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Modeling on comprehensive evaluation of groundwater quality status using Geographic Information System (GIS) and Water Quality Index (WQI): a case study of Bahir Dar City, Amhara, Ethiopia

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ABSTRACT

Groundwater is the most important natural resource, and many people throughout the world rely on it for drinking, particularly in rural areas. The present study was carried out to assess the status of groundwater quality and to check its suitability for domestic purposes in urban centres of Bahir Dar City, Ethiopia. Twelve shallow wells were selected for sampling. The sampled water was taken during the dry and summer seasons of the year 2019/2020. pH, turbidity, EC, TDS, chloride (Cl^-), nitrate (NO_3^-), phosphate (PO_4^{-3}), total hardness, and *Escherichia coli* were measured for the suitability analysis. Comparison of measured results with those of WHO and Ethiopian drinking water quality standards was done. Moreover, Geographic Information System (GIS) and Water Quality Index (WQI) data analysis techniques were applied in order to investigate the groundwater quality. The spatial distribution map showed that the city's core area had the poorest groundwater quality status. The WQI result obtained from the analysis showed that 41.67, 33.33, and 25% of the sampled groundwater has low, extremely poor, and unsafe quality for drinking purposes, respectively. The present study revealed that anthropogenic activities have a great impact on the quality of groundwater in the area, necessitating immediate mitigating actions.

Key words: anthropogenic, GIS, groundwater, pollution, spatial distribution, WQI

HIGHLIGHTS

- Anthropogenic activities influence the quality of groundwater.
- The groundwater quality is fully contaminated with fecal coliforms.
- The WQI and GIS techniques show a majority of the city groundwater is unfit for drinking purposes.
- The highest concentration occurred in the central and mid-southern regions of the surveyed field.

1. INTRODUCTION

Groundwater is a major and crucial natural resource in both rural and urban areas, which is not only used for drinking purposes but also plays a major role in many segments of the country's economy such as hydropower, irrigation, fisheries, industrial production, and livestock production (Amadi *et al.* 2012; Tyagi *et al.* 2013). Recently, groundwater contamination has become a serious problem worldwide (Yolcubal *et al.* 2016) because of the rapid rise in population growth, urbanization, the quick speed of industrialization, and climate change (Tyagi *et al.* 2013; Tiwari *et al.* 2014).

Human activities that introduce contaminants into the environment have a significant impact on groundwater quality. Groundwater availability and quality have been impacted by rapid urbanization, particularly in developing nations like Ethiopia, due to over-exploitation, inappropriate waste disposal, and mismanagement of underground water resources. Thus, groundwater quality is under a serious threat particularly in metropolitan areas (Ramakrishnaiah *et al.* 2009; Prasanth *et al.* 2012; Yousefi *et al.* 2018; Saleh *et al.* 2019). Groundwater is the ecosystem's most essential natural resource, renewable but subject to natural and anthropogenic influences. According to Khatri & Tyagi (2015) and Babiker *et al.* (2007), groundwater is one of the most vulnerable natural

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resources, as it is susceptible to contamination from industrial effluents as well as sewage created by residential and commercial activities.

Groundwater in Ethiopia has been shown to be contaminated as a result of inadequate sanitation provision, poor waste management practices, and due to poor agricultural fertilizer management practices (Alemayehu 2001; Goshu & Akoma 2011). Bahir Dar and its surroundings have become a focal point for industrial, urban, institutional, economic, and tourism development center. Human activities in and around Bahir Dar increase the amount of garbage dumped directlyinto open land fields. The bulk of pit latrines and septic tanks used by local people in the area are often poorly constructedand not maintained properly, thus resulting in regular overflow of septic tanks, which poses a larger risk of infiltration into groundwater.

In this area, there is relatively little research on groundwater quality status done on a regular basis, and its impact on community health and specified purposes such as drinking, domestic, irrigation, and other industrial activities. As a result, this research was carried out in order to provide the necessary data for determining the water quality status of groundwater as well as the key contrasting element that restricts its suitability for the intended (drinking) purpose. As it is very difficult to repair groundwater quality once it has been polluted by limiting pollutants at the source, it is critical to check the groundwater on a frequent basis to protect its quality (Hasan *et al.* 2014; Puri *et al.* 2015; Akale *et al.* 2017). As a result, modeling and monitoring the state of groundwater quality is critical for water management decision-making.

The Water Quality Index (WQI) is the most effective method for communicating information about water quality to concerned stakeholders and policy-makers, allowing them to make corrective and integrated measurements for the assessment of groundwater appropriateness for most residential applications (Kumar *et al.* 2007; Avvannavar & Shrihari 2008; Rajankar *et al.* 2011; Puri *et al.* 2015; Saleem *et al.* 2016; Khosravi *et al.* 2017; Abbasnia *et al.* 2019; Khangembam & Kshetrimayum 2019). It assesses groundwater quality using a simple mathematical equation that converts large water quality parameter data into a single integer and gives a score that indicates groundwater quality status. Similarly, Boateng *et al.* (2016) and Akter *et al.* (2016) studied the WQI as a method for converting several water quality parameter data into a single number and assessing the geographical and temporal quality of the tested water.

The most extensively used program for the assessment and management of natural and environmental resources, including groundwater is the Geographical Information System (GIS). It is the most widely used software for site suitability study, calculating water availability, predicting groundwater sensitivity to pollution potential from nonpoint sources, and assisting in the management of water resources (Singh & Khan 2011).

A spatial groundwater quality distribution map is required to monitor and evaluate the area of groundwater pollution and to show the level of contamination. Thus, a spatial analysis extension of ArcGIS v10.1 aids in the interpolation of groundwater quality parameter spatial distribution maps at unknown locations from known values by producing continuous surfaces, which aids in the understanding of water quality parameter geographic distribution (Sumathi *et al.* 2008; Selvam *et al.* 2014; Shabbir & Ahmad 2015). The most extensively utilized interpolation techniques available in ArcGIS v10.1 software for the creation of water quality distribution maps are Kriging and Inverse Distance weight (IDW) (Johnston *et al.* 2001).

The primary goal of this research is to provide an overview of current groundwater quality and its suitability for drinking purposes and present the results in the form of WQI- and GIS-plotted maps.

2. MATERIALS AND METHODS

2.1. Description of the study area

The research is being carried out at Bahir Dar City, Ethiopia, which is located in the Amhara National Regional State and is bordered to the north by Lake Tana, which represents the source of the Blue Nile River as seen in Figure 1. The area is roughly bounded by latitudes 11°32′0″ N and 11°38′0″ N, and longitudes 37°20′0″ E and 37°27′40″ E. The terrain is mostly flat, with a few minor hills to the east and west. The city is believed to be 62.22 km^2 in size, with an average height of 1,795 meters above sea level.

The temperature in the area is generally nice, with warm days and mild evenings. The average annual precipitation is 1,037 mm, with 54% falling in July and August and only 3% falling during the 4 dry months. The average yearly temperature is 16 °C. Maximum temperatures are most common from March through May, and the average monthly maximum temperature reaches 26 °C. Bahir Dar's soil type is represented by residual fine soils, such as silt clay or clay soil. The prevailing soil color in the research area is red, and no coarser soils can be detected in

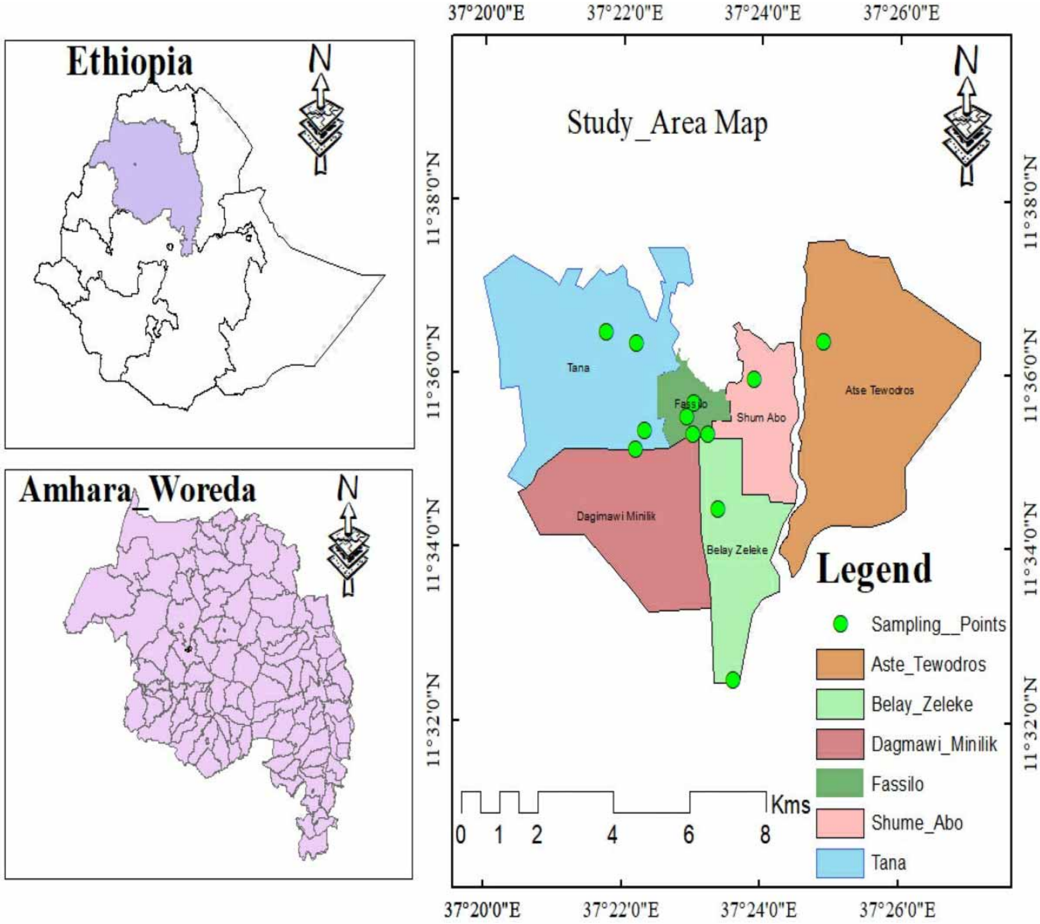

Figure 1 | Location map of the study area.

outcrops or deep-water well logs. As a result, permeability is estimated to be between 1×10^{-4} and 1×10^{-5} m day^{-1}. The underlying rocks, on the other hand, are worn and broken and hence have considerable permeability (Goshu & Akoma 2011).

Bahir Dar city is situated on the Southern shore of Lake Tana. Important landscapes include natural (church) forests with indigenous tree species (including shade-growing coffee), wildlife like hippopotamus, papyrus bed wetlands, important bird areas of key global species (nesting, feeding, and roosting sites), and agricultural landscapes. Bahir Dar's main attraction is the selection of Ethiopian Christian monasteries which are found on some of Lake Tana's 37 islands. Most of the Bahir Dar monasteries date from the 16th and 17th centuries and have changed little since their founding.

2.2. Sampling site and sampling design

A total of twelve (12) sampling stations from groundwater sources were chosen to examine the state of groundwater quality depending on the location and magnitude of human influence. Ten (10) of the sampled water sources are shallow wells, while two are moderately deep wells. From January to March 2019, groundwater samples were collected once a month and then again from June to August 2019. Table 1 and Figure 1 show the sampling station co-ordinates and location of sampling points in Bahir Dar city, respectively, which were collected using a Geographic Positioning System (GPS) with the designated model Aquaprobe-7000.

2.3. Measurement of groundwater samples

Water samples were taken from shallow groundwater at several sampling locations in 1-L pre-cleaned tightly closed polyethylene bottles, and the sampling container was washed (renised) twice or three times with distilled water or the water to be sampled.

Table 1 | GPS reading of sampling sites with brief descriptions

Station	*X*	*Y*	Well location	Well type	Well depth (m)
W_1	37°24.89′ E	11°36.37′N	Kebele 11	Moderately deep	25
W_2	37°23.89′E	11°35.93′N	Poly Campus	shallow hand dug	1.5
W_3	37°23.22′ E	11°35.29′N	kebele 4	shallow hand dug	3
W_4	37°23.00′E	11°35.30′N	kebele 15	shallow hand dug	6
W_5	37°23.02E	11°35.66′N	kebele 4	shallow hand dug	2
W_6	37°22.92′E	11°35.50′N	kebele 15	shallow hand dug	6
W_7	37°22.18′E	11°35.12′N	kebele 14	Moderately deep	25
W_8	37°22.31′E	11°35.34′N	kebele 16	shallow hand dug	8
W_9	37°22.18′E	11°36.34′N	kebele 13	shallow hand dug	4
W_{10}	37°21.75′E	11°36.47′N	kebele 13	shallow hand dug	4
W_{11}	37°23.38′E	11°34.44′N	Kebele 7	shallow hand dug	2
W_{12}	37°23.59′E	11°32.47′N	Waste dump site	Spring	0.3

The physico-chemical and bacteriological properties of sampled water quality were assessed in monthly samples collected from January to March 2019 and then again from June to August 2019. The container was then entirely filled with the sampled water, leaving no air space. All the methods used for sample analysis (Table 2) were according to the standard methods for water and wastewater examination as specified (APHA 1998, 2012).

Table 2 | Instruments used for onsite field measurements and laboratory test equipment

Parameter	Instrument/method	Instrument model	Standard method number
Turbidity	Turbiditymeter	Hanna HI 98708	APHA 2130B
EC	Multi-parameter water quality probe	Aquaprobe-7000	SUK: AP-7000
pH	Multi-parameter water quality probe	Aquaprobe-7000	SUK: AP-7000
TDS	Multi-parameter water quality probe	Aquaprobe-7000	SUK: AP-7000
Chloride (Cl^-)	Palin test (low range spectrophotometer)	Palintest 8000	Palintest photometer 8000
Nitrate (NO_3^-)	Palin test (low range spectrophotometer)	Palintest 8000	Palintest photometer 8000
Phosphate (PO_4^{-3})	Palin test (low range spectrophotometer)	Palintest 8000	Palintest photometer 8000
T.Hardness	Palin test (low range spectrophotometer)	Palintest 8000	Palintest photometer 8000
Faecal coliform	Membrane filtration method	N/A	APHA 9222

The groundwater source collection method was used on a regular basis; otherwise, the source should be cleaned continously before the sample. To remove all sediment, slime, and turbidity from hand pump sources, the water was pumped and washed for 3–5 min. The collected samples from each source were tagged and transported to the laboratory in an ice-box at a low temperature before being analyzed.

pH, turbidity, electrical conductivity (EC), total dissolved solids (TDS), chloride (Cl^-), nitrate (NO_3^-), phosphate (PO_4^{-3}), total hardness, and bacteriological analysis, including *Escherichia coli*, were all measured in the samples. The pH, EC, and TDS were measured *in situ* with an Aquaprobe-7000, whereas the ionic species (Cl^-), dissolved ion species (NO_3^- and PO_4^{-3}), and total hardness were determined in the laboratory with a Palin test 8000 spectrophotometer. According to the standard water and wastewater experimental method as specified by American Public Health Association standard methods (APHA 1998) during fecal coliform (*E. coli*) level testing, 100 ml sample of water was sucked through a filter using an electrically driven pump.

2.4. Quality assurance and control procedure

During sample collection and analysis, quality assurance and control procedure were followed so as to eliminate and or minimize errors. Hence, errors in the water quality data collection case may lead to mistakes and bring a wrong conclusion for the entire research work. Therefore, for quality assurance and control purposes, all water monitoring equipments are calibrated and any equipment failing calibration was not used for the entire data collection and record system.

3. DATA ANALYSIS

The Statistical Package for Social Sciences (SPSS v21) was employed to analyze the basic descriptive statistics such as minimum, maximum, average, and standard deviation. The data which were collected from the selected groundwater parameters were analyzed using the descriptive statistics method. The results of the analyzed groundwater parameters (Table 5) were compared to WHO (2011) and the Federal Democratic Republic of Ethiopian Ministry of Health (MoH, F.D.R.E 2011) drinking water quality guidelines.

3.1. Determination of WQI

To assess the water quality rate of the measured groundwater parameter and to provide insight into the degree to which water quality is affected by anthropogenic activity, a desirable level or defined water quality parameters aim was utilized. As a result, eight (8) water quality parameters were examined in the current study to determine the WQI rate: pH, turbidity, EC, TDS, chloride, nitrate, phosphate, and total hardness. Three steps were followed to calculate the WQI of the measured groundwater, as formulated by others (Abdul Hameed *et al.* 2010). The first stage was to assign a weight (W_i) to each of the water quality metrics, such as pH, turbidity, EC, TDS, chloride, nitrate, phosphate, and total hardness, based on their relative importance in the overall quality of groundwater for drinking purposes, which ranged from 3 to 5 (Khan & Jhariya 2017; Khosravi *et al.* 2017; Solangi *et al.* 2019; El Mountassir *et al.* 2020) as shown in Table 3. The highest weight of 5 is given to the water quality parameter if it has a significant impact on the water quality, while the lowest weight of 3 is given if it has no significant impact on the water quality.

Table 3 | The recommended standard value, ideal value, and weight factor of the selected parameter

Physico-chemical Parameter	Standard value	Ideal value	Weight (W_i)
pH	8.5	7	3
Turbidity (NTU)	5	0	3
Electrical conductivity (EC) (μS/cm)	1,000	0	3
TDS (mg/l)	500	0	5
Chloride (Cl^-) (mg/l)	250	0	5
Nitrate (NO_3^-) (mg/l)	45	0	5
Phosphate (PO_4^{-3}) (mg/l)	0.02	0	3
Total hardness (mg/l)	300	0	3

Secondly, the relative weight (W_i) of each water quality parameter is calculated as shown in Equation (1).

$$W_i = \frac{w_i}{\sum_{n=1}^{n} w_i} \tag{1}$$

where W_i denotes relative weight, w_i denotes the weight assigned to each water quality parameter, and n denotes the number of parameters. Finally, the quality rating scale (q_i) for each water quality parameter is calculated by dividing the concentration of each water quality parameter by its appropriate water quality standard (MoH, F.D.R.E 2011; WHO 2011) and then multiplying by 100 as stated in Equation (2).

$$q_i = \left[\frac{V_i - V_{id}}{S_i - V_{id}}\right] * 100 \tag{2}$$

where q_i is the ith water quality parameter's quality rating, V_i is the ith water quality parameter's measured value at a specific sample location, and S_i is the ith water quality parameter's standard value. In pure water,

V_{id} is the optimal value of ith parameter. Except for pH, which is 7, the optimum value for other parameters is zero.

Finally, using Equation (3), the SI_i is obtained for each physico-chemical water quality parameter before computing the WQI.

$$\mathrm{SI}_i = W_i * q_i \tag{3}$$

where SI_i is the sub-index of ith parameter whereas, q_i is the rating based on the concentration of ith parameter. Then, WQI can be calculated using Equation (4).

$$\mathrm{WQI} = \sum_{i=1}^{n} \mathrm{SI}_i \tag{4}$$

Table 3 shows the recommended standard value, ideal value, weight and relative weight of the selected physico-chemical water quality parameter.

As shown in Table 4, the WQI rate classification standard was used to calculate the groundwater quality status classification at each station (Sahu & Sikdar 2008; Ravikumar *et al.* 2013; Puri *et al.* 2015; Rabeiy 2018).

Table 4 | Water quality status classification based on the Water Quality Index

Water Quality Index range	Water quality status
<50	Excellent water quality
50–100	Good water quality
100.1–200	Poor water quality
200.1–300	Very poor water quality
>300	Unfit for drinking

3.2. Spatial analysis and GIS mapping

For the particular examination of physico-chemical and bacteriological groundwater quality parameters, the study used topographic sheets and the spatial analyst module in ArcGIS 10.1 software. For the creation of the water quality parameter spatial distribution and water quality index map of the study region, the well locations were collected using a GPS. For geographical modeling, IDW interpolation techniques were utilized, and the values of water quality parameters were categorized according to (WHO 2011) drinking water standards. The WQI map was created by computing the point data at each station using GIS and IDW interpolation techniques. The general methodologies adopted for this study are presented in Figure 2.

4. RESULTS AND DISCUSSION

The statistical summary of observed concentration of various physico-chemical and bacteriological parameters in the sampled groundwater is presented in Table 5.

The pH of all groundwater samples ranged between 7.21 and 7.31, with an average value of 7.27 as shown in Table 5. This implies that the groundwater remained somewhat alkaline in all test stations (confirms surplus hydroxyl ions with a pH value greater than 7). The presence of bi-carbonate content in the water, which is created by the free interaction of carbon di oxide (CO_2) with water to form carbonic acid, was largely connected with the modest high pH value in the research location (Azeez *et al.* 2000; Prasanth *et al.* 2012). The spatial distribution of pH (Figure 3(a)) depicted that all of the sampled stations had a pH value that was within a specific maximum acceptable limit as defined by WHO (2011) and MoH, F.D.R.E (2011)) guidelines. The minor variation in pH, on the other hand, may not have a negative impact on human health.

The turbidity value of all sampled groundwater ranged from 1.96 to 8.87 NTU, with an average value of 4.63 NTU (Table 5). The turbidity values at stations W_2, W_{11}, and W_{12} exceeded the acceptable limit set by WHO (2011) and MoH, F.D.R.E (2011) as shown in Table 6. Hence, it is an indication of light interference caused by the presence of suspended particles, which is mostly caused by a wide range of suspended particles

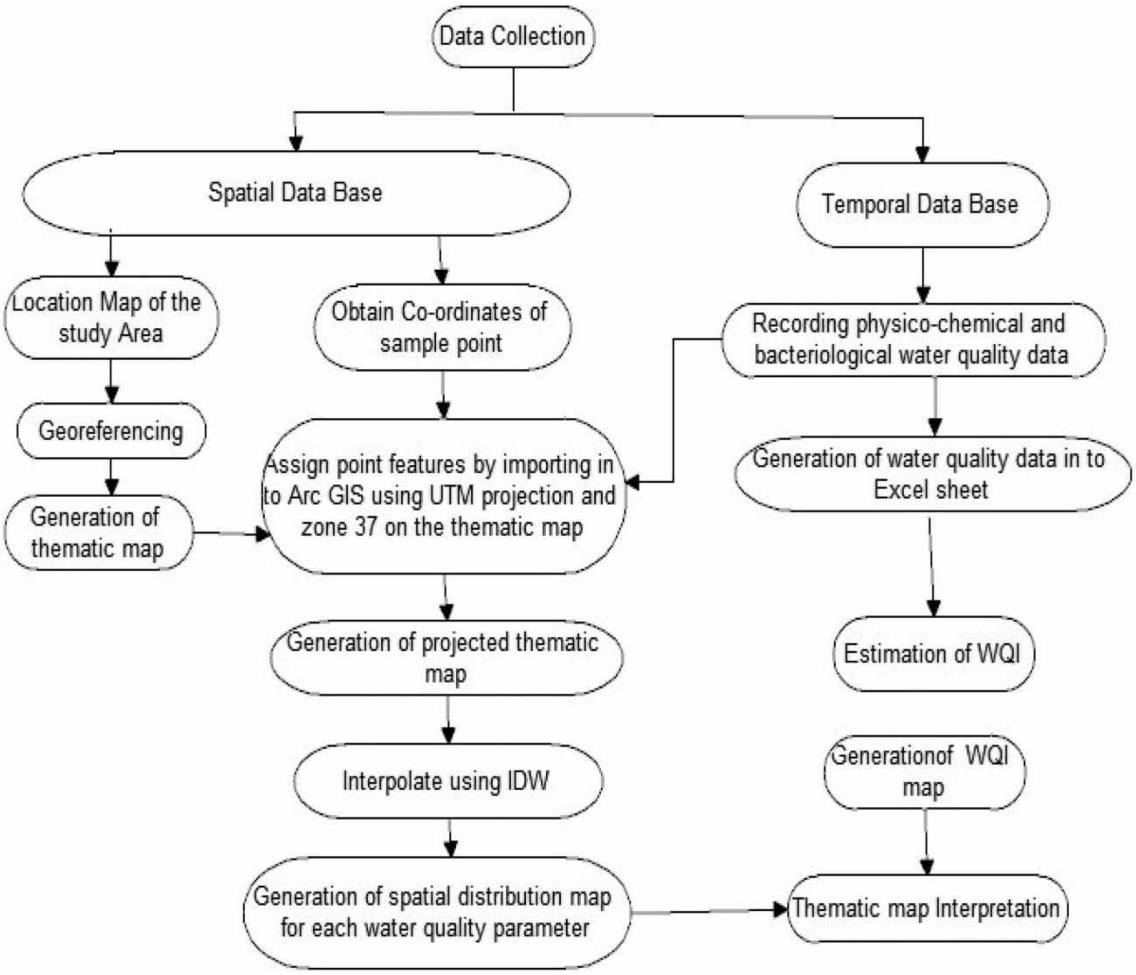

Figure 2 | General flowchart of methodology adopted for the study.

Table 5 | Statistical summary of various physico-chemical parameters of sampled groundwater

					Guide line	
Parameter (mg/l)	**Minimum**	**Maximum**	**Mean**	**Standard deviation**	**WHO (2011)**	**MoH, F.D.R.E (2011)**
pH	7.21	7.31	7.27	0.03	6.5–8.5	6.5–8.5
Turbidity (NTU)	1.96	8.87	4.63	1.89	<5	<5
E.Conductivity (μS/cm)	285	1313.39	652.11	274.55	1000	
TDS (mg/l)	185.33	853.22	412.27	175.63	500	1000
Chloride (Cl^-) (mg/l)	16.33	108.67	56.12	30.31	250	250
Nitrate (NO_3^-) (mg/l)	6.24	36.20	22.28	9.75	45	50
Phosphate (PO_4^{-3}) (mg/l)	0.24	0.53	0.36	0.09	0.02	
Total Hardness (mg/l)	83.94	294.67	157.7	54.63	300	300
E. coli (cfu/100 ml)	5	101	61	36	0	0

and is a sign of the presence of waste discharge in the studied water body. Furthermore, the spatial distribution map of turbidity depicted that the highest concentrations of turbidity were reported in the city's central and mid-southern regions, as shown in Figure 3(b).

The EC of the sampled groundwater varies greatly, ranging from 285 μS/cm to 1,313.39 μS/cm with a mean value of 652.11 μS/cm (Table 5). As stated in Table 6, the EC value in W_{11} exceeds the drinking water quality

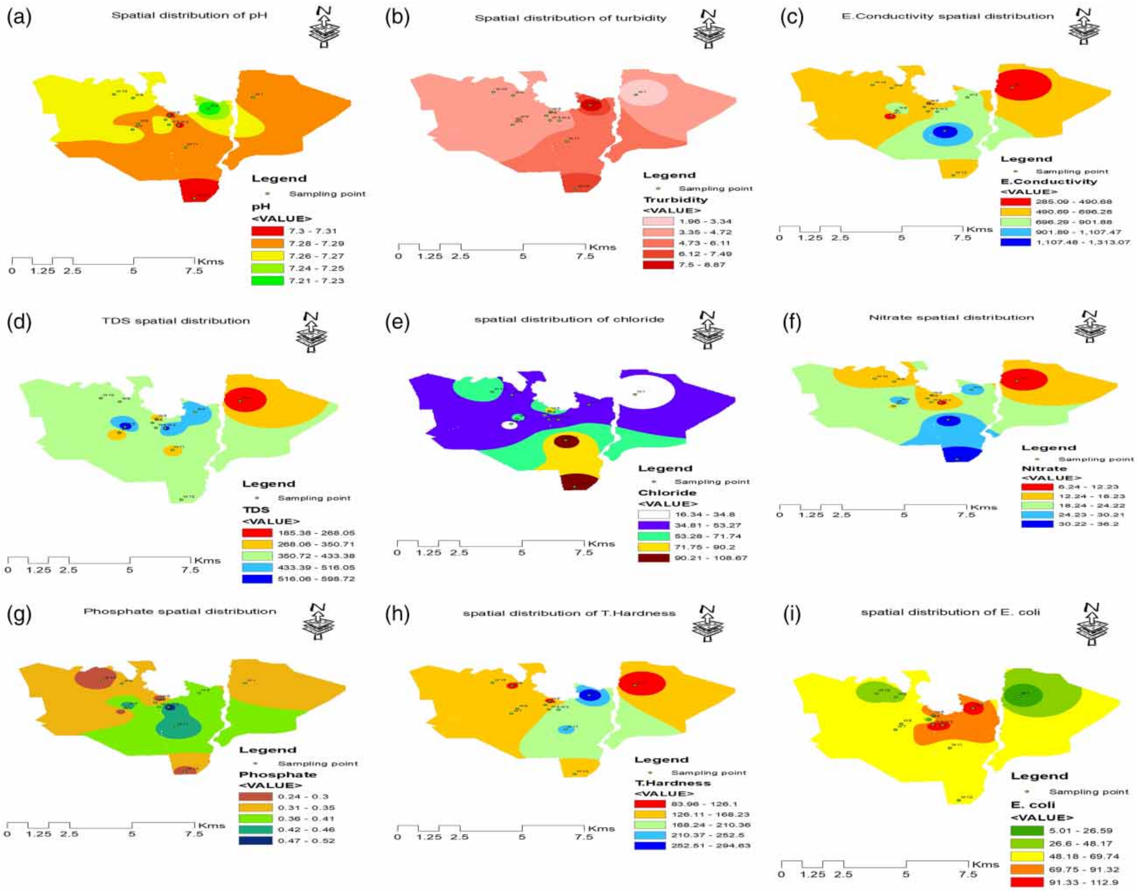

Figure 3 | Spatial distribution map of (a) pH, (b) turbidity, (c) EC, (d) TDS, (e) chloride, (f) nitrate, (g) phosphate, (h) total hardness, and (i) *E. coli*.

Table 6 | The physico-chemical and bacteriological properties of sampled groundwater

Station	**pH**	**Turbidity NTU**	**EC µS/cm**	**TDS mg/l**	**Cl^- mg/l**	**NO_3^- mg/l**	**PO_4^{-3} mg/l**	**T. Hardness mg/l**	***E.coli* cfu/100 ml**
W_1	7.29	1.96	285.00	185.33	16.33	6.24	0.30	83.94	5.00
W_2	7.21	8.87	777.61	503.83	39.83	28.23	0.38	294.67	101.00
W_3	7.29	4.97	816.31	398.41	52.14	32.36	0.53	161.63	102.00
W_4	7.25	4.22	538.78	348.44	44.28	15.87	0.38	164.89	113.00
W_5	7.30	3.38	465.61	303.72	87.22	17.32	0.26	110.72	92.00
W_6	7.25	3.73	623.33	404.78	30.28	14.89	0.30	148.67	24.00
W_7	7.26	3.78	393.06	254.94	23.44	16.91	0.27	125.39	52.00
W_8	7.29	4.87	917.11	598.89	60.00	31.00	0.46	160.11	63.00
W_9	7.25	3.53	620.78	404.61	45.72	17.30	0.32	121.50	42.00
W_{10}	7.26	3.43	512.89	333.11	59.44	15.83	0.24	144.78	37.00
W_{11}	7.29	5.55	1313.39	853.22	108.67	35.18	0.46	218.89	52.00
W_{12}	7.31	7.32	561.50	357.89	106.13	36.20	0.41	157.22	44.00

limit. The highest value was observed in the mid-southern section of the city, namely in W_{11} of the sample station, according to the EC distribution shown in Figure 3(c). This study shows that inorganic dissolved solids like nitrate and phosphate, as well as the geology of the area through which the water flows, affect the EC of the water, indicating the presence of TDS. Similarly, Vincy *et al.* (2015) and Wondie (2009) illustrated that the greater EC in groundwater is related to increased dissolved solids, and an increased ion concentration in the water body can increase the EC of the water (Meride & Ayenew 2016).

The TDS concentration ranges from 185.33 to 853.22 mg/l at all measured stations, with an average value of 412.27 mg/l (Table 5). The greatest concentration of TDS was detected in W_2, W_8, and W_{11} (Figure 3(d), Table 6). The greater TDS concentration in the area is mostly attributable to anthropogenic activities such as the leaching of domestic and institutional sewage. Similarly, Prasanth *et al.* (2012) explored whether water mixed with residential sewage might percolate into the groundwater, resulting in an increase in TDS concentration.

Chloride concentrations range from 16.33 to 108.67 mg/l at all measured sites, with an average of 56.12 mg/l (Table 5). People with heart and kidney illnesses may be harmed by the high content of chloride in their drinking water (Saleem *et al.* 2016). However, according to the analysis results obtained from this study, the chloride concentration was within the acceptable level (250 mg/l) for drinking purposes in all sampled stations, as shown in Table 6. The largest concentrations were found in W_{11} and W_{12} (Figure 3(e), Table 6) which is related to the leaching of domestic organic waste and detergents, as well as the leaching of animal manure near the sampling stations, fertilizers, and septic tanks. Similarly, Prasanth *et al.* (2012), Graham & Polizzotto (2013), Saleem *et al.* (2016), and Rabeiy (2018) looked into the possibility of chloride in groundwater being caused by domestic or municipal sewage.

The concentration of nitrate (NO_3^-) in groundwater samples ranged from 6.24 to 36.2 mg/l, with an average value of 22.28 mg/l (Table 5). Excess concentration of nitrate in drinking water can induce methaemoglobinemia or blue infants in babies, as well as gastric cancer and affect central neurological and cardiovascular systems. As indicated in Figure 3(f) and Table 6, the highest concentrations of nitrate were found in W_{11} and W_{12}, which is mostly attributable to the poor sanitary conditions and indiscriminate use of higher fertilizers, primarily animal dung, in the sampled area. Similarly, sewage, agricultural fertilizers, and animal dung are the main sources of nitrate in the water body, according to Graham & Polizzotto (2013) and Lawrence *et al.* (2001). However, the concentration of dissolved nutrients of NO_3^- in all sampled station was within the prescribed limit (MOH, F.D.R.E 2011; WHO 2011).

The phosphate (PO_4^{-3}) concentrations in all groundwater stations ranged from 0.24 to 0.53 mg/l, with an average of 0.36 mg/l (Table 5). The concentrations of dissolved nutrients of PO_4^{-3} in all measured stations were widely spread across the entire area, as indicated in Figure 3(g), and were all above the drinking water quality level. The existence of anthropogenic pollution activity in the area is primarily responsible for the higher phosphate concentration in the area. Similarly, higher phosphate concentrations are linked to high sediment accumulation from fertilized agricultural land, grazing cattle feces, and a high water table near the soil surface, all of which contribute to reduced soil conditions (Akale *et al.* 2017).

Water hardness is primarily induced by the presence of cations such as calcium and magnesium, as well as anions such as chloride, bi-carbonate, and carbonates in the water (Ravikumar *et al.* 2011). Total hardness concentrations in drinking water are allowed to be between 150 and 300 mg/l, but anything higher might cause kidney and cardiac problems. However, overall hardness concentrations in the research region ranged from 83.94 to 294.67 mg/l as $CaCO_3$, with an average value of 157.70 mg/l as $CaCO_3$ (Table 5). When compared to the standard 300 mg/l, the concentration of total hardness in all sampled groundwater sites was clearly within the allowed limit for drinking water quality (Table 6).

The total hardness spatial distribution map (Figure 3(h)) demonstrates that the bulk of the groundwater samples (50%) fall into the hard water category. Groundwater with total hardness concentrations of 75, 75–150, 150–300, and >300 mg/l are classified as soft, moderately hard, hard, and extremely hard, respectively, based on total hardness concentrations (Prasanth *et al.* 2012).

E.coli is most commonly found in wastewater from poorly built sanitation facilities such as pit latrines and septic tanks (Lawrence *et al.* 2001; Graham & Polizzotto 2013; Meride & Ayenew 2016). During the rainy season, severe contamination was seen due to wastewater seeping into shallow groundwater via preferential flow routes that short-circuit the surface with the groundwater. The highest level of *E.coli* in the area was detected in the central part of the city, which is likely caused by wastewater generated from institutional and commercial centers (Figure 3(i)). The bacteriological study in the area revealed that all twelve (12) sampling stations were quantitatively positive for fecal coliform count. The number of fecal coliforms in each sample station ranged from 5 to 113 colony/100 ml (Table 5). The *E.coli* levels found in all of the investigated sites were compared to WHO (2011) and MoH, F.D.R.E (2011) drinking water quality standards. In all of the sampled seasons, the results showed that 100% of the wells were infected with *E. coli*. This means the groundwater is contaminated and detrimental to people's health.

4.1. Water quality index (WQI) analysis and mapping

A Water Quality Index (WQI) is a tool that is used to summarize a significant quantity of data in a simple format for the purposes of consistent water quality and public health management (Puri *et al.* 2015). To assess the current state of Bahir Dar city groundwater quality, MoH, F.D.R.E (2011) and WHO (2011) drinking water quality standards were considered first, followed by assigning a weight (W_i) to each physico-chemical water quality parameter based on their perceived effect on public health (Saleem *et al.* 2016; Rabeiy 2018) as shown in Table 3. Because of their relevance in assessing groundwater quality, TDS, chloride, and nitrate have been given a maximum weight of five (5) (Srinivasamoorthy *et al.* 2008). Other water quality parameters, such as pH, turbidity, EC, phosphate, and total hardness, were given a weight of three (3) based on their importance in determining water quality for drinking.

Second, as indicated in the methodology section, the relative weight of each groundwater quality parameter is evaluated using Equation (1) (Shabbir & Ahmad 2015). Table 7 shows the computed relative weights of each physico-chemical water quality parameter.

Table 7 | The computed relative weight of each physico-chemical water quality parameter

Physico-chemical parameter	Relative weight (W_i)
pH	0.100
Turbidity	0.100
EC	0.100
TDS	0.167
Chloride	0.167
Nitrate	0.167
phosphate	0.100
Total hardness	0.100
	$\Sigma W_i = 1$

Thirdly, the quality rating scale (q_i) for each groundwater quality parameter is calculated by dividing the concentration of each water quality parameter by its respective water quality standard (WHO 2011) and multiplying by 100, as described in the methodology section. Table 8 shows the calculated quality rating scale (q_i) of each physico-chemical water quality parameter at each station.

Table 8 | The water quality rating scale of each physico-chemical water quality parameter at each station

	Water quality rating											
Parameter	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}	W_{11}	W_{12}
pH	19.48	13.78	19.15	16.59	19.85	16.44	17.52	19.15	16.41	17.48	19.52	20.41
Turbidity	39.14	177.38	99.32	84.47	67.62	74.66	75.62	97.48	70.54	68.54	110.9	146.5
EC	28.5	77.76	81.63	53.88	46.56	62.33	39.31	91.71	62.08	51.29	131.3	56.15
TDS	37.07	100.77	79.68	69.69	60.74	80.96	50.99	119.8	80.92	66.62	170.6	71.58
Chloride	6.53	15.93	20.86	17.71	34.89	12.11	9.38	24.00	18.29	23.78	43.5	42.45
Nitrate	13.86	62.74	71.91	35.27	38.48	33.10	37.58	68.89	38.43	35.17	78.2	80.45
Phosphate	1494.4	1897	2647	1916	1283	1486	1352	2316	1580	1208	2300	2025
Total hardness	27.98	98.22	53.88	54.96	36.91	49.56	41.80	53.37	40.50	48.26	73.00	52.41

Finally, as indicated in the methodology section, the sub-index of *i*th parameter (SI_i) is derived to compute the WQI for each physico-chemical water quality parameter. Table 9 shows the sub-index of the *i*th parameter that was analyzed in this study.

Table 9 | The sub-index of each physico-chemical water quality parameter at each station

	Sub-index of each parameter at each station											
Parameter	**W_1**	**W_2**	**W_3**	**W_4**	**W_5**	**W_6**	**W_7**	**W_8**	**W_9**	**W_{10}**	**W_{11}**	**W_{12}**
pH	1.95	1.38	1.92	1.66	1.99	1.64	1.75	1.91	1.64	1.75	1.95	2.04
Turbidity	3.91	17.74	9.93	8.45	6.76	7.47	7.56	9.75	7.05	6.85	11.09	14.65
EC	2.85	7.78	8.16	5.39	4.66	6.23	3.93	9.17	6.21	5.13	13.13	5.62
TDS	6.18	16.79	13.28	11.61	10.12	13.49	8.50	19.96	13.49	11.10	28.44	11.93
Chloride	1.09	2.66	3.48	2.95	5.81	2.02	1.56	4.0	3.05	3.96	7.24	7.08
Nitrate	2.31	10.46	11.9	5.88	6.41	5.52	6.26	11.48	6.41	5.86	13.03	13.41
Phosphate	149.4	189.7	264.7	191.7	128.3	148.6	135.28	231.7	158.1	120.8	230.0	202.5
Total hardness	2.8	9.82	5.39	5.5	3.69	4.96	4.18	5.34	4.05	4.83	7.30	5.24

The WQI at each station was determined by summing the sub-index value of each physico-chemical water quality parameter. The classification of water quality status at each station was classified by taking the standard water quality index bases which is presented in Table 10.

Table 10 | The estimated WQI value at each station

Station	***X*-co-ordinate**	***Y*-co-ordinate**	**WQI rate**	**Classification**
W_1	37.415	11.606	170.53	Poor water quality
W_2	37.398	11.599	256.34	Very poor water quality
W_3	37.387	11.588	318.86	Unfit for drinking
W_4	37.383	11.588	233.10	Very poor water quality
W_5	37.384	11.594	167.78	Poor water quality
W_6	37.382	11.592	189.94	Poor water quality
W_7	37.370	11.585	169.03	Poor water quality
W_8	37.372	11.589	300.28	Unfit for drinking
W_9	37.370	11.606	200.95	Very poor water quality
W_{10}	37.363	11.608	160.32	Poor water quality
W_{11}	37.390	11.574	312.19	Unfit for drinking
W_{12}	37.393	11.541	262.46	Very poor water quality

The results of this research (Table 10) revealed that 41.67% of sample stations have a low groundwater quality status, 33.33% have a very bad groundwater quality status, and the remaining 25% have groundwater that is unsafe for consumption. The WQI spatial distribution map (Figure 4) shows that three stations (W_3, W_8, and W_{11}) which are found in the Central and Mid-Southern areas of the city are deemed to be unfit for drinking purposes, and the rest stations have water quality indexes ranging from bad to extremely poor. In general, the quality of the city's groundwater is deteriorated in the central and Mid-Southern areas of the city.

5. CONCLUSION

In the present study, an attempt was made to assess and examine the groundwater quality status of Bahir Dar city which is found in the northern part of Ethiopia. The study evaluated the physico-chemical and bacteriological groundwater quality characteristics for the designated (drinking) water use. For the analysis of spatial patterns of groundwater quality, SPSS, GIS, and WQI have been applied.

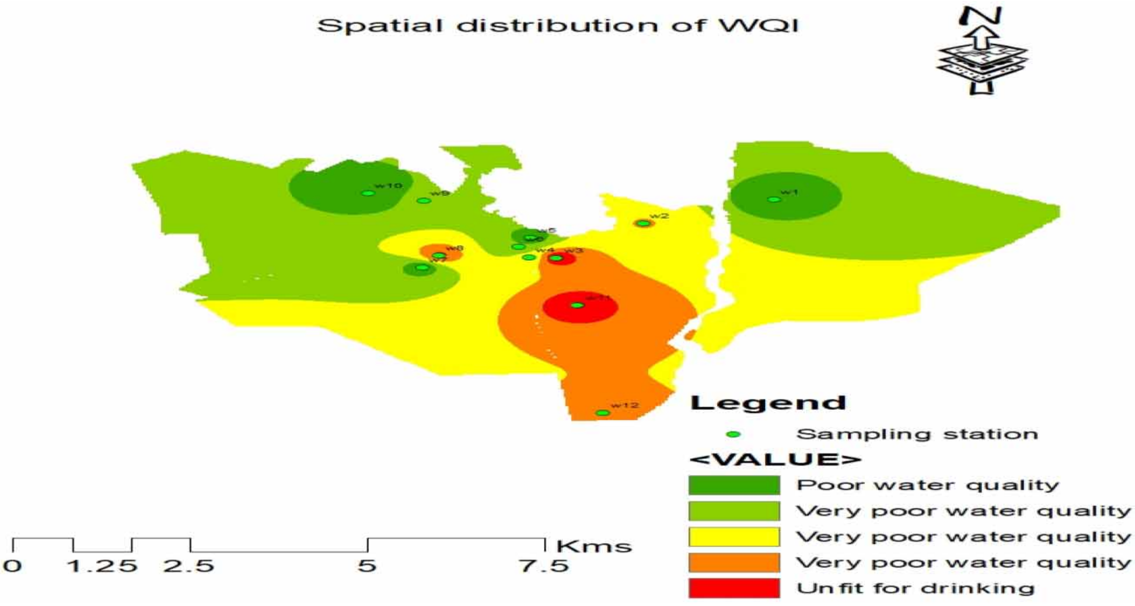

Figure 4 | Spatial distribution map of the Water Quality Index.

The spatial distribution of each physico-chemical and bacteriological map showed that the highest concentration was found in the Central and Mid-Southern regions of the surveyed field. In particular, turbidity, EC, TDS, phosphate, and *E.coli* concentrations in the Central and Mid-Southern regions were found beyond the drinking water quality standard. These highly polluted regions were located in the areas where higher groundwater table was available and this is mainly due to seepage of wastewater to the shallow groundwater from improperly constructed and designed sanitation facilities, animal dung from animal breeding areas and due to the seepage of fertilizers from agricultural area. Moreover, the evaluation of groundwater quality status using the WQI showed that 41.67% of sampling stations had poor groundwater quality, 33.33% of the sampling stations had very poor groundwater quality, whereas the remaining 25% of the sampling stations had unfit groundwater quality for drinking purpose.

The overall study indicates that almost more than half (>58%) of the sampled water showed that the groundwater quality status is very poor and is unfit for drinking purposes. From this study, it is suggested that proper treatment of the groundwater is essential before its use for domestic purposes in the study area.

6. RECOMMENDATION

It is recommended that residents of the Bahir Dar city shallow well-users should be conscientized about the status of the water they are using and the cheap effective possible methods of treatment of water such as boiling and use of chlorination tablets so as to prevent possible adverse health effects. In addition, the attention of concerned authorities must be made to take appropriate steps in providing necessary waste management facilities to supply safe drinking water to the residents such as the provision of a standard sanitary landfill system and proper lining of soak-away and pit-latrine should be enforced in the area so as to prevent the groundwater contamination. Also, continuous water quality control monitoring should be done to prevent and control pollution in order to safeguard human health and to facilitate Bahir Dar's attainment of the Sustainable Development Goals (SDGs) for water and sanitation. In general, the findings of this study will be useful for government, policy-makers as well as the public to be aware of the status of groundwater contamination and will be supportive of monitoring and managing the vulnerability of water resources to mitigate its adverse impacts on human health in the district.

AUTHOR CONTRIBUTIONS

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by C.M.A., Y.F.A., G.S.A., and S.S.E. The first draft of the manuscript was written by C.M.A. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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CONSENT FOR PUBLICATION

The paper reflects the authors' own research and analysis in a truthful and complete manner. All authors express their consent to publish.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT FOR INTEREST

The authors declare there is no conflict.

REFERENCES

Abbasnia, A., Yousefi, N., Mahvi, A. H., Nabizadeh, R., Radfard, M., Yousefi, M. & Alimohammadi, M. 2019 Evaluation of groundwater quality using water quality index and its suitability for assessing water for drinking and irrigation purposes: Case study of Sistan and Baluchistan province (Iran). *Human and Ecological Risk Assessment: An International Journal* **25**(4), 988–1005. doi: 10.1080/10807039.2018.1458596.

Abdul Hameed, M., Jawad, A., Haider, S. A. & Bahram, K. M. 2010 Application of water quality index for assessment of Dokan lake ecosystem, Kurdistan region, Iraq. *Journal of Water Resource and Protection* **2**(9), 792–798.

Akale, A. T., Dagnew, D. C., Giri, S., Belete, M. A., Tilahun, S. A., Mekuria, W. & Steenhuis, T. S. 2017 Groundwater quality in an upland agricultural watershed in the sub-humid Ethiopian highlands. *Journal of Water Resource and Protection* **9**(10), 1199–1212.

Akter, T., Jhohura, F. T., Akter, F., Chowdhury, T. R., Mistry, S. K., Dey, D. & Rahman, M. 2016 Water Quality Index for measuring drinking water quality in rural Bangladesh: A cross-sectional study. *Journal of Health, Population and Nutrition* **35**(1), 1–12.

Alemayehu, T. 2001 The impact of uncontrolled waste disposal on surface water quality in Addis Ababa, Ethiopia. *SINET: Ethiopian Journal of Science* **24**(1), 93–104.

Alemu, C. M., Aycheh, Y. F., Angualie, G. S. & Ejigu, K. M. 2022 Modelling on comprehensive evaluation of groundwater quality status using geographic information system (GIS) and water quality index (WQI) in case of Bahir Dar City, Amhara, Ethiopia. https://doi.org/10.21203/rs.3.rs-1474267/v1.

Amadi, A. N., Olasehinde, P. I., Yisa, J., Okosun, E. A., Nwankwoala, H. O. & Alkali, Y. B. 2012 Geostatistical assessment of groundwater quality from coastal aquifers of Eastern Niger Delta, Nigeria. *Geosciences* **2**(3), 51–59.

APHA. 1998 *Standard Method for Examination of Water and Waste Water*, 20th edn. American Public Health Association, Washington, DC, USA.

APHA. 2012 *Standard Methods for the Examination of Water and Wastewater*, 20th edn, Vol. 343 (Eaton, A. D., Clesceri, L. S. & Greenberg, A. E., eds). American Public Health Association, Washington.

Avvannavar, S. M. & Shrihari, S. 2008 Evaluation of water quality index for drinking purposes for river Netravathi, Mangalore, South India. *Environmental Monitoring and Assessment* **143**(1–3), 279–290.

Azeez, P. A., Nadarajan, N. R. & Mittal, D. D. 2000 The impact of a monsoonal wetland on ground water chemistry. *Pollution Research* **19**(2), 249–255.

Babiker, I. S., Mohamed, M. A. & Hiyama, T. 2007 Assessing groundwater quality using GIS. *Water Resources Management* **21**(4), 699–715.

Boateng, T. K., Opoku, F., Acquaah, S. O. & Akoto, O. 2016 Groundwater quality assessment using statistical approach and water quality index in Ejisu-Juaben Municipality, Ghana. *Environmental Earth Sciences* **75**(6), 489.

El Mountassir, O., Bahir, M., Ouazar, D., Ouhamdouch, S., Chehbouni, A. & Ouarani, M. 2020 The use of GIS and water quality index to assess groundwater quality of krimat aquifer (Essaouira; Morocco). *SN Applied Sciences* **2**, 1–16.

Goshu, G. O. R. A. W. & Akoma, O. C. 2011 Water quality assessment of underground and surface water resources of bahir Dar and periurban areas, north-west Ethiopia. *Global Journal of Environmental Sciences* **10**(1&2), 11–21.

Graham, J. P. & Polizzotto, M. L. 2013 Pit latrines and their impacts on groundwater quality: A systematic review. *Environmental Health Perspectives* **121**(5), 521–530.

Hasan, S., Adham, A., Islam, M. T. & Islam, D. 2014 *Effect of Climate Change on Groundwater Quality for Irrigation Purpose in A Limestone Enriched Area. Doctoral dissertation*.

Johnston, K., Ver Hoef, J. M., Krivoruchko, K. & Lucas, N. 2001 *Using ArcGIS Geostatistical Analyst*, Vol. 380. Esri, Redlands.

Khan, R. & Jhariya, D. C. 2017 Groundwater quality assessment for drinking purpose in Raipur city, Chhattisgarh using water quality index and geographic information system. *Journal of the Geological Society of India* **90**, 69–76.

Khangembam, S. & Kshetrimayum, K. S. 2019 Evaluation of hydrogeochemical controlling factors and water quality index of water resources of the Barak valley of Assam, Northeast India. *Groundwater for Sustainable Development* **8**, 541–553.

Khatri, N. & Tyagi, S. 2015 Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Frontiers in Life Science* **8**(1), 23–39.

Khosravi, R., Eslami, H., Almodaresi, S. A., Heidari, M., Fallahzadeh, R. A., Taghavi, M. & Peirovi, R. 2017 Use of geographic information system and water quality index to assess groundwater quality for drinking purpose in Birjand City, Iran. *Desalination and Water Treatment* **67**(1), 74–83.

Kumar, M., Kumari, K., Ramanathan, A. L. & Saxena, R. 2007 A comparative evaluation of groundwater suitability for irrigation and drinking purposes in two intensively cultivated districts of Punjab, India. *Environmental Geology* **53**(3), 553–574.

Lawrence, A. R., Macdonald, D. M. J., Howard, A. G., Barrett, M. H., Pedley, S., Ahmed, K. M. & Nalubega, M. 2001 *Guidelines for Assessing the Risk to Groundwater From on-Site Sanitation*.

Meride, Y. & Ayenew, B. 2016 Drinking water quality assessment and its effects on residents health in Wondo genet campus, Ethiopia. *Environmental Systems Research* **5**(1), 1.

MoH, F. D. R. E. 2011 The Federal Democratic Republic of Ethiopia Ministry of Health, National Drinking Water Quality Monitoring and Surveillance Strategy.

Prasanth, S. S., Magesh, N. S., Jitheshlal, K. V., Chandrasekar, N. & Gangadhar, K. 2012 Evaluation of groundwater quality and its suitability for drinking and agricultural use in the coastal stretch of Alappuzha District, Kerala, India. *Applied Water Science* **2**(3), 165–175.

Puri, P. J., Yenkie, M. K. N., Rana, D. B. & Meshram, S. U. 2015 Application of water quality index (WQI) for the assessment of surface water quality (Ambazari Lake). *European Journal of Experimental Biology* **5**(2), 37–52.

Rabeiy, R. E. 2018 Assessment and modeling of groundwater quality using WQI and GIS in Upper Egypt area. *Environmental Science and Pollution Research* **25**(31), 30808–30817.

Rajankar, P. N., Tambekar, D. H. & Wate, S. R. 2011 Groundwater quality and water quality index at Bhandara District. *Environmental Monitoring and Assessment* **179**(1–4), 619–625.

Ramakrishnaiah, C. R., Sadashivaiah, C. & Ranganna, G. 2009 Assessment of water quality index for the groundwater in Tumkur Taluk, Karnataka State, India. *E-Journal of Chemistry* **6**(2), 523–530.

Ravikumar, P., Somashekar, R. K. & Angami, M. 2011 Hydrochemistry and evaluation of groundwater suitability for irrigation and drinking purposes in the Markandeya River basin, Belgaum District, Karnataka State, India. *Environmental Monitoring and Assessment* **173**(1–4), 459–487.

Ravikumar, P., Mehmood, M. A. & Somashekar, R. K. 2013 Water quality index to determine the surface water quality of Sankey tank and Mallathahalli Lake, Bangalore urban district, Karnataka, India. *Applied Water Science* **3**(1), 247–261.

Sahu, P. & Sikdar, P. K. 2008 Hydrochemical framework of the aquifer in and around East Kolkata Wetlands, West Bengal, India. *Environmental Geology* **55**(4), 823–835.

Saleem, M., Hussain, A. & Mahmood, G. 2016 Analysis of groundwater quality using water quality index: A case study of greater Noida (Region), Uttar Pradesh (UP), India. *Cogent Engineering* **3**(1), 1237927.

Saleh, H. N., Panahande, M., Yousefi, M., Asghari, F. B., Oliveri Conti, G., Talaee, E. & Mohammadi, A. A. 2019 Carcinogenic and non-carcinogenic risk assessment of heavy metals in groundwater wells in Neyshabur Plain, Iran. *Biological Trace Element Research* **190**, 251–261. doi:10.1007/s12011-018-1516-6.

Selvam, S., Manimaran, G., Sivasubramanian, P., Balasubramanian, N. & Seshunarayana, T. 2014 GIS-based evaluation of water quality index of groundwater resources around Tuticorin coastal city, South India. *Environmental Earth Sciences* **71**, 2847–2867.

Shabbir, R. & Ahmad, S. S. 2015 Use of geographic information system and water quality index to assess groundwater quality in Rawalpindi and Islamabad. *Arabian Journal for Science and Engineering* **40**(7), 2033–2047.

Singh, P. & Khan, I. A. 2011 Ground water quality assessment of Dhankawadi ward of Pune by using GIS. *International Journal of Geomatics and Geosciences* **2**(2), 688–703.

Solangi, G. S., Siyal, A. A., Babar, M. M. & Siyal, P. 2019 Groundwater quality evaluation using the water quality index (WQI), the synthetic pollution index (SPI), and geospatial tools: A case study of Sujawal district, Pakistan. *Human and Ecological Risk Assessment: An International Journal* **26**, 1529–1549.

Srinivasamoorthy, K., Chidambaram, S., Prasanna, M. V., Vasanthavihar, M., Peter, J. & Anandhan, P. 2008 Identification of major sources controlling groundwater chemistry from a hard rock terrain – a case study from Mettur taluk, Salem district, Tamil Nadu, India. *Journal of Earth System Science* **117**(1), 49.

Sumathi, V. R., Natesan, U. & Sarkar, C. 2008 GIS-based approach for optimized siting of municipal solid. *Waste Management* **28**(11), 2146–2160.

Tiwari, A. K., Singh, P. K. & Mahato, M. K. 2014 GIS-based evaluation of water quality index of ground water resources in West Bokaro Coalfield, India. *Current World Environment* **9**(3), 843.

Tyagi, S., Sharma, B., Singh, P. & Dobhal, R. 2013 Water quality assessment in terms of water quality index. *American Journal of Water Resources* **1**(3), 34–38.

Vincy, M. V., Brilliant, R. & Pradeepkumar, A. P. 2015 Hydrochemical characterization and quality. assessment of groundwater for drinking and irrigation purposes: A case study of Meenachil River Basin, Western Ghats, Kerala, India. *Environmental Monitoring and Assessment* **187**(1), 4217.

WHO (World Health Organization). 2011 Guidelines for drinking water quality. *WHO Chronicle* **4**(38), 104–108.

Wondie, T. A. 2009 *The Impact of Urban Storm Water Runoff and Domestic Waste Effluent on Water Quality of Lake Tana and Local Groundwater Near the City of Bahir Dar, Ethiopia*. *Doctoral dissertation*, Cornell University.

Yolcubal, I., Gunduz, O. C. & Sonmez, F. 2016 Assessment of the impact of environmental pollution on groundwater and surface water qualities in a heavily industrialized district of Kocaeli (Dilovasi), Turkey. *Environmental Earth Sciences* **75**, 170.

Yousefi, M., Ghoochani, M. & Mahvi, A. H. 2018 Health risk assessment to fluoride in drinking water of rural residents living in the Poldasht city, Northwest of Iran. *Ecotoxicology and Environmental Safety* **148**, 426–430.

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