich et al., 2024b; Egbueri, 2020; Varol & Tokatli, 2023a, b). Even though *ERI* was originally introduced to evaluate the ecological risks of metals in sediments, it has recently been employed to evaluate the environmental risks of metals in water as well (Ben-tahar et al., 2025a; Real et al., 2024; Wen et al., 2019). In this study, seven PTEs (Ni, Cu, Zn, Hg, Pb, Cd, and Fe) were employed to calculate *ERI*, *HPI*, and *HEI* values. *MH*, *Na%*, *SAR*, and *KR* indices were utilized to evaluate the suitability of Kirazlı Stream and its tributaries for irrigation. The formulas and descriptions used in the calculations of these indices are provided in Table 1.

## Probable health risk assessment (PHRA)

It is very important to assess probable health risks to examine water quality and the implications for human health. This technique is commonly used to address the potential negative influences of polluted water on the health of children and adults who are exposed to contaminants in water due to ingestion and dermal contact (Adimalla, 2019; Çankaya et al., 2023; Chen et al., 2017; Zhang et al., 2020b).

PTEs from freshwater are taken from the human body through ingestion or skin contact. Non-carcinogenic and carcinogenic health effects from oral intake and skin contact may be estimated by experimental models. In the present study, the health risk evaluation method recommended by USEPA (2004) was used, and the toxicological parameters of PTEs are shown in Supplementary information Table S7 (Wang et al., 2017). The average daily dose (*ADD*) by direct digestion (*ADD* ingestion) and skin absorption (*ADD* dermal) was calculated using the formulas (2) and (3) below (Saleem et al., 2019; Zeng et al., 2015).

$$ADD_{ingestion} = \frac{C_{water} \times IR \times ABS_g \times EF \times ED}{BW \times AT} \quad (2)$$

$$ADD_{dermal} = \frac{C_{water} \times SA \times K_p \times ET \times EF \times ED \times CF}{BW \times AT} \quad (3)$$

where $ADD_{ingestion}$ expresses average daily dose by ingestion and, $ADD_{dermal}$ reveals average daily dose by dermal, µg/kg/day; $C_{water}$ shows level of the PTEs in freshwater, µg/L; *IR* indicates ingestion rate (L/day), 2 for adult, 0.64 for children in this study; *EF* reveals exposure frequency 365 day/year in this study; *ED* stands for exposure duration (in years), 70 for adults and 6 for children in this study; $K_p$ represents dermal permeability coefficient in water (cm/h); *ET* is the exposure time during bathing and shower, 0.6 h/day in this study; *CF* shows the unit conversion factor, 1 L/1000 $cm^3$; *BW* represents average body weight (kg), 70 for adults and 20 for children in this study; *AT* indicates averaging time (day), 25,550 for adults and 2190 for children in this study; SA expresses exposed skin area ($cm^2$), 18,000 for adults and 6600 for children in this study; $ABS_g$ which is dimensionless, was the gastrointestinal absorption factor (Xiao et al., 2019).

Hazard quotient (*HQ*) and hazard index (*HI*), representing the possible non-carcinogenic effects of PTEs taken with digestion and skin, were calculated by the following formulas (4), (5), and (6).

**Table 1** Equations, explanations, and ranking criteria of the water quality assessment and irrigation indices used in this study

| Indices | Equations | Explanations | Water quality | References |
|---|---|---|---|---|
| Water quality index (*WQI*) | $WQI = \sum \left[ W_i \times \left( \frac{C_i}{S_i} \right) \times 100 \right]$ | $W_i = wi/\Sigma wi$ $i$ is the relative weight. For a $W_i$ value, max 5 and min 1 are assigned. $C_i$ is the concentration of the parameters included in the calculation and $S_i$ is determined according to the standard value set by WHO (2011) for drinking water | 0–25 → excellent<br>25–50 → good<br>50–75 → poor<br>75–100 → very poor<br>> 100 → unsuitable | Ustaoğlu et al. (2020); Tokatli et al. (2022) |
| Heavy metal pollution index (*HPI*) | $HPI = \frac{\sum_{i=1}^{n}(Q_i W_i)}{\sum_{i=1}^{n} W_i}$<br>$Q_i = \frac{C_i}{S_i} \times 100 \; W_i = \frac{k}{S_i}$ | $Q_i$ refers to the sub-index of each metal; $C_i$ to the detected concentration value of metals; the standard values of $S_i$ parameters set by WHO (2011) as drinking water; $W_i$ refers to the unit weight of metals; and $k$ to a fixed value of "1" | < 15 → mow pollution<br>15–30 → moderate pollution<br>30–100 → moderate to heavy pollution<br>> 100 → heavy pollution | Mohan et al. (1996); Tokatli et al. (2023) |
| Heavy metal evaluation index (*HEI*) | $HEI = \sum_{i=1}^{n} \frac{H_C}{H_{MAC}}$ | *HC* refers to the value determined for each metal and $H_{MAC}$ to the maximum allowed concentration value (*MAC*) of each metal (WHO, 2011) | < 10 → low pollution<br>10–20 → medium pollution<br>> 20 → high pollution | Saleh et al. (2018) |
| Ecological risk index (*ERI*) | $ERI = \sum_{i=1}^{n} T_i x \frac{C_i}{S_i}$ | $T_i$ refers to the toxicity factor of the target metal. $T_i$ values are 5 for Ni, Cu, and Pb; 1 for Mn and Zn; 2 for Cr and B; 10 for As; and 30 for Cd (Hakanson, 1980) | < 110 → low risk<br>110–200 → moderate risk<br>200–400 → considerable risk<br>≥ 400 → very high risk | Sharifi et al. (2016); Tokatli et al. (2023) |
| Sodium adsorption ratio (*SAR*) | $SAR = \frac{[Na^{+}_{meq}]}{\sqrt{\frac{[Ca^{2+}_{meq}]+[Mg^{2+}_{meq}]}{2}}}$ | The concentration unit of all ions was converted from mg/L to meq/L | 0–10 → excellent<br>10–18 → good<br>18–26 → doubtful<br>> 26 → unsuitable | Muhammad and Ullah (2022) |
| Sodium percentage (%) | $Na\% = \frac{\left(Na^{+}_{meq} + K^{+}_{meq}\right) \times 100}{Na^{+}_{meq} + Ca^{2+}_{meq} + Mg^{2+}_{meq} + K^{+}_{meq}}$ | The concentration unit of all ions was converted from mg/L to meq/L | 0–20% → excellent<br>20–40% → good<br>40–60% → permissible<br>60–80% → doubtful<br>> 80% → unsuitable | Haq and Muhammad (2023) |
| Magnesium hazard (*MH*) | $MH = \left( \frac{Mg^{2+}_{meq}}{Ca^{2+}_{meq} + Mg^{2+}_{meq}} \right) \times 100$ | The concentration unit of all ions was converted from mg/L to meq/L | < 50% → suitable<br>> 50% → unsuitable | Cüce et al. (2022a) |

**Table 1** (continued)

| Indices | Equations | Explanations | Water quality | References |
|---|---|---|---|---|
| Kelley's ratio (*KR*) | $KR = \frac{Na^{+}_{meq}}{Ca^{2+}_{meq} + Mg^{2+}_{meq}}$ | The concentration unit of all ions was converted from mg/L to meq/L | < 1 → suitable<br>> 1 → unsuitable | Çankaya et al. (2023) |

$$HQ_{ingestion} = \frac{ADD_{ingestion}}{RfD_{ingestion}} \tag{4}$$

$$HQ_{dermal} = \frac{ADD_{dermal}}{RfD_{dermal}} \tag{5}$$

$$HI = \sum (HQ_{ingestion} + HQ_{dermal}) \tag{6}$$

$HQ < 1$ represents that exposure to any adverse health effects is not likely; while a $HI > 1$ value indicates that there may be non-carcinogenic effects from PTE contact (Mahjoub et al., 2024).

### Statistical analyses

To reveal seasonal variations, the Kruskal–Wallis test was applied to non-normally distributed parameters, and a one-way ANOVA test was used for normally distributed parameters ($p < 0.05$). *PCA*, *HCA*, and Spearman correlation analyses were performed to identify potential sources of water quality parameters (Cüce et al., 2022b; Haghnazar et al., 2023). Prior to these analyses, the data were standardized utilizing *Z*-scores. In *HCA*, the Euclidean distance and Ward's method were employed. Total absolute factor loadings were classified as weak (0.50–0.30), moderate (0.75–0.50), and strong (> 0.75) (Şimşek & Mutlu, 2023; Taş et al., 2021). The suitability of the dataset for *PCA* was confirmed using the Kaiser–Meyer–Olkin (*KMO*) test ($0.5 \leq KMO = 0.871$) and Bartlett's test of sphericity ($p < 0.001$), verifying the adequacy of the data for analysis.

## Results and discussion

### Changes in physicochemical water properties of Kirazli Stream

The seasonal average values and standard deviations of 24 physical and chemical parameters measured over 12 months in Kirazlı Stream are summarized in Table 2. The parameters are evaluated according to the threshold values of WHO (2011), EU (1998), and TSWQR (2021), as presented in Table 2. Dissolved oxygen (*DO*) was greater than 8 mg/L at all sampling points and during all seasons, classifying it as Class

**Table 2** Seasonal average values of physicochemical parameters at Kirazlı Stream stations

| Parameter | Winter | Spring | Summer | Autumn | *Mean* ± *st dev* | Min | Max | TSWQR (2021) | | | WHO | EU |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Class I | Class II | Class III | (2011) | 1998 |
| *DO* (mg/L) | 13.88$^{a}$ | 14.11$^{a}$ | 14.10$^{a}$ | 11.21$^{b}$ | 13.33 ± 1.52 | 9.34 | 14.94 | > 8 | 6 | < 6 | | |
| pH | 8.43$^{a}$ | 8.37$^{a}$ | 8.56$^{b}$ | 8.69$^{c}$ | 8.51 ± 0.22 | 8.09 | 9.01 | 6–9 | 6–9 | 6–9 | 6.5–8.5 | 6.5–9.5 |
| *WT* (°C) | 4.42$^{a}$ | 7.04$^{a}$ | 16.79$^{b}$ | 15.60$^{b}$ | 10.96 ± 6.88 | 3.80 | 25.90 | | | | | |
| *EC* (µs/cm) | 252.23$^{a}$ | 264.10$^{a}$ | 298.33$^{b}$ | 296.21$^{b}$ | 277.71 ± 21.01 | 226.76 | 337.22 | < 400 | 1000 | > 1000 | 1500 | |
| *TSS* (mg/L) | 1.26$^{a}$ | 1.97$^{b}$ | 2.96$^{c}$ | 2.92$^{c}$ | 2.28 ± 1.32 | 0.27 | 5.22 | | | | | |
| *COD* (mg/L) | 0.54$^{a}$ | 0.95$^{b}$ | 1.35$^{c}$ | 1.79$^{d}$ | 1.16 ± 0.67 | 0.40 | 2.64 | | | | | |
| *BOD* (mg/L) | 0.12$^{a}$ | 0.35$^{b}$ | 0.68$^{c}$ | 0.70$^{c}$ | 0.46 ± 0.42 | 0.02 | 2.02 | | | | 5 | |
| $Cl^-$ (mg/L) | 8.33$^{a}$ | 8.02$^{a}$ | 6.96$^{b}$ | 6.61$^{b}$ | 7.48 ± 1.36 | 3.96 | 10.38 | | | | 250 | |
| $Na^+$ (mg/L) | 35.92$^{a}$ | 44.30$^{b}$ | 42.70$^{b}$ | 33.63$^{a}$ | 39.14 ± 11.06 | 21.74 | 72.33 | | | | 200 | |
| $K^+$ (mg/L) | 5.22$^{a}$ | 6.48$^{b}$ | 6.31$^{b}$ | 5.80$^{ab}$ | 5.95 ± 1.62 | 1.86 | 8.81 | | | | 12 | 12 |
| $Mg^{+2}$ (mg/L) | 12.14$^{a}$ | 12.51$^{ab}$ | 12.82$^{b}$ | 12.32$^{a}$ | 12.45 ± 0.69 | 11.62 | 15.47 | | | | 50 | |
| $Ca^{+2}$ (mg/L) | 13.72$^{a}$ | 14.51$^{b}$ | 14.43$^{b}$ | 13.71$^{a}$ | 14.09 ± 1.13 | 12.60 | 17.05 | | | | 75 | |
| *TA* (mg/L) | 171.97$^{a}$ | 190.39$^{bc}$ | 195.37b | 186.57$^{c}$ | 186.07 ± 15.88 | 163.55 | 230.08 | | | | | |
| *TH* (mg/L) | 163.94$^{a}$ | 182.57b | 186.25$^{b}$ | 181.12$^{b}$ | 178.47 ± 15.58 | 155.34 | 219.61 | | | | 100 | |
| $SO_4^{-2}$ (mg/L) | 8.68$^{a}$ | 32.06$^{b}$ | 53.27$^{c}$ | 44.63$^{c}$ | 34.66 ± 26.03 | 0.97 | 78.38 | | | | 250 | |
| $NO_3^-$ (mg/L) | 0.84$^{a}$ | 1.17$^{a}$ | 2.43$^{b}$ | 2.43$^{b}$ | 1.72 ± 1.05 | 0.30 | 4.40 | < 3 | 10 | > 10 | 50 | 50 |
| $PO_4^{-3}$ (mg/L) | 0.01$^{a}$ | 0.01$^{a}$ | 0.03$^{b}$ | 0.03$^{b}$ | 0.02 ± 0.02 | 0.00 | 0.08 | < 0.05 | 0.16 | > 0.16 | | |
| Fe (µg/L) | 8.17$^{a}$ | 12.72$^{b}$ | 8.25$^{a}$ | 8.92$^{a}$ | 9.51 ± 4.28 | 2.00 | 24.00 | | | | 300 | |
| Pb (µg/L) | 1.15$^{a}$ | 1.68$^{b}$ | 1.28$^{a}$ | 1.14$^{a}$ | 1.31 ± 0.57 | 0.30 | 2.70 | | | | 10 | |
| Cu (µg/L) | 16.72$^{a}$ | 22.36$^{b}$ | 15.03$^{a}$ | 15.97$^{a}$ | 17.52 ± 7.53 | 3.00 | 36.00 | | | | 2000 | |
| Cd (µg/L) | 0.63$^{a}$ | 0.68$^{a}$ | 0.58$^{a}$ | 1.18$^{b}$ | 0.77 ± 0.41 | 0.20 | 1.90 | | | | 3 | |
| Hg(µg/L) | 0.005$^{a}$ | 0.009$^{b}$ | 0.007$^{ab}$ | 0.009$^{b}$ | 0.008 ± 0.004 | 0.002 | 0.022 | | | | 6 | |
| Ni (µg/L) | 6.42$^{a}$ | 8.69$^{b}$ | 6.72$^{a}$ | 7.14$^{ab}$ | 7.24 ± 3.08 | 3.00 | 15.00 | | | | 70 | |
| Zn (µg/L) | 7.81$^{a}$ | 15.11$^{b}$ | 10.83$^{c}$ | 9.28$^{ac}$ | 10.76 ± 5.11 | 3.00 | 26.00 | | | | 3000 | |

[a,b,c]Averages in the same row with different letters are statistically significant ($p < 0.05$)

I water quality. Dissolved oxygen (*DO*) is an important limiting factor in aquatic life. Oxygen produced by photosynthesis in aquatic ecosystems provides oxygen saturation (Boyd, 2015). In this study, *DO* is not at a level that will limit aquatic life according to TSWQR (2021). Ustaoğlu et al. (2020) also reported that *DO* levels (9.02–13.62 mg/L) in Turnasuyu Stream were not at a level that would limit life. The pH value, recommended to range between 6.5 and 8.5 by WHO (2011), was observed to exceed 8.5 during the summer and fall seasons. As shown in the results for all sampling points in Table 2, pH values ranging from 8.33 to 8.74 indicate an alkaline water characteristic. In eutrophic coastal systems, the production of inspired $CO_2$ compromises life in terms of dissolved oxygen and pH. Thus, when eutrophication processes occur in warm, stratified, and/or poorly mixed waters, they can cause hypoxia (depletion of dissolved oxygen) and acidification (decrease in pH), both of which can have adverse effects on aquatic life, affecting a range of physiological processes and increasing mortality rates (Tomasetti & Gobler, 2020). The average temperature ranged between 4.42 °C in winter and 16.79 °C in summer, reflecting seasonal norms due to the natural climate conditions of the study area. *TSS* in the analyzed water samples ranged between 1.26 and 2.96 mg/L, indicating the presence of particles larger than 2 µm in the water samples (Nyantakyi et al., 2024). Electrical conductivity (*EC*) increased with the presence of pollutants and rising temperatures (Şimşek & Mutlu, 2023; Şimşek et al., 2021).

According to the results in Table 2, conductivity increases proportionally with rising temperatures, ranging between 226.76 and 337.22 µS/cm. *EC* values were below 400 µS/cm at all sampling points, indicating Class I water quality. The seasonal averages of *COD*, *BOD*, $Cl^-$, $Na^+$, $Mg^{2+}$, $Ca^{2+}$, total hardness (*TH*), $SO_4^{2-}$, $NO_3^-$, and $PO_4^{3-}$ did not exceed WHO standards, while $K^+$ remained below the EU (1998) threshold of 12 mg/L. Similar to findings by Obiri et al. (2021) and Çankaya et al. (2023) for the water quality of Ghana's and the Tigris Rivers, the parameters in this study were within acceptable limits according to WHO (2011) standards, making them suitable for drinking water purposes. PTEs (Fe, Pb, Cu, Cd, Hg, Ni, and Zn) also did not exceed the WHO (2011) limit values. Several PTEs, such as zinc (Zn), iron (Fe), and copper (Cu), are essential for all living things at low levels (Sepúlveda et al., 2023). Intake of elements less than the required amounts can cause deficiency effects such as hair loss, poor wound healing, and anemia. However, essential elements can cause significant toxic effects at higher intakes (Tokatli et al., 2024). The PTE results measured in this study were much lower than those reported by Muhammad et al. (2021) for the Kunhar River Basin in Pakistan.

## Assessment of the quality of Kirazlı Stream for potable water purposes

*WQI* was used in assessing the quality of Kirazlı Stream's water resources for drinking purposes. The average *WQI* values ranged between 16.26 and 26.28 (Table 3 and SI Fig. S2). The lowest *WQI* at sampling point S1 indicated "excellent" water quality, while the highest *WQI* at S12 reflected "good" water quality. Seasonal averages demonstrated "excellent" water quality throughout all seasons. Excellent water quality samples were found in the southern and central regions of the study area, whereas good water quality samples were identified in the northern region. Similarly, Roy et al. (2024) reported that approximately 53% of their samples showed excellent water quality, whereas 45% exhibited good quality. Aydın et al. (2020) reported that *WQI* values in the water quality assessment of seven major rivers in Giresun province ranged from 25.69 (excellent) to 32.39 (good). While excellent water quality was observed at S1–S9 sampling points, the good water quality observed at S10, S11, and S12 sampling points located in the northern region can be attributed to more anthropogenic effects due to settlements and human activities in coastal areas. Although these water samples are not suitable for direct use as drinking water, they can be made potable after appropriate treatment processes (Basnet et al., 2024; Çankaya et al., 2023). In contrast to our study, Adimalla and Qian (2019) investigated the water quality for drinking purposes in an agricultural area in Nanganur, India, and out of sixty-one groundwater samples, 52 (86%) and 7 samples (11%) were categorized as poor and very poor quality type, respectively, and 2 samples were classified as good for drinking purposes in the study area.

**Table 3** *WQI*, *HPI*, *HEI*, *ERI*, *MH*, *SAR*, *Na%*, and *KR* values of physicochemical parameters of Kirazli Stream for drinking and irrigation purposes

| | WQI | water type | HEI | water type | HPI | water type | ERI | water type | MH | water type | %Na | water type | SAR | water type | KR | water type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 16.26 | | 0.16 | | 4.19 | | 2.39 | | 59.95 | | 6.37 | | 1.10 | | 0.61 | |
| S2 | 18.70 | | 0.31 | | 8.74 | | 4.79 | | 59.92 | | 8.96 | | 1.60 | | 0.88 | |
| S3 | 19.53 | | 0.36 | | 10.45 | | 5.71 | | 59.60 | | 9.05 | | 1.61 | | 0.89 | |
| S4 | 20.53 | | 0.42 | | 12.39 | | 6.81 | | 59.64 | | 9.48 | | 1.70 | | 0.93 | |
| S5 | 21.56 | | 0.48 | | 14.42 | | 7.94 | | 59.88 | | 10.05 | | 1.82 | | 1.00 | |
| S6 | 22.31 | | 0.54 | | 16.57 | | 9.13 | | 59.69 | | 10.39 | | 1.87 | | 1.02 | |
| S7 | 22.99 | | 0.58 | | 18.24 | | 10.04 | | 59.44 | | 10.81 | | 1.94 | | 1.05 | |
| S8 | 23.63 | | 0.62 | | 19.48 | | 10.73 | | 59.15 | | 11.22 | | 2.00 | | 1.07 | |
| S9 | 24.75 | | 0.70 | | 21.56 | | 11.94 | | 58.87 | | 11.63 | | 2.04 | | 1.08 | |
| S10 | 25.05 | | 0.70 | | 21.33 | | 11.76 | | 58.52 | | 11.85 | | 2.05 | | 1.07 | |
| S11 | 25.98 | | 0.78 | | 23.71 | | 13.14 | | 58.32 | | 12.02 | | 2.07 | | 1.07 | |
| S12 | 26.28 | | 0.79 | | 23.75 | | 13.21 | | 58.29 | | 12.25 | | 2.11 | | 1.09 | |
| Winter | 19.59 | | 0.45 | | 13.34 | | 7.36 | | 59.29 | | 9.58 | | 1.70 | | 0.93 | |
| Spring | 22.40 | | 0.58 | | 15.29 | | 8.38 | | 58.66 | | 11.55 | | 2.06 | | 1.10 | |
| Summer | 23.17 | | 0.46 | | 12.82 | | 7.04 | | 59.39 | | 11.17 | | 1.97 | | 1.04 | |
| Autumn | 24.01 | | 0.65 | | 23.35 | | 12.99 | | 59.65 | | 9.14 | | 1.59 | | 0.86 | |
| Mean | 22.29 | | 0.54 | | 16.20 | | 8.95 | | 59.25 | | 10.37 | | 1.83 | | 0.98 | |

Yellow: Excellent Blue: Good Orange: Low pollution and Low risk Grey: Moderate pollution Red: Unsuitable Green: Suitable

Assessment of heavy metal pollution indices

To assess heavy metal pollution levels at Kirazlı Stream's sampling points, the *HPI*, *HEI*, and *ERI* are utilized, with results summarized in Table 3. The *HEI* values ranged between 0.16 and 0.79; *HPI* values between 4.19 and 23.75; and *ERI* values between 2.39 and 13.21. The pollution levels indicated by these indices were found to be similar. Considering *HEI*, all sampling points and seasons exhibited low pollution. Similarly, *ERI* indicated low risk across all sampling points. Consistent with results reported by Varol and Tokatli (2023a, b) for Çorlu Stream in Turkey, the pollution levels between *HEI* and *HPI* indices were similar. In a study carried out by Tekin Özan et al. (2024) on Lake Karataş, *HPI* values ranged between 23.84 and 37.91, and *HEI* values between 3.08 and 6.21, indicating low levels of heavy metal pollution with no adverse health effects. In the present study, *HPI* results showed low pollution at S1–S5 sampling points (4.19–14.42), while moderate pollution was observed at S6–S12 (16.57–23.75). Seasonal means revealed low pollution in winter (13.34) and summer (12.82), and moderate pollution in spring and autumn. When the PTEs contributing to the *HPI* results were evaluated, there was no PTE above the limit values given in WHO (2011). However, Pb was close to the limit value of 10 mg/L with a max value of 2.7 mg/L, and similarly, Cd was close to the limit value of 3 mg/L with a max value of 1.9 mg/L, indicating a moderate level of *HPI* at S6–S12 sampling points. Similarly, while all PTEs in the Keban Dam Lake remained within the WHO (2011) limits by Canpolat et al. (2020); on the contrary, in the study conducted in Pakistan by Saleem et al. (2019), Cd, Cr, and Ni exceeded the limit values. As with other indices, pollution levels were higher in coastal regions due to increased residential and industrial activities when compared to inland areas. Overall, most sampling points exhibited low levels of heavy metal pollution.

Assessment of irrigation water quality

The ratios and concentrations of major ions in water play a critical role in analyzing its suitability for irrigation purposes (Boukich et al., 2025). The *SAR*, *Na%*, *KR*, and *MH* parameters are calculated to evaluate the irrigation water quality of Kirazlı Stream, and the results are presented in Table 3. High magnesium content in water is another parameter that adversely affects soil fertility (Şimşek & Mutlu, 2023). Similarly, *SAR* is a significant factor that reduces soil permeability, thereby hindering the input of agricultural crops to water (Singh et al., 2014). To mitigate or neutralize the adverse effects of excessive $Na^+$ in soil and water, higher concentrations of $Ca^{2+}$ and $Mg^{2+}$ may sometimes be required (Radingoana et al., 2020); however, when the *MH* exceeds 50%, adverse effects may occur. According to the study results, the *MH* ranged between 58.29 and 59.95, indicating that the water is unsuitable for irrigation. The *SAR* values ranged from 1.10 to 2.11 and fell within the 0–10 range at all sampling points, suggesting excellent water quality. Similarly, *Na%* values were between 6.37 and 12.25, reflecting excellent water quality. *KR* values varied from 0.61 to 1.09, with the water being deemed suitable at points S1–S4 but unsuitable at points S5–S12. Hossain et al. (2024) reported that *KR* values greater than 1 indicate the presence of additional $Na^+$ in the samples. Accordingly, the high $Na^+$ content in 75% of the sampling points suggests that these points are unsuitable for irrigation based on *KR*. Sodium in water replaces calcium and magnesium in soil, thereby reducing soil permeability (Gençer & Başaran, 2024; Ravikumar et al., 2013). Therefore, the higher $Na^+$ levels compared to $Mg^{2+}$ and $Ca^{2+}$ at the sampling points may have influenced the *MH* and *KR* results.

### Assessment of possible health risks

Consumption or contact with water containing PTEs above permissible limit values is harmful to health and may lead to various disorders (Bouaissa et al., 2022; Boukich et al., 2024a). To evaluate the potential health risks caused by Kirazlı Stream, the non-carcinogenic health risks of exposure to seven PTEs (Fe, Ni, Cu, Zn, Cd, Hg, and Pb) through ingestion and dermal contact were determined for adults and children. The results are presented in Table 4.

Considering exposure through ingestion, the *HQ* values for children ranged between 8.14E −06 and 1.02E −02, whereas it ranged between 7.27E −06 and 9.10E −03 for adults. For dermal exposure, the *HQ* values varied from 4.99E −05 to 1.56E −02 for children and from 9.50E −06 to 7.04E −03 for adults. When the average results were examined, the highest *HQ* value for ingestion was observed for Cu, with 7.99E −03 in children and 7.13E −03 in adults. Similarly, for dermal exposure, the highest *HQ* value was found for Cd, at 1.02E −02 for children and 4.59E −03 for adults. Since *HQ* values across all sampling stations were $< 1$, no non-carcinogenic risks are expected for either adults or children. *HQ* values determined for dermal exposure were consistently higher than the values determined for ingestion. Likewise, the *HI* values were also below the threshold. All *HI* values found for adults were lower than those for children. These results align with previous studies (Çankaya et al., 2023; Myers et al., 2023; Nyantakyi et al., 2024; Zhang et al., 2020b), which suggest that children are more susceptible to potential health risks than adults. This can be attributed to children's lower body weight, which results in higher pollutant exposure and greater sensitivity to toxicity compared to adults.

### Evaluation of possible pollution sources in Kirazlı Stream

The scope and degree of relationships among physicochemical parameters affecting the water quality of Kirazlı Stream are examined by making use of the Spearman correlation matrix, and the findings are shown in Table S5 (SI). *PCA* was carried out to estimate the origins of these parameters and determine whether they share a common source. The rotated component matrix values are shown in Table S6, and the scree plot of eigenvalues and rotated components is illustrated in Fig. 2.

As seen in the Spearman correlation matrix presented in SI, Table S5, pH reveals a strong positive correlation with $NO_3^-$ ($r = 0.805$) and a negative correlation with $Cl^-$ ($r = -0.428$) ($p < 0.01$). This is because the available ratio of chlorine is pH-dependent; as pH increases, the proportion of usable hypochlorous acid decreases, while it rises at lower pH levels (Saraç and Ölmez, 2009). *WT* exhibited a strong positive correlation with *EC*, *COD*, $SO_4^{2-}$, and $NO_3^-$ ($r > 0.8$). The increase in conductivity and the breakdown of pollutants are associated with rising water temperatures. *EC* was found to have a strong positive correlation with *TSS* ($r = 0.894$), *COD* ($r = 0.848$), *BOD* ($r = 0.868$), $SO_4^{2-}$ ($r = 0.911$), and $NO_3^-$ ($r = 0.939$) ($p < 0.01$), and a moderate negative correlation with *Cl* ($r = -0.538$). Similarly, *TSS* showed a strong positive correlation with *COD*, *BOD*, $SO_4^{2-}$, and $NO_3^-$ ($r > 0.85$; $p < 0.01$). *COD* and *BOD* are two critical indicators used in water quality assessments to assess pollution levels associated with organic matter (WHO, 2011; Oseke et al., 2021; Sanae et al., 2023). The presence of agricultural organic pollution loads in Kirazlı Stream can explain the strong positive correlation ($r = 0.921$) between *COD* and *BOD*. $NO_3^-$ exhibited moderate to high positive correlations with $PO_4$ and $SO_4$.

**Table 4** Non-carcinogenic health risks of PTEs in Kirazlı Stream (seasonal and annual averages)

| | $ADD_{ing}$ | | $ADD_{derm}$ | | $HQ_{ing}$ | | $HQ_{derm}$ | | *HI* | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Adult | Child | Adult | Child | Adult | Child | Adult | Child | Adult | Child |
| Winter | | | | | | | | | | |
| Fe | 3.27E − 03 | 3.66E − 03 | 1.22E − 03 | 2.70E − 03 | 4.67E − 06 | 5.23E − 06 | 8.70E − 06 | 1.93E − 05 | 1.34E − 05 | 2.45E − 05 |
| Ni | 7.33E − 03 | 8.21E − 03 | 1.91E − 04 | 4.24E − 04 | 3.67E − 04 | 4.11E − 04 | 2.39E − 04 | 5.29E − 04 | 6.06E − 04 | 9.40E − 04 |
| Cu | 2.72E − 01 | 3.05E − 01 | 2.49E − 03 | 5.52E − 03 | 6.81E − 03 | 7.63E − 03 | 3.12E − 04 | 6.90E − 04 | 7.12E − 03 | 8.32E − 03 |
| Zn | 4.46E − 02 | 5.00E − 02 | 6.98E − 04 | 1.55E − 03 | 1.49E − 04 | 1.67E − 04 | 1.16E − 05 | 2.58E − 05 | 1.60E − 04 | 1.92E − 04 |
| Cd | 8.93E − 04 | 1.00E − 03 | 9.32E − 05 | 2.06E − 04 | 1.79E − 03 | 2.00E − 03 | 3.73E − 03 | 8.25E − 03 | 5.51E − 03 | 1.03E − 02 |
| Pb | 3.84E − 03 | 4.31E − 03 | 1.72E − 05 | 3.80E − 05 | 2.75E − 03 | 3.08E − 03 | 4.08E − 05 | 9.04E − 05 | 2.79E − 03 | 3.17E − 03 |
| Hg | 1.08E − 05 | 1.21E − 05 | 8.08E − 07 | 1.79E − 06 | 3.61E − 05 | 4.04E − 05 | 3.85E − 05 | 8.51E − 05 | 7.46E − 05 | 1.26E − 04 |
| Spring | | | | | | | | | | |
| Fe | 5.09E − 03 | 5.70E − 03 | 1.90E − 03 | 4.20E − 03 | 7.27E − 06 | 8.14E − 06 | 1.36E − 05 | 3.00E − 05 | 2.08E − 05 | 3.81E − 05 |
| Ni | 9.94E − 03 | 1.11E − 02 | 2.59E − 04 | 5.74E − 04 | 4.97E − 04 | 5.56E − 04 | 3.24E − 04 | 7.17E − 04 | 8.21E − 04 | 1.27E − 03 |
| Cu | 3.64E − 01 | 4.08E − 01 | 3.34E − 03 | 7.38E − 03 | 9.10E − 03 | 1.02E − 02 | 4.17E − 04 | 9.22E − 04 | 9.52E − 03 | 1.11E − 02 |
| Zn | 8.63E − 02 | 9.67E − 02 | 1.35E − 03 | 2.99E − 03 | 2.88E − 04 | 3.22E − 04 | 2.25E − 05 | 4.99E − 05 | 3.10E − 04 | 3.72E − 04 |
| Cd | 9.72E − 04 | 1.09E − 03 | 1.02E − 04 | 2.25E − 04 | 1.94E − 03 | 2.18E − 03 | 4.06E − 03 | 8.98E − 03 | 6.00E − 03 | 1.12E − 02 |
| Pb | 5.62E − 03 | 6.29E − 03 | 2.51E − 05 | 5.55E − 05 | 4.01E − 03 | 4.49E − 03 | 5.97E − 05 | 1.32E − 04 | 4.07E − 03 | 4.63E − 03 |
| Hg | 1.70E − 05 | 1.90E − 05 | 1.27E − 06 | 2.81E − 06 | 5.67E − 05 | 6.35E − 05 | 6.04E − 05 | 1.34E − 04 | 1.17E − 04 | 1.97E − 04 |
| Summer | | | | | | | | | | |
| Fe | 3.30E − 03 | 3.70E − 03 | 1.23E − 03 | 2.72E − 03 | 4.71E − 06 | 5.28E − 06 | 8.79E − 06 | 1.94E − 05 | 1.35E − 05 | 2.47E − 05 |
| Ni | 7.68E − 03 | 8.60E − 03 | 2.01E − 04 | 4.44E − 04 | 3.84E − 04 | 4.30E − 04 | 2.51E − 04 | 5.55E − 04 | 6.35E − 04 | 9.85E − 04 |
| Cu | 2.45E − 01 | 2.74E − 01 | 2.24E − 03 | 4.96E − 03 | 6.12E − 03 | 6.85E − 03 | 2.80E − 04 | 6.20E − 04 | 6.40E − 03 | 7.47E − 03 |
| Zn | 6.19E − 02 | 6.93E − 02 | 9.69E − 04 | 2.15E − 03 | 2.06E − 04 | 2.31E − 04 | 1.62E − 05 | 3.58E − 05 | 2.23E − 04 | 2.67E − 04 |
| Cd | 8.33E − 04 | 9.33E − 04 | 8.70E − 05 | 1.93E − 04 | 1.67E − 03 | 1.87E − 03 | 3.48E − 03 | 7.70E − 03 | 5.15E − 03 | 9.57E − 03 |
| Pb | 4.29E − 03 | 4.80E − 03 | 1.91E − 05 | 4.24E − 05 | 3.06E − 03 | 3.43E − 03 | 4.56E − 05 | 1.01E − 04 | 3.11E − 03 | 3.53E − 03 |
| Hg | 1.43E − 05 | 1.61E − 05 | 1.07E − 06 | 2.37E − 06 | 4.78E − 05 | 5.35E − 05 | 5.09E − 05 | 1.13E − 04 | 9.87E − 05 | 1.66E − 04 |
| Autumn | | | | | | | | | | |
| Fe | 3.57E − 03 | 3.99E − 03 | 1.33E − 03 | 2.94E − 03 | 5.10E − 06 | 5.71E − 06 | 9.50E − 06 | 2.10E − 05 | 1.46E − 05 | 2.67E − 05 |
| Ni | 8.16E − 03 | 9.14E − 03 | 2.13E − 04 | 4.71E − 04 | 4.08E − 04 | 4.57E − 04 | 2.66E − 04 | 5.89E − 04 | 6.74E − 04 | 1.05E − 03 |
| Cu | 2.60E − 01 | 2.91E − 01 | 2.38E − 03 | 5.27E − 03 | 6.50E − 03 | 7.28E − 03 | 2.98E − 04 | 6.59E − 04 | 6.80E − 03 | 7.94E − 03 |
| Zn | 5.30E − 02 | 5.94E − 02 | 8.30E − 04 | 1.84E − 03 | 1.77E − 04 | 1.98E − 04 | 1.38E − 05 | 3.06E − 05 | 1.91E − 04 | 2.29E − 04 |
| Cd | 1.69E − 03 | 1.89E − 03 | 1.76E − 04 | 3.90E − 04 | 3.37E − 03 | 3.78E − 03 | 7.04E − 03 | 1.56E − 02 | 1.04E − 02 | 1.94E − 02 |
| Pb | 3.83E − 03 | 4.28E − 03 | 1.71E − 05 | 3.78E − 05 | 2.73E − 03 | 3.06E − 03 | 4.06E − 05 | 8.99E − 05 | 2.77E − 03 | 3.15E − 03 |
| Hg | 1.88E − 05 | 2.10E − 05 | 1.40E − 06 | 3.10E − 06 | 6.26E − 05 | 7.01E − 05 | 6.67E − 05 | 1.48E − 04 | 1.29E − 04 | 2.18E − 04 |
| *Mean* | | | | | | | | | | |
| Fe | 3.80E − 03 | 4.26E − 03 | 1.42E − 03 | 3.14E − 03 | 5.43E − 06 | 6.09E − 06 | 1.01E − 05 | 2.24E − 05 | 1.56E − 05 | 2.85E − 05 |
| Ni | 8.27E − 03 | 9.27E − 03 | 2.16E − 04 | 4.78E − 04 | 4.14E − 04 | 4.63E − 04 | 2.70E − 04 | 5.97E − 04 | 6.84E − 04 | 1.06E − 03 |
| Cu | 2.85E − 01 | 3.20E − 01 | 2.61E − 03 | 5.78E − 03 | 7.13E − 03 | 7.99E − 03 | 3.27E − 04 | 7.23E − 04 | 7.46E − 03 | 8.71E − 03 |
| Zn | 6.15E − 02 | 6.89E − 02 | 9.63E − 04 | 2.13E − 03 | 2.05E − 04 | 2.30E − 04 | 1.60E − 05 | 3.55E − 05 | 2.21E − 04 | 2.65E − 04 |
| Cd | 1.10E − 03 | 1.23E − 03 | 1.15E − 04 | 2.54E − 04 | 2.20E − 03 | 2.46E − 03 | 4.59E − 03 | 1.02E − 02 | 6.79E − 03 | 1.26E − 02 |
| Pb | 4.38E − 03 | 4.90E − 03 | 1.95E − 05 | 4.32E − 05 | 3.13E − 03 | 3.50E − 03 | 4.65E − 05 | 1.03E − 04 | 3.17E − 03 | 3.61E − 03 |
| Hg | 2.00E − 05 | 2.24E − 05 | 1.49E − 06 | 3.30E − 06 | 6.67E − 05 | 7.47E − 05 | 7.10E − 05 | 1.57E − 04 | 1.38E − 04 | 2.32E − 04 |

Anthropogenic sources, such as improper disposal of domestic wastewater and washing laundry along riverbanks in rural areas, may have contributed to their presence in surface water samples (Obiri et al., 2021). $Na^{+}$ showed strong positive correlations with $Ca^{2+}$ ($r = 0.853$), $Mg^{2+}$ ($r = 0.804$), Fe ($r = 0.801$), and Cu

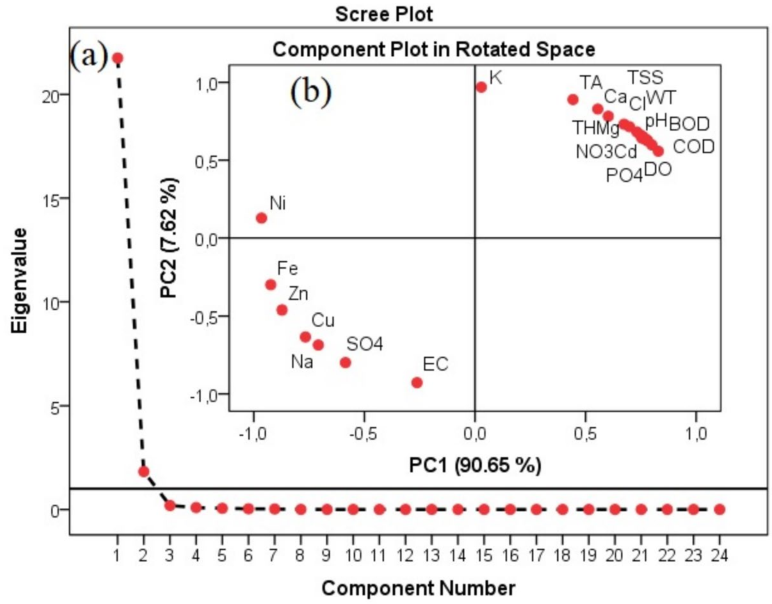


**Fig. 2** *PCA* by **a** display drawing of eigenvalues; **b** component drawing in rotated space

($r$ = 0.803), while *TH* correlated positively with *TA* ($r$ = 0.975) and $Mg^{2+}$ ($r$ = 0.775). *TA* also showed positive correlations with $Ca^{2+}$ ($r$ = 0.785) and $Mg^{2+}$ ($r$ = 0.815). These results suggest that the ions are likely related with the weathering of carbonate rocks at the sampling points in Kirazlı Stream (Çankaya et al., 2023; Pant et al., 2018). Among metal ions, Fe exhibited high positive correlations with Cu-Hg-Ni-Zn ($r$ > 0.75), Pb correlated with Cu-Ni-Zn, Cu with Hg-Ni-Zn, Hg with Ni-Zn, and Ni with Zn ($p$ > 0.01).

*PCA* was performed for 24 parameters affecting the water quality of Kirazlı Stream, revealing two factors with eigenvalues greater than 1 that accounted for 98.275% of the total variance (SI, Table S6). Factor 1 (*PC*1), accounting for 90.652% of the total variance, displayed high positive loadings for *DO*, *COD*, Hg, $PO_4^{3-}$, *BOD*, Pb, Cd, pH, *WT*, $NO_3^-$, and $Cl^-$, and negative loadings for Ni, Fe, Zn, Cu, and $Na^+$. The observed strong positive correlations among organic parameters such as *COD*, *BOD*, $PO_4^{3-}$, and $NO_3^-$ explain *PC1* as the "organic factor," which can be attributed to agricultural activities and the presence of domestic wastewater (Ustaoğlu & Tepe, 2019). The presence of Na and Cl ions may be linked to regional geology, silicate weathering, and agricultural runoff from fields (Dimri et al., 2021; Vialle et al., 2011). Factor 2 (*PC*2), accounting for 7.624% of the total variance, showed negative loadings for *EC* and $SO_4$ and positive loadings for $K^+$, *TA*, $Ca^{2+}$, *TH*, *TSS*, and $Mg^{2+}$. This factor can be termed the "ionic factor." The levels of calcium salts affect water hardness, and the very low concentrations of this essential element in Kirazlı Stream water samples indicate that Ca originates from natural sources (WHO, 2017). The inclusion of *Mg*, *TH*, and *TA* in this factor, with their high correlations (*TA*–$Mg^{2+}$, $r$ = 0.815; *TH*–$Mg^{2+}$, $r$ = 0.775), reflects the dominance of carbonate mineral weathering (Khalid, 2019; Sethy et al., 2016).

The *HCA* results, presented in SI, Fig. S1, validating the *PCA*, indicate the presence of two distinct data clusters. The first cluster includes 21 parameters (*DO*, *COD*, *Hg*, $PO_4^{3-}$, *BOD*, Pb, Cd, pH, *WT*, $NO_3^-$, $Cl^-$, Ni, Fe, Zn, Cu, $SO_4^{2-}$, *TSS*, $K^+$, $Na^+$, $Mg^{2+}$, and $Ca^{2+}$), while the second cluster comprises three parameters (*EC*, *TH*, and *TA*). In this study, strong correlations were identified among parameters within the same principal component and cluster.

## Conclusion

Monitoring the quality of existing water resources is essential to safeguard them. This study aims to assess the water quality of Kirazlı Stream located in Çatalzeytin district of Kastamonu province, Turkey for irrigation and domestic applications and evaluate the potential health risks. Parameters such as *COD*, *BOD*, $Cl^-$, $Na^+$, $Mg^{2+}$, $Ca^{2+}$, *TH*, and

$SO_4^{2-}$ remained within the limit values determined by WHO (2011). While *WQI* indicated (16.26–26.28) excellent and good water quality, *HEI* (0.16–0.79) − *ERI* (2.39–13.21) indicated low pollution and HPI (4.19–23.75) indicated to moderate pollution.

Regarding irrigation water quality, *SAR* and *Na%* classified the water as excellent. However, *KR* indicated that 25% of the sampling points were suitable for irrigation, whereas 75% were deemed unsuitable. This discrepancy is attributed to the proximity of the unsuitable sampling points to urban areas and coastal regions, where anthropogenic activities likely have a greater impact. For *MH*, the mean value of 59.25 across all sampling points classified the water as unsuitable for irrigation. *PCA* results showed that the primary sources of pollution are a combination of natural factors and anthropogenic pollutants. This result is attributed to runoff from surrounding agricultural lands and the discharge of untreated sewage due to the lack of a wastewater treatment facility. The geology of the region also highlights the influence of soil-rock weathering and carbonate mineral dissolution. Non-carcinogenic health risks showed that children are more vulnerable to health risks compared to adults.

The findings of this study provide a comprehensive framework, albeit on a small scale, regarding water quality in the Kastamonu, a coastal region of the Black Sea, within the scope of the UN Sustainable Development Goals and the European Green Deal. This framework could facilitate the use of advanced technologies and scientific advancements, such as deep learning and artificial neural network modeling, to enable large-scale monitoring and pollution prevention.

**Author contribution** A.Şimşek: Conceptualization, Methodology, Formal analysis, Writing—Original Draft, Visualization.F.Ustaoğlu: Conceptualization, Methodology, Formal analysis, Visualization. E.Mutlu: Sampling, Investigation, Methodology, Supervision, Editing.

**Data availability** Data can be provided upon request.

**Declarations**

**Ethics approval** Not applicable.

**Conflict of interest** The authors declare no competing interests.

## References


Adesakin, T. A., Oyewale, A. T., Bayero, U., Mohammed, A. N., Aduwo, I. A., Ahmed, P. Z., Abubakar, N. D., & Barje, I. B. (2020). Assessment of bacteriological quality and physicochemical parameters of domestic water sources in Samaru community, Zaria. *Northwest Nigeria. Heliyon, 6*, e04773. https://doi.org/10.1016/j.heliyon.2020.e04773

Adimalla, N. (2019). Controlling factors and mechanism of groundwater quality variation in semi-arid region of South India: An approach of water quality index (WQI) and health risk assessment (HRA). Environ. Geochem. Health 1–28. https://doi.org/10.1007/s10653-019-00374-8.

Adimalla, N., Li, P., & Venkatayogi, S. (2018). Hydrogeochemical evaluation of groundwater quality for drinking and irrigation purposes and integrated interpretation with water quality index studies. *Environ. Sci. Process, 5*, 363–383. https://doi.org/10.1007/s40710-018-0297-4

Adimalla, N., & Qian, H. (2019). Groundwater quality evaluation using water quality index (WQI) for drinking purposes and human health risk (HHR) assessment in an agricultural region of Nanganur, South India. *Ecotoxicol Environ Saf, 176*, 153–161. https://doi.org/10.1016/j.ecoenv.2019.03.066

Agyeman, P. C., Kebonye, N. M., John, K., Haghnazar, H., Borůvka, L., & Vašát, R. (2022). Compositional mapping, uncertainty assessment, and source apportionment via pollution assessmentbased receptor models in urban and peri-urban agricultural soils. *Journal of Soils and Sediments, 23*, 1451–1472. https://doi.org/10.1007/s11368-022-03417-3

Ahmed, M. T., Hasan, M. Y., Monir, M. U., Samad, M. A., Rahman, M. M., Islam Rifat, M. S., Islam, M. N., Khan, A. A. S., Biswas, P. K., & Jamil, A. H. M. N. (2020). Evaluation of hydrochemical properties and groundwater suitability for irrigation uses insouthwestern zones of Jashore. *Bangladesh. Groundw. Sustain. Dev., 11*, 100441. https://doi.org/10.1016/j.gsd.2020.100441

Ali, G., Chaudhari, M. P., Syed, S., Rajpurohit, D., Sanyal, M., & Shrivastav, P. S. (2024). Hydrogeochemical investigation and water quality assessment of the Indus River in the semiarid region of Ladakh, India. *Marine Pollution Bulletin, 211*, 117413. https://doi.org/10.1016/j.marpolbul.2024.117413

APHA/AWWA/WEF (2017) Standard methods for the examination of water and wastewater, 23rd edn. American Public Health Association, American Water Works Association, Water Environment Federation, Denver

Aydin, H., Ustaoğlu, F., Tepe, Y., & Soylu, E. N. (2020). Assessment of water quality of streams in northeast Turkey by water quality index and multiple statistical methods. *Environmental Forensics, 22*(1–2), 270–287. https://doi.org/10.1080/15275922.2020.1836074

Babu, M.S., Sreelakshmi, S., S.V.C.S. et al. (2024) Advancing water quality assessment and monitoring with a robust stacked ensemble method. Water Resour Manage. https://doi.org/10.1007/s11269-024-04062-w

Bakan, G., Ozkoç, H. B., Tülek, S., & Cüce, H. (2010). Integrated environmental quality assessment of the Kızılırmak River and its coastal environment. *Turkish Journal of Fisheries and Aquatic Sciences, 10*, 453–462. https://doi.org/10.4194/trjfas.2010.0403

Basnet, N., Sitaula, S., Bohara, R., Bhattarai, S., Rawal, S., Uprety, M. P., Awasthi, M. P., Varol, M., Kayastha, S. P., & Pant, R. R. (2024). Hydro-chemical characteristics of Biring and Tangting Rivers (Nepal) and evaluation of water quality for drinking and irrigation purposes. *Environmental Research, 261*, 119697. https://doi.org/10.1016/j.envres.2024.119697

Ben-tahar, R., Basraoui, Ne., Boukich, O., et al. (2025a). Potentially toxic elements contamination and health risk assessment of coastal sediments in Betoya Bay. *Morocco. Environ Monit Assess, 197*, 19. https://doi.org/10.1007/s10661-024-13495-0

Ben-tahar, R., Basraoui, N. E., Boukich, O., & El guerroujSmiri, B. Y. (2025b). Health risks associated with potentially toxic elements in three fish species from Betoya-Bay, Morocco: An integrated approach to human health risk assessment. *Mar. Poll. Bull., 210*, 117341. https://doi.org/10.1016/j.marpolbul.2024.117341

Ben-tahar, R., BasraouiBoukich, N. E. O., & El guerroujSmiri, B. Y. (2025). Impact of a harbor construction on the water quality: A case study of Nador West Med Harbor, Betoya Bay, Morocco. *Mor. J. Chem., 13*(1), 186–204.

Bouaissa, M., Gharibi, E., Ghalit, M., Taupin, J. D., Boukich, O., & El Khattabi, J. (2022). Groundwater quality evaluation using the pollution index and potential non-carcinogenic risk related to nitrate contamination in the karst aquifers of Bokoya massif, northern Morocco. *International Journal of Environmental Analytical Chemistry, 104*(17), 5423–5443. https://doi.org/10.1080/03067319.2022.2125308

Boukich, O., Bentahar, R., Basraoui, N., Gharibi, E., Elguerrouj, B., & Smiri, Y. (2024). Assessment of heavy metal pollution and related risks to human health: A case of Angads Plain, Morocco. *Journal of Ecological Engineering, 25*(9), 354–366.

Boukich, O., Ben-tahar, R., Brahmi, M., Alzain, M. N., Noman, O., Shahat, A. A., & El guerroujSmiri, O. Y. (2025). Assessment of groundwater quality for irrigation using a new customized irrigation water quality index. *Journal of Hydrology: Regional Studies, 59*(102346), 2214–5818. https://doi.org/10.1016/j.ejrh.2025.102346

Boukich, O., Ben-tahar, R., Gharibi, E., et al. (2024b). Assessment of groundwater quality and nitrate related risks to human health: A case of Angads Plain, Morocco. *Water Air Soil Pollut, 235*, 787. https://doi.org/10.1007/s11270-024-07605-4

Boyd, C.E., (2015). Water quality: An introduction, https://doi.org/10.1007/978-3-319-17446-4

Çankaya, Ş, Varol, M., & Bekleyen, A. (2023). Hydrochemistry, water quality and health risk assessment of streams in Bismil plain, an important agricultural area in southeast Türkiye. *Environmental Pollution, 331*(Pt 1), 121874. https://doi.org/10.1016/j.envpol.2023.121874

Canpolat, Ö., Varol, M., Okan, Ö. Ö., Eriş, K. K., & Çağlar, M. (2020). A comparison of trace element concentrationsin surface and deep water of the Keban Dam Lake (Turkey) and associated health risk assessment. *Environmental Research, 190*, 110012. https://doi.org/10.1016/j.envres.2020.110012

Chen, Z., Wu, Q., Wu, G., & Hu, H. Y. (2017). Centralized water reuse system with multiple applications in urban areas: Lessons from China's experience. *Resources, Conservation and Recycling, 117*, 125–136.

Cüce, H., Kalipci, E., Ustaoğlu, F., et al. (2022b). Integrated spatial distribution and multivariate statistical analysis for assessment of ecotoxicological and health risks of sediment metal contamination, Ömerli Dam (Istanbul, Turkey). *Water, Air, and Soil Pollution, 233*, 199. https://doi.org/10.1007/s11270-022-05670-1

Cüce, H., Kalıpcı, E., Ustaoğlu, F., Kaynar, İ, Baser, V., & Türkmen, M. (2022a). Multivariate statistical methods and GIS based evaluation of the health risk potential and water quality due to arsenic pollution in the Kızılırmak River. *International Journal of Sediment Research, 37*(6), 754–765.

Dey, M., Aker, A., Islam, A., Dey, S. C., Choudhury, T. R., Fatema, K. J., & Begum, B. A. (2021). Assessment of contamination level, pollution risk and source apportionment of heavy metals in the Halda River water, Bangladesh. *Heliyon, 7*, 08625. https://doi.org/10.1016/j.heliyon.2021.e08625

Dimri, D., Daverey, A., Humar, A., & Sharma, A. (2021). Monitoring water quality of River Ganga using multivariate techniques and WQI (Water Quality Index) in Western Himalayan region of Uttarakhand, India. *Environ. Nanotech. Monit. Manag., 15*, 100375. https://doi.org/10.1016/j.enmm.2020.100375

Dippong, T., Mihali, C., Marian, M., Roșca, O. M., & Resz, M. (2023). Correlations between chemical, hydrological and biotic factors in rivers from the protected area of Tisa Superioară, Romania. *Process Saf Environ Prot., 176*, 40–55. https://doi.org/10.1016/j.psep.2023.06.002

Egbueri, J. C. (2020). Groundwater quality assessment using pollution index of groundwater (PIG), ecological risk index (ERI) and hierarchical cluster analysis (HCA): A case study. *Groundwater for Sustainable Development, 10*(2020), 100292. https://doi.org/10.1016/j.gsd.2019.100292

EU (1998). The quality of water intended to human consumption, Directive 1998/83/EC, Official Journal L330/05.12.1998, European Community 32–54.

Gençer, E., & Başaran, C. (2024). Water quality assessment and pollution of Akarçay River. *Türkiye. Kuwait Journal of Science, 51*(1), 100077. https://doi.org/10.1016/j.kjs.2023.07.003

Gholami, V., Khaleghi, M. R., Pirasteh, S., et al. (2022). Comparison of self-organizing map, artificial neural network, and co-active neuro-fuzzy inference system methods in simulating groundwater quality: Geospatial artificial intelligence. *Water Resources Management, 36*, 451–469. https://doi.org/10.1007/s11269-021-02969-2

Haghnazar, H., Soltani-Gerdefaramarzi, S., Ghasemi, M., & Johannesson, K. H. (2023). Receptor model-based approach to estimate urban road dust pollution by heavy metal (loid) s exposed to desert dust storms in a rapidgrowing city of Iran. *Environment and Earth Science, 82*(12), 316. https://doi.org/10.1007/s12665-023-11000-3

Hakanson, L. (1980). An ecological risk index for aquatic pollution control. A sedimentological approach. *Water Research, 14*, 975–1001.

Haq, A. U., & Muhammad, S. (2023). Spatial distribution of drinking and irrigation water quality indices of Ghizer River Basin, northern Pakistan. *Environmental Science and Pollution Research, 30*, 20020–20030. https://doi.org/10.1007/s11356-022-23478-8

Hasan, M. M., Shuvho, M. B. A., Chowdhury, M. A., Alam, A. A., Hassan, M., & Hossain, N. (2022). Water criteria evaluation for drinking and irrigation purposes: A case study in one of the largest rivers of Sundarbans World Heritage region. *Water Supply, 22*, 5800.

Hoque, M. M., Islam, A., & Mahammad, S. (2022). Assessing the surface and bottom river water quality for drinking purpose and human health risk analysis: A study of Damodar River, India. *Arab J Geosci, 15*, 1734. https://doi.org/10.1007/s12517-022-10987-6

Horton, R. K. (1965). An index number system for rating water quality. *Journal of Water Pollution Control Federation, 37*(3), 300–306.

Hossain, M. S., Nahar, N., Shaibur, M. R., Bhuiyan, M. T., Siddique, A. B., Al Maruf, A., & Khan, A. S. (2024). Hydro-chemical characteristics and groundwater quality evaluation in south-western region of Bangladesh: A GIS-based approach and multivariate analyses. *Heliyon., 10*(1), e24011. https://doi.org/10.1016/j.heliyon.2024.e24011

Howladar, M. F., Chakma, E., Jahan Koley, N., Islam, S. M., Numanbakth, M. A., Ahmed, Z. U., Chowdhury, T. R., & Akter, S. (2021). The water quality and pollution sources assessment of Surma river, Bangladesh using, hydrochemical, multivariate statistical and water quality index methods. *Groundwater for Sustainable Development, 12*, 100523.

Kangabam, R. D., Bhoomınathan, S. D., Kanagaraj, S., & Govındaraju, M. (2017). Development of a water quality index (WQI) for the Loktak Lake in India. *Appl Water Sci, 7*(6), 2907–2918. https://doi.org/10.1007/s13201-017-0579-4

Khalid, S. (2019). An assessment of groundwater quality for irrigation and drinking purposes around brick kilns in three districts of Balochistan province, Pakistan, through water quality index and multivariate statistical approaches. *Journal of Geochemical Exploration, 197*, 14–26. https://doi.org/10.1016/j.gexplo.2018.11.007

Khatri, N., & Tyagi, S. (2015). Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Front. Life Sci., 8*(1), 23–39. https://doi.org/10.1080/21553769.2014.933716

KPESR, (2023). Kastamonu Province Environmental Status Report for 2022. Kastamonu Provincial Directorate of Environment, Urbanization and Climate Change, Kastamonu, Türkiye.

Kükre, S., & Mutlu, E. (2019). Assessment of surface water quality using water quality index and multivariate statistical analyses in Saraydüzü Dam Lake, Turkey. *Environ Monit Assess, 191*, 71. https://doi.org/10.1007/s10661-019-7197-6

Li, X., Huang, X., & Zhang, Y. (2021). Spatio-temporal analysis of groundwater chemistry, quality and potential human health risks in the Pinggu basin of North China Plain: Evidence from high-resolution monitoring dataset of 2015–2017. *Science of the Total Environment, 800*, 149568. https://doi.org/10.1016/j.scitotenv.2021.149568

Mahjoub, M., Ben-Tahar, R., Omari, A., Arabi, M., Boukich, O., Slamini, M., & Smiri, Y. (2024). Hg, Cd, and Pb in fish of the Moulouya River, Morocco, and human health risk. *Food Additives & Contaminants: Part B, 17*(3), 241–250. https://doi.org/10.1080/19393210.2024.2367476

Ministry of Agriculture and Forestry, (2023). General Directorate of Water Management. https://www.tarimorman.gov.tr/SYGM/Haber/1144/Kuraklik-Ile-Mucadelede-Surdurulebilir-Su-Yonetimi (access date:10.10.2024)

MLAP, (2018). Ministry of Environment and Urbanization, Kastamonu Provincial Directorate of Environment and Urbanization, Kastamonu Province, Marine Litter Action Plan, MLAP (2019–2024), Kastamonu, Turkey.

Mohan, S. V., Nithila, P., & Reddy, S. J. (1996). Estimation of heavy metals in drinking water and development of heavy metal pollution index. *J. Environ. Sci. Health A Tox., 31*(2), 283–289.

Muhammad, S., & Ullah, I. (2022). Spatial and seasonal variation of water quality indices in Gomal Zam Dam and its tributaries of south Waziristan District, Pakistan. *Environ. Sci. Pollut. Res, 29*(19), 29141–29151. https://doi.org/10.1007/s11356-022-18524-4

Muhammad, S., Ullah, S., Ali, W., Jadoon, I. A. K., & Arif, M. (2021). Spatial distribution of heavy metal and risk indices of water and sediments in the Kunhar River and its tributaries. *Geocarto International, 37*(20), 5985–6003. https://doi.org/10.1080/10106049.2021.1926557

Myers, R. A., Gyimah, E., Gbemadu, K., Osei, B., & Akoto, O. (2023). Appraising groundwater quality and the associated health risks of heavy metal contamination at Suame magazine. *Scientific African, 21*, e01794. https://doi.org/10.1016/j.sciaf.2023.e01794

Nong, X., Shao, D., Zhong, H., & Liang, J. (2020). Evaluation of water quality in the South-to-North Water Diversion Project of China using the water quality index (WQI) method. *Water Research, 178*, 115781. https://doi.org/10.1016/j.watres.2020.115781

Nyantakyi, J. A., Sarpong, L., Mensah Roland, B., & Wiafe, S. (2024). Surface water quality assessment and probable health threats of metal exposure in the Tano District, Ghana. *Scientific African, 26*, e02437. https://doi.org/10.1016/j.sciaf.2024.e02437

Obiri, S., Addico, G., Mohammed, S., et al. (2021). Water quality assessment of the Tano Basin in Ghana: A multivariate statistical approach. *Applied Water Science, 11*, 49. https://doi.org/10.1007/s13201-021-01374-9

Ölmez, M., Saraç, D. (2009). Importance of pH for aquatic products, Süleyman Demirel University Eğirdir Faculty of Aquatic Products, Agricultural Engineering, Number 353, Isparta, Türkiye.

Oseke, F. I., Anornu, G. K., Adjei, K. A., & Eduvie, M. O. (2021). Assessment of water quality using GIS techniques and water quality indexin reservoirs affected by water diversion. *Water-Energy Nexus, 4*, 25–34. https://doi.org/10.1016/j.wen.2020.12.002

Pant, R. R., Zhang, F., Rehman, F. U., Wang, G., Ye, M., Zeng, C., & Tang, H. (2018). Spatiotemporal variations of hydrogeochemistry and its controlling factors in the Gandaki River Basin. *Central Himalaya Nepal. Sci Total Environ., 622–623*, 770–782. https://doi.org/10.1016/j.scitotenv.2017.12.063

Pashaeifar, M., Dehghanzadeh, R., Ramazani, M.E., Rafeyan, O., Nejaei, A. (2021) Spatial and temporal assessment of groundwater quality and hydrogeochemical processes in Urmia Lake Basin, Iran. Water Sci Tech-W Sup. https://doi.org/10.2166/ws.2021.180

Perveen, S., & Amar, U. H. (2023). Drinking water quality monitoring, assessment and management in Pakistan: A review. *Heliyon, 9*(3), e13872. https://doi.org/10.1016/j.heliyon.2023.e13872

Poursaeid, M., Poursaeed, A. H., & Shabanlou, S. (2024). Water resources quality indicators monitoring by non-linear programming and simulated annealing optimization with ensemble learning approaches. *Water Resour Manag*. https://doi.org/10.1007/s11269-024-04006-4

Radingoana, M. P., Dube, T., & Mazvimavi, D. (2020). An assessment of irrigation water quality and potential of reusing greywater in homegardens in water-limited environments. *Physics and Chemistry of the Earth, 116*, 102857. https://doi.org/10.1016/j.pce.2020.102857

Ravikumar, P., Aneesul Mehmood, M., & Somashekar, R. K. (2013). Water quality index to determine the surface water quality of Sankey tank and Mallathahalli lake, Bangalore urban district, Karnataka, India. *Applied Water Science, 3*, 247–261. https://doi.org/10.1007/s13201-013-0077-2

Real, M. K. H., Varol, M., Rahman, M. S., & Islam, A. R. M. T. (2024). Pollution status and ecologicalrisks of metals in surface water of a coastal estuary and health risk assessment for recreational users. *Chemosphere, 348*, 140768. https://doi.org/10.1016/j.chemosphere.2023.140768

Rehman, N. U., Ali, W., Muhammad, S., & Tepe, Y. (2024). Evaluation of drinking and irrigation water quality, and potential risks indices in the Dera Ismail Khan district. *Pakistan, Kuwait Journal of Science, 51*, 100150. https://doi.org/10.1016/j.kjs.2023.11.001

Roy, B. N., Roy, H., Rahman, K. S., Mahmud, F., Bhuiyan, M. K., Hasan, M., Bhuiyan, A. A. K., Hasan, M., Mahbub, M. S., Jahedi, R. M., et al. (2024). Principal component analysis incorporated water quality index modeling for Dhaka-based rivers. *City Environ. Interact., 23*, 100150. https://doi.org/10.1016/j.cacint.2024.100150

Sabbagh, K., Haghnazar, H., Somma, R., et al. (2024). Human footprints on sediment quality in the Shadegan International Wetland, Northwest of the Persian Gulf. *Water, Air, and Soil Pollution, 235*, 825. https://doi.org/10.1007/s11270-024-07609-0

Saleem, M., Iqbal, J., & Shah, M. H. (2019). Seasonal variations, risk assessment and multivariate analysis of trace metals in the freshwater reservoirs of Pakistan. *Chemosphere, 216*, 715–724. https://doi.org/10.1016/j.chemosphere.2018.10.173

Saleh, H. N., Panahande, M., Yousefi, M., Asghari, F. B., Oliveri Conti, G., Talaee, E., & Mohammadi, A. A. (2018). Carcinogenic and non-carcinogenic risk assessment of heavy metals in groundwater wells in Neyshabur Plain. *Iran Biol Trace Elem Res, 190*, 251–261. https://doi.org/10.1007/s12011-018-1516-6

Sanae, B., Mohammed, B. A., Nisrine, I., Youness, G., Nariman, O., Azeddin, E. B., Mustapha, T., Hanane, T., & Zakia, R. (2023). Assessment of surface water quality: Case study of Oued Fez catchment areas (Morocco). *Environmental and Sustainability Indicators*. https://doi.org/10.1016/j.indic.2023.100326

Sengupta, N., & Ghosh, G. (2024). Assessment of groundwater suitability using water quality index and health risk analysis in upper catchment area of Kangsabati river, India. *Total Environment Advances, 11*, 200114. https://doi.org/10.1016/j.teadva.2024.200114

Sepúlveda, C. H., et al. (2023). Biomonitoring of potentially toxic elements through oysters (Saccostrea palmula and Crassostrea corteziensis) from coastal lagoons of Southeast Gulf of California, Mexico: Health risk assessment. *Environmental Geochemistry and Health, 45*, 2329–2348.

Sethy, S. N., Syed, T. H., Kumar, A., & Sinha, D. (2016). Hydrogeochemical characterization and quality assessment of groundwater in parts of Southern Gangetic Plain. *Environment and Earth Science, 75*(3), 232.

Sharifi, Z., Hossaini, S. M. T., & Renella, G. (2016). Risk assessment for sediment and stream water polluted by heavy metals released by a municipal solid waste composting plant. *Journal of Geochemical Exploration, 169*, 202–210. https://doi.org/10.1016/j.gexplo.2016.08.001

Şimşek, A., Sancak, Ş., Bakan, G. (2021) Monitoring of heavy metal pollution in water and sediments at the mid-Black Sea Region by using passive sampling method diffusive gradients in thin films Turk J Agric Food. Sci Technol 9:1076–1086. https://doi.org/10.24925/turjaf.v9i6.1076-1086.4217

Şimşek, A., Küçük, K., & Bakan, G. (2019). Applying AQUATOX for the ecological risk assessment coastal of Black Sea at small industries around Samsun. *Turkey. Int. J. Environ. Sci. Technol., 16*, 5229–5236. https://doi.org/10.1007/s13762-019-02251-4

Şimşek, A., & Mutlu, E. (2023). Assessment of the water quality of Bartın Kışla (Kozcağız) Dam by using geographical information system (GIS) and water quality indices (WQI). *Environmental Science and Pollution Research International, 30*(20), 58796–58812. https://doi.org/10.1007/s11356-023-26568-3

Şimşek, A., Teuchies, J., Haghnazar, H., Blust, R., & Bakan, G. (2023). Evaluation of bioaccumulation and toxicity of Tubifex tubifex exposed to contaminated river sediment by potentially toxic elements—A case study of the Middle Black Sea, Turkey. *Journal of Geochemical Exploration, 252*, 107263. https://doi.org/10.1016/j.gexplo.2023.107263

Singh, A. K., & Giri, S. (2014). Risk assessment, statistical source identification and seasonal fluctuation of dissolved metals in the Subarnarekha River, India. *J. Hazard. Mater., 265*, 305–314.

Singh, R., Majumder, C. B., & Vidyarthi, A. K. (2023). Assessing the impacts of industrial wastewater on the inland surface water quality: An application of analytic hierarchy process (AHP) model-based water quality index and GIS techniques. *Physics and Chemistry of the Earth, 129*, 103314. https://doi.org/10.1016/j.pce.2022.103314

Taş, B., Yılmaz, Ö., Ustaoğlu, F. (2021) Assessment of stream water quality in a temperate Turkish river basin using

multivariate analysis and biological approaches. Act Aqua Tur 17(1):34–55.https://doi.org/10.22392/actaquatr.751773.
Tekin-Özan, S., Tunç, M., & Bakioğlu-Acar, B. (2024). Evaluation of someheavy metals and selenium pollution in Karataş Lake (Burdur/Türkiye) using various pollution indices and statistical analysis. *Marine Pollution Bulletin, 199*, 115927. https://doi.org/10.1016/j.marpolbul.2023.115927
Tian, K., Wu, Q., Liu, P., Hu, W., Huang, B., Shi, B., Zhou, Y., Kwon, B., Choi, K., Ryu, J., Khim, J. S., & Wang, T. (2020). Ecological risk assessment of heavy metals in sediments and water from the coastal areas of the Bohai Sea and the Yellow Sea. *Environment International, 136*, 105512. https://doi.org/10.1016/j.envint.2020.105512
Tokatli, C., Mutlu, E., Ustaoğlu, F., et al. (2024). Spatiotemporal variations, health risk assessment, and sources of potentially toxic elements in potamic water of the Anday Stream Basin (Türkiye), Black Sea Region. *Environ Monit Assess, 196*, 420. https://doi.org/10.1007/s10661-024-12580-8
Tokatli, C., Titiz, A. M., Uğurluoğlu, A., Islam, M. S., Ustaoğlu, F., & Islam, A. R. M. T. (2022). Assessment of the effects of COVID-19 lockdown period on groundwater quality of a significant rice land in an urban area of Türkiye. *Environmental Science and Pollution Research, 29*(47), 71752–71765. https://doi.org/10.1007/s11356-022-20959-8
Tokatli, C., Varol, M., & Ustaoğlu, F. (2023). Ecological and health risk assessment and quantitative source apportionment of dissolved metals in ponds used for drinking and irrigation purposes. *Environmental Science and Pollution Research, 30*(18), 52818–52829. https://doi.org/10.1007/s11356-023-26078-2
Tomasetti, S.J., Gobler, C.J. (2020) Dissolved oxygen and pH criteria leave fisheries at risk. Science. 24;368(6489):372–373. https://doi.org/10.1126/science.aba4896.
TSWQR (2021). Surface water quality regulation of Turkey. Official Gazette, 16 June 2021, No:31513.
USEPA (2004). Environmental protection agency, risk assessment guidance for superfund, Vol. 1, Human health evaluation manual (part a), Washington, DC.
Ustaoğlu, F., & Tepe, Y. (2019). Water quality and sediment contamination assessment of Pazarsuyu Stream, Turkey using multivariate statistical methods and pollution indicators. *Int Soil Water Conserv Res, 7*, 47–56. https://doi.org/10.1016/j.iswcr.2018.09.001
Ustaoğlu, F., Tepe, Y., & Taş, B. (2020). Assessment of stream quality and health risk in a subtropical Turkey river system: A combined approach using statistical analysis and water quality index. *Ecological Indicators, 113*, 105815. https://doi.org/10.1016/j.ecolind.2019.105815
Üstün Odabaşı, S., & Ceylan, Z. (2023). Water quality and health risk assessment of potentially toxic elements in water of Samsun Rivers of the Mid-Black Sea, Turkey. *Environ Earth Sci, 82*, 501. https://doi.org/10.1007/s12665-023-11189-3
Varol, M., Gökot, B., Bekleyen, A., & Şen, B. (2011). Water quality assessment and apportionment of pollution sources of Tigris River (Turkey) using multivariate statistical techniques—A case study. *River Research and Applications, 28*, 1428–1438. https://doi.org/10.1002/rra.1533
Varol, M., & Tokatli, C. (2023). Evaluation of the water quality of a highly polluted stream with water quality indices and health risk assessment methods. *Chemosphere, 311*, 137096. https://doi.org/10.1016/j.chemosphere.2022.137096
Varol, M., & Tokatli, C. (2023b). Evaluation of the water quality of a highly polluted stream with water quality indices and health risk assessment methods. *Chemosphere, 311*, 137096. https://doi.org/10.1016/j.chemosphere.2022.137096
Vialle, C., Sablayrolles, C., Lovera, M., Jacob, S., Huau, M. C., & Montrejaud Vignoles, M. (2011). Monitoring of water quality from roof runof: Interpretation using multivariate analysis. *Water Research, 45*(12), 3765–3775. https://doi.org/10.1016/j.watres.2011.04.029
Wang, J., Liu, G., Liu, H., & Lamc, P. (2017). Multivariate statistical evaluation of dissolved trace elements and a water quality assessment in the middle reaches of Huaihe River, Anhui, China. *Science of the Total Environment, 583*, 421–431. https://doi.org/10.1016/j.scitotenv.2017.01.088
Wen, X., Lu, J., Wu, J., Lin, Y., & Luo, Y. (2019). Influence of coastal groundwater salinization on the distribution and risks of heavy metals. *Science of the Total Environment, 652*, 267–277. https://doi.org/10.1016/j.scitotenv.2018.10.250
WHO. (2011). *Guidelines for drinking water quality* (4th ed.). World Health Organization.
WHO. (2017). *Guidelines for drinking-water quality. First addendum to the* (4th ed.). World Health Organization.
Xiao, J., Wang, L., Deng, L., & Jin, Z. (2019). Characteristics, sources, water quality and health risk assessment of trace elements in river water and well water in the Chinese Loess Plateau. *Science of the Total Environment, 650*, 2004–2012. https://doi.org/10.1016/j.scitotenv.2018.09.322
Zeng, X., Liu, Y., You, S., Zeng, G., Tan, X., Hu, X., … Li, F. (2015). Spatial distribution, health risk assessment and statistical source identification of the trace elements in surface water from the Xiangjiang River, China. Environ Sci Pollut Res, 22, 9400–9412. https://doi.org/10.1007/s11356-014-4064-4
Zhang, L., Zhao, L., Zeng, Q., Fu, G., Feng, B., Lin, X., Liu, Z., Wang, Y., & Hou, C. (2020a). Spatial distribution of fluoride in drinking water and health risk assessment of children in typical fluorosis areas in North China. *Chemosphere, 239*, 124811. https://doi.org/10.1016/j.chemosphere.2019.124811
Zhang, Q., Xu, P., & Qian, H. (2020b). Groundwater quality assessment using improved water quality index (WQI) and human health risk (HHR) evaluation in a semi-arid region of Northwest China. *Exposure and Health, 12*, 487–500. https://doi.org/10.1007/s12403-020-00345-w