



# Multivariate and Water Quality Index Approaches for Spatial Water Quality Assessment in Lake Ziway, Ethiopian Rift

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**Abstract** Information on water quality in aquatic environments is essential for managing and protecting surface water resources, such as lakes, reservoirs, and rivers. This study investigates the spatial status of water quality and the sources of contamination in Lake Ziway, Ethiopian Rift. Evenly distributed lake water sampling, including the major feeding streams and effluents from floriculture and domestic waste that might have an impact on the lake's water quality, was carried out. For hydrochemical analysis, multivariate techniques and water quality index (WQI) approaches were applied based on 44 water quality parameters. The water quality analysis result showed a non-uniform distribution of the measured

physico-chemical and organic matter load indicators across the lake area. Multiple pollutants are present in the lake water at levels that exceed the World Health Organization's recommendations. TU, EC, pH, DO, BOD, COD, Na<sup>+</sup>, K<sup>+</sup>, HCO<sub>3</sub><sup>-</sup>, Mn<sup>2+</sup>, and a few samples for F<sup>-</sup>, Ni<sup>2+</sup>, and Pb<sup>2+</sup> were the most commonly desecrated. Principal component analysis (PCA) identified four major components with 74.35% cumulative variance, and cluster analysis (CA) resulted in three clusters representing the central, southern, and northern sectors of the lake. The results of PCA and CA indicated that the water quality of the lake is largely controlled by sediments, nutrients, and organic sources as the key lake pollution sources. The overall water quality analysis (WQI > 300) of Lake Ziway and its major feeding rivers is categorized as unsuitable for domestic uses as well as aquatic life. The combined application of multivariate and WQI analysis showed how human-induced activities in the watershed, such as soil erosion, agriculture, industrialization, and urbanization, had a significant impact on the lake water quality and ecological integrity.

**Keywords** Lake Ziway · Ethiopian Rift · Physico-chemical parameters · Multivariate analysis · Water quality index

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## 1 Introduction

Lakes are one of the most treasured natural resources on our planet and have profound significance (Dudgeon et al., 2006). Among the many values of lakes, some to mention are (i) source of water for domestic and irrigation uses, (ii) home for wild habitats (fish, birds, and other aquatic life), (iii) source of food and nutrition, and (iv) recreational, aesthetic, and scenic values. But lake ecosystems are highly fragile when exposed to various environmental stresses resulting from natural processes and/or anthropogenic activities. Lakes are vulnerable to change over time as a result of natural processes such as precipitation, rock weathering, and soil erosion processes. Extensive exposure to human-driven activities, including deforestation, industrialization, irrigation, and increased water withdrawals, can further accelerate the rate of change and strongly influence the water quality, water level, and ecological integrity of aquatic ecosystems (Ogutu-Ohwayo et al., 1997; Dudgeon et al., 2006; Qadir et al., 2008). The combined effects natural and human activities can undergo rapid environmental changes, often leading to significant declines in the above-noted values and aquatic ecosystem functions (Grzybowski and Glińska-Lewczuk, 2019).

The Ethiopian Rift Valley (ERV) is one of the most fascinating natural wonders of our planet, distinguished by its linear chain of lakes and wetlands, including their feeding rivers. The ERV is a result of volcanic and tectonic activities that created a volcano–tectonic depression that later filled with water and turned into a series of lakes (Street, 1979). These chain of lakes are found within the rift floor/adjacent escarpments confined by ancient lacustrine terraces or scarps of lava flows. These lakes have unique hydrological and ecological characteristics, providing considerable economic, environmental, cultural, scientific, and geoheritage significance (Ayenew and Legesse, 2007; Asrat, 2018). Of the ERV lakes, Ziway Lake is the second largest freshwater lake situated in the central ERV. Ziway Lake is a valuable water resources in the area and provide wide-ranging services for local communities.

Despite its importance, Lake Ziway is recently facing multiple threats and challenges that might have a potential impact on the lake's ecological integrity and its environs. As a result of its strategic location in terms of favorable land masses, cheap labor,

proximity to the capital city, and low salinity level, the region surrounding Lake Ziway has undergone a significant agricultural transformation over the past few decades (Teklu et al., 2018). Small- to large-scale horticulture activities and flower companies are mushrooming along the shoreline of the lake. To increase their productivity, these small- to large-scale farms in the area utilize chemical fertilizers, pesticides, and herbicides and are producing a multitude of waste products and effluents that are discharging directly into the lake. Furthermore, the continued clearing of forest and woodland for fuel wood and commercial charcoal production and expansion of farm lands over the past four decades have affected the lake watershed (Desta and Fetene, 2020; Mechal et al., 2022). These deforestation and expansion of farming in the lake watershed are causing severe soil erosion with subsequent increases in sediment and nutrient loads in the lake (Molla et al., 2017; Desta et al., 2017). The current unregulated manner of disposing of untreated effluents and waste from floriculture industries and agricultural fields and accelerating sediment deposition into the lake through its feeding rivers can potentially alter the water quality and cause severe aquatic life destruction. Moreover, consumption of the lake water for drinking and other domestic uses directly without any prior treatment would have detrimental medical, social, and economic impacts for residents nearby the lake. Cleaning up/reversing such problems costs billions of dollars (Ogutu-Ohwayo et al., 1997), which developing nations like Ethiopia cannot afford. Therefore, this delicate lake deserves to be investigated to protect it from the ongoing natural and anthropogenic stresses in the area so that it can offer multiple benefits to the local community, researchers, and national and international tourists.

Numerous investigations have been carried out on the Ziway Lake and its watershed, such as lake level changes due to increasing abstraction rates (Scholten, 2007), land use/land cover (LULC) (Hengsdijk and Jansen, 2006; Abraham and Nadew, 2018; Mechal et al., 2022), climate change (Abraham et al., 2018; Hordofa et al., 2022; Molla et al., 2023), and water chemistry (e.g., Zinabu, 2002; Reimann et al., 2003; Rango et al., 2009; Tibebe et al., 2022). Nevertheless, except for a few investigations (Nigussie et al., 2010; Masresha et al., 2011; Yohannes et al., 2014; Teklu et al., 2018), it has been noted that comprehensive limnological studies focusing on the impacts of

development activities on Ziway Lake have generally been quite limited as compared to other rift lakes elsewhere (e.g., Mergeay et al., 2005; Ballot et al., 2009; Oyoo–Okoth et al., 2011) with similar characteristics and environmental challenges. Although the current studies are very insightful, the primary aim of the lake water quality assessment was to compare each water quality variable with its respective standard levels, depending on its intended use. This kind of approach does not give meaningful hydrochemical interpretations and a complete image of lake water quality for the general public and policymakers who need concise information, especially when multiple water quality degraders coexist. Moreover, most of the studies mainly focus on data collected on parts of the lake (the south–western shoreline) with limited water quality parameters and do not consider the different sources of the lake. This approach might not give a clear picture of the overall status of the lake water quality, identify the pollution sources, and understand the association of the contaminants. Hence, lake-wide water sampling, including its major sources of water, is required to get important spatial data for the purpose of producing more beneficial ecological and water quality information for planning, mitigation, and cleanup processes.

The idea of a water quality index (WQI) and multivariate analysis are quite effective and beneficial approaches to address the problems identified. These methods have been used successfully by numerous researchers, who discovered that they are straightforward and efficient for assessing the composite lake's water quality status and locating contaminants and their sources (Dutta et al., 2018). For the purpose of expressing data with a wide parameter range in a simplified and logical approach, WQI has the capacity to convert the majority of the information into a single value (Brown et al., 1972). It incorporates data from several sources to create an overall assessment of a body of water (Darvishi et al., 2016). WQI also provides policymakers with a broad overview of the necessary steps to be taken to rejuvenate water bodies (Gupta et al., 2021). On the other hand, a thorough water quality monitoring program involves the analysis of a huge amount of pertinent data, which can result in a massive, intricate, and challenging to understand data matrix. Multivariate statistical methods, particularly CA (cluster analysis) and PCA (principal component analysis), can be used to reduce data and examine a number of physio-chemical and organic

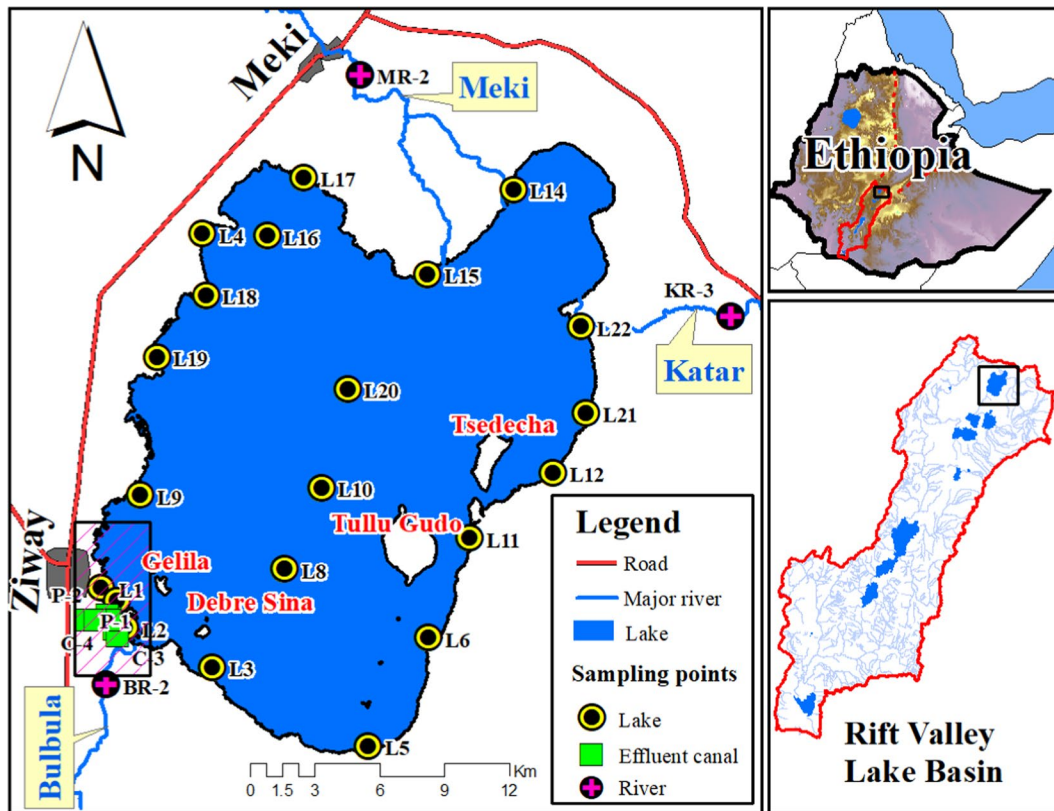
matter load indicators (Vega et al., 1998). It also permits tracing the likely sources of pollutants that might impact water resources. Therefore, the combined application of WQI and multivariate statistical methods enables effective management of water resources and the discovery of speedy solutions to pollution problems (Dutta et al., 2018; Wu et al., 2021).

The prime aim of this hydrochemical investigation is, therefore, to provide pertinent information for Ziway Lake watershed ecosystem management. More specifically, the objectives of this study were to (i) evaluate and map Lake Ziway water quality situation based on physicochemical and biological variables; (ii) identify pollution sources and major contaminants exceeding drinking water guidelines; and (iii) utilize multivariate analysis to evaluate relationships between the various water quality metrics. To achieve this objective, lake-wide water sampling, including its sources of water, was carried out, which had not been comprehensively considered in previous research. The information provided in this paper is supposed to help in the monitoring, management, and sustainability of the lake's water resources.

## 2 Study Area

### 2.1 Location and Accessibility

Lake Ziway is one of the volcano–tectonic lakes occupying the floor of the Ethiopian Rift (Fig. 1), which is mainly covered by volcano-lacustrine and fluvio-lacustrine deposits (Benvenuti et al., 2002). It is the second-largest freshwater lake in the ERV, stretching 20 km in width and 31 km in length (areal extent 434 km<sup>2</sup>), with a mean depth of about 2.5 m and a maximum depth of 9 m (Hengsdijk and Jansen, 2006). The lake catchment area is approximately bounded between 7°21'30" and 8°30'12" N, and 38°14'26" and 39°30'12" E, covering a total area of about 7300 km<sup>2</sup>. The lake is primarily fed by the Meki and Katar, two major streams that originate in the west and east, respectively, and is drained by the Bulbar before emptying into Lake Abijatta. The lake also receives a considerable amount water from the surroundings aquifer system (Ayenew, 1998). It is adorned by five islands (Galila, Debre Sina, Tulu Gudo, Birds Island, and Tsedecha; Fig. 1) that are home to a monastery where the Ark of the Covenant is thought to have hosted in



**Fig. 1** The location map of Lake Ziway and water sampling sites. The hatched box represents the location of floriculture plants

the ninth century. There are two asphalt routes from Addis Ababa to the lake region: a 174 km from Addis Ababa to Alem Gena–Butajera–Ziway and a 163 km from Addis Ababa to Mojo–Ziway.

Agriculture is the most dominant LULC type (74.42%) in the watershed contributing to the livelihoods of the majority of the population (Desta and Fetene, 2020; Mechal et al., 2022). The population of the lake watershed is about 2 million (Meshesha et al., 2012). A significant portion of this population resides in the major cities (e.g., Ziway, Meki, and others) and villages situated adjacent to the lake (Fig. 1), which are directly or indirectly related to the lake water and feeder rivers.

Ziway Lake region has sub-arid climate (Nicholson et al., 1996) with mean annual temperature ranging from 14.09 to 19.30°C. The maximum and minimum temperature is from March to May and November to January months, respectively. The rainfall over the lake region is characterized by erratic and bimodal type, with one dry season, the Bega (ONDJ), and two

rainy seasons, the major wet season (JJAS) and minor wet season (FMAM) (ENMA, 2007).

## 2.2 Lake Water Use

Lake Ziway and its major feeding streams are important water resources in the area with wide significances. As the groundwater in the adjacent area of the lake is highly saline and loaded with toxic elements (F, As, Mn, Pb, and others) (Reimann et al., 2003; Rango et al., 2009; Tekle–Haimanot et al., 2006; Mechal et al., 2022), the lake water is utilized for community water supply as alternative for the majority of residents dwelling around the lake. The floor of the Lake Ziway watershed, specifically the lands adjacent to the lake, is very favorable for flower farm and cash crop production by abstracting water from the lake and major rivers (Ayenew, 1998; APHRD, 2010; EHPEA, 2011). As the lake is fresh water lake, it is a home for several aquatic life including fishes. Thus, the lake provides a livelihood for many fishermen and

their families, as well as food for communities in the lake region and beyond. Due to the presence of bird sanctuaries, hipotoman, scenic islands with monasteries, and a rich tropical fauna, the lake is also a popular tourism attraction site for both local and foreign tourists (Desta and Bersisa, 2019).

### 3 Materials and Methods

#### 3.1 Sampling Design and Analysis Procedure

The water sampling setup was designed to cover a wide range of sources that can adequately represent the water quality of the lake system, including major streams, effluents from floriculture, and domestic waste that could have a potential impact on the water quality (Fig. 1). Lake water sampling (21) was taken along the NNE–SSW in transects at the specified intervals following the general lake water flow direction. The first and third transects represent the eastern and western lake shorelines, while the second represents the central part of the lake. Three samples from the major rivers (Katar, Meki, and Bulbula) were collected from the lower water column nearby the site where the rivers enter and leave the lake. Dense water sampling was made in the vicinity of the floriculture industry effluents (7 water samples from effluent discharging canals (C1–C5) and biological lagoons (C6 and C7)). The density of the sampling is much denser to catch the impacts of the small-scale and horticultural activities.

Water samples were taken during the transition phase between the dry and wet seasons (December and January, 2019). In accordance with Forrest (2000), water samples were collected using a 2-l open water grab sampler with a simple pull-ring that enabled sampling at various water depths (0.6–4.24 in.). Triplicate samples were taken from each sampling location in high-density polyethylene (HDPE) plastic bottles that were clean, dry, and well-washed before being filled with the sample for cation (100 ml), anion (100 ml), and biological (500 ml) analysis. The water samples were filtered using a 0.45- $\mu$ m filter membrane immediately after sampling for an analysis of major ions and trace elements. Ultra-pure 6N HNO<sub>3</sub> was added to samples for major cation and trace element analysis in order to prevent major precipitation/adsorption to the container wall. All water samples

were tightly sealed with a double cap, labeled, and kept at 4 °C until they arrived at the lab.

Field measurements such as water temperature, pH, TDS (total dissolved solids), EC (electrical conductivity), DO (dissolved oxygen), and TU (turbidity) were conducted during each sampling occasion using a thermometer, a digital pH, EC, TDS, DO, and TU meter, respectively. TSS (total suspended solids), BOD (biological oxygen demand), COD (chemical oxygen demand), and nutrients such as nitrate (NO<sub>3</sub><sup>-</sup>) and phosphate (PO<sub>4</sub><sup>3-</sup>) were analyzed at Addis Ababa University. Major ion and trace element analyses were conducted at the Chinese Academy of Sciences' Institute of Geology and Geophysics laboratory in Beijing, China. Ion chromatography was used to examine the major ions Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup>, K<sup>+</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, and F<sup>-</sup> using Dionex DX-120 equipment. Titration technique was used to determine the total alkalinity (HCO<sub>3</sub><sup>-</sup>). LC-6500 atomic fluorescence photometer was utilized to analyze arsenic (As), whereas ICP-MS (inductively coupled plasma mass spectrometry) was used to determine other heavy metals (Li, Sc, Be, V, Ti, Cr, Co, Ni, Mn, Cu, Ga, Zn, Rb, Cd, Mo, Sb, Ba, Pb, U, Bi, and Sr).

The analytical precision of the measured parameters was assessed and controlled by running the known standard solutions. For all of the examined samples, the overall precision, given as a RSD (percentage relative standard deviation), was found to be within 5%. The overall accuracy of the analysis results was assessed using the charge on balance error (CBE) equation of Freeze and Cherry (1979) and found to be within acceptable limits ( $\pm 10\%$ ).

#### 3.2 Data Analysis Methods

##### 3.2.1 Multivariate Analysis

Multivariate techniques such as multiple correlation coefficient analysis (MCCA), CA, and principal component analysis (PCA) were applied to identify the plausible processes that might control the hydrochemical signature of the Lake Ziway water. The multivariate analysis was carried out using SPSS (Version 26), taking into account the parameters thought to have a substantial effect on the lake water quality. In this research, the approach given by Güler et al. (2002) was used to prepare the water quality data for the analysis. Prior to multivariate analysis,

each parameter was standardized using CLRT (centered log–ratio transformation) to reduce the effect of different parameters and their corresponding units of measurement. The CLRT transformation was conducted following the procedure applied by Sunkari et al. (2019).

The MCCA is a fundamental statistical method utilized to determine the degree of association between two or more parameters in order to infer whether the parameters have the same origin (Batabyal, 2014). Among the available options in SPSS (Version 26), the Pearson correlation coefficient (Pearson, 1895) is utilized to determine the association of the water quality data sets. Based on the obtained values of the correlation coefficient ( $r$ ), the strength of the association between variables was classified as high if “ $r$ ” was between 0.7 and 1.0, moderate if “ $r$ ” was between 0.4 and 0.7, weak if “ $r$ ” was between 0.1 and 0.4, and inconsequential if “ $r$ ” was below 0.1 (Pearson, 1895; Christian et al., 2014).

According to Massart et al. (1988), CA is a method for classifying samples into groups that have a high degree of internal (within-clusters) similarity and a high degree of external (between-clusters) heterogeneity. In this research, to examine the lake water quality data for spatial similarity, hierarchical CA was applied. The CA was carried out on the normalized data sets by means of Ward’s (1963) method as a linkage and Euclidean distances as a measure of difference or resemblance. In the present research, the water quality data was processed using Q–mode CA (Sunkari et al., 2019).

PCA is one of the most popular and frequently used statistical methods in various fields. It was introduced initially by Pearson (1901) and later improved to its present form by Hotelling (1933). PCA is designed to explore the most important information from a large dataset by reducing data dimension based on a summary of the statistical correlation between parameters with the least possible loss of the initial information (Vega et al., 1998; Kazi et al., 2009). During the PCA analysis, the original set of parameters is converted into new uncorrelated parameters called the principal components (PCs), which are weighed linear combinations of the original parameters (Vega et al., 1998; Qadir et al., 2008; Thu et al., 2017). The significance of the PCs is measured by eigenvalues, while the correlation of the PCs and original parameters

is given by factor loadings. In this study, only PCs with eigenvalues  $>1$  were retained. Factor loadings are categorized based on absolute score values as strong ( $> 0.75$ ), moderate (0.75–0.50), and weak (0.50–0.30) correlations (Liu et al., 2003).

### 3.2.2 Drinking Water Quality Index

Based on Harkins et al. (1974), WQIs are one of the most simple and efficient methods for informing concerned citizens and policymakers about the water quality status of various water bodies (e.g., lake water). The WQI is a mathematical tool that converts several water quality characteristics (parameters) of an individual water sample into a single value. The weighted arithmetic WQI approach (Tyagi et al., 2013; Lukhabi et al., 2023) was used in this study to evaluate the appropriateness of the water quality for human consumption. In this method, the WQI computation was conducted in three steps. The detailed calculation procedure of WQI is described by many authors (e.g., Brown et al., 1972; Boateng et al., 2016).

The first step involves choosing the water quality indicators to take into account when calculating the drinking WQI. In the current study, 44 parameters measuring the quality of the water were examined. However, only 20 parameters (pH, EC, DO, BOD, COD, TU,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{F}^-$ ,  $\text{PO}_4^{3-}$ ,  $\text{NO}_3^-$ ,  $\text{As}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Ni}^{2+}$ , and  $\text{Pb}^{2+}$ ) that significantly affect the quality of drinking water were taken into account in this study (Table 1).

In the second step, the chosen parameters were assigned a weight ( $AW_i$ ) based on their relative importance in the overall quality of the lake water for human consumption. The parameters such as  $\text{NO}_3^-$ , DO, BOD, COD, TU,  $\text{PO}_4^{3-}$ , and  $\text{F}^-$  have been given a maximum AW of 5 and a minimum of 1 has been weighted to the  $\text{K}^+$  and  $\text{Cl}^-$  ions, which are thought to be not harmful (Srinivasamoorthy et al., 2012). Based on their significance in the overall quality of the lake water for drinking use, the remaining parameters were weighted between 1 and 5. Subsequently, the relative weight (RW) of each parameter was computed (Eq. 1). Table 1 presents the AW and the calculated RW values.

$$RW = \frac{AW_i}{\sum_1^n AW_i} \quad (1)$$

**Table 1** Physio-chemical and biological parameters used in drinking WQI computation based on the  $AW_i$ ,  $RW_i$ , and WHO (2011) standards values of each parameters

Parameters	WHO (2011)	$W_i$	$RW_i$
pH	7.5	4	0.06
EC ( $\mu\text{S}/\text{cm}$ )	1000	4	0.06
DO (mg/l)	5	5	0.07
BOD (mg/l)	5	5	0.07
COD (mg/l)	10	5	0.07
TSS (mg/l)	500	5	0.07
TU (NTU)	5	5	0.07
$\text{Ca}^{+2}$ (mg/l)	75	2	0.03
$\text{Mg}^{+}$ (mg/l)	50	2	0.03
$\text{Na}^{+}$ (mg/l)	200	3	0.04
$\text{K}^{+}$ (mg/l)	12	1	0.01
$\text{HCO}_3^{-}$ (mg/l)	120	1	0.01
$\text{Cl}^{-}$ (mg/l)	250	2	0.03
$\text{SO}_4^{-2}$ (mg/l)	250	3	0.04
$\text{NO}_3^{-}$ (mg/l)	50	5	0.07
$\text{PO}_4^{-3}$ (mg/l)	5	5	0.07
$\text{F}^{-}$ (mg/l)	1.5	5	0.07
$\text{As}^{+2}$ ( $\mu\text{g}/\text{l}$ )	10	5	0.07
$\text{Ni}^{+2}$ ( $\mu\text{g}/\text{l}$ )	20	2	0.03
$\text{Mn}^{+2}$ ( $\mu\text{g}/\text{l}$ )	40	4	0.06
$\text{Pb}^{+2}$ ( $\mu\text{g}/\text{l}$ )	10	3	0.04
		$\sum W_i=76$	$\sum RW_i=1$

where  $n$  denotes the number of parameters,  $AW_i$  denotes the assigned weight of each parameter; and  $RW$  denotes the relative weight.

In the third step, a quality ranking ( $Q_i$ ) is computed for each parameter:

$$Q_i = \left[ \frac{C_i}{S_i} \right] * 100 \tag{2}$$

where  $Q_i$  is the quality rating,  $C_i$  is the content of each parameter, and  $S_i$  (mg/l) corresponds to the WHO (2011) standard for each parameter (Table 1).

Lastly, in the fourth step, the water quality sub-index  $SI_i$  (Eq. 3) and the integrated drinking WQI (Eq. 4) were obtained by multiplying the quality rate by the  $RW$  of each parameter and summing the sub-indices, respectively.

$$SI_i = RW * Q_i \tag{3}$$

$$WQI = \sum_{i=1}^n SI_i \tag{4}$$

where  $SI$  is the sub-index of the  $i$ th variable,  $RW_i$  is the relative weight of each parameter, and  $Q_i$  is the rating based on the content of  $i$ th parameter. The drinking WQI value was obtained by summing each  $SI_i$  values of the lake water samples (Eq. 4).

## 4 Result and Discussion

### 4.1 Lake Water Spatial Characteristics

The basic statistics, such as average, range, and STD (standard deviation), of the analyzed water quality parameters for the lake, river, and effluent channel are provided in Table 2. The spatial variability of the most influential parameters of the lake water is also presented. To identify parameters responsible for lowering the water quality, the mean values of the parameters were compared to the maximum allowable limits suggested by the WHO (2011).

### 4.2 Physical Parameters

In this investigation, several physical characteristics were taken into account: temperature, pH, EC, turbidity, and TSS (Table 2). The temperature of Lake Ziway, effluent canals, and major rivers ranges from 21.4 to 25.7, 17.6 to 23.4, and 17.5 to 21.3 °C, respectively. The water temperature does not show significant variability (STD = 1.2) over the lake area but is higher than the major inflows (Table 2). The higher temperature might be due to a higher surface air temperature in the rift axis, close to 30 °C/year (Hordofa et al., 2022).

The pH of Lake Ziway and major rivers ranges from near sub-alkaline (8.1) to alkaline (9.1), with a mean value of 8.7 and 8, respectively (Table 2). However, the pH values of the effluent canals from the flower farm range from 7.9 to 10.96 and appear to show high alkalinity, with an average value of 8.9. The measured pH values of Lake Ziway are in agreement with previous researchers (Tamire and Mengistou, 2012; Teklu et al., 2018; Tibebe et al., 2022). The pH value over the lake area varied marginally but showed an overall sub-alkaline nature (Fig. 2a),

**Table 2** Statistical description of physical and biological parameters. All units are in mg/l except temp. (°C), pH, EC (µS/cm), and TU (NTU)

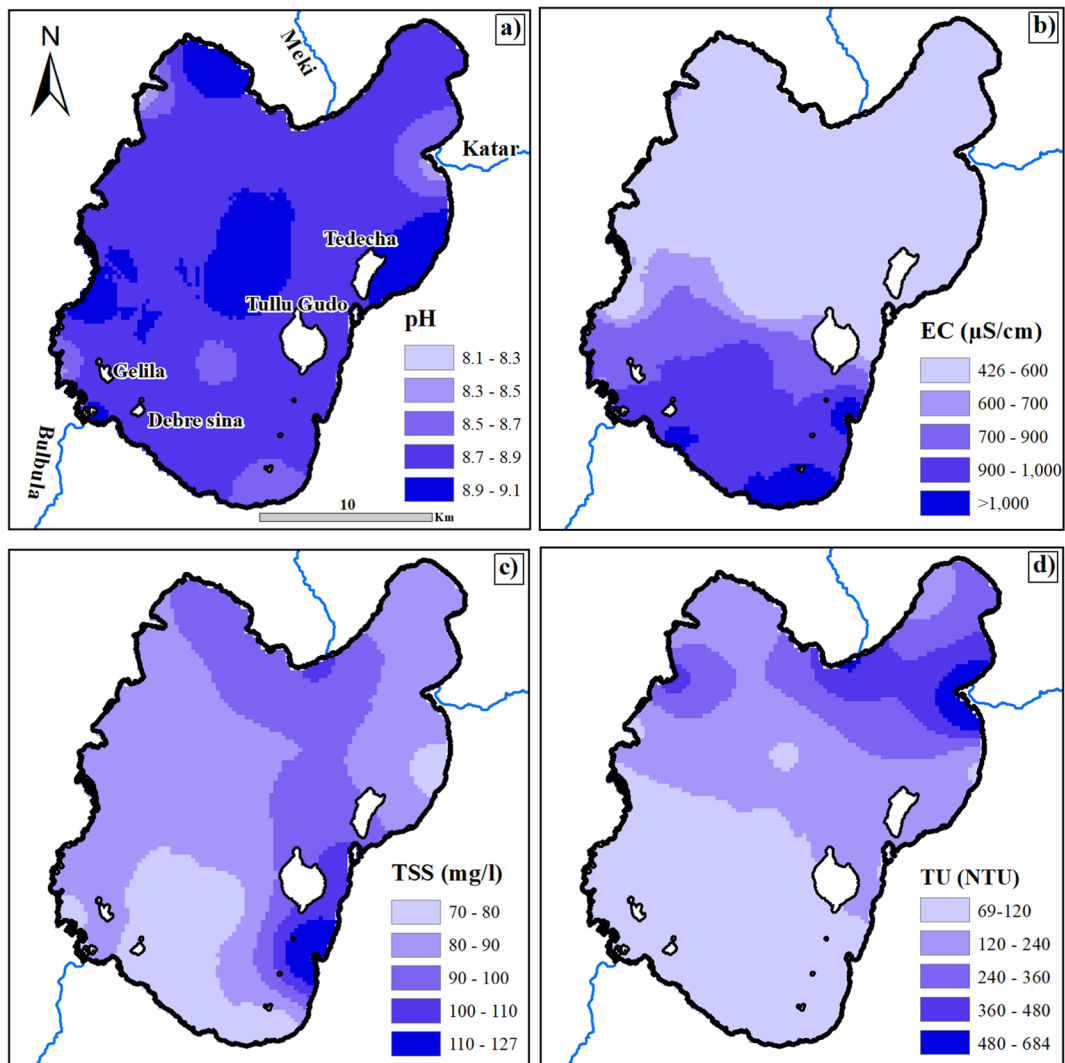
Source	WHO (2011)	Temp. (25 °C)	pH (6.5–8.5)	EC (1000)	TSS (500)	TU (5)	DO (5)	COD (10)	BOD (5)	NO <sub>3</sub> <sup>-</sup> (50)	PO <sub>4</sub> <sup>-3</sup> (5)
Lake Ziway	Range	21.4–25.7	8.1–9.1	426–1234	70–127	69–684	4.94–5.72	30–330	24–264	1.6–17	0.63–1.64
	Mean	22.9	8.8	540.6	85.8	180.1	5.33	181.3	145	8.8	1
	Std	1.2	0.3	252.5	14.1	157.3	0.1	94.5	75.6	3.2	0.3
Effluent canals	Range	17.6–23.4	7.9–10.9	479–1481	76.0–96	3.5–47.7	4.94–5.98	40–390	32–312	3.7–17	0.5–152
	Mean	20.6	8.9	385.4	89.3	33	5.46	148.6	118.9	8.2	22.8
	Std	2.2	1.1	360.3	8.2	18	0.2	117.5	94	4.6	57
Major rivers	Range	17.5–21.3	7.6–8.4	157.4–170.5	90–92	842–1000	4.96–5.33	260–299	208–240	1.86–1	1.26–2.8
	Mean	19.4	8	164	91	921	5.15	279.5	224	6	2
	Std	2.7	0.6	9.3	1.4	111.7	0.86	27.6	22.6	5.9	1.1

which is a common characteristic of Ethiopian Rift lakes (Zinabu et al., 2002). This may be explained by the greater HCO<sub>3</sub><sup>-</sup> concentration, which is mostly due to the highly evolved groundwater from the surrounding alkaline volcanic aquifers. According to WHO (2011) and APHA (1999), pH levels between 6.5 and 8.5 are suitable for drinking and aquatic life. Although the slightly increased pH of the lake water may not directly affect the aquatic biota, it can have a substantial impact on the solubility and accessibility of chemicals in the lake and may exacerbate nutrient-related issues (Menberu et al., 2021). For instance, a higher pH may make phosphate and nitrate more soluble, making them more available for plant growth and raising the long-term need for DO.

The EC values of Lake Ziway varied from 420 to 1234 µS/cm, with an average value of 660 µS/cm. Similarly, the EC values of the effluent from canals and major rivers range from 479 to 1481 and 157.4 to 170.5 µS/cm, respectively, with an average values of 385.4 and 164 µS/cm, respectively (Table 2). The spatial map of the lake EC exhibits relatively lower EC (<600 µS/cm) values in the northern zone; however, the EC value gradually increases towards the outlet (south) of the lake. The mean EC values were below the 1000 µS/cm threshold, which is the upper limit for freshwater bodies (WHO, 2011). However, the mean EC value of Lake Ziway is 400% higher than the major feeding rivers (Meki and Katar) and 40% lower than the effluent channels. Along with evaporative enrichment, human activity nearby the lake zone, including waste disposal from urban areas and agro-chemical runoff from agricultural and apicultural activities, is responsible for the greater EC relative to the major feeding rivers. More importantly, the extremely higher EC values measured above the allowable limit in the western sector of the lake, which have a similar signature to effluent canals, might be associated with the floriculture area (Fig. 2a).

The average EC values generally agree with previous studies (Tilahun and Ahlgren, 2010; Teklu et al., 2018; Tamire and Mengistou, 2012; Tibebe et al., 2022). As compared with other Ethiopian Rift lakes, the EC values of Lake Ziway were lower than those of lakes Hawasa, Chamo, Langano, Abaya, Abijata, Bishoftu, and Chitu (Tilahun and Ahlgren, 2010; Masresha et al., 2011), but higher than those of lake Koka (Masresha et al., 2011) and Lake Naivasha





**Fig. 2** Spatial variability of physical parameters: pH (a), EC (b), TSS (c), and Turbidity (d)

(Yongo et al., 2022). Based on the EC value, Lake Ziway appears to be appropriate for aquatic life and drinking purposes; nevertheless, ongoing human activity in the lake zone and its watershed area could cause the lake to become salinized and unsuitable for the survival, growth, or reproduction of any aquatic life.

Turbidity (TU) has been used as a measure of water quality based on the relative cloudiness or clarity of the water, which is mostly related to the presence of dissolved colored particulate matter and suspended particles. Over Lake Ziway, TU was found to be highly variable and ranged from 69 to 684 NTU,

with a mean value of 180.05 NTU. The measured TU was far higher than many Ethiopian (e.g., Awassa (Lencha et al., 2021), Beseka (Umer et al., 2020), Chamo (Utaile and Sulaiman, 2016), Abaya (Teffer et al., 2018)), and Kenyan (e.g., Naivasha; Ndungu et al., 2015) rift lakes. The TU values measured are significantly higher than 5 NTU, the allowable limit for human consumption and aquatic life (CME, 2001; USEPA, 2003; WHO, 2011). When exposed for extended periods of time to water with a TU of 100–500 NTU or more, some fish species may experience stress (USEPA, 2005). Higher TU values in Lake Ziway might be mainly credited to the high loading

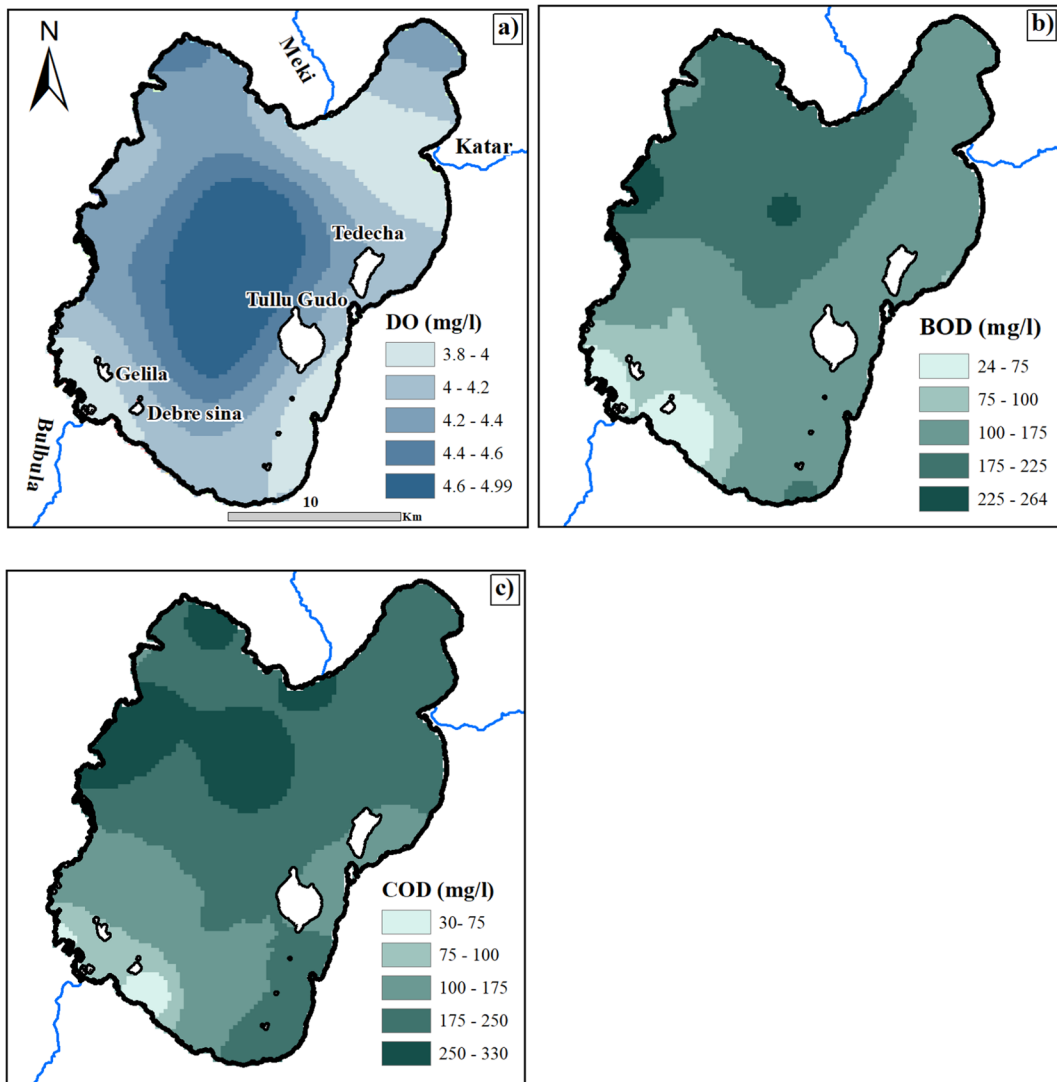
of particulate matter from the major inflowing rivers (Meki and Katar) associated with the ongoing soil erosion in the watershed (Aga et al., 2019; Kalsido and Berhanu, 2020; Mechal et al., 2022). The mean value of the TU of the inflowing rivers is five times higher than that of the lake (Table 2), suggesting that the TU of the lake Ziway water is largely controlled by major rivers water. As shown in Fig. 2 d, the higher loading of TU gradually declines from the mouth of the major rivers towards the outlet of the lake, indicating the settlement of the particulate matter as lake water flows southward. Water with such high TU can significantly impact water clarity, salinity, nutrient content, and lake depth (Saturday et al., 2023). The measured TU across the lake area was found to be extremely high, and it is expected to have a significant impact on the productivity of fish and other aquatic life as it hinders light penetration and reduces available DO (USEPA, 2003). The high TU in the lake, especially in areas with over 300 up to 684 NTU, represents a major decline in the ecosystem of Lake Ziway and calls for watershed and soil conservation to mitigate soil erosion and lake sediment deposition.

TSS levels in Lake Ziway varied from 70 to 127 mg/l, with an average value of 85.81 mg/l, whereas TSS in the effluent canals and major rivers ranged from 76.0 to 96 with a mean value of 89.3 mg/l and 90–92 with a mean value of 91 mg/l, respectively. The zonal comparison of TSS exhibited a reducing trend from north to south, though a slightly higher value in the south eastern zone, which is associated with the growing effect of the nearby heavily cultivated lands. The TSS concentrations were far below the WHO guideline (500 mg/l). However, the relatively elevated value of TSS in the eastern lake shore has a tendency to pollute the lake water and must be seriously handled.

Organic matter load indicators DO defines the level of readily available free, non-compound oxygen in water. In surface waters, such as lakes, DO is a clear sign of suitability of water for aquatic life as well as an indication of organic contamination from various sources (Qadir et al., 2008). In Lake Ziway, the DO content varied from 4.94 to 5.72 mg/l, with a mean value of 5.33 mg/l. Similar DO levels are also detected in the effluent canals and major rivers (Table 2). Figure 3 a presents the spatial distribution

map of DO, showing a relatively lower DO level in the eastern and central sectors of the lake. The detected DO content in the present study was lower than that documented in the same lake by Tibebe et al. (2022). Comparatively, Lake Ziway's mean DO concentrations are almost identical to those found in the majority of Ethiopian Rift lakes (Lencha et al., 2021). A typical DO value for fisheries and aquatic life varies from 5.0 to 9.0 mg/l; however, aquatic life suffers when it drops below 4.0 mg/l (FEPA, 2003). The value of DO in the current study is quite close to the minimum limit allowed based on EU (1998) and WHO (2011) recommendations. The low DO is attributed to agro-chemicals from the agricultural fields in the watershed, improper discharge of floriculture effluent, and solid waste from adjacent towns and villages. As physical, chemical, and biological processes can cause lakes' oxygen levels to rise or fall, monitoring DO in aquatic systems is crucial.

BOD and COD serve as key indicators of organic waste pollution (Bhateria and Jain, 2016). BOD is an indicator of how much oxygen is needed to decompose organic matter by bacteria and other microbes under aerobic conditions. COD, on the other hand, refers to the amount of oxygen required for the chemical oxidation of the available organic matter in water. In Lake Ziway, the BOD and COD content varied from 24 to 264 mg/l and 30 to 330 mg/l, respectively, with an average values of 145.1 and 180.26 mg/l, respectively. Similar results were also obtained for the major rivers and effluent canals, though the mean value is elevated for effluent canals (Table 2). The average ratio of COD to BOD in the lake water is close to 0.8, indicating biodegradable organic matter is significant (Moon and Kim Moon, 2021). Both BOD and COD spatial maps indicated that the northern sector had increased concentrations compared to the southern end. The measured BOD and COD values in all sampling sites are high above the WHO (2011) standards' upper allowed levels. These might be brought on by continued discharge of local waste from the adjacent towns (e.g., Ziway, Meki, and others), untreated effluents from floricultural industries, waste from fish markets near the lake, and agrochemical runoff from the agricultural fields in the lake watershed.



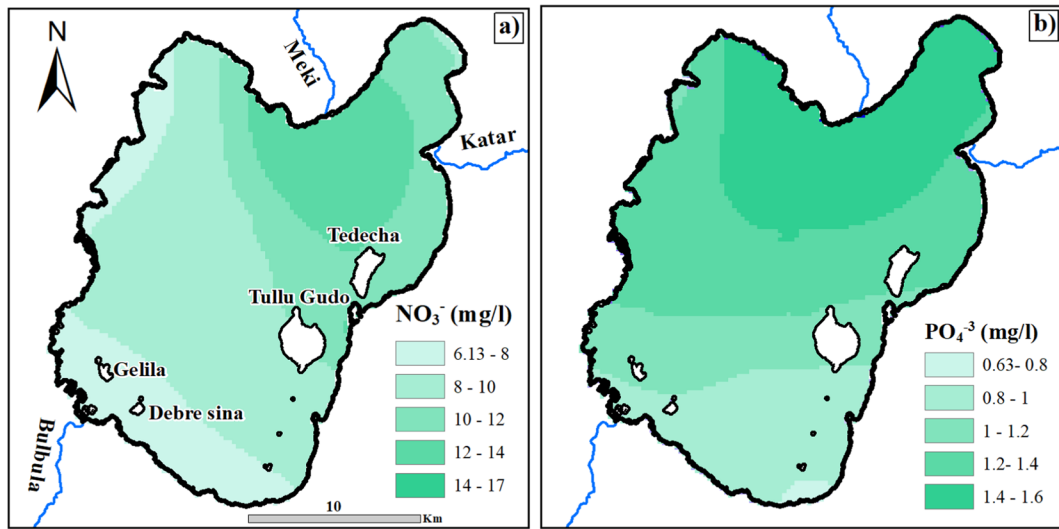
**Fig. 3** Spatial variability of biological parameters: DO (a), BOD (b), and COD (c)

#### 4.3 Nutrients

Nutrients are vital for the growth and survival of aquatic plants; however, very high contents can create a conducive environment for accelerated growth of plants and algal blooms, leading to low DO and the death of aquatic life (Bhateria and Jain, 2016). In Lake Ziway, the  $\text{NO}_3^-$  and  $\text{PO}_4^{3-}$  concentrations varied from 1.6 to 17 mg/l and 0.5 to 1.6 mg/l, respectively, with a mean value of 8.8 and 1.02 mg/l, respectively (Table 2; Fig. 4). The concentrations of  $\text{NO}_3^-$  and  $\text{PO}_4^{3-}$  varied from 3.7 to 17 mg/l and 0.5 to

152 mg/l, with a mean value of 8.2 and 22.8 mg/l in effluent canals, respectively, whereas the  $\text{NO}_3^-$  and  $\text{PO}_4^{3-}$  content in the major rivers varied from 1.86 to 10 mg/l and 1.26 to 2.8 mg/l with a mean value of 6 and 2 mg/l, respectively.

The spatial map shows that increased  $\text{NO}_3^-$  and  $\text{PO}_4^{3-}$  were detected in the northern sector of the lake, indicating the major rivers are the main nutrients conveyer to the lake. The contents of  $\text{NO}_3^-$  and  $\text{PO}_4^{3-}$  in the lake water were lower than 50 and 5 mg/l, which are the allowable limits for drinking uses (WHO, 2011; Table 2), respectively. However, these



**Fig. 4** Spatial variation of nutrients:  $\text{NO}_3^-$  (a) and  $\text{PO}_4^{3-}$  (b)

scales of magnitude in  $\text{NO}_3^-$  and  $\text{PO}_4^{3-}$  can affect aquatic life by reducing the available DO dissolved oxygen through heavy algal blooms (USEPA, 2000). According to Lau et al. (2002), these situations have a potential to trigger the eutrophication process in Lake Ziway.

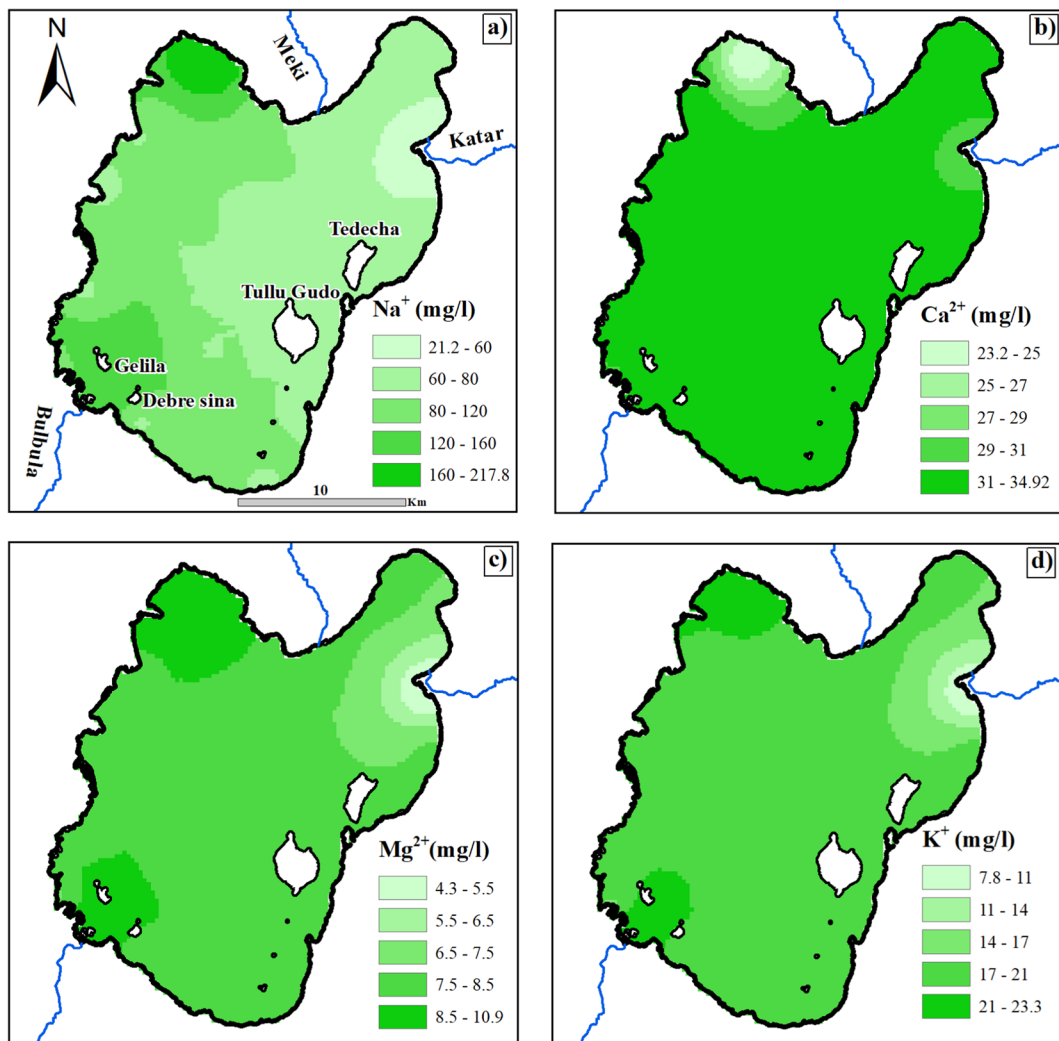
#### 4.4 Major Ions

In Lake Ziway water, the abundance of major cations is in the order of  $\text{Mg}^{2+} < \text{K}^+ < \text{Ca}^{2+} < \text{Na}^+$  (Table 3), in agreement with other Ethiopian Rift lakes (e.g., Awassa, Shala, and Beseka) (Zinabu, 2002; Reimann et al., 2003; Klemperer and Cash, 2007). Sodium dominates among major cations ranging from 21.15

to 217.77 mg/l, with a mean value of 81.5 mg/l contributing above 50% of the cation budget. The content of  $\text{Ca}^{2+}$  (23.17 to 34.92 mg/l with a mean value of 32.15 mg/l) is in second place. It is followed by  $\text{K}^+$  (7.78 to 23.33 with a mean value of 18 mg/l) and  $\text{Mg}^{2+}$  (4.3–10.87 mg/l with a mean value of 7.88 mg/l). The major cations do not show significant variability across the lake area (Fig. 5a–d), though they are slightly higher towards the outlet of the lake and locally higher associated with effluent from agricultural and floricultural fields. It is observed that the content of major cations in the lake is higher than the major feeding rivers but lower than the effluent channels (Table 3), suggesting a mixture of these sources. The content of  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ , and  $\text{Mg}^{2+}$  in the lake water

**Table 3** Descriptive statistics of major ions analysis result (concentration is mg/l)

Source	WHO (2011)	$\text{Ca}^{+2}$ (75)	$\text{Mg}^{+2}$ (50)	$\text{Na}^+$ (200)	$\text{K}^+$ (12)	$\text{HCO}_3^-$ (120)	$\text{Cl}^-$ (250)	$\text{SO}_4^{-2}$ (250)	$\text{F}^-$ (1.5)
Lake Ziway	Range	23.2–34.9	4.3–10.9	21.2–217.8	7.8–23.3	132.4–790.4	2.9–30.4	3.9–13.5	0.4–2.6
	Mean	32.2	7.9	81.2	18	306.14	14.7	11	1.2
	Std	3.3	1.4	37.8	3.8	128.3	5.8	3.4	0.5
Effluent canals	Range	29.7–48.7	8.1–11.1	82.4–451.2	20.2–29.5	297.9–633.8	13.7–36.1	14.6–188.9	1.0–8.7
	Mean	39.3	9.6	193.4	25.2	438.9	23.3	95.3	2.6
	Std	7.2	1.2	124.8	3.1	127.5	9	70.5	2.8
Major rivers	Range	16.8–42	5.2–20.9	15–56	5–12	125–409	4–16	1–25	1.5–1.6
	Mean	29.4	13.1	35.5	8.5	267	10	13	1.6
	Std	17.8	11.1	29.0	4.9	200.8	8.5	17	0.1

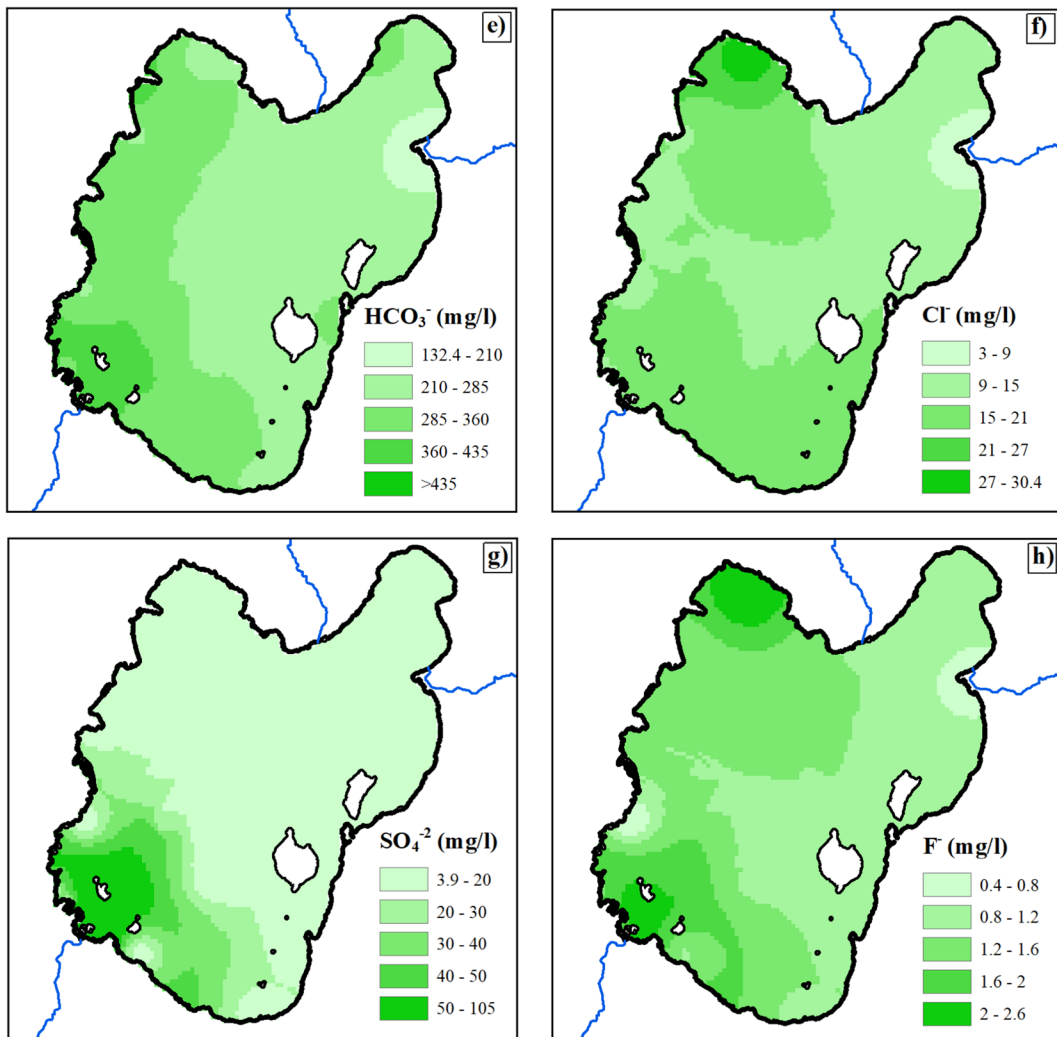


**Fig. 5** Spatial variability of major ions:  $\text{Na}^+$  (a),  $\text{Ca}^{2+}$  (b),  $\text{Mg}^{2+}$  (c),  $\text{K}^+$  (d),  $\text{HCO}_3^-$  (e)  $\text{SO}_4^{2-}$  (f),  $\text{Cl}^-$  (g), and  $\text{F}^-$  (f)

is within the WHO-recommended permissible limit (2011). However, the concentration of  $\text{K}^+$  exceeds the permissible limit in a vast portion of the lake (Fig. 5d).

On the other hand, the major anion content in Lake Ziway is in the order of  $\text{F}^- < \text{SO}_4^{2-} < \text{Cl}^- < \text{HCO}_3^-$  (Table 3). The anion chemistry was dominated by  $\text{HCO}_3^-$  constituting close to 90% of the total anions, which is a peculiar characteristic of Ethiopian Rift lakes (Gizaw, 1996).  $\text{HCO}_3^-$  concentration ranges between 132.36 and 790.41 mg/l, with a mean value of 306.14 mg/l. The  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  concentrations ranged from 2.78 to 30.35 mg/l and 3.92 to 13.53 mg/l, respectively, with average values of

14.69 and 11.03 mg/l, respectively. The concentration of  $\text{F}^-$  ranges from 0.36 to 2.63 mg/l, with an overall mean of 1.16 mg/l. The extremely high fluoride content observed in the rift floor aquifer system surrounding the lake is not well recognized. This might be related to the dilution effect. The measured level of  $\text{F}^-$  was substantially lower than what had been reported in lakes Abiyata (202 mg/l), Shala (264 mg/l), and Beseka (32.2 mg/l) in the Ethiopian Rift (Tekle-Haimanot et al., 2006; Zinabu, 2002) and higher than Ethiopian highland lakes such as Tana (1 mg/l; Tekle-Haimanot et al., 2006) and Haramaya (1.1 mg/l; Tebeje, 2012). Higher  $\text{SO}_4^{2-}$  and  $\text{F}^-$  contents are recorded in the effluent canals as compared



**Fig. 5** (continued)

to the major rivers and lake water. Except  $\text{HCO}_3^-$  and  $\text{F}^-$ , the other above-mentioned cations are far below the recommended value by WHO (2011), 1.5 and 250 mg/l for drinking water, respectively.

#### 4.5 Heavy Metals

Heavy metals (HMs) are usually identified based on the fact that their concentration in water is lower than 1 mg/l (Gaillardet et al., 2003). Despite their lower concentrations, several HMs have an impact on human health that can be either positive or negative effect (WHO, 2011). To identify potentially toxic HMs, the contents of HMs in the lake, effluent canals,

and major rivers water samples were assessed against drinking water quality guidelines (WHO, 2011).

With the exception of As, the analyzed HMs (Ti, Mn, Mo, U, Cr, Pb, Li, Sr, V, Co, Cu, Ni, Ga, Zn, Cd, Sc, Rb, Be, Sb, Bi, and Ba) were identified in the majority of water samples. For most of the HMs (Ti, Mo, U, Cr, Li, Sr, V, Co, Cu, Ga, Zn, Cd, Sc, Rb, Be, Sb, Bi, and Ba) analyzed, the measured content was quite below the WHO guideline values as well as industrial effluent standards recommended by the Ethiopian Government (FEPA, 2003) and is unlikely to affect human health. Nevertheless, some of the HMs, such as  $\text{Mn}^{2+}$ ,  $\text{Ni}^{2+}$ , and  $\text{Pb}^{2+}$ , exceeded the permissible limits (WHO, 2011; Table 4) and

**Table 4** Selected HMs concentration in Lake Ziway, major rivers, and effluent canals flowing to the lake surpassing the WHO (2011) limit (concentration is  $\mu\text{g/l}$ )

Source	WHO (2011)	As <sup>+2</sup> (10)	Mn <sup>+2</sup> (40)	Ni <sup>+2</sup> (20)	Pb <sup>+2</sup> (10)
Ziway Lake	Range	*	83.06–354.0	11.8–22.4	2.8–19.5
	Mean	*	116.6	15.1	5.3
	Std	*	74.8	1.26	1.3
Effluent canals	Range	0.9–11.7	50.6–818	13.2–22	0.72–0.44
	Mean	3.4	343.7	16.5	2.07
	Std	4.1	281.3	3.3	1.31
Major rivers	Range	0.6–3.34	7.1–146	3.39–14.55	0.44–4.07
	Mean	1.52	80.4	9.1	1.65
	Std	1.59	69.8	5.58	2.10

\*The content is below the detection limit

may have human health and potential environmental hazards.

Manganese ( $\text{Mn}^{2+}$ ) is the most prevalent HM in Lake Ziway, major rivers, and effluent canals.  $\text{Mn}^{2+}$  is a vital element for humans. Nevertheless, overconsumption of  $\text{Mn}^{2+}$  beyond the acceptable limit (40  $\mu\text{g/l}$ ; WHO, 2011) may lead to infertile, immune system dysfunction, and signs similar to Parkinson's disease (Erikson and Aschner, 2003). Measured  $\text{Mn}^{2+}$  in Lake Ziway ranges from 83.06 to 354.00  $\mu\text{g/l}$ , with an average value of 116.6  $\mu\text{g/l}$ . The effluent discharge from the floriculture plants (that eventually enters Lake Ziway) contained 50.60 to 818.00  $\mu\text{g/l}$  of  $\text{Mn}^{2+}$  with a mean value of 343.7  $\mu\text{g/l}$  (Table 4).  $\text{Mn}^{2+}$  in rivers varied from 7.1 to 146  $\mu\text{g/l}$  with a mean value of 80.4  $\mu\text{g/l}$ . All the studied sites in Lake Ziway are much higher than the allowable limit for water consumption (Table 4; Fig. 6). Relatively, the  $\text{Mn}^{2+}$  level is low in the major rivers. In contrast with other rift lakes, the average  $\text{Mn}^{2+}$  content of Lake Ziway (116.6  $\mu\text{g/l}$ ) is observed to be lower than that in Koka (422  $\mu\text{g/l}$ ; Masresha et al., 2011), and Abaya (127.6  $\mu\text{g/l}$ ; Masresha et al., 2011), but greater than that in lake Chamo (14  $\mu\text{g/l}$ ; Zinabu and Pearce, 2003) and Hawasa (18.1  $\mu\text{g/l}$ ; Masresha et al., 2011). The high  $\text{Mn}^{2+}$  content documented in the groundwater system of the lake region (Rango et al., 2009; Mechal et al., 2022) points out that the higher content of  $\text{Mn}^{2+}$  in the lake water might be associated with the combined effects of weathering of the rocks and the floriculture farm industries.

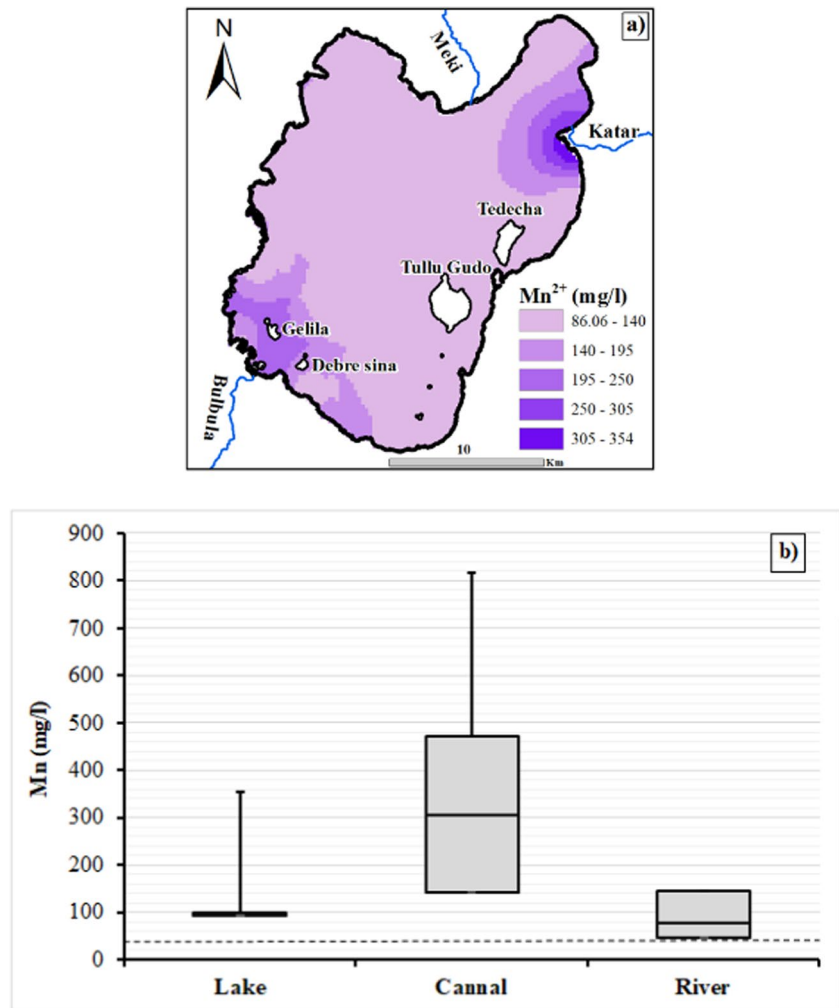
Nickel ( $\text{Ni}^{2+}$ ) content in the Lake Ziway water varied from 11.8 to 22.4  $\mu\text{g/l}$ , with an average value of 15.1  $\mu\text{g/l}$ . In the effluent canals, the  $\text{Ni}^{2+}$  content varies from 13.2 to 22  $\mu\text{g/l}$ , with an average value of

16.5  $\mu\text{g/l}$ . Very limited lake and effluent canal water samples surpassed the WHO (2011) prescribed limit (10  $\mu\text{g/l}$ ) for drinking purposes. On the contrary, in the major rivers, the  $\text{Ni}^{2+}$  is content quite below the allowable limit. Consumption of  $\text{Ni}^{2+}$  rich water can harm the lungs, stomach, and kidneys. Comparing with other rift lakes, we noted that the mean  $\text{Ni}^{2+}$  concentration in Lake Ziway is higher than that in the majority of the Ethiopian Rift lakes (Masresha et al., 2011; Zinabu and Pearce, 2003).

Lead ( $\text{Pb}^{2+}$ ) concentrations ranged between 2.8 and 19.5  $\mu\text{g/l}$ , with an average value of 5.3  $\mu\text{g/l}$ . The  $\text{Pb}^{2+}$  levels in the Lake Ziway water are typically very low, although anomalous concentrations higher than the WHO (2011) permissible value (10  $\mu\text{g/l}$ ) are detected in the north-west of Lake Ziway (Fig. 1). The analyzed  $\text{Pb}^{2+}$  content in lake Ziway is within the range of other lakes in the Ethiopian Rift as reported by Zinabu and Pearce (2003) and Masresha et al. (2011). Several authors have proven that regular overconsumption of  $\text{Pb}^{2+}$  can cause fatigue, anemia, hypertension, irritability, and damage of intellectual abilities (Jaishankar et al., 2014).

Arsenic ( $\text{As}^{2+}$ ) has been the focus of research in the groundwater chemistry of the lake watershed due to its toxic nature (Rango et al., 2009; Mechal et al., 2022). The pronounced  $\text{As}^{2+}$  content observed in the groundwater of the watershed is not reflected in the lake and its feeding rivers and is quite below the WHO (2011) permissible value (10  $\mu\text{g/l}$ ) for drinking use. However, the effluent canals originating from the floriculture industries convey contaminated water into the lake, characterized by a relatively higher  $\text{As}^{2+}$  content surpassing the allowable limit (Table 4).

**Fig. 6** Spatial variability of  $Mn^{2+}$  over the lake area (a) and Box plot showing the variability of  $Mn^{2+}$  in the lake, effluent cannels, and major rivers. The "permissible" value is represented by the broken line (WHO, 2011) (b)



In comparison with other lakes in the rest of the globe, we noticed that  $Mn^{2+}$ ,  $Ni^{2+}$ ,  $Pb^{2+}$ , and  $As^{2+}$  concentrations in Ziway Lake are lower than those detected in Lake Nakuru, but comparable with Lake Bogoria in Kenya (Jirsa et al., 2013). Sapanca Lake in Turkey had a relatively lower  $Mn^{2+}$  content than the current studied lakes, but  $Ni^{2+}$ ,  $Pb^{2+}$ , and  $As^{2+}$  in this lake were less than what we documented (Kükrer and Mutlu, 2019). For example, elevated HM content was detected in Lake Manchar in Pakistan (Kazi et al., 2009) and Lake Pulicat (Dhinamala et al., 2015) in India, suggesting that the lakes in Pakistan and India were greatly contaminated compared to Lake Ziway in Ethiopia. The potential health hazard associated with HMs,  $Mn^{2+}$ ,  $Ni^{2+}$ ,  $Pb^{2+}$ , and  $As^{2+}$  surpassing the allowable limit cannot be disregarded as the lake water is utilized for human and cattle consumption.

However, the continuous discharge of effluents from floriculture plants and its inflows might further concentrate these HMs and others sooner or later and will be a health issue for the community consuming it. Therefore, appropriate treatment mechanisms should be followed before discharging HMs contaminated water into the lake.

#### 4.6 Multivariate Statistical Analyses

##### 4.6.1 Multiple Correlation Coefficient Analysis

The correlation matrix of 20 parameters for lake water samples is presented in Table 5. Moderate to strong correlations between the parameters are marked in bold. Except for DO and  $NO_3$ , pH shows a low negative and positive association with other variables,



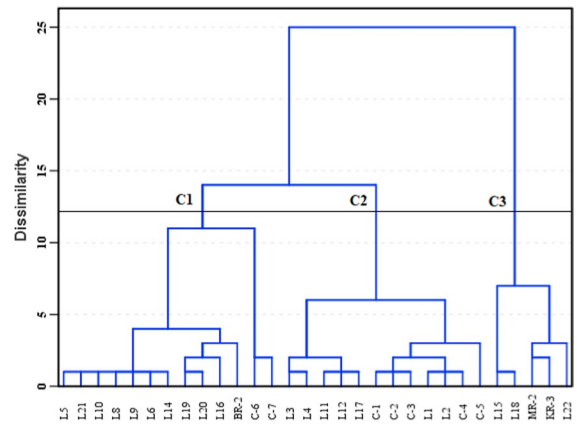
**Table 5** Pearson's correlation matrix between different water quality parameters analyzed

	pH	EC	TSS	TU	DO	COD	BOD	PO <sub>4</sub>	NO <sub>3</sub>	Ca	Mg	Na	K	HCO <sub>3</sub>	Cl	SO <sub>4</sub>	F	Mn	Ni	Pb	
pH	1.0																				
EC	0.1	1.0																			
TSS	-0.1	-0.1	1.0																		
TU	-0.3	-0.5	0.2	1.0																	
DO	<b>0.5</b>	0.0	-0.2	-0.4	1.0																
COD	-0.2	-0.5	0.2	<b>0.4</b>	-0.1	1.0															
BOD	-0.2	-0.5	0.2	<b>0.4</b>	-0.1	<b>1.0</b>	1.0														
PO <sub>4</sub>	-0.1	0.3	0.0	-0.1	0.0	0.0	0.0	1.0													
NO <sub>3</sub>	<b>0.4</b>	-0.1	0.1	0.0	0.3	0.0	0.0	<b>0.5</b>	1.0												
Ca	0.2	0.3	0.2	-0.2	-0.1	0.0	0.0	0.1	-0.1	1.0											
Mg	0.0	0.1	0.1	0.3	0.1	0.1	0.1	0.2	-0.3	<b>0.5</b>	1.0										
Na	0.1	<b>0.6</b>	0.1	-0.4	0.3	-0.2	-0.2	<b>0.8</b>	-0.1	0.3	0.3	1.0									
K	0.3	<b>0.6</b>	0.1	-0.6	<b>0.5</b>	-0.3	-0.3	0.3	0.1	<b>0.5</b>	0.3	<b>0.8</b>	1.0								
HCO <sub>3</sub>	0.1	<b>0.8</b>	0.1	-0.2	0.0	-0.2	-0.2	<b>0.4</b>	-0.2	<b>0.5</b>	<b>0.4</b>	<b>0.6</b>	<b>0.6</b>	1.0							
Cl	0.1	<b>0.6</b>	0.1	-0.4	<b>0.4</b>	-0.2	-0.2	<b>0.4</b>	-0.1	<b>0.4</b>	<b>0.5</b>	<b>0.9</b>	<b>0.8</b>	<b>0.6</b>	1.0						
SO <sub>4</sub>	0.1	<b>0.7</b>	0.1	-0.3	0.1	-0.3	-0.3	<b>0.6</b>	-0.1	<b>0.4</b>	0.3	<b>0.8</b>	<b>0.6</b>	<b>0.6</b>	<b>0.7</b>	1.0					
F	-0.1	<b>0.4</b>	0.1	-0.1	0.1	0.0	0.0	<b>0.9</b>	-0.2	0.1	0.3	<b>0.9</b>	<b>0.4</b>	<b>0.5</b>	<b>0.7</b>	<b>0.7</b>	1.0				
Mn	-0.3	0.1	0.2	-0.1	-0.2	0.1	0.1	-0.1	0.1	<b>0.4</b>	0.0	0.0	0.2	0.0	0.1	0.1	-0.1	1.0			
Ni	0.1	<b>0.4</b>	0.0	-0.5	0.3	-0.3	-0.3	<b>0.4</b>	-0.2	<b>0.4</b>	0.0	<b>0.5</b>	<b>0.5</b>	0.3	<b>0.5</b>	<b>0.5</b>	<b>0.4</b>	0.1	1.0		
Pb	-0.2	-0.1	0.0	-0.2	0.2	-0.1	-0.1	-0.1	-0.2	0.0	-0.1	-0.1	0.0	-0.1	0.0	-0.3	-0.2	-0.1	<b>0.5</b>	1.0	

signifying that pH has little to no effect on the lake water chemistry. There exists a moderate to strong dependency between EC and variables such as  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{HCO}_3^-$ ,  $\text{SO}_4^{2+}$ ,  $\text{Cl}^-$ , and  $\text{Mn}^{2+}$ . These associations suggest that these parameters contribute to the conductivity of water (Christian et al., 2014). Moderate to strong correlation was found between  $\text{HCO}_3^-$  with  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , and  $\text{Na}^+$ . This scale of association indicates that the lake water chemistry may have been the result of various processes, including water–rock interaction, making  $\text{HCO}_3^-$  a dominant ion.  $\text{Na}^+$  and  $\text{Cl}^-$  possess a very strong positive association (0.9) between each other, indicating that they are coming from the same source, evaporation enrichment (Kumar et al., 2009). Correlation analysis indicated a high correlation between COD and BOD. The exhibited strong correlation between BOD and COD is associated with the fact that they are closely linked with organic pollution, reflecting anthropogenic influence in the lake watershed (Vega et al., 1998). A good positive correlation exists between TU and COD, BOD, and TSS. In contrast, TU and TSS are negatively correlated with DO, indicating the negative effects of high TU and TSS in the lake water. There is also a good association between  $\text{NO}_3^-$  and  $\text{PO}_4^{3-}$  signifying that they are likely from the same source. This positive correlation indicated that there had been considerable applications of nitrogen and phosphorus fertilizers in the lake watershed, which enters the lake through river channels and flash floods in the adjacent area of the lake.

#### 4.6.2 Cluster Analysis

The CA was used to identify groups of water samples based on their spatial heterogeneity (similarity and dissimilarity) across the lake area and relate them to potential sources of pollution. The results of the CA of the 31 water samples from lake, major rivers, and effluent canals are shown in the dendrogram (Fig. 7). In the CA analysis, HMs detected with very low concentrations far below the drinking guidelines were excluded. The dendrogram is used to visually classify the data into clusters; more or fewer groups may be defined by shifting the phenon-line (Güler et al., 2002). The phenon-line that was selected in this instance across the dendrogram at a linkage distance of 12 resulted in three statistically significant CAs, a grouping that is nearly consistent with the findings of Tibebe et al.



**Fig. 7** Cluster Analysis of physico-chemical parameters in Lake Ziway based on water samples. The broken lines in dendrograms represent Phenon-lines

(2022). The water samples in CAs-1 and 2 are hydrochemically unique from the water samples in cluster 3, as shown by the linkage distance between clusters 1 and 2 being 12 and cluster 3 being 25, respectively.

CA-1 was characterized by (L9, L10, L11, L12, L16, L19, L20, L21, L23, C6, C7, and BR) samples and represented the central sector of the lake. This cluster water chemistry is mainly influenced by rock weathering and evaporation, with minimal urban development and growth in industrialization effects. In this category, samples C6 and C7 represent the biological lagoons inside the floriculture farms, which are constructed to reduce the amount of contaminants. It seems that the biological lagoons were found to reduce the amounts of contaminants having a similar hydrochemical signature with the central part of the lake. Bulbula River (BR) is also clustered with this group, as it is an outlet from the south part of the lake. CA-2 is represented by (C1, C2, C3, C4, C5, L1, L2, L3, L4, L5, L6, and L8) water samples and are obtained from the western part of the lake. This cluster is found to be strongly associated with the water samples collected in the effluent canals conveying polluted water from floriculture industries into the lake. This sector of the lake is characterized by different shoreline human activities such as floriculture industries, urban centers, vein yards, irrigation activities, and fish productions (Teklu et al., 2018; Merga et al., 2020; Fig. 1). Therefore, CA-2 indicates that the south-west part of the lake is heavily affected by the inflow of concentrated effluents from the domestic wastes, agricultural

practices, and floriculture industries, which directly enter and pollute the lake water. CA–3 is characterized by (MR, KR, L15, L18, and L22) samples and represents the northern sector of the lake. Lake water samples in CA–3 have been defined by low EC, but high TU, TSS, DO, BOD, COD,  $\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$ , and  $\text{Mn}^{2+}$ . As opposed to the findings of numerous scholars (e.g., Teklu et al., 2018; Merga et al., 2020; Tibebe et al., 2022), the northern part of the lake that corresponds to CA–3 represents the heavily polluted part of the lake. This is due to the combined effects of the heavy agrochemical and sediment loads generated from the agricultural fields and directly entering the lake through the major feeding rivers.

#### 4.6.3 Principal Component Analysis

To explore parameter relationships and origins, PCA was conducted for physico-chemical and organic matter load indicators in Lake Ziway water samples. PCA highlighted four PCs with eigenvalues >1 and explained 74.35% of the total variability in water quality parameters. The eigenvalues and their corresponding percentage variability are presented in Table 6.

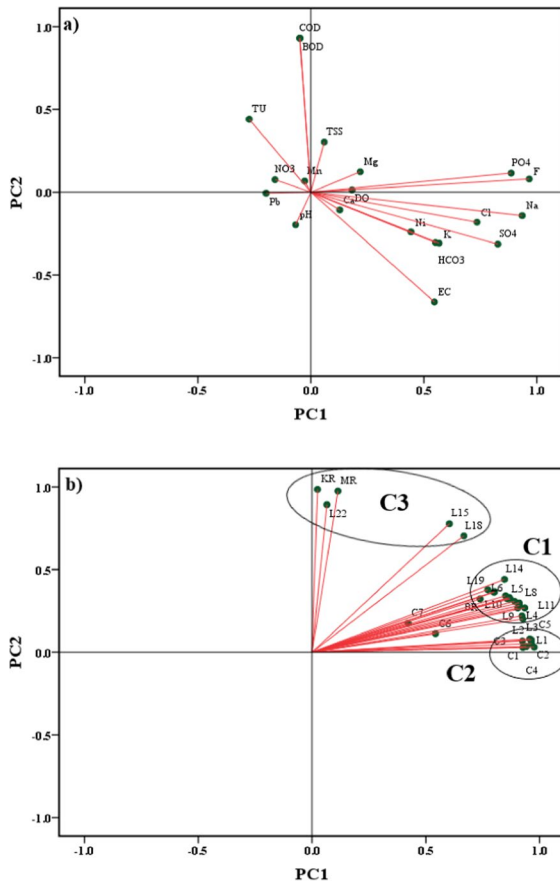
The first component (PC1) accounted for 41.54% of the total variance and possess strong positive loadings on EC,  $\text{PO}_4^{3-}\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{F}^-$  (Table 5; Fig. 8a). A preliminary water balance estimate shows that about 50% of the total inflow to the central Ethiopian Rift lakes is groundwater (Ayenew, 1998). Therefore, the majority of the PC1 parameters are geo-genic, mainly derived from the interaction of the groundwater with volcanic rocks and lacustrine sediments in the lake watershed. The strong associations ( $R^2 > 0.6$ ) found between the major elements in PC1 further reflect that the source of these parameters is similar and there is strong water–rock interaction before terminating in the lake. This PC corresponds to cluster 3 of the CA classification in the earlier observation, which represents the central part of the lake water samples (Fig. 8b). The second component, PC2, explains 14.3% of the total variance and is principally contributed by TU, COD, and BOD, whereas pH and DO have a negative loading to this PC. This PC can be explained by a combination of organic pollution and soil erosion in the lake watershed, which comes as a regular discharge of domestic wastewater together with sediments into the major streams that eventually enter the lake. In the

**Table 6** The factor loadings values and explained variance of the water quality parameters on the four prominent PCs (moderate to strong positive and negative loadings are marked bold)

Parameters	PC1	PC2	PC3	PC4
pH	0.19	<b>-0.51</b>	0.5	-0.10
EC	<b>0.76</b>	-0.16	-0.14	-0.36
TSS	0.02	0.40	0.38	-0.03
TU	-0.52	<b>0.53</b>	-0.06	-0.22
DO	0.32	<b>-0.50</b>	0.25	0.46
COD	-0.41	<b>0.67</b>	0.31	0.37
BOD	-0.41	<b>0.67</b>	0.31	0.37
$\text{PO}_4^-$	<b>0.63</b>	0.44	-0.36	0.15
$\text{NO}_3^-$	-0.16	-0.34	<b>0.52</b>	-0.12
$\text{Ca}^{2+}$	0.47	0.15	<b>0.55</b>	-0.03
$\text{Mg}^{2+}$	0.38	0.43	0.29	-0.05
$\text{Na}^+$	<b>0.92</b>	0.18	-0.09	0.07
$\text{K}^+$	<b>0.86</b>	-0.19	0.36	0.10
$\text{HCO}_3^-$	<b>0.74</b>	0.19	0.06	-0.19
$\text{Cl}^-$	<b>0.89</b>	0.10	0.12	0.11
$\text{SO}_4^{2-}$	<b>0.86</b>	0.19	-0.06	-0.25
$\text{F}^-$	<b>0.73</b>	0.45	-0.30	0.09
$\text{Mn}^{2+}$	0.07	0.18	<b>0.52</b>	0.00
$\text{Ni}^{2+}$	0.49	-0.20	-0.10	<b>0.63</b>
$\text{Pb}^{2+}$	-0.03	-0.28	-0.22	<b>0.73</b>
% of variance	<b>41.54</b>	<b>14.30</b>	<b>9.72</b>	<b>8.79</b>
Cumulative %	<b>41.54</b>	<b>55.84</b>	<b>65.56</b>	<b>74.35</b>

lake watershed, it is a common practice to discharge domestic wastes into open landscape and nearby streams without proper treatment. Aggressive LULC change, mainly the conversion of various LULC types into agricultural land, is prompting soil erosion and increasing the sediment loads of the major rivers that eventually enter the lake (Aga et al., 2019). The negative loading of DO and pH can be interpreted by the fact that a high content of organic matter consumes the available DO in a water body. According to Vega et al. (1998), domestic wastewater mostly consists of organic matter (lipids, carbohydrates, and proteins), which undergoes aerobic decomposition when DO levels fall, releasing organic acids and ammonia and resulting in a low pH of the water body.

The third PC explains 9.72% of the total variance and is moderately loaded by  $\text{NO}_3^-$ ,  $\text{Ca}^{2+}$ , and  $\text{Mn}^{2+}$ , which can be deciphered as nutrient pollution as well as mineral dissolution in the water body. The presence of nutrients ( $\text{NO}_3^-$ ) in PC3 showed the influence of agricultural activities with the aid of fertilizers and

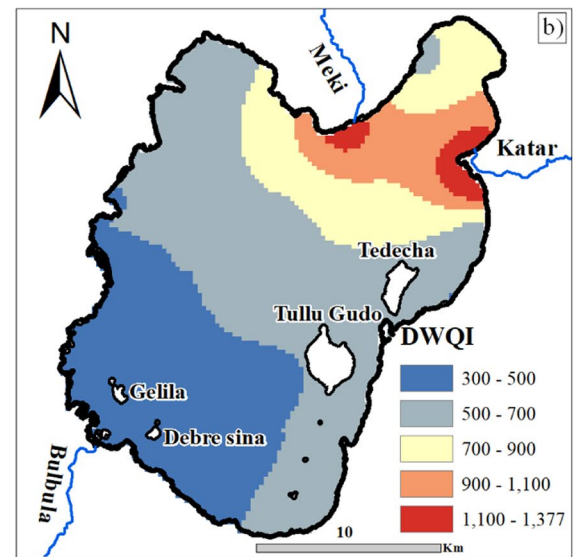
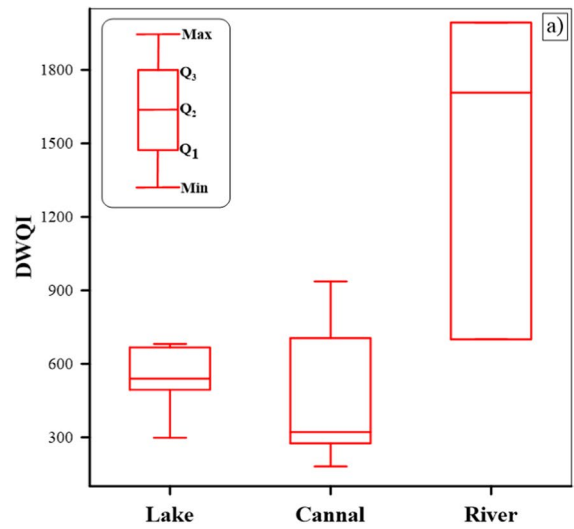


**Fig. 8** Scatter plot displaying the association between the measured water quality parameters (a) and distribution of water samples on the space created by the scores of the first two PCs (b)

pesticides in the environment of the lake ecosystem (Meshesha et al., 2012). On the other hand,  $Ca^{2+}$  and  $Mn^{2+}$  might be contributed by the weathering of volcanic rocks. The fourth PC explains 8.79% of the variance and is greatly contributed by  $Ni^{2+}$  and  $Pb^{2+}$ , which can be explained as the HM pollution of the lake water resulting from point pollution from floriculture industries and domestic wastewater. From the correlation table (Table 5), it is clear that these HMs are well associated with each other.

4.6.4 Drinking Water Quality Index

Drinking WQI is one of the most effective approaches for informing concerned citizens and policy-makers about the quality of water bodies by condensing



**Fig. 9** Spatial variation of WQI Class II

Class III

of lake Ziway water (a) and the summarized results of drinking WQI for Lake Ziway, effluent canals, and major rivers (b)

bulk information into a simple form (Harkins, 1974; Tyagi et al., 2013). The calculated drinking WQI value for the lake water samples varied from 298.33 to 1377, major feeding rivers ranged from 703.34 to 1980.79, and effluent canals ranged from 330.24 to 934.74 (Fig. 9a). According to Brown et al. (1972) classification, the WQI analysis results of this research work suggest that the lake and major rivers waters are very poor in quality and are not appropriate for human consumption. With

this magnitude of WQI, the lake water is also unfit for recreational purposes and aquatic life (Lencha et al., 2021). Though both sources are unsuitable for human consumption, the river water displays substantially high drinking WQI. On the other hand, for drinking reasons, the quality of the effluent canal water samples falls into two categories: good (42.9% of the samples) and poor (57.1% of the samples).

Figure 8 illustrates the spatial variability of the computed WQI of the water sample values in the entire stretch of Lake Ziway. On the spatial map, it is evident that the WQI values, which ranged from 298.33 to 1377, declined from north to south across the lake area (Fig. 9b). The systematic drop in WQI in the north–south direction is associated with the most influencing parameters, such as TU, DO, BOD, COD,  $K^+$ ,  $HCO_3^-$ , and  $Mn^{2+}$  (Fig. 9b). These parameters have reached a critical value and could have significantly contributed to the poor quality of the lake water. Though the lake water is unfit for human use in the entire stretch, an extremely high WQI value is detected at the inlet area of the Meki and Katar rivers (Fig. 9b). The elevated WQI values close to the entrance of the Meki and Katar rivers indicate that the primary source of Lake Ziway was brought on by the influx of the two rivers. Before terminating into the lake, these rivers flow mainly through agricultural fields and urban centers, transporting agrochemical effluents along with sediments (Desta et al., 2017; Tibebe et al., 2022; Kalsido and Berhanu, 2020) and significantly contributing to the high drinking WQI. The recent agricultural transformation and growing population in the watershed are expected to aggravate soil erosion and the discharge of agrochemicals, which could escalate the deterioration of the lake water. It is obvious that shoreline activity is affecting the lake water quality; however, the upper lake watershed activities have a greater influence than the lakeshore activities, as manifested by relatively lower WQI values towards the floricultural industrial sites. Recent studies (e.g., Teshome, 2020; Zemedet et al., 2021; Lencha et al., 2021) conducted in Lake Hawassa (southern main Ethiopian Rift) obtained comparable WQI values, suggesting that the water quality of the lake and feeding rivers was unfit for different uses. The result of the WQI analysis pointed out that human-induced activities such as soil erosion, urban runoff, effluent discharge from industrial facilities, excessive application of nutrients in agricultural

lands, and others have become more intense in the past few decades. Therefore, government agencies and other stakeholders should devise and implement proper protection and conservation mechanisms to restore and maintain the water quality in order to deliver the most essential ecosystem services.

## 5 Conclusion

In the current investigation, multivariate statistical and WQI approaches were used to provide information concerning the spatial variability of Lake Ziway water quality in the Ethiopian Rift. A comprehensive water sampling from lake, rivers, and effluent discharges was collected and assessed for physical, biological, major, and trace elements. The measured water quality parameters showed a non-uniform distribution within the lake area. Several water quality parameters (EC, DO, BOD, COD, TU,  $Na^+$ ,  $K^+$ ,  $HCO_3^-$ ,  $NO_3^-$ ,  $PO_4^{3-}$ ,  $F^-$ ,  $As^{2+}$ ,  $Ni^{2+}$ ,  $Mn^{2+}$ , and  $Pb^{+2}$ ) of the lake, rivers, and effluents from canals are well above the allowable limit (WHO, 2011) for drinking purposes, rendering Lake Ziway water unsuitable for human consumption and aquatic life. The higher level of the parameters is attributed to the combined effects of natural processes and anthropogenic factors in the lake watershed.

The CA detected three distinct clusters based on the spatial similarity/dissimilarity of the water samples. The first CA is relatively less polluted and is associated with the central part of the lake. The central lake water chemistry is mainly influenced by water rock-interaction and evaporation enrichment, with little urbanization and industrialization effects. CA–2 represents the southern part of the lake and corresponds to a moderately polluted lake area due to the presence of the floriculture industries, urbanization, and small-scale agricultural activities that release untreated effluents into the lake, while CA–3 belongs to the northern sector of the lake. This cluster represents the heavily polluted zone due to the sediments and agrochemical loads resulting from the runoff from surface water and releases from agricultural activity in the watershed entering the lake through the major rivers. PCA analysis identified the effect of both geo-genic and anthropogenic influences on the water quality. In addition, PCA identified human-induced activities such as soil erosion

and discharges from agricultural activities and floriculture industries as the key sources of pollution.

The overall lake water quality for drinking purposes, drinking WQI values, shows spatial variation in the lake area varying from 300 to 1370 with an average of 587.17. The drinking WQI suggests that the overall lake water quality is inappropriate for direct human intake. The low lake water quality is associated with an increase in TU, EC, pH, DO, BOD, COD, Na<sup>+</sup>, K<sup>+</sup>, HCO<sub>3</sub><sup>-</sup>, and F<sup>-</sup> paired with the existence of some hazardous HMs such as Mn<sup>2+</sup>, Ni<sup>2+</sup>, and Pb<sup>2+</sup>. The extremely high WQI value in the northern sector of the lake is related with the combined influence of sediment and agrochemical loads entering the lake through the major feeding rivers. This indicates that the primary causes of Lake Ziway water quality degradation might originate from activities upstream of the lake watershed, in addition to the widely known domestic waste, effluents from the floriculture sector, and small- and large-scale agricultural practices adjacent to the lake. The multivariate and WQI analyses identified that water quality was relatively better in the center, which is less disturbed by human activities. However, the northern and western areas where the major streams drain into the lake and in the vicinity of major towns, respectively, were strongly affected. Therefore, the management of soil erosion and excessive utilization of agrochemicals in the lake watershed should receive top priority to prevent further deterioration of the lake water quality and to eventually restore the lake useful use. No effluents from floriculture industries, irrigation fields, or urban areas adjacent to the lake should be disposed of before receiving appropriate treatment. A regulatory body should be set up to implement and control the appropriate environmental regulatory protocols in order to ensure the safety of the lake.

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**Data Availability** The data that support the findings of this research are available from the corresponding author, upon request.

**Declarations**

**Competing Interests** The authors declare no competing interests.

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