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Using Two Water Quality Indices for Evaluating the Health and Management of a Tropical Lake †

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† This article belongs to the Topic Climate Change and Human Impact on Freshwater Water Resources: Rivers and Lakes.

Abstract: With increasing pressure on freshwater resources in developing countries due to population growth, further research and potential interventions are crucial. Lake Tana, located in the headwaters of the Blue Nile, serves as a critical example of these precious freshwater resources. This study evaluated the water quality of Lake Tana for both ecological health and drinking purposes using the Arithmetic Weighted Water Quality Index (AW WQI) and the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI). Samples were collected from 20 lake sampling stations four times between July 2018 and June 2019 to calculate the two water quality indices using ten measured parameters. The average annual AW WQI ranged from good to very poor for ecological health and very poor to unsuitable for drinking water. The CCME WQI categorized Lake Tana's water quality as poor to fair for both uses. According to the water quality indices, the water quality was most impacted by turbidity, dissolved oxygen, ammonium, and phosphorus. However, except for ammonium, these factors were immaterial for lake management because the lake was nitrogen-limited, and the turbidity resulted from sediment stirred up by waves from the lake bottom, which cannot be managed easily. Dissolved oxygen is related to turbidity. Moreover, the WQIs did not identify two pesticides in the lake that negatively affected the fish. Thus, WQI indices may document water quality changes over time. Therefore, in addition to a favorable economic and political climate, improving lake water management requires insights from experts, the scientific literature, and possibly additional monitoring in addition to what is provided by the WQIS.

Keywords: water quality index; aquatic life; ecological health; Lake Tana; Ethiopia

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Citation: Nerae, M.D.; Zimale, F.A.; Steenhuis, T.S.; Kebedew, M.G. Using Two Water Quality Indices for Evaluating the Health and Management of a Tropical Lake. *Hydrology* **2024**, *11*, 212. https://doi.org/10.3390/hydrology11120212

Academic Editor: Roohollah Noori

Received: 12 October 2024
Revised: 2 December 2024
Accepted: 2 December 2024
Published: 8 December 2024

1. Introduction

Lakes are vital sources of freshwater for both human life and natural systems [1,2]. In Europe and North America, robust environmental regulations have improved lake water quality over the past 50 years [3,4]. However, in developing countries, water quality has declined due to increased nutrient runoff from urban populations, agricultural practices, and a lack of enforcement of environmental laws [5,6]. Lake water quality depends on various physical, chemical, and biological parameters, with single parameters being insufficient to assess overall quality [7–9].

For this reason, composite water quality indices (WQIs) have been developed to combine individual parameter measurements into a single value to aid in reporting and interpreting water quality [5,10–14]. However, they have limitations related to data aggregation and subjective parameter weighting, and there is no universally accepted index worldwide [13,15,16].

Research on water quality indices (WQIs) has grown exponentially, with around 1300 publications annually from 2020 to 2022, primarily from China, India, and the USA, with few contributions from African countries [17]. A search in the Science Citation Index revealed only 13 publications related to the keywords "WQI", "Africa", and "Lake". In Ethiopia, the WQI indicated that Lake Hawassa was unsuitable for drinking, aquatic life, and recreational purposes [18]. Also, in Lake Basaka, the water quality was poor [19]. Water quality assessments in these publications are often based on the Arithmetic Weighted WQI (AW WQI) and the Canadian Council of Ministers of the Environment WQI (CCME WQI), both of which were developed in countries with robust environmental regulations [7,17,20,21]. The CCME WQI is adaptable to local conditions and has been used globally, including in China [22–24], India [25,26], Turkey [27], Iran [28], Namibia [29], and Ethiopia, [30–32] for various purposes like irrigation, drinking water, and ecological health.

Because of the relative scarcity of WQI applications in Africa, the current study focuses on Lake Tana, Ethiopia's largest freshwater lake, covering 3050 km^2. Densely populated areas with intensive agriculture surround it. It plays a crucial role in the country's socioeconomic development and the health of the Abay (Blue Nile) [33]. Once pristine in the 1930s [34], the lake has since degraded, with a decrease in fish catches [35] and the appearance of water hyacinths in 2011 [36].

Previous research in Lake Tana focused on dissolved phosphorus [37–40], water quality assessment using Landsat 7 ETM+ Images [38] and MODIS images [41], lake water balance [42–44], bottom sediment characteristics [39], fish composition [45,46], suspended solids [47], geomorphology of the Lake Tana basin [48], eutrophication status [49,50], water hyacinth infestation [36], and sediment inflow into the lake [51–53]. Another study found a relatively high concentration of strongly adsorbed chlorpyrifos and endosulfan pesticides [54], which the World Health Organization bans because they were identified as a serious threat to fish and those eating them [54].

In a previous paper [50], we utilized PCA and a Factor Analysis to explore the factors affecting water quality degradation. Despite this and earlier research efforts, comprehensive assessments of lake-wide water quality and pollution status are still lacking. Therefore, this study aims to evaluate the water quality of Lake Tana for ecological health and drinking water through two water quality indices, assessing their effectiveness in recommending practices to enhance the lake water quality. We employed the Arithmetic Weighted and Canadian Council of Ministers of the Environment Water Quality Indices for this assessment. This study will help state and federal agencies in Ethiopia decide on the minimum information required for making sound management decisions to improve lake water quality in Lake Tana and many other lakes in Ethiopia. Globally, the results will aid in deciding the utility of WQIs.

2. Materials and Methods

2.1. Lake Tana and Its Watershed

The 3050 km^2 Lake Tana is the largest lake in Ethiopia [39,45]. It is situated in the northwestern highlands of Ethiopia at an elevation of 1786 m a.s.l. (Figure 1). It has an average depth of 9.7 m, with a maximum depth of 15 m during rainy seasons [39]. The water level is usually the highest in September and decreases around 3 m, with the lowest in May. Because of its shallow depth, the lake is well mixed. Wave action suspends the bottom sediment. Lake circulation is complex and is described later, together with the observed sediment and nutrient concentrations.

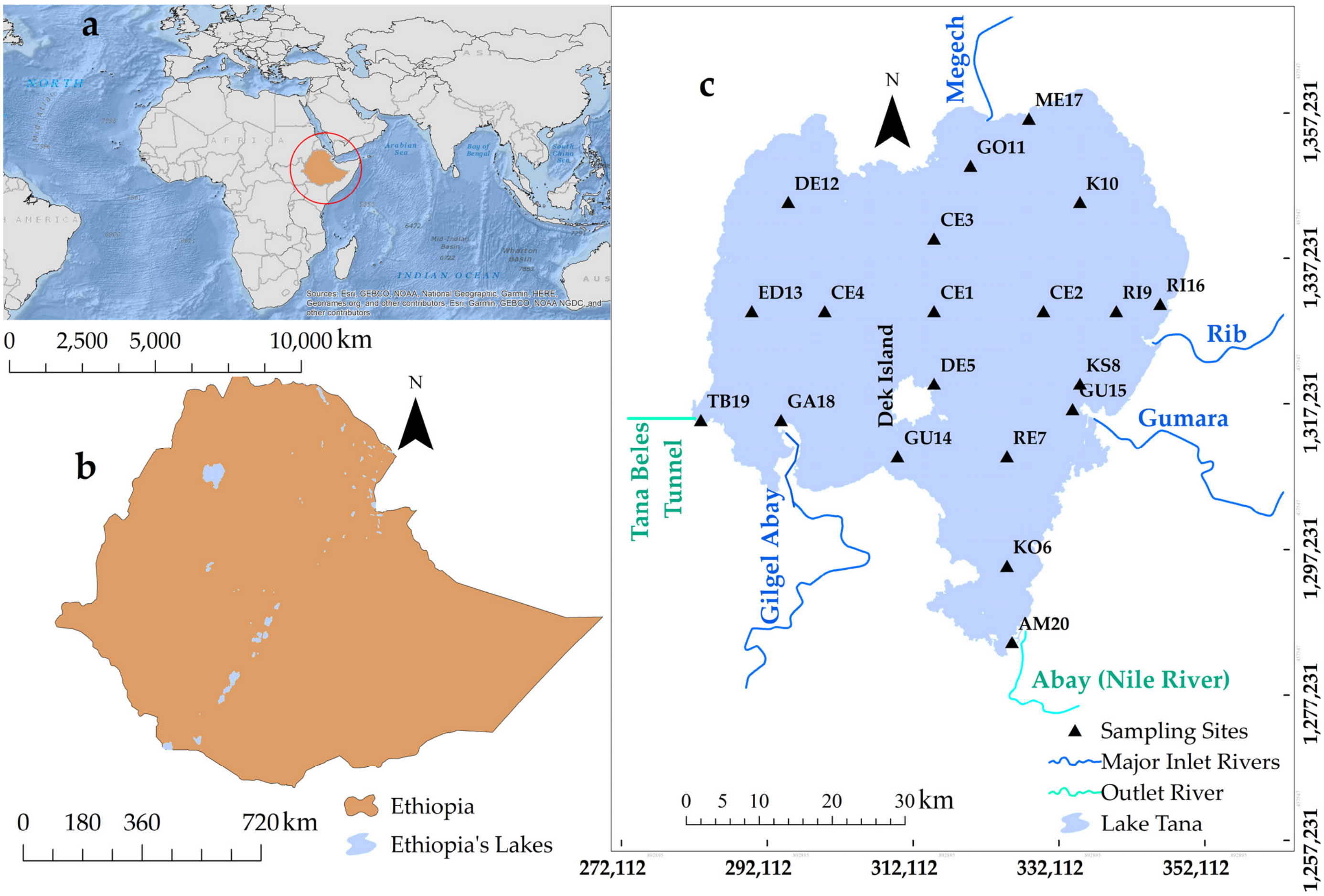

Figure 1. Maps of the study area: (**a**) Ethiopia in Africa, (**b**) a map of Ethiopia and its lakes, (**c**) the location of sampling sites in Lake Tana and the major contributing rivers. Coordinates of sampling sites are given in Table S1 in the Supplementary Materials.

Rainfall decreases to the north, with average dry-phase rain at 117 mm and rain-phase precipitation at 1400 mm. The mean annual temperature is 23 °C at the lowest elevations, ranging from 15 °C to 20 °C at higher altitudes [55]. More than 40 small intermittent streams and four major perennial rivers join Lake Tana (Figure 1) [43]. Intermittent rivers contribute 10% of the total discharge to the lake [44]. They start flowing at the beginning of the rain phase and two to three months after the rains have ended. The Gilgel Abay is the largest river entering the lake from the southwest of the four main rivers. The Gumara and the Rib Rivers, which together are nearly the same size as Gilgel Abay, enter the lake from the east. In the north, the Megech River, which is the smallest of the four rivers, flows into the lake [43]. According to Mammo et al. [56], there is no significant inflow to the lake, but there is an outflow or leakage of around 1000 hm^3/year through a fault in the south of the lake that may recharge the deep aquifers [42,56]. During the rain phase, large flood plains are inundated at the entrance of the four large rivers [48,57]. The lake provides various ecological benefits, such as transportation, hydropower generation, irrigation, fishing, and ecotourism [34].

The lake is home to more than 25 fish species, and 70% can only be found there [45]. Unfortunately, the fish population is declining [58]. Hippos also reside in the lake, along with various species of birds, including pelicans, colorful songbirds, and the majestic African fish eagle. Lake Tana has islands harboring ancient monasteries [45]. These monasteries serve as a refuge for wildlife. The lake also provides a livelihood for the over 30,000 people living on the islands, serving as their primary source of drinking water [59].

The lake serves as a natural reservoir for three hydropower plants [60]. Since 1995, the Chara Chara Weir has managed the lake level to regulate water flow in the Blue Nile. The Tis Abay I and II hydropower plants are located near the Blue Nile Falls, about 30 km south of the lake. Additionally, the Tana Beles plant, operational in 2010, generates 460 kW and is situated west of the lake. It receives water through a 26 km tunnel that leads to the Beles River.

The Lake Tana basin (including the lake) is 15,100 km^2. Slopes range from 0% to 39%, with elevations between 1785 m and 4094 m, averaging 2418 m. The main land use is cropland on the hillsides; grazing land can be found in the periodically saturated valley bottoms, and shrubs are on the poorest soils. Crops grown are mainly maize and teff. Eucalyptus acreage has expanded in the last 20 years. Gondar in the north and Bahir Dar in the south are the main cities in the Lake Tana basin.

2.2. Water Sampling and Data Collection

Twenty sampling sites were identified by considering vicinity and access, anthropogenic activity, and agricultural runoff entering the lake (Figure 1). Water samples were collected from the 20 monitoring stations from July 2018 to June 2019 during the rain phase, post-rainy phase, dry phase, and pre-rainy phase. Samples were collected using acid-washed polyethylene bottles. Turbidity, water temperature, electric conductivity, total dissolved solids (TDSs), pH, nitrate, phosphate, ammonium, a Secchi disk, and dissolved oxygen were determined for each sampling location. Sixteen hundred data entries from 160 water samples were obtained and summarized into 200 average water quality data points (see Supplementary Materials Table S2). Since the lake is shallow and well mixed [39], depth measurements were unnecessary [61].

To assess the ecological health and drinking water quality of Lake Tana [62], the following parameters were determined for each water sample: temperature, electric conductivity (EC), turbidity, pH, total dissolved solids (TDSs), Secchi-disk depth/light transparency (SD), dissolved oxygen (DO), phosphate, nitrate, and ammonium. The physical parameters were measured using the multi-Maji parameter (field kit instrument) by dipping the probe 40 cm below the water surface. The pH, electric conductivity, TDS, and DO were also measured using an Aqua probe-7000 directly in the field campaigns. Samples collected for analyzing nutrients (nitrate, phosphate, and ammonium) and turbidity were put immediately in cold storage and transported to the Bahir Dar Institute Technology Water Quality and Hydrology Laboratory. Turbidity was measured using the Nephelometric Turbidity Unit (model 2100A). Nitrate, phosphate, and ammonium were analyzed using the Palintest Automatic Wavelength instrument (Phot.63). All the water quality analyses were conducted according to the [63] standard procedures.

2.3. Water Quality Indices (WQIs)

Two WQI methods, namely the Arithmetic Weighted Water Quality Index (AW WQI) and the Canadian Council of Ministries of the Environment Water Quality Index (CCME WQI), were employed to assess the quality of both the ecological health and drinking water in Lake Tana. The AW WQI method, a modified form of Horton's formula, was chosen because it is the most common analytical method for describing and assessing general water quality (Patel et al. [64]). The CCME WQI, developed by the CCME in 2001 for Canadian waters, is widely used in Canada and internationally. Developing countries have accepted using the CCME as a WQI for surface and groundwater quality monitoring and assessment [27].

For the evaluation of drinking water quality, eight out of the ten measured water quality parameters were considered: turbidity, temperature, electric conductivity, total dissolved solids (TDSs), pH, nitrate, phosphate, and ammonium. Parameters such as dissolved oxygen and Secchi depth were excluded from the calculation since they do not directly impact drinking water quality, according to the World Health Organization [64].

All ten parameters, including dissolved oxygen and Secchi depth, were considered for assessing ecological health.

2.3.1. Arithmetic Weighted Water Quality Index (AW WQI)

The AW WQI method assesses water quality according to its level of purity. In the initial step, the value of each parameter is normalized by subtracting the value associated with clean water and dividing it by the permissible level available [64,65]. Subsequently, the weight for each parameter is determined based on its allowable limits. The AW WQI is calculated as the ratio of the sum of all normalized values to the sum of all weights.

$$WQI = \frac{\sum_{i=1}^{n} Q_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

where the quality rating (Q_i) of the water quality indicator is defined as

$$Q_i = 100\frac{V_{actual,i} - V_{ideal,i}}{V_{standard,i} - V_{ideal,i}} \tag{2}$$

where W_i is unit weight; $V_{actual,i}$ is the concentration of the i^{th} indicator in the examined water, $V_{ideal,i}$ is the ideal value of the indicator in clear water and $V_{standard,i}$ is the recommended standard of the i^{th} parameter for ecological health and drinking requirements [64,65]. The unit weight (W_i) is determined as

$$W_i = \frac{K}{X_i} \tag{3}$$

where

$$K = \frac{1}{\sum_{i=1}^{n}\left(\frac{1}{X_i}\right)} \tag{4}$$

where X_i is the standard of the limited value for the i^{th} parameter, and K is the proportionality constant. According to Petal et al. [64], a water body with a score of 0 indicates the highest quality, while a score of 100 reflects very poor quality. Water with a score exceeding 100 is considered highly polluted or unsuitable (Table 1).

Table 1. The classification of the scores of the water quality indices [64,66]. AW WQI is the Arithmetic Weighted Water Quality Index, and CCME WQI is the Canadian Council of Ministries of the Environment Water Quality Index.

Rating	AW WQI Score	CCME WQI Score	Description
Excellent	0–25	95–100	Water quality is at pristine levels.
Very good	-	89–94	Water quality is very close to pristine levels.
Good	26–50	80–88	Water quality rarely departs from desirable levels.
Fair	-	65–79	Water quality sometimes departs from desirable levels.
Marginal	-	45–64	Water quality often departs from desirable levels.
Poor	51–75	0–44	Water quality usually departs from desirable levels.
Very poor	76–100	-	Water quality is nearly unsuitable.
Unsuitable	>100	-	Highly polluted.

2.3.2. The Calculation of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI)

In CCME WQI, three factors are assimilated scientifically from designated water quality goals [28]. These are scope (*F*1), frequency (*F*2), and amplitude (*F*3). They provide an arithmetic range of CCME WQI water quality status classified in five descriptive classes between 0 (poor) and 100 (excellent), as labeled in Table 1 [27,66].

The CCME WQI is defined as

$$CCME\ WQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{173.2} \quad (5)$$

F_1 (scope) denotes the number of water quality parameters that failed the standard:

$$F_1 = \left(\frac{number\ of\ failed\ variables}{total\ number\ of\ variables}\right) \times\ 100 \quad (6)$$

F_2 (frequency) represents the percentage of each test that does not meet the guideline values ("failed tests"):

$$F_2 = \left(\frac{number\ of\ failed\ tests}{total\ number\ of\ tests}\right) \times\ 100 \quad (7)$$

F_3 (amplitude) represents the extent to which failed test values do not agree with their standards.

$$F_3 = \left(\frac{nse}{0.01nse + 0.01}\right) \quad (8)$$

where *nse* is the normalized sum of excursion. Excursion is the number of times a single observation exceeds (or falls below when the objective is a minimum) the objective value [66]. The amplitude (F_3) is calculated in three steps as follows:

$$normalized\ sum\ of\ excursions\ (nse) = \frac{\sum_{i=1}^{n} excursion_i}{total\ number\ of\ tests} \quad (9)$$

where the value of the test (measured result) must not be greater than the objective or acceptable limit:

$$excursion_i = \frac{failed\ test\ value_i}{objective_i} - 1 \quad (10)$$

when the measured result must be less than the objective (acceptable limit):

$$excursion_i = \frac{objective_i}{failed\ test\ value_i} - 1 \quad (11)$$

2.4. Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the impact of various variables included in calculating the indices. Rickwood and Carr [67] introduced the method in 2009. The sensitivity analysis involves removing each variable from the index calculation one at a time from either the AW WQI or the CCME WQI and comparing the resulting indices to the original index with all measured variables to ascertain if removing any single variable significantly impacted the index [68].

2.5. Statistical Analysis

The maximum, minimum, mean, and standard deviation WQIs were calculated in Microsoft Excel 2019 and are shown in the Supplementary Materials. In addition, the spatial and temporal distributions of WQIs in maps were created using the Kriging Interpolation GIS extension tool in ArcMap 10.5.

3. Results

3.1. Water Quality Indicators

Ten water quality indicators were sampled four times from August 2018 to April 2019 at 20 monitoring stations. Figure 2 and Table S2 in the Supplementary Materials present the averaged data from the four sample runs. Turbidity varied across space and time, ranging from 11.5 to 273 NTU. The average values ranged from 22 at station DE5, very close to the largest island, to 232 NTU close to the entrance of Rib River (RI16). Major river entry points (Rib, Gumara, Megech, and Gilgel Abay) exhibited significant turbidity concentrations, often exceeding 50 NTU (Figure 2a). The highest turbidity occurred during the rainy phase, while turbidity was lowest after the rainy phase. The temperature fluctuated between 18 °C in the rainy phase and 29.5 °C in the dry phase (Figure 2b). The minimum temperature of 18 °C was recorded at station S10 in August 2018, and a maximum of 30 °C was observed at station S17 in February 2019. Electrical conductivity (EC) varied from 101 to 169 µS/cm (Figure 2d), and total dissolved solids (TDSs) from 67 to 109 mg/L (Figure 2c). Both EC and TDS were lower during the rainy phase than the dry phase.

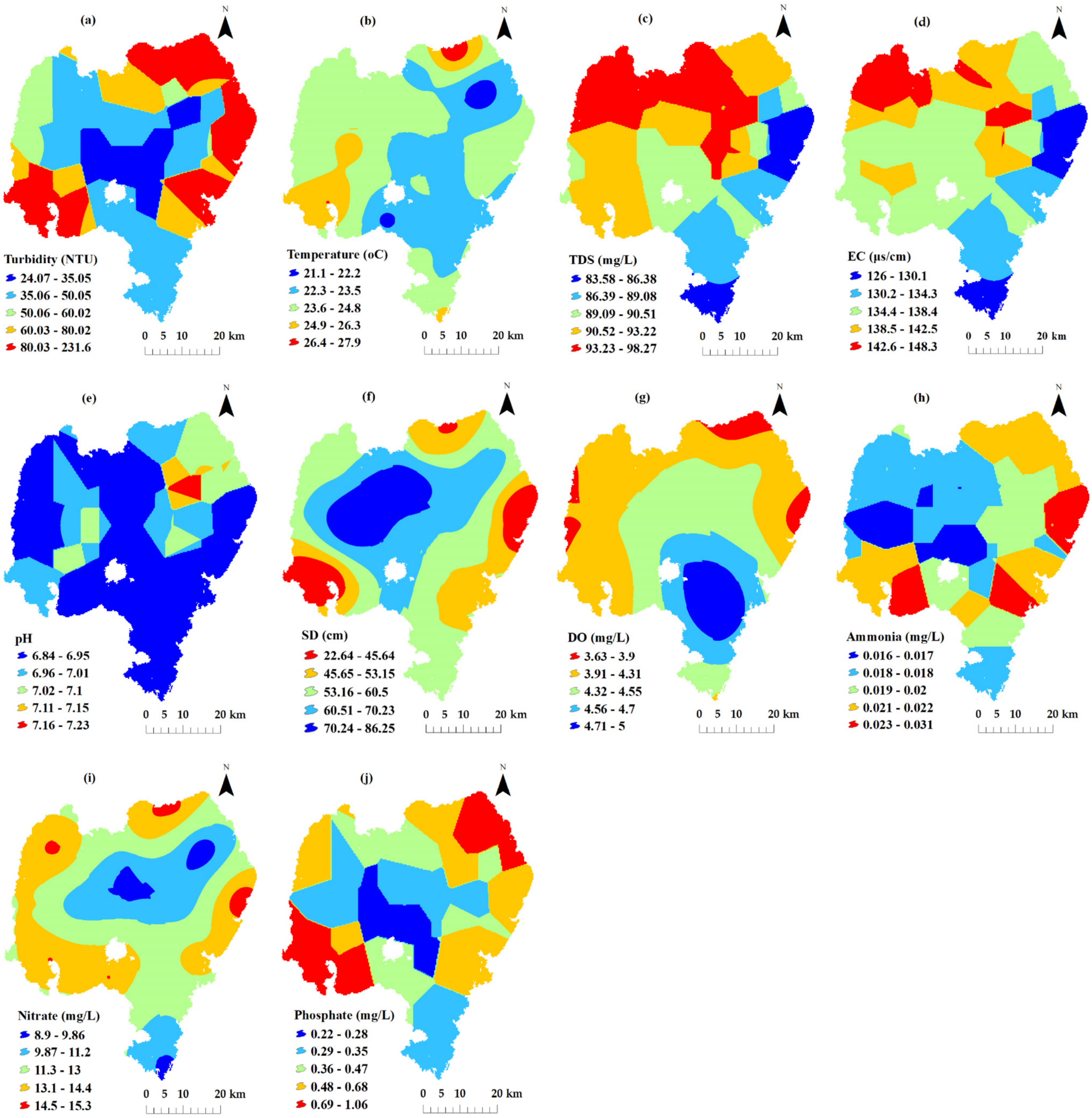

Figure 2. Spatial distribution maps of averaged water quality parameters in Lake Tana between June 2018 and 2019: (**a**) turbidity (NTU); (**b**) temperature (°C); (**c**) total dissolved solids, TDSs (mg/L); (**d**) EC (µs/cm); (**e**) pH; (**f**) Secchi-disk depth, SD (cm); (**g**) DO (mg/L); (**h**) ammonium (mg/L); (**i**) nitrate (mg/L); and (**j**) phosphate (mg/L).

The pH values varied throughout the year, with annual averages between 6.8 and 7.2 (Figure 2e). The lowest pH (acidic tendency) occurred at station S15 in August 2018, while the highest (alkaline tendency) was measured at station S19 in April 2019 (pre-rainy phase). Spatially, higher pH levels were observed in the northeastern part of the lake (stations S10 and S17) near the entrance of the Megech River (Figure 2e). Secchi depths (SDs) varied between 15 and 107 cm, with an overall average of 69 cm (Figure 2f). The minimum (15 cm) was observed during the rainy phase, and the maximum (107 cm) was observed before the rainy phase (Figure 2f). Dissolved oxygen (DO) levels ranged from 3.1 to 5.9 mg/L (Figure 2g and Table S2 in the Supplementary Materials). The average DO ranges from 3.5 to 4.9 mg/L, with an overall average of 4.3 mg/L.

Lake Tana shows ammonium concentrations ranging from 0.006 to 0.07 mg/L, with an average of 0.02 mg/L. The western side measures 0.014 mg/L, while the southwestern part measures 0.033 mg/L (Figure 2h and Table S2 in the Supplementary Materials). Notably, ammonium concentrations in the eastern and southern regions of the lake were maximum. The nitrate levels ranged from 7 mg/L to 18 mg/L and nitrate N had average values between 9 mg/L and 15 mg/L. Nitrate concentrations were higher in the western (S18 and S19), eastern (S15 and S16), and northern (S11, S12, and S17) regions compared to open water and southern (outflow) areas, as illustrated in Figure 2i. Seasonally, nitrate levels tend to increase from dry to rainy phases. Lake phosphate concentrations (Figure 2j) varied across the lake, ranging from 0.03 mg/L to 0.61 mg/L. The average phosphate levels differed by monsoon phase: 0.58 mg/L (during the rainy phase), 0.51 mg/L (after the rainy phase), 0.45 mg/L (during the dry phase), and 0.50 mg/L (before the rainy phase at the end of the dry phase). The phosphate concentrations in the lake near the outlets of the Gumara in the east and Gilgel Abay in the southwest of the lake exhibited the greatest phosphate concentrations.

3.2. Water Quality Indices

3.2.1. Lake Water Quality Indices

The AW WQI values for ecological health, shown in Table 1, vary from a low value of 33 (indicating good quality)—to a high value of 111 (indicating unsuitable for aquatic life). The aerial weighted mean of the lake ecological health of the four monsoon phases was within one standard deviation. It was slightly better in the post-rainy phase and marginally less in the dry phase. Drinking water WQIs were between 36 (good) and 416 (unsuitable). The drinking water quality in the rainy phase was less poor than during the other three phases.

A lower score indicates poorer water conditions for the CCME WQI in Table 2. Values ranged from a low of 37 for drinking water (poor quality) to a high of 83 for ecological health (good). The average calculated ecological health for Lake Tana varies minimally between monsoon phases. However, average drinking water quality—unlike the AW WQI—is considered the least poor in the dry phase.

Table 2. Water quality indices for ecological health and drinking water in Lake Tana determined with the AW WQI for the 2018 rainy phase (RF), 2018 post-rainy phase (PRF), 2019 dry phase (DF), and 2019 pre-rainy phase (PF).

Monitoring Stations	AW Water Quality Index							
	Ecological Health				Drinking Water			
	RF	PRF	DF	PS	RF	PRF	DF	PF
CE1	52	70	65	50	72	82	98	124
CE2	64	58	68	50	95	249	308	340
CE3	45	36	59	66	59	218	127	193
CE4	68	65	33	54	115	113	41	34
DE5	52	35	52	64	72	158	256	53
KO6	58	34	73	54	58	106	227	224

Table 2. *Cont.*

Monitoring Stations	AW Water Quality Index							
	Ecological Health				Drinking Water			
	RF	**PRF**	**DF**	**PS**	**RF**	**PRF**	**DF**	**PF**
RE7	70	66	73	47	59	173	186	74
KS8	67	42	65	46	63	254	139	112
RI9	73	65	66	46	68	151	171	91
K10	75	72	65	70	155	127	127	86
GO11	64	44	70	66	70	163	214	167
DE12	57	46	67	71	40	94	212	108
ED13	65	50	43	58	124	204	275	52
GU14	79	68	57	83	54	282	203	78
GU15	88	79	61	97	178	398	268	163
RI16	89	73	61	104	91	210	246	204
ME17	80	56	90	76	70	144	195	186
GA18	74	66	111	78	78	165	416	133
TB19	65	49	46	70	94	142	263	35
MA20	64	39	69	74	36	64	200	80
Maximum	89	79	111	104	178	398	416	340
Minimum	45	34	33	46	36	64	41	34
SD	11	14	15	16	35	77	80	74
Mean	67	56	64	66	83	175	209	127
** Rank	P	P	P	P	VP	U	U	U

** Average water quality scores: F—Fair; M—Marginal; and P—Poor.

3.2.2. Spatial Distribution of Lake Water Quality

The spatial distribution of aquatic and drinking water quality in Lake Tana for the two WQIs averaged over the four phases is shown in Figure 3. Since the numeric scores between the two indices vary, the color bars were designed such that red is the poorest water quality. orange and yellow colors represent less poor conditions, the green color means that water quality standards are often not met, and the blue color is when the water is near the desired pristine levels most of the time.

Both water quality indicators show that the lake is certainly not in the pristine condition of the 1930s when Major Cheesman [35] documented the lake water quality for the first time. Still, regarding ecological health, when averaged over all monsoon phases, the central, northwestern, and southeast parts near the outlet of the lake to the Abay (Blue Nile) are in good condition (AW WQI, Figure 3a, Figure S1 in the Supplementary Materials), or in the terminology of CCME WQI, the water quality only sometimes departs from desirable levels (Figure 3c). Both indices also indicate that in the northeastern part near the shore, the ecological health is poor, which is also the main location of the water hyacinths (sampling stations ME17, K10, and RI16, Tables 2 and 3; Figure 3). Also, according to the CCME WQI, the water quality in the southwest part could be better. There is a disagreement between both indicators on the south-central part of the lake. The AW WQI shows it was poor (Figure 3a), while the CCME WQI considers the water quality as mostly good (Figure 3c, Figure S3 in the Supplementary Materials).

For drinking water use, both water quality indicators indicate that lake water is generally not suitable as drinking water without treatment (Figure 3b,d; Figures S2 and S4 in the Supplementary Materials). The AW WQI scores (Figure 3b) put it all in the poorest category, while the CCME WQI is more nuanced but still considers the drinking water unsuitable except for the blue-green-colored water in the middle of the lake just north of the island (Figure 3d).

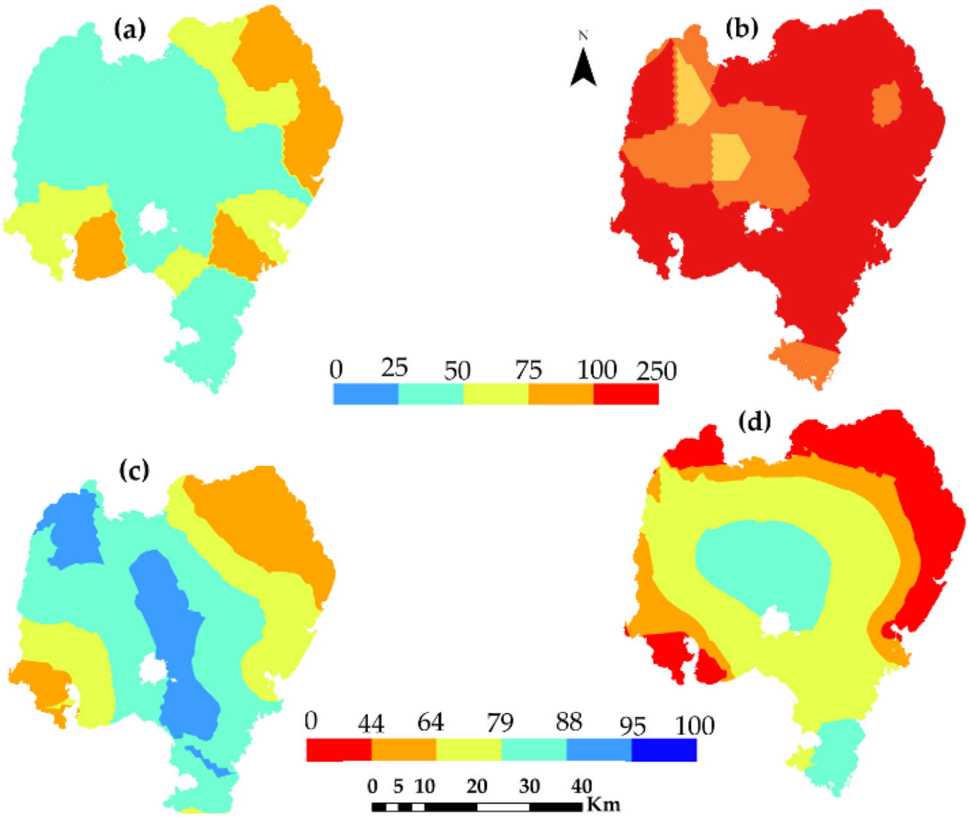

Figure 3. The spatial distribution of WQIs in Lake Tana averaged over four monsoon phases: (**a**) AW WQI for aquatic, (**b**) AW WQI for drinking, (**c**) CCME WQI for aquatic, and (**d**) CCME WQI for drinking evaluations. The meanings of the numeric scores are given in Table 1.

Table 3. Water quality indices for ecological health and drinking water in Lake Tana determined with the CCME WQI for the 2018 rainy phase (RF), 2018 post-rainy phase (PRF), 2019 dry phase (DF), and 2019 pre-rainy phase (PF).

Monitoring Stations	CCME Water Quality Index							
	Ecological Health				Drinking Water			
	RF	PRF	DF	PS	DRF	PRF	DF	PF
CE1	66	58	75	67	44	44	65	65
CE2	73	66	59	59	35	41	52	59
CE3	66	59	67	83	41	34	52	60
CE4	51	67	43	75	43	44	70	72
DE5	58	67	67	75	51	45	48	65
KO6	55	64	75	67	40	41	58	60
RE7	63	72	67	75	46	41	45	56
KS8	54	63	67	51	38	32	43	51
RI9	60	63	58	75	36	39	43	52
K10	44	48	47	42	37	43	40	45
GO11	52	61	66	51	41	30	41	42
DE12	63	64	67	75	40	34	44	54
ED13	63	64	59	75	31	32	48	59
GU14	65	58	67	67	40	32	43	54
GU15	50	40	49	65	28	29	36	39
RI16	45	55	51	57	30	25	32	32
ME17	37	37	52	43	33	27	36	37
GA18	60	46	50	49	35	29	36	39
TB19	54	63	50	37	36	31	41	51
MA20	50	66	67	54	43	45	54	57
Maximum	73	72	75	83	51	45	70	72
Minimum	37	37	43	37	28	25	32	32
SD	9	9	10	13	6	7	10	10
Mean	56	59	60	62	38	36	46	52
** Rank	M	M	M	M	P	P	M	M

** Average water quality scores: F—Fair; M—Marginal; and P—Poor.

3.2.3. Temporal Distribution of Lake Water Quality

Ecological health in each of the four monsoon phases is evaluated using the two indices (Figure 4). According to the AW WQI, the post-rainy phase shows the best water quality, with 50% of the stations rated as good (WQI < 50). In contrast, the CCME WQI index of 70% of the water was marginal or poor in the post-rain phase (Figure 4). The good-rated water quality with the AW WQI index during the three other phases decreased to below 20% of the stations sampled. The CCME WQI only rated the water quality as good for ecological health for one station in the pre-rainy phase (Table 2, Figure 4). The CCME WQI index also found that the stations reporting fair water quality (WQI > 65) increased from 25% in the rainy phase to 55% in the dry phase and 50% in the pre-rainy phase. The trend of improving water quality for the CCME WQI is different than that of the AW WQI because the AW WQI does not have such a fair category, and if the water quality ranking goes directly from good to poor.

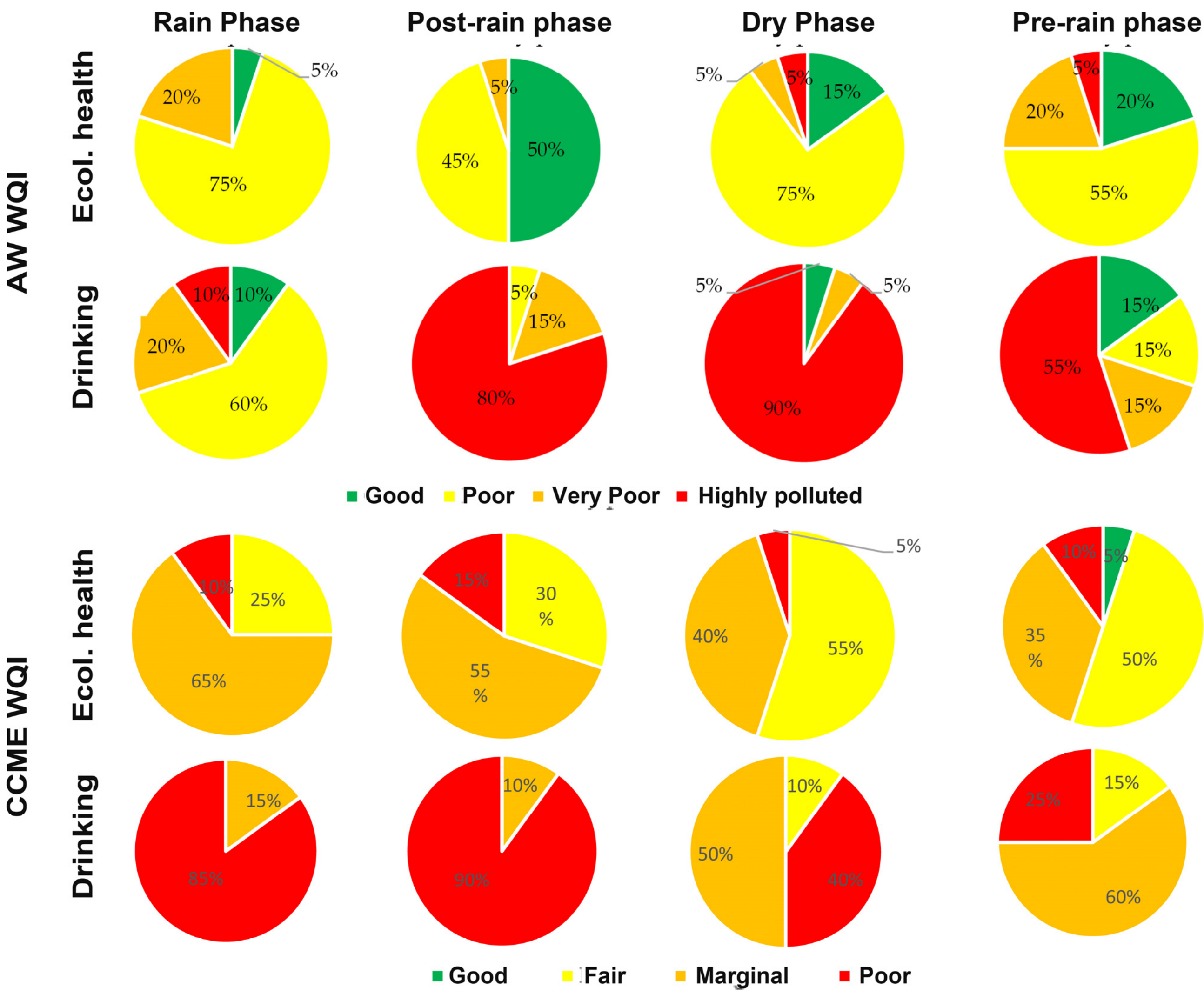

Figure 4. Water quality scores during the four monsoon phases based on AW WQIs and CCME WQIs in Lake Tana for ecological health and drinking water usage.

Both water quality indices agree that the water quality is not good, but to what degree it is marginal, poor, or highly polluted varies greatly among the two indices (Table 1). They also agree that during the post-rain phase, more than 80% of the drinking water quality falls in the worst water quality indicator: highly polluted in the case of the AW WQI and poor according to the CCME WQI. While the AW WQI finds the drinking water to be of better quality in the rain phase than during the post-rain phase, the CCME WQI considers the quality almost the same. The opposite is true for the dry phase, where the AW WQI finds a greater portion of the drinking water highly polluted than during the post phase, while the CCME considers that the quality is improved (Table 1). Both indices agree that the drinking water improves (although not of good quality) during the pre-rain phase.

4. Discussion

The relationship between the observed water quality parameters and lake circulation is discussed first, followed by a sensitivity analysis of the two water quality indices and, lastly, the utility of these indices in lake management.

4.1. Lake Circulation, Lake Depth, and WQIs

The lake circulation and depth can explain the spatial and temporal distribution of the water quality indicators in Figure 2 and WQI in Figure 5. Kebedew et al. [60] modeled the lake current pattern and showed that most of the flow of the largest river, the Gilgel Abay, flows to the inlet of the Tana-Beles. hydro powerplant west of the Gilgel Abay. Once the lake is full, excess inflow flows to the Blue Nile inlet to the east. The water from the Gilgel Abay has a short retention time, directly affecting lake water quality. Water from the Rib and the Gumara mainly flows to the north, where it combines with the water from the Megech, then to the east, and finally to the south along the western shore [60]. Most of the water from these three rivers is lost to evaporation, and only a small portion reaches the Tana Beles intake after being mixed with the water of the Gilgel Abay [39].

In addition to the lake currents, the lake depth affects the WQIs because the lake is, on average, only 9 m deep, with the deepest depth of 14 m in the central part of the lake. In shallow lakes such as Lake Tana, wave action suspends the bottom sediments. The shallower the lake, the greater the sediment concentration. The shallowest part of the lake is due to the elevated sediment loads of large rivers that carry sediment (more than 1% by weight [52]) during high flows and the lake currents that carry the fine particles after the sand fraction drops out at the outlets. The shallowest parts are around the river mouths and the northeast of the lake where the sediments of Gumara and Rib settle and near the Tana Beles intake from the Gilgel Abay. Hence, there are high turbidity and low Secchi-disk readings (red color) near Gumara and Rib in the east, and the inlet of the Gumara is in the southwest (Figure 1a). The turbidity readings are high in the northeastern part of the lake, but the Secchi depth readings are intermediate. This can be explained by the fact that water hyacinths are found in the northeast. The lowest turbidity readings and high Secchi-disk reading are in the middle of the lake where the lake is the deepest and sediment suspension by wave action is minimal.

A comparison of Figure 2a,g shows that greater turbidity readings and smaller Secchi-disk readings were generally linked with decreased dissolved oxygen levels. Turbidity prevents sunlight from entering the water, thus prohibiting plant growth that would increase oxygen [69,70]. Moreover, longer retention times mean a smaller portion of river water with higher oxygen levels [71].

The phosphate concentration (Figure 2j) is greatest in the northeast of the lake due to the shallow depth causing resuspension and from the legacy sediment available in the bottom sediments [39]. Resuspension decreases with depth, indicating less phosphate concentration at the greatest depths (Figures 2j and 5). The elevated values in the southwest, the entrance of Gilgel Abay, are associated with the large load of the river [40].

The ammonia concentration in Figure 2h is the greatest near the three largest river outlets. These rivers have a relatively high concentration of ammonia due to the leaching of the urea fertilizer in the rain phase applied to the cropped fields [72,73]. Once in the lake, ammonium is converted to nitrate, or some might even volatize. Explaining the spatial distribution of nitrate in the lake in Figure 2i needs more research on the transformation in the lake. Notably, however, there is a similarity between the nitrate pattern (Figure 2i) and the Secchi-disk reading (Figure 2f), where greater disk readings are associated with lower nitrate readings. This suggests that better sunlight penetration increases biological activity that will improve the nitrate take-up rate. Interestingly, this would confirm that the lake is nitrogen-limited.

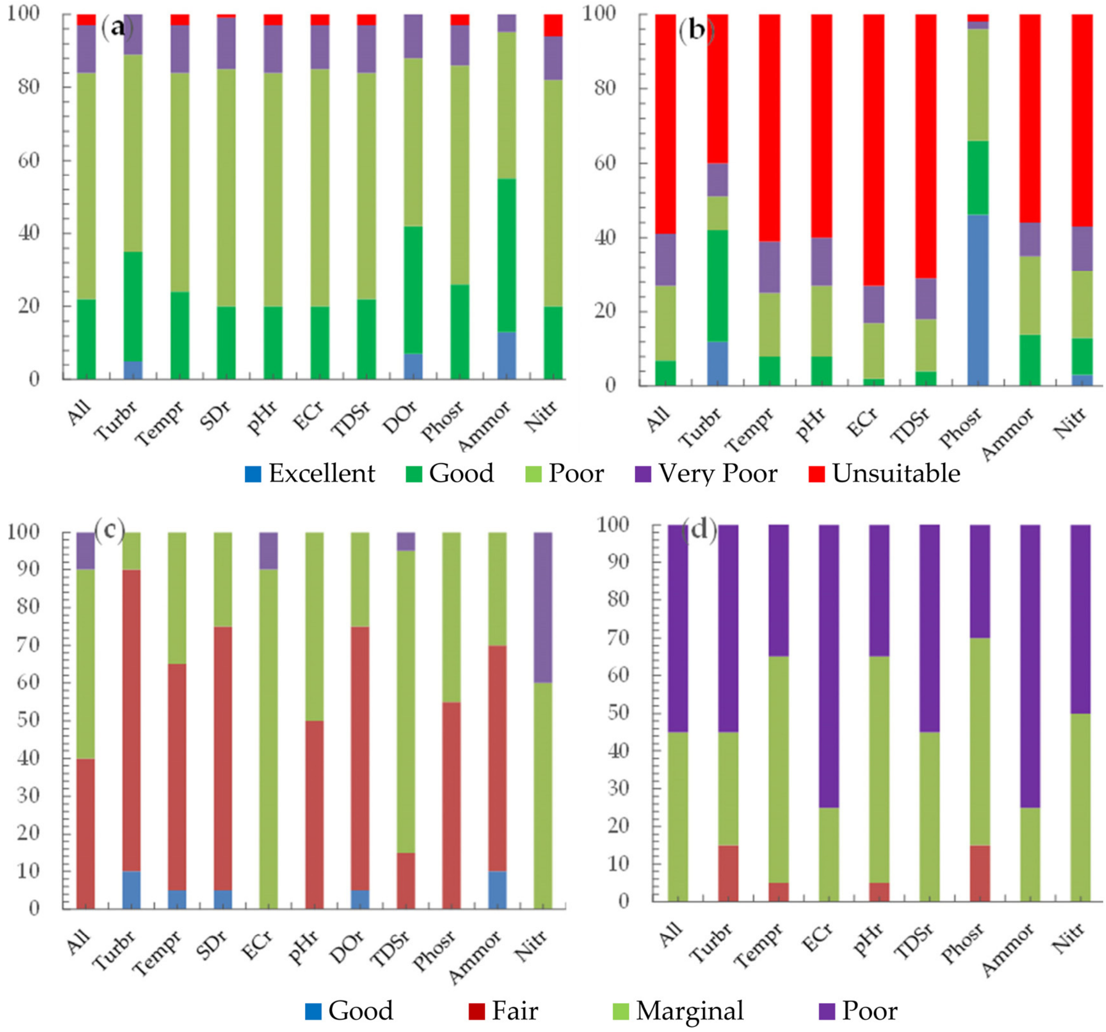

Figure 5. Sensitivity analyses: designations of (**a**) AW WQI for ecological health suitability, (**b**) AW WQI for drinking water usage, (**c**) CCME WQI for ecological health suitability, and (**d**) CCME WQI for drinking usage, calculated using the average water quality values in the 20 monitoring stations and four phases, which indicate the contributions of each parameter. All represent WQI when all the all parameters are included in the calculation except for the listed parameter on the *x*-axis. The meaning of the abbreviations are turbidity (Turbr), temperature (Tempr), phosphate (Phosr), ammonium (Ammor), electric conductivity (ECr), pH (pHr), total Dissolved Solids (TDSr), Secchi-disk (SDr), and Nitrate (Nitr) Total dissolved solids (TDS, Figure 2c) and electric conductivity (EC, Figure 2d) increase when the lake water evaporates, thus illustrating the lake circulation. In the upper half of the lake, the lowest EC and TDS values (dark and light blue colors) are around the outlets of the Gumara and Ribb on the east side. This water from these two rivers flows north and then west. On its way north, water evaporates; consequently, the EC and TDS values are the greatest in the northwest (red color). Then, flowing south, it mixes with the water from the Gilgel Abay, and the values of EC and TDS decrease. The low EC and TDS values also illustrate the short retention time in the lower part of the lake. It is not immediately clear why the values at the Gilgel Abay outlet are not lower.

Based on the data in Table 2, the water quality index tends to deteriorate during the rainy phase. It is caused by excess nutrients and sediment that are the highest in the rivers at the beginning of the season and are transported into the lake [52–55]. Water quality improves when sediment concentrations decrease later in the season and become minimal during the dry phase. It is generally the best before the rains commence (Tables 2 and 3). Despite variations in how long water stays in the lake (spatial residence time), excess nutrients begin to flush out [52–55] in August or September [60] when the lake reaches its maximum stage, and excess inflow is released through the Nile outlet, leading to a gradual improvement in the WQI (Tables 2 and 3). The lowest water quality index in the northeastern part of the lake is due to the accumulation of nutrients as a result of the lake circulation patterns and the resuspension of bottom sediment nutrients by wind-induced mixing enhanced by the shallow depth [39,60]. This pattern of improving water quality while the lake level decreases likely might be only valid for Lake Tana and other semi-humid and humid monsoon climates but also in semi-arid climates such as for Lake Kinneret, where water quality decreases with falling lake levels [15].

4.2. Key Parameters for Improving Water Quality Based on Sensitivity Analysis

To check which water quality parameters were responsible for the deteriorating water quality since Major Cheesman [35] first described the lake as pristine, we removed the parameters, making up the indicators one by one in the calculation of the WQI. The assumption is that when not including the indicator increases the WQI, the indicator causes the lowered water quality. In the ecological health AW WQI (Figure 5a, Table S3 in the Supplementary Materials), removing turbidity, dissolved oxygen (DO), and ammonium significantly improved the WQI from the current level. Specifically, eliminating ammonium increased the percentage of stations classified as excellent from 0% to about 13% and those classified as good from 22% to 42% (Figure 5a). Similarly, in the sensitivity analysis, removing DO from the AW WQI equation improved the water quality status of 7% of the stations to excellent and 35% to good.

According to the sensitivity analysis, the drinking water AW WQI improves most by removing phosphate and turbidity (Figure 5b, Table S4 in the Supplementary Materials). When turbidity was removed, the percentage of stations with poor water quality decreased, and the portion with good and excellent quality increased. Likewise, eliminating phosphate reduced the number of stations with poor water quality and increased the percentage with good and excellent water quality. However, as shown by [40], the lake is nitrogen-limited. Thus, it is unlikely that, as suggested by this WQI analysis, the water quality will be improved by reducing phosphorus from the present state.

Using CCME WQI shows that in addition to turbidity, DO, and ammonium (similar to AW-WQI), turbidity, as determined by the Secchi-disk depth readings, greatly impacts Lake Tana's ecological health (Figure 5c, Table S5 in the Supplementary Materials). For instance, removing SD from the analysis increased the 40% fair state to 70% and decreased the marginal water quality status from 50% to 25%. Like the AW WQI, the turbidity and phosphate CCME WQI also greatly affected Lake Tana's drinking water quality (Figure 5d, Table S6 in the Supplementary Materials). In the next section, we will discuss how realistic it is that by reducing phosphorus and sediment input in the lake as suggested by the WQI, the original 0% fair status of the lake water quality will increase to 15% of the sampling stations.

4.3. Managing and Improving the Water Quality of Lake Tana

The deterioration of lake water quality is frequently attributed to population pressure and intensified agriculture. Addressing this issue requires reducing the impact of the most harmful factors, turbidity, Secchi depth, phosphorus concentrations, and dissolved oxygen levels, in Lake Tana.

Although individual water quality indicators can be analyzed, several authors indicate that a more comprehensive assessment than the WQI should be used to determine the management practices needed for drinking and ecological health [7,17,20]. For example, for Lake Tana, improving the turbidity and increasing the Secchi depth by reducing erosion by best management practices will likely fail to improve the lake water quality in the short term since the lake is shallow. Wave action suspends the bottom sediment in the water column, and more sediment is suspended when the lake becomes shallower [39]. The deep parts of the lake have lower turbidity, as shown in Figure 2a, whereas dark blue indicates that the lowest turbidity corresponds to the deepest part of the lake. Thus, reducing sediment influxes from the four large rivers will likely only affect the lake water quality during and shortly after the rainy phase because it takes time for the sediment to settle. However, once settled out, concentration depends on the lake depth, and any best management practices in the lake will not lower the turbidity or increase the Secchi-disk reading.

In addition, as mentioned above, reducing phosphorus input from the watershed likely will not improve water quality since the tropical lake is nitrate-limiting [40], unlike most phosphorus-limited temperate lakes [70]. Thus, to enhance water quality, the nitrogen input to the lake must be reduced to below the natural denitrification capacity [54]. Reducing nitrogen can be accomplished by decreasing the application of urea fertilizers in hydrologically sensitive areas, which will also aid in lowering ammonium concentration since the high ammonium concentrations are at the outlets of the major rivers, indicating that the rivers transport ammonium from the urea fertilizer leached by the high rainfall from the agricultural fields [54]. Ammonium is highly toxic to fish at low concentrations, especially with increased pH and temperature [74].

4.4. Comparison with Other Tropical Lakes and Reservoirs

Several recent studies in the literature were selected to understand how Lake Tana compares to other tropical lakes. Ecological health water quality in Adolfo López Mateos Dam in Mexico Lake was evaluated with the widely used AW WQI model, similar to Lake Tana's range of good to poor. Chlorophyll, total organic phosphorus, and nitrogen concentrations were high [75]. The water quality of Lake Poyang, China's largest natural lake, was studied using the AW WQI method over six years. Seasonal variations were observed, with good quality during the rainy season (WQI: 35.5), very poor quality during the dry season (WQI: 95), and moderate quality during other seasons. Nitrate and phosphate were the main factors influencing the water quality indices [24,76]. In a study of Nigeria's Ekulu River [77], water quality for the AW WQI was ranked from "excellent water" (<50) to "unsuitable" for aquatic, irrigation and drinking purposes (>300). An AW-WQI study was also conducted in Lake Victoria, the world's largest tropical lake [78]. The WQIs in Lake Victoria typically varied between 43 and 73. The key water quality indicators were nitrate and phosphate [79]. In Lake Hawassa, located in southern Ethiopia, the researchers found that the water quality was generally unsuitable, with AW WQI scores ranging from 120 to 228 [30]. Thus, all tropical and subtropical lakes show that none are pristine, and the water quality varies from good to highly polluted. Lake Tana also falls in this range.

4.5. Drawbacks of Using Water Quality Indicators

The water quality indices are based on readily available parameters or can be measured easily. For this reason, trace levels of organic and inorganic parameters are not included. Two trace chemicals found in the Lake Tana surface waters were chlorpyrifos and endosulfan [54,80]. They originated from pesticide applications in the watershed; since these pesticides are highly toxic to fish, they were banned by the World Health Organization. Thus, one of the management practices that should be implemented in the Lake Tana watershed to improve the water quality is replacing intense pesticides with less toxic ones. The practice will not be recommended when water quality indices are used.

Another drawback of using the water quality indices is that the water quality status depends on the particular index used for the evaluation, as demonstrated in the temporal water quality analysis in Figure 3 and discussed in Section 3.2.3. As noted in several publications cited above, the water quality index is best used to evaluate whether, for the same lake, the water quality improves over time, provided that the index weights are correct (i.e., weighing nitrate more than phosphorus for Lake Tana) and that the most critical parameters are included, which is not the case for Lake Tana because chlorpyrifos and endosulfan were not included as part of the index.

5. Conclusions

The study assessed the water quality in Lake Tana using two water quality indices, AW WQI and CCME WQI. The study identified sensitive water quality indicators and found that the ecological health in Lake Tana was fair in some parts and poor in areas near the inlet of the major rivers according to the CCME water quality index. The AW WQI index considers the lake water quality as poor except in the post-rainy phase when the water quality of 50% of the lake was good. Both indices indicated that untreated lake water is generally unsuitable as drinking water.

The two WQIs identified high ammonium concentration and turbidity and low dissolved oxygen concentrations as the cause of the poor ecological health of some parts of the lake, especially near the outlets of the four major rivers. Drinking water quality degradation was caused by high phosphate concentration and turbidity. However, except for ammonium, these factors are immaterial for lake management because the lake is nitrogen-limited, and the turbidity results from sediment stirred up by waves from the lake bottom, which cannot be managed easily. Dissolved oxygen is a function of turbidity. Moreover, the WQIs did not identify two pesticides in the lake that negatively affected the fish. Thus, WQI indices can document water quality changes over time, but management for improving lake water requires a further analysis.

Based on our findings, we conclude that Lake Tana's water quality needs improvement. However, management practices that are effective in a monsoon climate—where rainfall occurs multiple times during the growing season—have not yet been tested in this context. Therefore, it will be extremely challenging to enhance the lake's water quality in the short term, even if economic and political conditions improve significantly.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/hydrology11120212/s1, Table S1: Geographical location of sample stations in Lake Tana. Table S2: Statistical summary of Lake Tana water quality data. Table S3: Sensitivity Analysis using AW WQI for ecological health in twenty monitoring stations of Lake Tana. Table S4: Sensitivity Analysis using AW WQI for drinking water in twenty monitoring stations of Lake Tana. Table S5: Sensitivity Analysis using CCME WQI for ecological health in twenty monitoring stations of Lake Tana. Table S6: Sensitivity Analysis using CCME WQI for drinking water use in twenty monitoring stations of Lake Tana. Figure S1: The distribution of the water quality index using AW WQI in Lake Tana for ecological health in the case of four study phases: rainy phase (a), post-rainy phase (b), dry phase (c), and pre-rainy phase (d). Figure S2: Distribution of water quality index using AW WQI in Lake Tana for drinking purposes in four phases: rainy phase (a), post-rainy phase (b), dry phase (c), and pre-rainy phase (d). Figure S3: Distribution of water quality index using CCME WQI in Lake Tana for ecological health in four phases: rainy phase (a), post-rainy phase (b), dry phase (c), and pre-rainy phase (d). Figure S4: Distribution of water quality index using CCME WQI in Lake Tana for drinking purposes in four phases: rainy phase (a), post-rainy phase (b), dry phase (c), and pre-rainy phase (d).

Author Contributions: M.D.N. made significant contributions to the conceptualization of the study, data collection, analysis of the collected data, and drafting of the initial article, and incorporating revisions based on reviewer feedback. M.G.K. provided valuable input regarding research approaches, sampling design, structuring the paper, and offering insightful comments. T.S.S. significantly contributed to re-writing and improving the initial draft, adding important sections to the paper and improving the overall language and grammar of the article. F.A.Z. provided important feedback and suggestions, contributing to the finalization of the manuscript for submission. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by the Blue Nile Water Institute and Bahir Dar Institute of Technology (BiT) of Bahir Dar University, Ethiopia.

Data Availability Statement: Lake-quality data will be made available upon request.

Acknowledgments: The authors gratefully acknowledge the invaluable assistance of Getahun Birara and Simachew Necho during the sample collection process from Lake Tana. Their unwavering dedication and perseverance in overcoming challenges during the four fieldwork trips were commendable.

Conflicts of Interest: The authors declare no conflicts of interest.

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