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Assessment of the Impact of Industrial Wastewater on the Water Quality of Rivers around the Bole Lemi Industrial Park (BLIP), Ethiopia

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Abstract: The discharge of industrial waste into water bodies without significant treatment can be a source of water pollution. This study was conducted to assess the impact of industrial wastewater on the water quality in rivers around the Bole Lemi Industrial Park (BLIP). Data were collected from six sampling stations in midstream, downstream, and upstream locations between May and June 2021. In situ (pH, electrical conductivity [EC], total suspended solids [TSS], and temperature) and ex situ (chemical oxygen demand [COD], total nitrogen [TN], total dissolved solids [TDS], total phosphorus [TP], and biological oxygen demand [BOD]) determinations of water quality were conducted. The quality of the water samples was examined using the weighted arithmetic water quality index (WQI) method. A statistical analysis showed that there are significant differences in the water quality parameters among the sampling stations along the river. The results showed different levels of temperature, EC, pH, TSS, TDS, COD, BOD, TN, and TP. The pH values were higher than the pH ranges (6.5–8.5) of USEPA, EU, CES, and WHO at two sampling stations. The results of the WQI showed that the analyzed water samples were in the "unsuitable for consumption" water quality category. These results will be useful for the city administration of Addis Ababa in crafting strategies for the protection and sustainable management of the Bole Lemi River.

Keywords: water quality assessment; industrial wastewater; physicochemical parameters; river; Ethiopia

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1. Introduction

Freshwater resources are critical ecosystems that support human and animal life [1]. However, they are the most threatened ecosystems in the world as a result of anthropogenic activities [2] which impair their natural stability [3]. Rivers are important components of freshwater resources with beneficial effects on human beings as they require water for various uses [4]. As a natural resource, rivers are essential for human survival and development [5]. They provide resources (water, food, etc.) and livelihood to mankind [6]. Their water is used for various purposes, such as drinking and other human consumption, animal drinking, agricultural irrigation, industry, recreation, etc. [7,8]. According to the 2018 United Nations World Water Development projection, nearly six billion people in the world may face severe water shortages by 2050 [9]. However, globally, many rivers are polluted with chemicals [10,11]. The water quality in rivers can be changed by various anthropogenic factors. These include the accidental or intentional emission of industrial wastes. According to [12], many developing countries face pollution from industrial discharge, which triggers eutrophication [13]

Urban rivers play an important role in supporting economic and social development [6,14]. Rapid urbanization and industrialization have attracted large numbers of people to cities, resulting in large amounts of industrial wastewater and domestic sewage pollution increasing the pollutant load on these water bodies [6,15,16]. These problems deteriorate their water quality and weaken their ecosystems [17–19]. Due to urbanization and industrialization, river water pollution has become a severe problem in developing countries, impacting the sustainability of water resources [20] and impacting human health [21]. This has led to a high incidence of harmful diseases in humans and will harm sustainable economic development in the long run [22].

Water quality is a general term used to describe the characteristics (physical, chemical, and biological) of water resources. It plays an important role in determining aquatic ecosystems and public health [23,24]. It is a concern across the world due to the widespread release of pollutants into freshwater ecosystems [25]. It plays a vital role in maintaining the ecological integrity of the river ecosystem [26]. As an important indicator of river health, water quality deterioration is a challenge to humanity [25] and is a critical challenge faced by many countries in Africa [9,27,28] and other regions [29]. With increasing economic and societal development, the deterioration of river water quality has become increasingly prominent [30]. Maintaining a good level of river water quality is crucial for sustainable development and human health [24,31]. Studies about the changing characteristics of water quality and their causes have become a hot issue in the field of water sciences [32]. River water quality is an important environmental concern that must be monitored [33]. With a rise in people's awareness of environmental protection, the monitoring of water quality in rivers has gained extensive attention for its use in sustainable urban development [34]. Physicochemical water quality parameters play significant roles in assessing and monitoring river water [35].

Strong economic growth and urbanization contribute to the increase in industrial and domestic waste [36]. Effluents can easily be discharged directly into rivers without wastewater treatment, resulting in reduced water quality [37]. Although rivers are essential natural resources that support socioeconomic development (human use, livestock drinking, irrigation, industries, transportation, recreation, etc.), they have largely been subjected to various anthropogenic sources of pollution [38]. These include industries, among other sources [39,40], that cause the deterioration of river water quality. According to Worku and Giweta [41], poorly treated and untreated industrial wastewater discharged into rivers has resulted in the pollution of rivers in Ethiopia. Although industrial parks provide economic benefits, their environmental costs—such as water pollution, loss of biodiversity, etc.—result in the degradation of ecosystem functions and services [42]. In this trade off, a well-developed and science-based management of aquatic ecosystems is required. Such management should include knowledge of water quality (physical, chemical, and biological) data and other information [43].

The city of Addis Ababa in Africa is undergoing rapid urbanization and industrialization. The city has an area of 540 km^2. The rivers of the city are heavily polluted by waste generated from various sources, mainly industrial and domestic. According to Tamiru et al. (2005) [44], between 90% and 96% of industrial waste is discharged without treatment into water bodies and open spaces in Ethiopia. There is a need for monitoring and assessing the water quality of aquatic ecosystems such as rivers. This study aimed to determine the Bole Lemi River's water quality status in Addis Ababa, Ethiopia, using water quality indicators and the water quality index (WQI) assessment methods. The levels of water quality indicators were evaluated based on the standards of USEPA, EU, CES, and WHO for water resources. A one-way analysis of variance (ANOVA) was conducted to determine the water quality parameters among the sampling stations. The assessment and monitoring of water quality provides empirical evidence to support decision makers and natural-resource managers in managing aquatic resources. Knowing the existing conditions of the Bole Lemi River through water quality analysis could help decision makers create plans for sustainably managing the river.

2. Materials and Methods

2.1. Description of the Study Area

This study was conducted on the Bole Lemi River, which is found very close to the BLIP in the city of Addis Ababa, Ethiopia. The industrial park is located at the coordinates 8°58′17.2200′′ N and 38°51′24.5088′′ E (Figure 1).

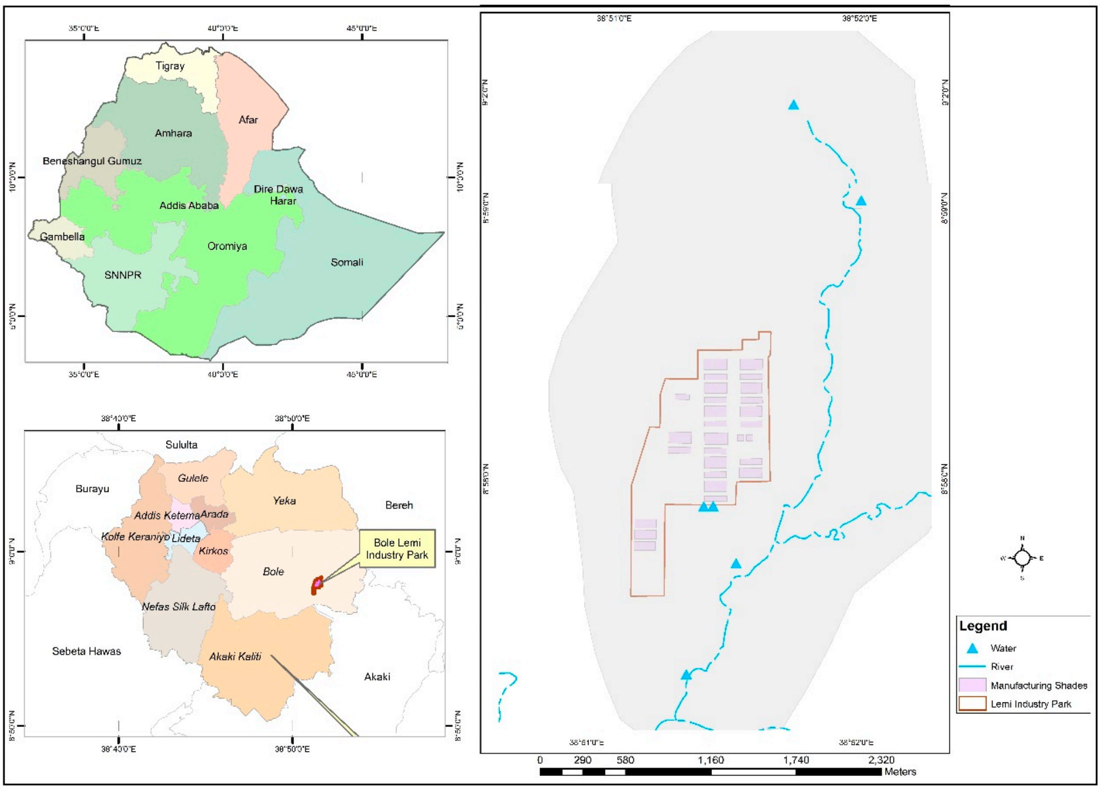

Figure 1. Map representing the BLIP and the sampling sites along the Bole Lemi River, Addis Ababa, Ethiopia.

2.2. Description of Sampling Sites

The sampling sites along the river were purposively selected to assess the impacts of the BLIP's wastewater discharge on the water quality of Bole Lemi River. Six sampling sites were considered for the study. The sites were classified as being midstream, downstream, or upstream of the river (see Table 1).

2.3. Method of Data Collection

In situ and ex situ determination was performed to assess water quality. Water samples were collected from upstream, midstream, and downstream sites from the six sampling points (Figure 1) along the Bole Lemi River between May and June of 2021. This period was chosen for data collection because, in Ethiopia, it represents a transition between the dry and wet seasons. The analyses were carried out on nine water quality parameters. For the determination of water quality, the parameters collected for in situ included pH, water temperature, electrical conductivity (EC), and total suspended solids (TSS), and the parameters for ex situ included chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), total dissolved solids (TDS), and biological oxygen demand (BOD). The in situ parameters were collected using a portable device. For ex situ parameters, water samples from the three sites were collected and submitted for laboratory analysis using standard protocols (Table 2).

Table 1. Description of Sampling Sites for Water Sampling Stations.

Sample Site	X-Coordinate	Y-Coordinate	Altitude	Brief Description of the Site
Site 1	0481164	1001030	2660	Upper stream (Wendraide station).
Site 2	0485375	0992975	2261	At Gabriel Church, where the river is polluted with domestic wastes, runoff, etc.
Site 3	0484305	0990893	2244	The site at which effluents were released from the BLIP to the inside compound of the treatment plant.
Site 4	0484369	0990895	2242	The site at which effluents were released from the BLIP to the outside of the treatment plant.
Site 5	0484525	0990508	2218	The site at which effluents released from the BLIP join the Lemi River.
Site 6	0484187	0989757	2202	The site downstream of the Bole Lemi River where local communities use the wastewater for irrigation purposes.

Table 2. Water quality parameters and types of analysis methods employed.

Parameters	Water Quality Technique/Method Used for Analysis
pH	pH meter
Temp. (°C)	EC meter
EC (µS/cm)	EC meter
BOD (mg/L)	Standard method
COD (mg/L)	HACH-DR6000 UV VIS—Spectrophotometer
TN (mg/L)	HACH-DR6000 UV VIS—Spectrophotometer
TP (mg/L)	HACH-DR3900 UV Spectrophotometer
TSS (mg/L)	Gravimetric method
TDS (mg/L)	EC meter

Water sample collection for the physicochemical analysis was performed according to the standards of the American Public Health Association [45]. Accordingly, twelve water samples were collected using the composite sampling method. The samples were collected in clean 2 L plastic bottles, each labeled with full information regarding the sample's code, date, time, source, and type and the name of the sample's collector. They were then preserved in a refrigerator at 4 °C. The collected samples were submitted as quickly as possible to the Oromia Environmental Laboratory Center in the town of Burayu to avoid the deterioration of the samples. The samples were analyzed using standard methods, such as COD and TN using the HACH-DR6000 UV—VIS spectrophotometer, and total phosphorous (TP) using the HACH-DR3900 UV spectrophotometer (Table 2).

Water quality estimation using the water quality index (WQI) method: The water quality index (WQI) assessment method can be used to determine the quality of water in a single value [20,46] and is used to evaluate the quality of river water and gather information about the state of the river [47–50]. The WQI was calculated using the weighted arithmetic index method, developed following the three steps of [51].

The weighted arithmetic WQI was used for estimating the water quality in the river using nine water quality variables (Table 3). For this estimation, the standard values of the different water quality parameters were used, as recommended by the World Health Organization (WHO) and USEPA.

Table 3. Water quality parameters recommended by WHO and USEPA.

Parameter	Standard Value	Recommended Agency
pH	8.5	WHO
Temp. (°C)	15	WHO
EC (µS/cm)	400	WHO
BOD (mg/L)	60	WHO
COD (mg/L)	150	WHO
TN (mg/L)	10	USEPA
TP (mg/L)	1	USEPA
TSS (mg/L)	60	WHO
TDS (mg/L)	500	WHO

WQIs of the collected water samples were calculated using the following three steps [51]:

(a) Unit Weight (Wn) Calculation

The unit weight (Wn) of the n^{th} parameter is inversely proportional to the recommended standards value (Sn) and can be calculated using the following formula:

$$\mathrm{Wn} = \frac{\mathrm{K}}{\mathrm{Sn}} \tag{1}$$

where Sn = standard permissible value of the n^{th} parameter and K = proportional constant. K can be estimated from the following relation:

$$\mathrm{K} = \frac{1}{\sum\left(\frac{1}{\mathrm{Sn}}\right)} \tag{2}$$

(b) Estimation of Quality Rating (Sub-index) (qn)

Sub-index, i.e., water quality rating, refers to the relative value of the n^{th} parameter concerning the standard value set by the recommending agencies.

$$\mathrm{K} = \frac{100(\mathrm{Vn} - \mathrm{Vio})}{(\mathrm{Sn} - \mathrm{Vio})} \tag{3}$$

where K = quality rating (sub-index), Vn = estimated value of the n^{th} parameter in a sample, Vio = desirable value of the n^{th} parameter in a sample for it to be considered "pure," and Sn = standard permissible value of the n^{th} parameter.

(c) Estimation of WQI

A WQI is a numerical expression used to show the quality of a water source for human use as indicated in Table 4. The WQI of a sample can be calculated using the following mathematical relationship:

$$\mathrm{Wi} = \mathrm{K}/\mathrm{Sn} \tag{4}$$

$$\mathrm{WQI} = \frac{\sum_{n=1}^{n} \mathrm{qnWn}}{\sum_{n=1}^{n} \mathrm{Wn}} \tag{5}$$

where WQI = water quality index, Wn = unit weight of a parameter, and qn = quality rating or sub-index.

Table 4. Weighted arithmetic WQI values used as presented by Brown et al. (1972).

WQI	Water Quality Status
0–25	Excellent
26–50	Good
51–75	Poor
76–100	Very Poor
>100	Unsuitable for Consumption

2.4. Data Analysis

The collected water quality data were compared to the existing water quality standards of WHO and USEPA. The data analysis included descriptive statistics and fundamental statistical measures for the studied water quality indicators that were analyzed. A one-way analysis of variance and descriptive statistics were used to verify the changes to the collected water quality parameters. A significant difference in the water quality parameters among sample sites was determined using a level of significance set at $p < 0.05$. A statistical analysis of the data was performed using the SPSS software, version 25.0.

3. Results and Discussion

Investigating the concentration of water quality parameters is important for future river water quality monitoring [16], which is an essential task because rivers are a source of water for any community [52]. The regular assessment of water quality helps in formulating policies and taking appropriate measures to alleviate the health impacts of water pollution [53]. The water samples collected from different sampling stations were analyzed for water quality parameters such as water temperature, pH, EC, TSS, TDS, COD, BOD, TN, and TP using mean and standard deviation. The mean and standard deviation values of the physicochemical parameters recorded at the six sampling stations are shown in Table 5.

Table 5. Analysis of water sample results for physicochemical parameters (mean ± SD).

	Water Quality Parameters								
Study Site	**pH**	**EC (µS/cm)**	**BOD (mg/L)**	**COD (mg/L)**	**TN (mg/L)**	**TP (mg/L)**	**TSS (mg/L)**	**TDS (mg/L)**	**Temp. (°C)**
Site 1	7.90 ± 0.57	262.67 ± 3.77	8.00 ± 8.49	146.50 ± 37.01	31.33 ± 2.83	4.27 ± 0.28	25.50 ± 34.65	155.30 ± 0.85	15.25 ± 4.17
Site 2	8.20 ± 0.04	575.00 ± 66.93	15.50 ± 19.09	132.83 ± 3.54	21.48 ± 8.27	4.02 ± 0.12	31.50 ± 14.85	347.00 ± 40.55	14.70 ± 4.24
Site 3	8.84 ± 0.23	650.00 ± 6.60	28.00 ± 32.1	139.17 ± 13.91	15.65 ± 0.03	4.74 ± 1.18	13.50 ± 4.95	389.67 ± 8.49	15.45 ± 4.17
Site 4	8.92 ± 0.16	644.33 ± 18.38	7.50 ± 7.78	112.50 ± 12.02	15.03 ± 0.03	3.89 ± 0.12	13.50 ± 10.61	389.50 ± 9.19	16.45 ± 2.76
Site 5	8.24 ± 0.19	437.17 ± 125.16	22.5 ± 17.68	105.67 ± 4.24	17.28 ± 8.27	3.95 ± 0.31	50.50 ± 0.71	332.33 ± 22.63	15.25 ± 4.45
Site 6	8.35 ± 0.17	570.83 ± 65.76	21.50 ± 2.12	121.34 ± 3.30	15.78 ± 0.78	5.35 ± 0.17	170 ± 147.79	336.67 ± 43.84	16.65 ± 1.63

pH: pH is one of the most important water quality parameters that can affect the suitability of water for various uses [54,55]. The pH value of water is closely related to its concentrations of carbon dioxide (CO_2) and alkaline substances [56]. In this study, the pH values were found to be alkaline, ranging from 7.90 to 8.92 (Figure 2). The maximum pH value was recorded at Sampling Site 4, where industrial effluents are discharged from industrial treatment plants (Table 5). This indicates a slightly alkaline river water, possibly due to untreated industrial wastewater discharge [54,57]. In addition, a higher pH value indicates a higher alkalinity, which indicates the presence of $CO^{3+}{}_2$, Ca^{2+}, and Mg^{2+} in the river [58]. The lowest pH value was recorded at Sampling Site 1, an upstream sample site. This may be attributed to a relatively low anthropogenic influence.

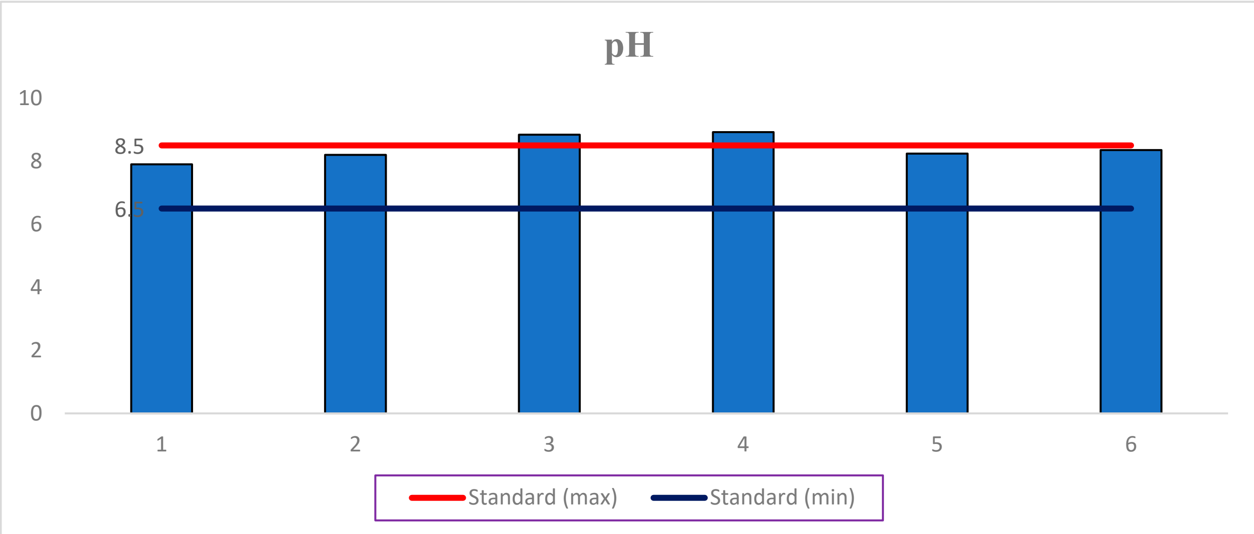

Figure 2. pH values recorded at the six sampling sites.

Other factors, such as temperature, oxygen levels, available anions, and cations, can affect pH value [56]. The optimum pH to support aquatic life is 6.5–8.2 [59]. However, the detected pH value was not significantly different among all sampling sites (p = 0.06). According to this study, the pH values for all sites except Site 3 (8.84) and Site 4 (8.92) were within the range of 6.5 to 8.5 as recommended by the USEPA (2009), EU (1998), CES (2013) and WHO (2011) standards and guidelines for drinking water and FAO (2013) for water irrigation. Similarly, all the pH values analyzed during this study in all the sampling stations were within the UNU-EHS/UNEP (2013) recommendations, which have standard values ranging from 6.5 to 9.0 for the water quality of an ecosystem. An increase or decrease in the pH levels of water could be due to either natural or anthropogenic activities. Surface runoff containing carbonate minerals in the soil may cause an increase in the pH levels of water during the rainy season. Wastewater discharge that contains chemicals such as detergents and soap-based products can increase water pH levels (Fondriest Environmental Inc., Fairborn, OH, USA, 2013). The high levels of pH in the Site 3 and Site 4 sampling stations may indicate an alkalinity in the wastewater due to the discharge of contaminated effluents by industries near these sampling points.

Water temperature: Water temperature affects the water quality parameters and plays an important role in aquatic life. Temperature is an important physical measure of water quality that affects the amount of dissolved oxygen (DO) in water ([57]. The temperature of polluted water may significantly affect its DO concentration [60]. The Lemi River receives wastewater from industrial parks, which may release warm water into the river system. The direct discharge of warm water from industries elevates water temperature [61]. This may raise the temperature of the river alongside its direct exposure to sunlight. The lowest and highest mean water temperature levels detected during the wet season of 2021 were 14.70 °C at Site 2 and 16.65 °C at Site 6, respectively. Yet, there was no significant difference (p = 0.99) in water temperature among the sampling stations (Figure 3). This deviates from the findings of [62] who reported that the highest water temperature in various water bodies in Nigeria was 28 °C, but is very similar to those of a study conducted in the town of Bahir Dar (15–20 °C) and to the Canadian recommended level of 15 °C [63].

There is slight temperature variation due to variation in altitude, which effects solar radiation and levels of pollution in water [64]. Similar findings were also reported in Ethiopia for the Modjo River (21.50–24.93) [65] and Kebena River (17–21) [66]. However, lower values were reported in India for the Hindon and Garra Rivers (15.6 to 34.70 and 28.70 to 31.1, respectively) [57,67]. Riparian trees maintain low water temperatures by providing shade, which reduces light and, in turn, photosynthesis [68].

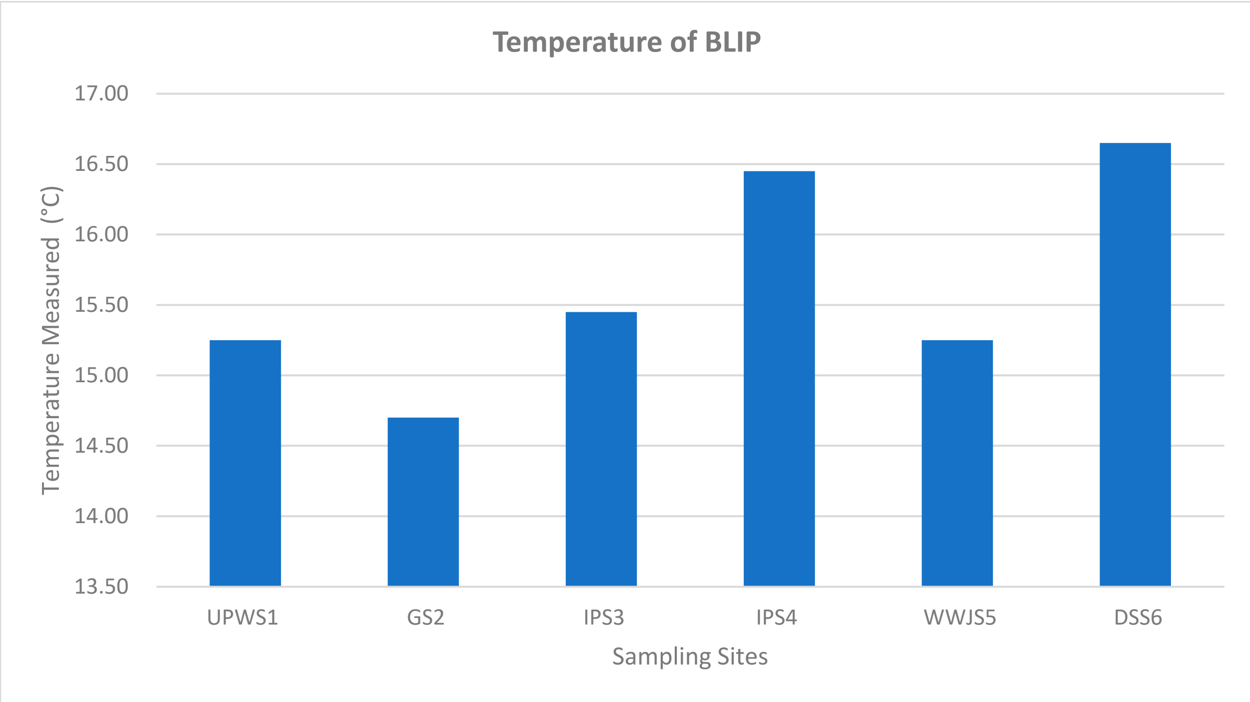

Figure 3. Temperature records (°C) at the sampling points along the river.

Electrical conductivity (EC): This is an indicator of the number of salts and carbonates in water. EC is a measure of the ability of a solution to conduct the flow of current depending on the presence of ionic particles [69]. Like TDS, EC denotes the salinity nature of the river water [50]. It is affected by the presence of inorganic dissolved solids, such as chlorides, nitrate, sulfate, phosphate, sodium, magnesium, calcium, iron, and aluminum ions [70,71]. Inorganic ions have an important effect on water conductivity. The more ions present in a body of water, the higher its conductivity level. EC refers to the number of dissolved salts and minerals in the water, which indicates the pollutants released into the river system [54]. Water turbidity is an important parameter that affects the penetration of sunlight into the bottom of the water, affecting aquatic life [55,56]. High turbidity reduces the amount of sunlight reaching underwater phytoplankton by scattering sunlight and obstructing incoming light with suspended fine particulate matter, such as mud, algae, detritus, and fecal material clay. A sudden increase or decrease in the conductivity level of water can indicate pollution.

The mean EC recorded in this study was between 262.67 and 650 µS/cm (Figure 4). The lowest mean EC value was detected at the Site 1 sampling station, while the highest was recorded at Site 3. This may be due to the discharge of industrial and domestic waste in the area. Water turbidity can be caused by fine organic and inorganic matter [72]. High levels of suspended solids and turbidity impair the recreational use of river waters because they reduce visibility and cleanliness in the water body and affect the safety and aesthetics of recreational waters [73]. The analysis revealed statistically significant differences ($p = 0.01$) in EC among the sampling stations. The average EC values recorded were within the EU standard for drinking water (1998), which is 2500 µS/cm at 20 °C, the FAO standard for irrigation water (2013), 700 to 3000 µS/cm, and the WHO standard of 400 µS/cm. According to the United States Environmental Protection Agency (USEPA), a body of water that can support fisheries should have a range of 0.15 mS cm^{-1} to 0.50 mS cm^{-1}. Based on the collected data, the conductivity of the Seven Lakes is suitable for aquaculture.

River water conductivity may be controlled by various factors, such as watershed geology, watershed size, wastewater from point sources, runoff from nonpoint sources, atmospheric inputs, evaporation rates, and bacterial metabolism [74].Agricultural runoff and sewage leakage can increase conductivity as a result of their chloride, phosphate, and nitrate ions [75].

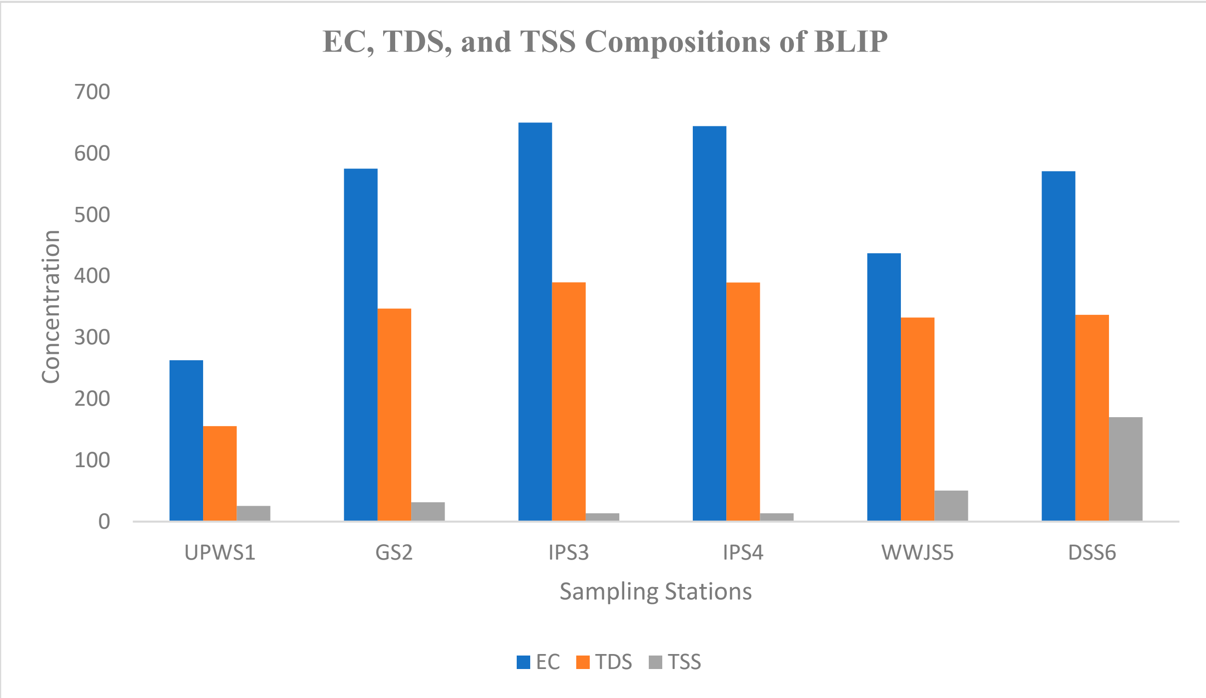

Figure 4. EC (µS/cm), TDS (mg/L), and TSS (mg/L) compositions at six different sampling stations.

Total suspended solids (TSS): Like TDS, TSS can also affect surface water quality. TSS are one of the most widely used indicators of surface water quality, which has both indirect (toxicity) and direct (physical, biological, and ecological) effects on aquatic environments [76]. High rates of TSS affect light transmission and aquatic life [77]. Total suspended solids (TSS) are a measure of the specific suspended solids in a body of water and are used to describe the level of pollution in wastewater. Additionally, the amount of TSS present serves as a good indicator of water turbidity [78]. The mean value of TSS in this study ranged from 13.50 to 170.50 mg/L (Figure 4). The lowest and highest mean values of TSS were at the Site 3/Site 4 and Site 6 sampling stations, respectively. Higher amounts of TSS might be due to suspended solids in the wastewater from the industrial parks' waste generation [79]. The mean values of TSS in this study were within the WHO (2006) wastewater discharge limit of 60 mg/L, except for the one at the sampling station of Site 6 (170.50 mg/L). High concentrations of suspended solids can affect the normal functions of aquatic ecosystems and the photosynthetic activity of aquatic plants by decreasing light penetration and increasing water temperature [80]. Excessive concentrations of TSS in irrigation water samples can cause negative effects; e.g., soil crust formation inhibits waterlogging and affects soil aeration, and suspended particles can coat plant leaves and reduce plant photosynthetic activity [81]. Similarly, the average concentrations of suspended solids exceeded the Australia and New Zealand (2000) guideline limits (TSS $\frac{1}{4} < 0.03$ mg/L) of water quality for aquaculture. Statistically, there was no significant difference ($p = 0.24$) in TSS among the sampling stations. There was no significant difference ($p = 0.24$) in TSS between sampling sites.

Total dissolved solids (TDS): The level of TDS in a body of water is directly related to its level of conductivity [50]. High rates of TDS influence the taste, hardness, and corrosion properties of water and makes it unsuitable for drinking [82]. According to a study performed by [74], the spatial and temporal monitoring of electrical conductivity and TDS is a good indicator of water quality. Sources of TDS include point source water pollution from industrial and domestic waste, agricultural runoff, and the leaching of soil contamination (DENR-EMB 2005). TDS affect the ability of water to dissolve various inorganic minerals and some organic minerals or salts. TDS, salinity, and TSS can affect surface water quality. The concentration of TDS can affect the water balance in the cells of aquatic organisms, and its excess concentration affects the taste of water [77]. The mean values of TDS recorded in this study ranged from 155.3 to 389.67 mg/L (Figure 4). The lowest and highest mean values were recorded at the Site 1 and Site 3 sampling stations, respectively. The highest concentrations of TDS may be a result of dissolved solids in the river system due to human activities, i.e., generating wastewater from industrial parks. According to) [59], high rates of TDS in river water may originate from salt and organic matter, which indicates that sewage has been released into the river system. The confirmed TDS values were significantly different ($p = 0.0009$) among the sampling stations. The mean TDS values recorded in this study followed the drinking water authorization standards of USEPA (2009), EU (1998), CES (2013), and WHO and the irrigation standards of FAO (2013). According to the World Health Organization, a TDS level below 300 mg/L is excellent, 300–600 mg/L is good, 600–900 is fair, 900–1200 is poor, and above 1200 mg/L is not acceptable. The average concentrations of TDS in the sampling sites (from 155.30 to 389.5 mg/L) does not exceed the WHO limit for drinking water (500 mg/L) (WHO, 2011) or the maximum concentration level (500 mg/L) (USEPA, 2009). The presence of high rates of TDS in water affects the taste and flavor of the water [77].

Biological oxygen demand (BOD): Biochemical oxygen demand is the measurement of total dissolved oxygen consumed by microorganisms for the biodegradation of organic matter, such as food particles or sewage [83]. Like chemical oxygen demand (COD) and dissolved oxygen (DO), BOD is an indicator of water quality. It refers to the amount of DO that microorganisms use to degrade and mineralize organic matter in water under aerobic conditions [56]. Relative to the levels of dissolved oxygen, the higher the BOD, the more rapidly oxygen is depleted in water, reducing the amount of oxygen available to aquatic organisms [71]. High BOD levels result in a higher intake of oxygen to break down organic materials. The process of breaking down organic materials can decrease the dissolved oxygen concentration in water, which can cause an anoxic state [84].

The mean values of BOD recorded in this study ranged from 7.5 to 28.3 mg/L (Figure 5).

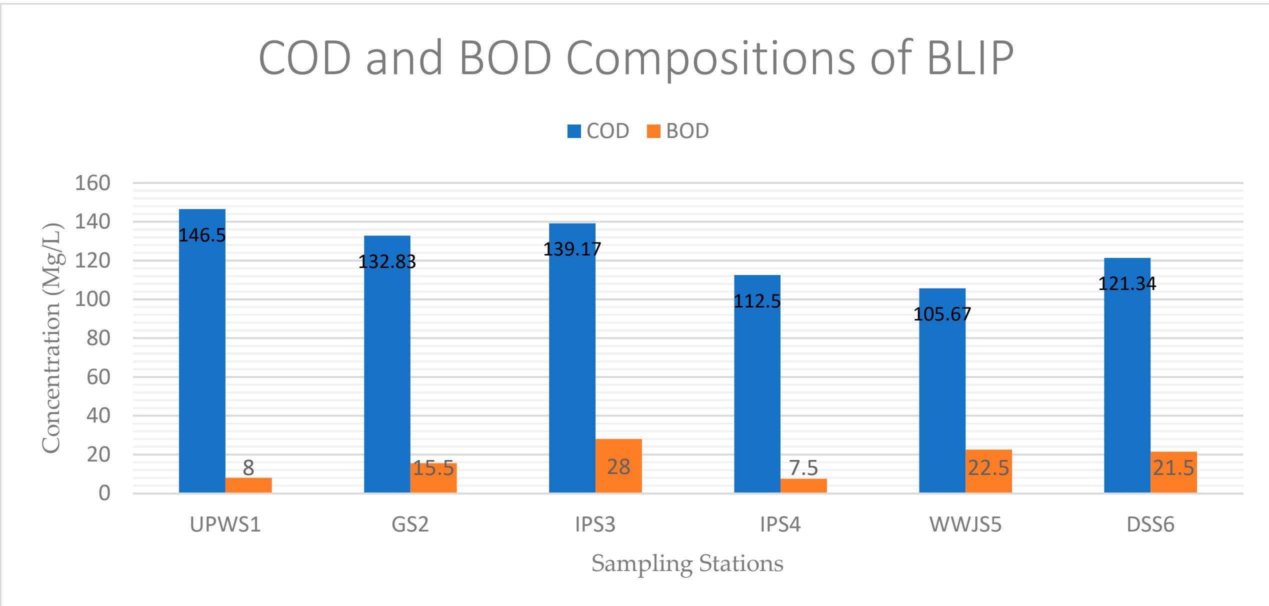

Figure 5. BOD and COD compositions at the six sampling sites.

Higher BOD loading implies the presence of organic pollutants from untreated industrial wastewater [85,86]. The tolerance limit of BOD in surface water is 5 mg/L for aquatic life, and it reflects the amount of unstable organic matter in waterbodies [87,88]. The lowest and highest mean values of BOD were recorded at the Site 4 and Site 3 sampling stations, respectively. The differences in BOD values were not significantly different ($p = 0.80$). However, the recorded values complied with the WHO (2006) standards (60 mg/L) for BOD levels. Like those of COD, low concentrations of BOD at the sampling sites also indicate a low organic load to the river under study. This might indicate that the number of organic pollutants at the sampling sites is too low to affect the river's water quality, change its color to black, or produce bad odor as a result of the absence of domestic waste, sewage lines, and septic tank connections, unlike other rivers in the country. Levels > 12.0 ppm can generally kill fishes due to suffocation [89].

Chemical oxygen demand (COD): COD is an important indicator of water quality. It measures the amount of oxygen needed to oxidize soluble and particulate organic matter in water [88]. The COD values recorded in this study ranged from 105.67 to 146.50 mg/L at the Site 5 and Site 1 sampling stations, respectively (Figure 5). The levels of COD were also found to be higher than those of BOD. This is because more organic compounds can be chemically oxidized than biologically oxidized [90]. A higher COD value is an indication of discharged effluents from industrial processes [91].

The differences in COD values among the sampling stations were not statistically significant ($p = 0.26$). The COD value mentioned (Table 5)was also not significantly different ($p = 0.26$) among the sampling stations. COD is a measure of the oxygen equivalent of the organic content in a sample, which can be oxidized using a strong chemical oxidizing agent. It is an assessment used to measure the degree of pollution from organic substances in water [78]. The levels recorded at all sampling stations were within the limit recommended by *the Guideline Ambient Environment Standards for Ethiopia*, EPA/UNIDO (2003), which is 150 mg/L. For the Challawa River in the state of Kano, high COD values with mean concentrations between 170 and 260 mg/L were observed [92]. Osibanjo et al. (2011) [93] also reported high COD values in water samples from the Ona and Alaro Rivers in Nigeria and attributed the situation to leaching from landfills and agricultural and urban runoff. The lowest concentrations of COD at the sampling sites indicate a low organic load on the river. Both BOD and COD often provide an indication of the level of organic pollutants in water and wastewater [94]. Wastewater with BOD and COD values above 0.6 is biodegradable and can be treated biologically [95].

Total nitrogen (TN): TN is a measure of nitrogen (organic and inorganic) and is the sum of all forms of nitrogen: Kjeldahl nitrogen (organic and reduced nitrogen), ammonia, and nitrate–nitrite. The excessive accumulation of nutrients such as nitrate, ammonia, and phosphate can affect surface water quality in several ways. For example, when the concentration of ammonia in water exceeds the permissible level, it causes eutrophication and eventually decreases DO levels and increases water temperature, becoming toxic to aquatic biota [54,56].

The TN values recorded in this study ranged from 15.03 to 31.33 mg/L at the Site 4 and Site 1 sampling stations, respectively (Figure 6). The difference in the detected values was statistically significant ($p = 0.03$). The mean TN values found at all of the sampling stations were outside the international UNU-EHS/UNEP (2013) guideline for the ecosystem, which is <0.7 mg/L, but they were within the standard authorized by FAO (2013) for irrigation, which is between 5 and 30 mg/L. According to [96], high nitrogen values present in substances stimulate plant growth. Nitrogen pollution studies in the United States and the Netherlands indicate that 60–80% of nitrogen comes from dispersed agricultural resources ([97]. Alvarez Cobelas et al. (2008) [98] also reported that NT exports from the watershed quadrupled those of forest basins as a result of crops. The mean TN values recorded were higher than the mean TN concentrations in the surface waters of the Tai Lake area (6.4 mg/L) [99]. The highest concentrations of nitrogen may be attributed to point sources from the industrial park and chemical fertilizer runoff from farmlands around the areas. Such a high concentration in water may cause various health impacts on organisms, e.g., making fish susceptible to diseases [100]. High levels of nitrogen in the form of nitrates and ammonia may be related to point sources in the industrial park and the chemical fertilizers used by local farmers. Such a high content in the water can cause various health problems and make the fish susceptible to other diseases.

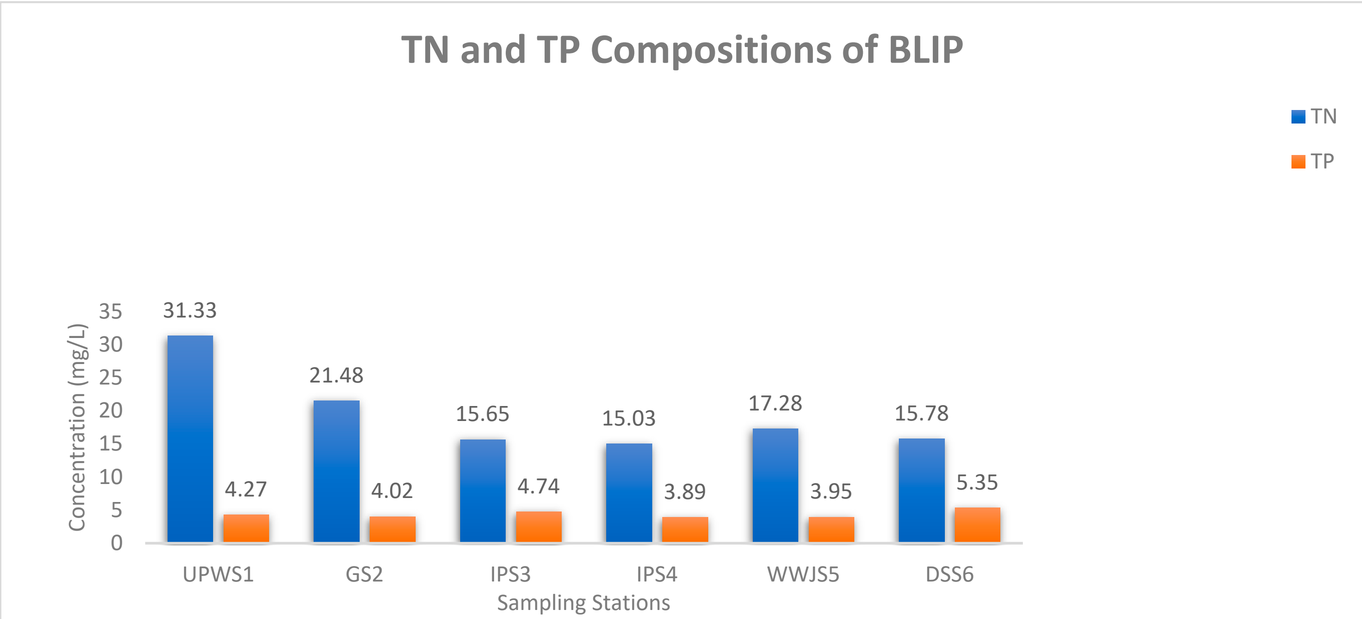

Figure 6. TN and TP compositions at different six sampling stations.

The total nitrogen concentration at the Site 4 and Site 2 sampling stations (15.03 and 21.48 mg/L, respectively) was higher than the maximum permissible limit for drinking water for rural people set by the Ethiopian Ministry of Water Resources (1.5 mg/L) (MoWR, 2001). However, compared to the TN concentration reported by [101], the values of 0.5 to 43 mg/L, recorded at all sampling sites, were found to be acceptable concentrations.

Total phosphorus (TP): Phosphorus is a common element in agricultural fertilizers and organic waste from sewage and industrial wastewater. Phosphate is an important nutrient found in aquatic plants, such as algae and plankton, and used as food for fish. However, too much phosphate in a body of water can cause an overgrowth of aquatic plants that quickly consume and reduce the amount of DO in the water and kill other aquatic life [57]. The major sources of phosphorus in the form of phosphate are, namely, waste from garment factories, laundry, domestic wastewater, and agrochemicals used in large-scale irrigated vegetable production.

Too much phosphorus in lakes, rivers, and streams can cause algae to grow. Water covered with algae is less attractive for fishing and swimming. Agricultural activities consume large quantities of inputs such as pesticides and fertilizers, which are the main sources of nitrogen and phosphorus. This trend is exacerbated by the increase in agricultural land. Irrigation has played a role in improving rural productivity and living standards, yet it is the source of runoff from agrochemical pollutants into water bodies. Soil particles may have been removed from the soil profile. In animal husbandry, there are often collection sites on both sides of the streams so that animal manure such as urine can enter these streams directly. Manure is usually collected as organic fertilizer, and its excessive use can cause widespread water pollution [102]

In this study, the mean TP values at the sampling stations ranged from 3.89 to 5.35 mg/L (Figure 6). These are higher than the limit of the WHO guidelines for drinking water (0.5 mg/L). Such concentrations can cause eutrophication in river water [103]. This can reduce the diversity of aquatic species and, ultimately, increase aquatic life mortality [40]. Excessive nutrient loading in the river may affect the rural population's ability to use this river water for various purposes.

The results of this study found that the TP content ranged from 0.03 to 0.56 mg/L, which is higher than the Shending River average content of 0.43 mg/L [96]. The mean values of TP are <0.02 μg/L for the aquatic ecosystem, which are in line with the approved international guidelines of UNU-EHS/UNEP (2013).

Estimation of the WQI of the River Water

According to Brown et al. (1972) [51], WQIs indicate the quality and desirability of water samples. It is estimated by using a single value derived from the set of water quality parameters. This study estimated the WQI by using water samples collected from six different sampling points along the Bole Lemi River. The Lemi River provides significant benefits for the life of the community around it. Determining its WQI helps conservation experts and decision makers to understand the river's ecological condition.

The WQI value of the river was estimated using the nine water quality parameters. Based on this value, the desirability/suitability of the river water at the different sampling sites was examined. In general, according to Brown et al. (1972) [51], a WQI value between 0 and 25 can be considered excellent. Similarly, good values are 26–50, poor are 51–75, very poor are 75–100, and unsuitable for consumption are >100.

The results of the WQI for the water samples collected from the six sites along the river are summarized and presented as shown in Figure 7. It shows that all of the water samples analyzed during the study were found to be unsuitable for consumption and that the Lemi River's water is not suitable for human use without treatment, but it might be acceptable for other purposes.

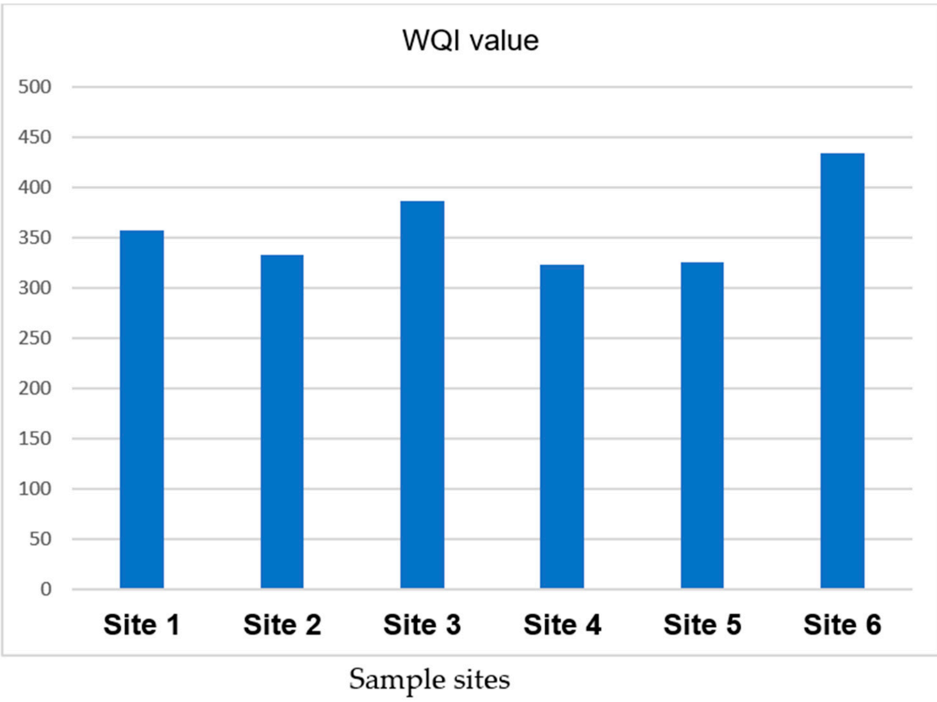

Figure 7. WQI values for the six water sampling stations.

4. Conclusions

Water quality assessment is an important aspect of water resource management that can provide empirical evidence for investigating the level of water quality deterioration and implementing appropriate measures to reduce the effects of pollution. This study applied water quality analyses to assess the impact of industrial parks on the water quality of the Bole Lemi River in Addis Ababa, Ethiopia. This study was conducted on a section of the river by analyzing nine water quality parameters and estimating the WQI of the sample sites to investigate the impact of the BLIP on the current water quality in the river.

The results of the water quality parameters were compared against the USEPA and WHO standards to determine the condition of the river.

This study shows that there are lower values of water quality parameters in the samples collected from the upstream sampling stations as compared to the samples from the downstream sampling stations. Physicochemical parameters of the river, such as pH at the Site 3 and Site 4 sampling stations, were above the allowable parameters set by USEPA, EU, WHO, and CES for drinking water. The TSS value at Site 6 was not within the WHO criteria, and the TN and TP values were above the acceptable UNU-EHS/UNEP international guidelines for ecosystems (2013). This shows that the discharge of industrial effluents from the BLIP has contributed to the deterioration of the water quality in the river. According to the WQI assessment, the river is at a critical level in terms of water quality.

Water quality control should be the priority of Addis Ababa's administration to protect and maintain the city's river resources. In this sense, the results of this study will be useful for the city administration to design appropriate strategies for protecting and maintaining rivers in the city in a sustainable manner. Broadly speaking, this study provides a scientific basis for the Addis Ababa Environmental Protection Authority and the city's River Protection and Development Office to prevent further water pollution and protect rivers around industrial parks. The city administration should be aware of the condition of the river and should raise awareness on how to protect water quality. Continuous discharge of untreated industrial waste into the Bole Lemi River will cause the water quality in the river to deteriorate. It is, therefore, important to properly treat industrial wastewater entering the river and prevent other waste sources from degrading the water quality. This study recommends that industrial parks in Ethiopia should be controlled because of their operational activities that pollute water resources. This study may provide useful references for the protection of other rivers in vulnerable areas in Ethiopia.

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