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ORIGINAL RESEARCH ARTICLE

Assessment of groundwater quality in Borana Zone, Ethiopia: A multidimensional analysis using groundwater pollution index, nitrate pollution index, and water quality index

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Abstract: This study assessed groundwater quality in Yabelo, Elewaye, Gomole, and Duduluk towns in Ethiopia, analyzing 60 samples across 19 physicochemical parameters. The groundwater pollution index (GPI), nitrate pollution index (NPI), and water quality index (WQI) were used to evaluate drinking water suitability. Results showed turbidity, pH, bicarbonate, nitrite, and copper levels were within the World Health Organization recommended limits. However, 20% of the samples had high total dissolved solids and sulfate levels. Total hardness exceeded limits in 60% of the samples, and 40% had elevated nitrate concentrations. Chromium and fluoride were elevated by 10%, while total iron and manganese exceeded standards by 20%. The GPI indicated "Insignificant pollution" in 80% of samples and "Low pollution" in 20%. Among the samples, the NPI classified 50% as "Clean", 10% as "Low pollution", 30% as "Moderate", and 10% as "Very high pollution". The WQI rated 20% as "Good", 30% as "Very good", and 50% as "Excellent". This study provides valuable insights to help authorities in identifying protective measures and treatment methods for water resources.

Keywords: Borana Zone; Drinking water; Ethiopia, Groundwater; Groundwater pollution index; Nitrate pollution index; Physicochemical parameter; Water quality index

1. Introduction

Water is essential for life; without it, existence is impossible.[1] Groundwater is becoming an increasingly vital source of drinking water worldwide, as surface water is increasingly affected by pollution and climate change.[2,3] It is estimated that only 3% of Earth's water is freshwater, with 2.97% of this being locked in ice caps and glaciers, leaving only 0.03% available as surface and groundwater for human use.[4] In both urban and rural areas worldwide, groundwater serves as a crucial source of water for household consumption.[5] Water contamination can result from both anthropogenic sources, such as industrial activities, agricultural practices, improper waste disposal, and inadequate sewage systems, as well as natural sources, including microbial activity, geological factors, and naturally occurring contaminants.[6] To ensure water is safe for consumption, it is crucial to assess its quality, as potable water must be free from physical, chemical, and biological contaminants.[7]

Most people in developing nations obtain their drinking water from unprotected or contaminated sources, which heightens the risk of outbreaks of waterborne diseases.[8] Efforts to prevent and control waterborne diseases continue to depend on the quality of drinking water, which serves as a vital environmental indicator of public health.[9] Waterborne diseases, such as dysentery, cholera, diarrhea, and typhoid are caused by the consumption of contaminated water and can lead to pre-mature death, particularly in developing countries.[10]

Ethiopia has the lowest rate of access to safe drinking water among sub-Saharan African nations.[11] In recent times, the demand for water and subsequent groundwater abstraction has increased across Ethiopia, as surface water bodies have become increasingly prone to pollution.[12] Although the government does not have regular and comprehensive water quality testing programs, there are growing concerns about the pollution of both surface and groundwater sources in some areas.[4]

Evaluating water quality based on the concentrations of various components can be challenging.[3] To effectively summarize water quality while preserving scientific integrity, the water quality index (WQI) method is highly valuable.[13] The WQI serves as a powerful tool for conveying groundwater quality information to the public and policymakers. Its primary objective is to transform complex water quality data into understandable and actionable information, focusing on the suitability of groundwater for human consumption.[14] This index assigns a single value that reflects the overall water quality at a specific location and time, based on a range of water quality parameters. It also enhances the interpretability of these parameters and facilitates comparisons across different sampling sites.[15,16] Conversely, the groundwater pollution index (GPI), developed by Rao,[17] is another methodology used to assess groundwater quality. The GPI has been effectively applied in monitoring drinking water quality in various regions, as shown in studies by Sanad *et al.*[13] and Al-Aizari *et al.*[18] On the other hand, the nitrate pollution index (NPI) is a numerical value used to assess the extent of nitrate contamination in groundwater.[19]

However, limited studies in Ethiopia have assessed groundwater quality using the WQI, GPI, and NPI. Even more concerning is the absence of such studies in the Borana Zone of the Oromia region, an arid area where access to fresh drinking water remains a significant challenge and groundwater serves as the primary source of drinking water. Despite its significance, the physicochemical quality of groundwater sources in the Borana Zone, particularly in the towns of Yabelo, Dubuluk, Elewaye, and Gomole, has not been thoroughly studied.

Therefore, this exploratory study aimed to: (1) assess the physicochemical properties of groundwater sources in the Borana Zone, particularly in the towns of Yabelo, Dubuluk, Elewaye, and Gomole; and (2) conduct a comprehensive evaluation of groundwater quality in the designated study area using the WQI, GPI, and NPI techniques to assess its suitability for drinking.

This comprehensive approach provides a holistic perspective on groundwater quality and its implications for the suitability of drinking water sources, while also enabling the identification of associations between groundwater characteristics and their potential impacts on human health. Comprehending the complex relationships between groundwater quality and the suitability of drinking water is crucial for developing effective water resource management strategies. Moreover, it is crucial for minimizing the undesirable impacts of deteriorating water quality on water use and eventually human well-being.

1.1. Description of the study area

The Borana Zone of the Oromia region is located in the southernmost part of Ethiopia (Figure 1), bordering the West Guji Zone to the north, Kenya to the south, the Guji Zone and Somali Regional State to the east, and the Southern Nations region to the west. Its geographical location is 3°30′N – 5°25′N latitude and 36°40′E – 39°45′E longitude. The area is characterized by a semi-arid to arid climate and is primarily inhabited by pastoral and agro-pastoral Borana communities. The town of Yabelo, located 575 km south of Addis Ababa along the route to Moyale-Kenya, is the administrative seat of the Borana Zone. The zone covers an area of approximately 95,000 km^2, with 75% classified as lowland, and has an overall population density of six inhabitants per square kilometer.[20,21]

The Borana Zone's ephemeral drainage system is located within the Genale-Dawa River Basin. Groundwater levels in the study area are generally deep, and there are no perennial rivers. Rainfall in the zone is highly variable, both spatially and temporally. As a result, rural communities in Borana Zone have limited access to clean drinking water. The primary water sources for pastoralists in the area include open surface water, such as runoff, floodwater, ponds, and micro-dams, as well

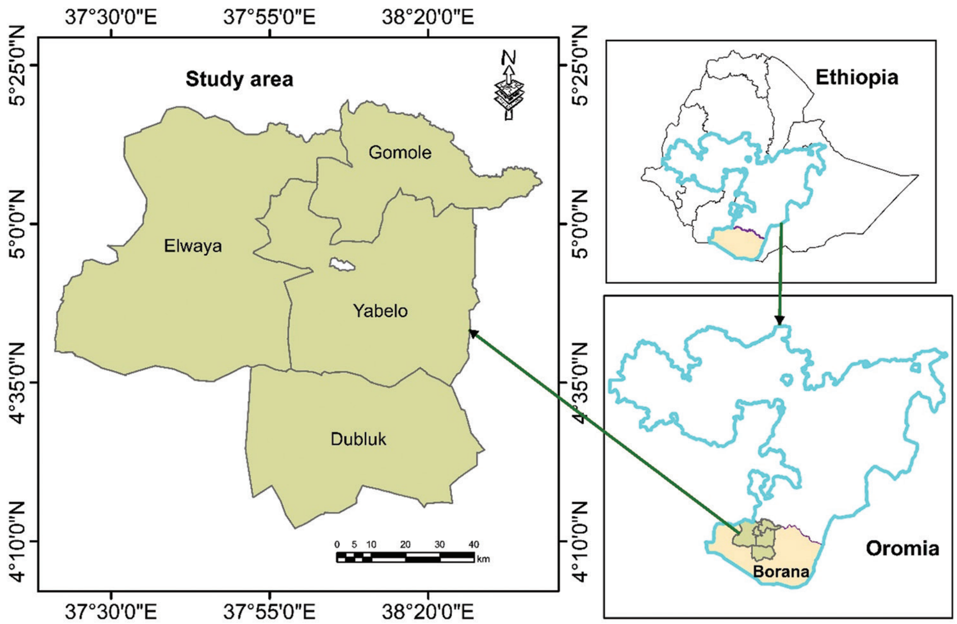

Figure 1. Location map of the study area showing the locations of Yabelo, Dubluk, Elwaya, and Gomole

as groundwater sources, such as boreholes, shallow wells (locally known as "Adadi" or "Tula wells"), and motorized pumps. These water sources are used for both domestic purposes and livestock consumption, depending on the season. During the wet season, runoff and floodwater are used, whereas ponds, boreholes, and micro-dams become the primary water sources during the dry season. The remaining water sources are mainly used during periods of drought.[22,23]

2. Materials and methods

2.1. Water sampling and preservation

In addition to Yabelo Township, which includes Borana University, the water sampling process encompassed three surrounding towns: Elewaye, Dubluk, and Gomole (Figure 1). These towns were selected using a purposive sampling method, based on the community concerns and dissatisfaction with the quality of some available ground water sources for drinking. The study included all four borehole sources that supply drinking water to Yabelo town, as well as two randomly selected groundwater sources from each Elewaye, Dubluk, and Gomole towns (Table 1). In total, water samples were collected from ten sampling sites, as outlined in Table 1.

Water samples were collected in 1 L polyethylene plastic bottles from June to August 2023, with a 2-week interval between each collection, to analyze nineteen physicochemical parameters, following the methodologies outlined by Gintamo *et al.*,[24] and Garoma *et al.*[25] Before sampling, the bottles were thoroughly cleaned using detergents according to the protocol described by Gebresilasie *et al.*[5] The bottles were then treated with 5% nitric acid (HNO_3) (Nanjing Taibai Chemical Co., Ltd, China) and left to acidify for 24 h. After acidification, the bottles were rinsed twice with distilled water and subsequently rinsed 3 times with sample water before being filled with the groundwater sample.

A total of 60 water samples were collected from 10 different sampling sites (Table 1), with two bottles per site during each sampling event, and each sampling event repeated 3 times. The first bottle was acidified with HNO_3 for major ion analysis, while the second bottle remained unacidified for the analysis of other physicochemical parameters.[26,27] To ensure the samples accurately reflect the groundwater chemistry, the water volume was flushed at least twice during pumping to obtain fresh groundwater before sampling, as described by Sanad *et al.*[13]

Each sample bottle was labeled with a unique sample code and stored at 4°C in a dark place to maintain stable conditions until analysis.[19,28]

2.2. Analysis of water samples

2.2.1. Determination of physical parameters

Temperature, turbidity, pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured *in situ* at each sampling site. Water temperature was measured using a mercury thermometer (Jiangsu Exact

Table 1. Description of groundwater sampling sites of the study area

Sampling site	Location/town	Description of sampling site
Y1	Yabelo	Dollolo Hola deep tube well 1
Y2	Yabelo	Dollolo Hola deep tube well 2
Y3	Yabelo	Garbi spring water
Y4	Yabelo	Mebiratu private deep tube well
E1	Elewaye	China-constructed deep tube well
E2	Elewaye	Turk-constructed deep tube well
S1	Gomole	Protected Hund dung well ("Tula well")
S2	Gomole	Goro Gudina shallow tube well
D1	Dubuluk	Ali scheme shallow tube well
D2	Dubuluk	Manhariya scheme shallow tube well

Instrument Technology Co., Ltd. China), which was calibrated using the ice-water method. Turbidity and pH were determined using a portable turbidity meter (Model 2100Q, HACH, USA) and a portable pH meter (Model HI9024, HANNA Instruments, Italy), respectively. The turbidity meter was calibrated using turbidity standards of 0.5, 10, and 20 NTU, prepared by diluting precise volumes of a 100 NTU Stablcal Stabilized Formazin Turbidity Standard solution (HACH, UK) with deionized water in a volumetric flask. Meanwhile, the pH meter was calibrated using standard buffer solutions of pH 4.01, 7.01, and 10.01, ensuring coverage of a broad pH range.[29] The EC and TDS were measured using a portable digital multi-parameter meter (Model HQ440D, HACH, USA) after calibrating with the Myron L KCl-1800 Conductivity/TDS standard solution (Myron L Company, USA), which has a potassium chloride (KCl) concentration equivalent to 1800 μS/cm.

2.2.2. Determination of chemical parameters

The chemical composition of the drinking water samples was analyzed for the following parameters: bicarbonate (HCO_3^-), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), total hardness (TH), total alkalinity (TA), sulfate (SO_4^{2-}), nitrate (NO_3^-), nitrite (NO_2^-), phosphate (PO_4^{3-}), copper (Cu^{2+}), manganese (Mn^{2+}), total iron (total Fe), fluoride (F^-), and chromium (Cr^{6+}). These tests were conducted at the drinking water quality control laboratory of the Oromia National Regional State in Addis Ababa, Ethiopia. The concentrations of K^+, SO_4^{2-}, NO_3^-, NO_2^-, PO_4^{3-}, Cu^{2+}, Mn^{2+}, total Fe, F^-, and Cr^{6+} were measured using a ultraviolet-visible (UV-Vis) spectrophotometer (DR6000, HACH, USA), following the standard procedures outlined by American Public Health Association.[30] The methods and reagents employed for analyzing the parameters using the DR 6000 UV-VIS spectrophotometer are outlined in Table 2. Sample cup 9418100 was used for phosphate testing, while sample cell 2495402 was used for testing the other parameters, utilizing reagent powder pillow additions, with both tests conducted using the DR 600 UV-Vis spectrophotometer.

Ca^{2+}, Mg^{2+}, and total hardness (TH) levels were determined using complexometric titration with ethylene diamine tetra acetic acid (EDTA) (Henan Honghai Chemical Co., Ltd, China) in the presence of the eriochrome black T (EBT) indicator (Sigma-Aldrich, China).[13,19,24] Bicarbonate (HCO_3^-) concentration of the water sample was measured using a titrimetric method with a standard sulfuric acid solution, along with a mixed indicator solution (Sigma-Aldrich, China) of bromocresol green and methyl red, which turned pink at the endpoint of the titration.[16,31] The total alkalinity (TA) of the water sample was calculated based on its bicarbonate (HCO_3^-) concentration. For the analysis of Cu^{2+}, total Fe, Mn^{2+}, and Cr^{6+}, the water samples were initially digested to eliminate organic impurities and prevent interference during the analysis.[7] Concentrated nitric acid (*DFPCL, India*) was used for digestion, in accordance with a published methodology.[5]

2.3. Determination of GPI

The GPI, developed by Rao,[17] is a methodology designed to assess groundwater quality. The calculation of the GPI follows five key steps, as demonstrated in the study by Sanad *et al.*[13] In the first step, individual water quality parameters were assigned weights (w_i) ranging from 1 to 5, based on their significance in determining the overall quality of groundwater and their potential impact on human health. These weights, as outlined in

Table 2. Methods and reagents used for chemical composition analysis using the ultraviolet-visible spectrophotometer

Parameter	Test method	Method number	Sample cell/ cup number	Reagent	Test range* (mg/L)
K^+	Tetraphenylborate	8049	2495402	Potassium 1 Reagent Powder Pillow	1.0 – 70.0
Cu^{2+}	USEPA[1,2] and bicinchoninate method[3]	8506	2495402	CuVer® 1 Copper Reagent Powder Pillow	0.04 – 5.00
Total Fe	USEPA[1] and FerroVer® method[2]	8008	2495402	FerroVer® Iron Reagent	0.02 – 3.00
Mn^{2+}	USEPA[1] and periodate oxidation method[2]	8034	2495402	Sodium Periodate and Manganese powder pillows	0.1 – 20.0
Cr^{6+}	USEPA[1] and 1,5-diphenylcarbohydrazide method[2]	8023	2495402	ChromaVer ® 3 Chromium Reagent Powder Pillows	0.010 – 0.700
NO_3^-	Cadmium reduction	8039	2495402	NitraVer® 5 Nitrate Reagent Powder Pillow	0.3 – 30.0
NO_2^-	USEPA diazotization method[1]	8507	2495402	NitriVer® 3 Reagent Powder Pillows	0.002 – 0.300
SO_4^{2-}	USEPA[1] and SulfaVer 4 method[2]	8051	2495402	SulfaVer® 4 Reagent Powder Pillows	2.0 – 70.0
PO_4^{3-}	Phosphomolybdate (ascorbic acid) method[1]	10279	9418100	Phosphate Low Range Chemkey® Reagents	0.02 – 4.00
F^-	USEPA SPADNS method[1]	8029	2495402	SPADNS Fluoride Reagent AccuVac® Ampuls	0.02 – 2.00

Notes: *The ranges given are for the pre-calibrated instrument readout. For sample sites where the concentrations of the parameters under investigation exceeded the upper quantification limit of the analytical method, the samples were diluted with deionized water to reduce the concentrations within the test range of the method.
Abbreviation: USEPA: United States Environmental Protection Agency.

Table 3. The weight assigned to each parameter for GPI calculation in previous studies and the present study

Parameter	Berhe[12]	Sanad *et al.* [13]	Al-Aizari *et al.* [18]	Panneerselvam *et al.* [19]	Ha *et al.* [32]	Present study
TDS	-	2	4	4	5	5
pH	-	4	4	4	4	4
HCO_3^-	1	2	-	3	2	1
K^+	2	3	1	-	2	2
Mg^{2+}	3	3	2	2	3	3
Ca^{2+}	3	3	2	2	3	3
TH	-	3	4	-	4	4
SO_4^{2-}	5	4	5	4	5	5
NO_3^-	5	5	5	5	5	5
PO_4^{3-}	1	4	-	-	-	1
Cu^{2+}	2	-	-	-	-	2
Total Fe	4	-	-	-	-	4
F^-	5	-	-	4	-	5

Abbreviations: TDS: Total dissolved solids; TH: Total hardness.

Table 3, were determined based on previous studies by Berhe,[12] Sanad *et al.,*[13] Al-Aizari *et al.,*[18] Panneerselvam *et al.,*[19,] and Ha *et al.*[32]

In the second step, the relative weight (W_i) (Table 4) for each parameter is calculated using Equation I, as described by Panneerselvam *et al.*[19]

$$Wi = \frac{wi}{\sum_{i=n}^{n} wi} \quad (I)$$

Where W_i is the relative weight, w_i is the weight of each parameter, and n is the number of parameters selected.

In the third step, the concentration status (Sc) for each parameter was calculated by dividing the concentration of individual chemical variables in each water sample by the corresponding drinking water quality standards (WQS) set by the World Health Organization (WHO),[33,34] using Equation II, as described by Al-Aizari *et al.*[18] In the fourth and fifth steps, the overall chemical quality of the water (Ow) and the GPI were assessed using Equations III and IV, respectively, as outlined by Sanad *et al.*[13]

$$Sc = \frac{C}{WQS} \quad (II)$$

where Sc is the concentration status, C is the concentration of individual physicochemical water quality parameters in each water sample and WQS is the drinking water quality standard of each physicochemical parameter set by the WHO.[33,34]

$$Ow = Wi \times Sc \quad (III)$$

where Ow is the overall chemical quality of the water, Wi is the relative weight, and Sc is the concentration status.

$$GPI = \sum_{i=n}^{n} Ow = \sum_{i=n}^{n} Wi \times Sc \quad (IV)$$

where GPI is the groundwater pollution index, Ow is the overall chemical quality of water and n is the number of parameters selected.

2.4. Determination of NPI

The NPI is a key indicator used to assess the level of nitrate contamination in groundwater. It plays a crucial role in evaluating water pollution caused by nitrates, particularly in areas impacted by human activities.[18] The NPI was calculated using Equation V, as outlined by Sanad *et al.*[13] Although the WHO guidelines[34] recommend a maximum nitrate concentration of 50 mg/L in drinking water, the human acceptable value (HAV) for nitrates is set at 20 mg/L. This threshold, supported by studies conducted by Sanad *et al.,*[13] Al-Aizari *et al.*,[18] and Panneerselvam *et al.,*[19] was used for calculating the NPI in the present study.

Table 4. The WHO standards[33,34] for drinking water quality, assigned wi, and calculated Wi for each parameter

Parameters	WQS	Wi	Wi
TDS	1000	5	0.114
pH	7	4	0.091
HCO_3^-	500	1	0.023
K^+	12	2	0.045
Mg^{2+}	50	3	0.068
Ca^{2+}	75	3	0.068
TH	500	4	0.091
SO_4^{2-}	250	5	0.114
NO_3^-	50	5	0.114
PO_4^{3-}	5	1	0.023
Cu^{2+}	2	2	0.045
Total Fe	0.3	4	0.091
F^{-}	1.5	5	0.114
		=44	=1

Abbreviations: WHO: World health organization; WQS: Water quality standards; TDS: Total dissolved solids; TH, Total hardness; wi: Weight values; Wi: Relative weight. Note: The pH value is reported in pH units, while concentrations of all other parameters are expressed in mg/L.

$$NPI = \frac{Cs - HAV}{HAV} \quad (V)$$

where NPI is the nitrate pollution index, Cs is the nitrate concentration in the groundwater (mg/L), and HAV denotes the human acceptable value for nitrate and is taken as 20 mg/L. The NPI values for all groundwater samples were then classified into one of five categories, as shown in Table 5.

2.5. Determination of WQI

The groundwater quality in the study area was assessed using the standard WQI model. This model was selected due to its widely recognized, standardized approach, which ensures consistent and reliable results across various studies and regions, thereby facilitating direct comparisons with other research findings.[3] The WQI calculation includes thirteen physicochemical

Table 5. Results of groundwater quality assessment in the ten sampling sites

Parameter	Sampling sites										Min.	Max.	ESA	WHO
	Y1	Y2	Y3	Y4	E1	E2	S1	S2	D1	D2				
Temperature	27	26.3	26.9	27.1	27	26.7	28.2	28.3	28.6	28.3	26.3	28.6	NGL	<15
Turbidity	0	0	0	0	2	1	1	4	0	0	0	4	5	5
TDS	701	582	99	626	346	326	371	144	1930	1560	99	1930	1000	1000
pH	6.96	6.46	6.39	6.51	8.11	6.78	6.92	6.25	6.38	6.62	6.25	8.11	6.5 – 8.5	6.5 – 8.5
HCO_3^-	178.2	134.2	217.2	190.3	273.3	297.7	164.7	158.6	366	439.2	134.2	366	NGL	500
TA	146	110	178	156	224	244	135	130	300	360	110	360	200	120
K^+	4.4	3.6	1.2	4.3	6.5	4.7	9.50	4.0	46.25	38.75	0.9	46.25	1.5	12
Mg^{2+}	21.12	52.8	9.12	6.24	5.76	27.36	4.80	16.8	79.2	74.4	4.80	79.2	50	50
Ca^{2+}	159.2	112	22.2	158.4	40.8	80.0	88	40	284	220	22.2	284	75	75
TH	486	500	96	422	126	314	240	170	1040	960	96	1040	300	500
SO_4^{2-}	210	122	2.5	140	17	3	62.5	11	360	325	2.5	360	250	250
NO_3^-	100.8	59.4	2.2	58.52	3.52	3.53	4.40	3.08	58.96	36.94	2.2	100.8	50	50
NO_2^-	0.003	0.003	0.005	0.008	0.006	0.004	0.006	0.009	0.006	0.008	0.003	0.009	3	3
PO_4^{3-}	0.35	0.38	0.21	0.2	0.28	0.2	0.70	1.22	0.22	0.30	0.2	1.22	NGL	5
F^-	1.01	0.98	0.32	1.18	2.52	0.59	0.43	0.40	1.19	1.29	0.32	2.52	1.5	1.5
Cu^{2+}	0.65	0.45	0.08	0.69	0.05	0.62	0.07	0.09	0.15	0.08	0.05	0.69	2	2
Cr^{6+}	0.011	0.008	0.021	0.012	0.06	0.015	0.015	0.013	0.023	0.026	0.011	0.06	0.05	0.05
Mn^{2+}	DL	DL	DL	0.06	DL	0.02	0.20	0.30	0.60	0.10	DL	0.60	0.5	0.4
Total Fe	0.03	0.04	0.02	0.03	0.02	0.05	0.04	0.50	0.03	0.19	0.02	0.50	0.3	0.3

Note: Turbidity in NTU, temperature in °C, and the concentrations of other parameters in mg/L.
Abbreviations: ESA: Ethiopian standards agency; NGL: No guideline value; DL: Detection limit; TH: Total hardness; TA: Total alkalinity; TDS: Total dissolved solids; Min: Minimum; Max.: Maximum; WHO: World Health Organization.

parameters—pH, TDS, HCO_3^-, Ca^{2+}, Mg^{2+}, K^+, SO_4^{2-}, NO_3^-, PO_4^{3-}, TH, Cu^{2+}, Fe, and F^-—along with their corresponding WHO standard values (Table 4).[33,34] These parameters were selected based on recommendations from previous studies.[12,16,32,35]

The calculation of the WQI involves four steps, as described by Berhe,[12] Ha *et al.,*[32] and Sanad *et al.*[13]. In the first step, the physicochemical parameters were assigned weights (wi) on a scale of 1 – 5, as presented in Table 4. These weights were determined based on similar studies conducted by Berhe,[12] Sanad *et al*.,[13] Al-Aizari *et al*.,[18] Panneerselvam *et al*.,[19] and Ha *et al*.[32]

In the second step, the relative weight (W_i) for each parameter was calculated using Equation I, as shown in Table 4. The third step involved assigning a quality rating scale (q_i) to each parameter using Equation VI.

$$q_i = \left[\frac{C_i}{S_i}\right] \times 100 \quad \text{(VI)}$$

where Ci represents the experimental concentration of each parameter in each water sample, measured in mg/L, and Si refers to the standard concentration for each water quality parameter in drinking water, as recommended by the WHO,[33,34] also in mg/L.

Finally, the sub-index (SI_i) value for each water quality parameter was calculated using Equation VII, and the WQI for each groundwater source was calculated using Equation VIII. The resulting scores were classified into five water quality categories, as shown in Table 6.

$$SI_i = W_i \times q_i \quad \text{(VIII)}$$

where the SI_i is the sub-index value of i^{th} parameter, q_i is the rating based on the concentration of i^{th} parameter and n is the number of parameters.

$$WQI = \sum_{i=1}^{n} SI_i = \sum_{i=n}^{n} Wiqi \quad \text{(VIII)}$$

where the SI_i is the sub-index value of i^{th} parameter, Wi is the relative weight, q_i is the rating based on the concentration of i^{th} parameter and n is the number of parameters.

2.6. Data analysis

Descriptive statistics, including percentages, means, and ranges, were computed for the physicochemical data of drinking water samples. A Pearson correlation matrix (*r*) analysis was performed to quantify the relationships among the physicochemical parameters and between the physicochemical parameters and the WQI. All data analyses were conducted using Microsoft Excel 2016.

3. Results and discussion

3.1. Physicochemical analysis

The average values of the physicochemical parameters used to assess the quality of groundwater in the study area are presented in Table 5, alongside comparisons with the drinking water quality standards established by the Ethiopian Standards Agency (ESA)[36] and the WHO.[34]

3.1.1. pH

Table 6. Water quality classifications of samples based on the GPI, NPI, and WQI values[12,13,18,32]

Sample site	GPI value	Category	NPI value	Category	WQI value	Category
Y1	0.816	Insignificant pollution	4.04	Very high pollution	88.1	Good
Y2	0.644	Insignificant pollution	1.97	Moderate pollution	72.2	Good
Y3	0.190	Insignificant pollution	−0.89	Clean (unpolluted)	19.4	Excellent
Y4	0.757	Insignificant pollution	1.93	Moderate pollution	71.9	Good
E1	0.458	Insignificant pollution	−0.82	Clean (unpolluted)	45.7	Excellent
E2	0.416	Insignificant pollution	−0.82	Clean (unpolluted)	40.5	Excellent
S1	0.398	Insignificant pollution	−0.78	Clean (unpolluted)	38.9	Excellent
S2	0.406	Insignificant pollution	−0.85	Clean (unpolluted)	41.2	Excellent
D1	1.444	Low pollution	1.95	Moderate pollution	143.6	Poor
D2	1.29	Low pollution	0.85	Low pollution	128.6	Poor

Abbreviations: GPI: Groundwater pollution index; NPI: Nitrate pollution index; WQI: Water quality index.

The mean pH values of the water samples from the study area ranged from 6.25 to 8.11. The majority of the samples (60%, $n = 10$) fell within the recommended pH range of 6.50 – 8.50 as established by the WHO.[34] However, 40% of the samples had pH values below the recommended lower limit of 6.50. Notably, almost all the samples (90%) exhibited acidic pH levels, with the exception of one sample (10%) from the E1 sampling site, which was slightly basic (pH = 8.11) (Table 5).

3.1.2. Turbidity

The turbidity values of the water samples ranged from 0 to 4 NTU. Of the ten samples analyzed, four (40%) had turbidity values >0 NTU. However, all samples remained below the maximum allowable turbidity level of 5 NTU, as recommended by the WHO.[34]

3.1.3. TDS

The water samples analyzed in this study exhibited TDS concentrations ranging from 99.0 to 1930.0 mg/L (Table 5). Notably, except for two samples (20% of the total, $n = 10$) collected from the D1 and D2 sampling sites, all other samples had TDS concentrations below the public acceptability threshold of 1000 mg/L recommended by the WHO.[34] Based on these TDS values and the palatability ratings for drinking water provided by the WHO,[37] the groundwater sources in the study area were categorized as follows: Two sources (20%) (Y3 and S2) were classified as excellent for potable use, while four sources (40%) (Y2, E1, E2, and S1) were rated as good for drinking; two sources (20%) (Y1 and Y4) were considered fair for human consumption, and the remaining two sources (D1 and D2) were classified as unacceptable for human consumption and require close monitoring. The elevated TDS values observed in certain samples, particularly from the D1 and D2 sites, may be attributed to natural interactions between rocks and water sources in the area, as noted by Berhe.[12] This interaction can lead to the dissolution of minerals and the subsequent release of dissolved solids into the water, increasing the TDS concentrations.

3.1.4. TA

The TA concentrations in the water samples ranged from 110 to 360 mg/L (Table 5). The Ethiopian Standards Agency[36] recommends that TA should not exceed 200 mg/L in drinking water. Of the ten water samples analyzed, four (40%) – E1, E2, D1, and D2 sampling sites – had TA values that exceeded this maximum permissible limit. Bicarbonate alkalinity, primarily attributed to HCO_3^- ions, was the dominant form of alkalinity observed in the water samples, as all measured pH values were below 8.3 (Table 5).

3.1.5. Ca^{2+} and Mg^{2+} levels

Elevated levels of Ca^{2+} can lead to abdominal issues and are undesirable for domestic use, as they contribute to encrustation and scaling.[38] The mean concentrations of Mg^{2+} and Ca^{2+} in the water samples were 4.80 – 79.2 mg/L and 22.2 – 284 mg/L, respectively (Table 5). The mean concentrations of Ca^{2+} and Mg^{2+} at the D1 sampling site were 3.79 and 1.58 times higher than the standards set by the ESA[36] and the WHO,[33] which are 75 mg/L and 50 mg/L, respectively. Similarly, at the D2 sampling site, the mean concentrations of Ca^{2+} and Mg^{2+} were 2.93 and 1.49 times higher than the recommended values.

3.1.6. TH

The water samples analyzed showed TH values ranging from 96.00 to 1040.00 mg/L as $CaCO_3$. According to the WHO,[34] the maximum permissible limit for TH in drinking water is 300 mg/L as $CaCO_3$. Sixty percent of the water samples, including those from the Y1, Y2, Y4, E2, D1, and D2 sampling sites, had TH concentrations ranging from 1.05 to 3.47 times higher than the maximum tolerable limit set by the WHO.[34] These sources, therefore, require treatment as they are not suitable for human consumption. In contrast, 40% of the samples, specifically those from the Y3, E1, S1, and S2 sites, met the WHO[34] standards for drinking water TH levels. Based on the laboratory test results and the TH classification method used by the WHO,[33] the investigated groundwater sources were categorized as follows: Seven sources (70%) – Y1, Y2, Y4, E2, S1, D1, and D2 – were classified as very hard water; one source (10%) – Y3 – was classified as moderately hard; and two sources (20%) – E1 and S2 – were classified as hard water. Consequently, all of the investigated groundwater sources in the research area were considered to be hard water. Water hardness is primarily related to the concentrations of Ca^{2+} and Mg^{2+}.[16,39] As a result, all water samples with elevated levels of Ca^{2+} and Mg^{2+} exhibited correspondingly high TH values.

3.1.7. K^+ levels

Increased potassium levels in drinking water, as highlighted by Gintamo *et al.*,[24] can contribute to neurological and digestive issues.

The measured concentrations of K^+ in the water samples ranged from 1.2 to 46.25 mg/L (Table 5). The maximum permissible limits for K^+ in drinking water are 1.5 mg/L and 12 mg/L, according to the ESA[36] and WHO,[34] respectively. Among the ten groundwater sources investigated, only one sample (10%) from the Y3 sampling site had a K^+ concentration (0.9 mg/L) below the maximum permissible limits set by both ESA[36] and WHO.[34] The remaining 90% of the samples had K^+ concentrations that were 2.4 – 30.8 times higher than the standards suggested by the ESA.[36] Except for the sample from the Y3 site, the K^+ concentrations measured in all other samples were higher than those reported in other regions of Ethiopia.[12,40] The elevated K^+ concentrations observed in the water samples from the D1 (46.25 mg/L) and D2 (38.75 mg/L) sampling sites could be attributed to localized chemical weathering of potash feldspars, as noted by Dawit *et al.*[40]

3.1.8. SO_4^{2-} levels

High levels of SO_4^{2-} in drinking water may induce a laxative effect.[25] The measured concentrations of SO_4^{2-} in the water samples ranged from 2.5 to 360 mg/L. Of the ten water samples analyzed, eight (80%) had SO_4^{2-} concentrations within the public acceptability guideline value of 250 mg/L, as recommended by the WHO.[34] However, two samples (20%) from the D1 and D2 sampling sites exceeded this guideline, with concentrations of 360 mg/L and 325 mg/L, respectively. The elevated levels of SO_4^{2-} in the water samples from the D1 and D2 sites may be attributed to the presence of sulfate-containing minerals, such as gypsum or anhydrous calcium sulfate, which can dissolve in water and increase sulfate ion concentrations, as noted by Gebresilasie *et al.*[5] The results for SO_4^{2-}in this study were consistent with the findings of Gebresilasie *et al.*[5] and Abegaz and Midekssa.[41] However, they were inconsistent with the findings of Adamou *et al.*[16]

3.1.9. NO_3^- and NO_2^- levels

Elevated levels of NO_3^- and NO_2^-in drinking water can lead to "blue baby" syndrome (methemoglobinemia).[25,34] The concentrations of NO_3^- in the water samples ranged from 2.2 to 100.8 mg/L (Table 5). The health-based guidelines for NO_3^- in drinking water, as recommended by both the ESA[36] and the WHO,[34] is 50 mg/L. Among the ten water samples analyzed, six (60%) – Y3, S1, S2, E1, E2, and D2 sampling sites – had NO_3^-concentrations that were 0.74 – 22.73 times lower than the health-based guideline values. These findings align with previous studies[5,12,25,39,42,43] conducted in Ethiopia, all of which reported NO_3^-concentrations within the prescribed limit of 50 mg/L.

The recorded NO_2^- concentrations ranged from 0.003 to 0.009 mg/L (Table 5). All tested water samples had NO_2^- concentrations significantly below the health standard value of 3 mg/L, as recommended by both the ESA[36] and the WHO.[34] These findings are consistent with those of Berhe,[12] who reported that NO_2^-concentrations in water from various locations in Kombolcha town, Ethiopia, were within the recommended limits.

3.1.10. F^- levels

The F^- concentrations in the drinking water samples from the present study ranged from 0.32 to 2.52 mg/L, as shown in Table 5. The WHO[34] and the ESA[36] recommend a maximum permissible limit of 1.5 mg/L for F^- in drinking water. Concentrations exceeding this threshold increase the risk of dental fluorosis, and higher levels further elevate the risk of skeletal fluorosis.[44] Nearly 90% (n = 10) of the analyzed water samples had F^- concentrations below the recommended limit of 1.5 mg/L. However, one sample from the E1 sampling site recorded an F^- concentration of 2.52 mg/L, surpassing the limit. Similar studies in Ethiopia by Mengstie *et al.*[43] and Garoma *et al.*[25] reported F^- concentrations in water samples that were consistent with the 90% compliance observed in the present study. In contrast, the results of the present study differ from those of Amanial,[39] who reported F^- concentrations in spring water samples from Arba Minch town, Ethiopia, ranging from 2.048 to 4.415 mg/L, significantly exceeding the standard limit.

3.1.11. Cu^{2+} levels

In the present study, the analyzed water samples exhibited varying concentrations of Cu^{2+}, ranging from 0.05 to 0.69 mg/L (Table 5). Notably, the Cu^{2+} concentrations in these samples were significantly lower, approximately 2.9 – 40 times below the health-based guideline value of 2.0 mg/L, as recommended by both the WHO[34] and the ESA[36] for drinking water. These results are consistent with the findings of Berhe[12] and Lewoyehu,[42] who reported that Cu^{2+} concentrations in water samples from Kombolcha Town and the Mecha District, Ethiopia, were also below the recommended limit.

3.1.12. Cr^{6+} levels

According to the data presented in Table 5, the concentration of Cr^{6+} in the analyzed water samples ranged from 0.01 to 0.06 mg/L. Remarkably, almost all (90%, n = 10) of the water samples exhibited Cr^{6+} concentrations that were 1.92 – 6.25 times lower than the WHO[34] recommended provisional guideline value of 0.05 mg/L for total chromium in drinking water. However, it is important to note that these findings contrast with a study by Gebresilasie *et al.,*[5] which reported that chromium levels in all hand-dug well water samples from Kafta Humera District, Ethiopia, were below the detection limit (DL) of the method used. These differing results underscore the variations in Cr^{6+} concentrations across different geographical locations and water sources.

3.1.13. Mn^{2+} levels

Analysis of water samples revealed that the concentration of Mn^{2+} ranged from the method DL to 0.60 mg/L (Table 5). Of the ten samples examined, five (50%) showed detectable levels of Mn^{2+}. However, the Mn^{2+} concentrations in these samples were significantly lower—from 1.3 to 20 times below the WHO[34] health-based recommended guideline value of 0.4 mg/L for drinking water. Among the samples, only the water collected from the D1 sampling site exhibited an Mn^{2+} concentration of 0.60 mg/L, which exceeded the health-based recommendation value. The Mn^{2+} concentrations measured in this study were lower compared to those reported by Garoma *et al.*[25] but higher than those reported by Gebresilasie *et al.*[5] in Ethiopia.

3.1.14. Total Fe

The water samples examined in this study showed total Fe concentrations ranging from 0.02 to 0.50 mg/L. Among the ten samples analyzed, only one (S2 sampling site) exhibited a total iron concentration of 0.50 mg/L, exceeding the WHO[34] recommended taste threshold for iron in drinking water, which is set at 0.3 mg/L. The total iron concentrations observed in this study were lower compared to findings from various regions in Ethiopia, as reported by Shigut *et al.,*[45] Gebresilasie *et al.*[5], and Lewoyehu.[42] The variations in iron levels may be attributed to factors such as geological characteristics, water sources, agricultural practices, and other local influences on water quality.

3.2. GPI

According to Sanad *et al.,*[13] the GPI is used as a comprehensive metric that accounts for the combined effects of various chemical factors on groundwater quality, offering a single value that reflects the overall level of groundwater pollution.

The GPI value effectively reflects the degree of groundwater contamination.[18] The GPI values classify water quality into the following categories: "Insignificant pollution" (GPI < 1), "Low pollution" (1 < GPI < 1.5), "Moderate pollution" (1.5 < GPI < 2.0), "High pollution" (2.0 < GPI < 2.5), and "Very high pollution" (GPI > 2.5), as outlined by Sanad *et al.*[13] The calculated GPI values, presented in Table 6, ranged from 0.190 to 1.44, categorizing the water quality into two distinct groups: "Insignificant pollution" and "Low pollution". The results showed that 80% of the 10 ground drinking water sources investigated (Y1, Y2, Y3, Y4, E1, E2, S1, and S2) were in the "Insignificant pollution" category, indicating excellent suitability for drinking. In contrast, 20% of the sources, specifically D1 and D2, were classified as having "Low pollution". Notably, the highest GPI value of 1.44 was recorded at D1 (Table 6).

3.3. NPI

In this study, NPI values ranged from −0.89 to 4.04, with an average of 0.658. The NPI is a tool used to assess water pollution caused by elevated nitrate concentrations.[46] The NPI values classify water quality as follows: "Clean (unpolluted)" (NPI < 0.0), "Low pollution" (0.0 < NPI < 1.0), "Moderate pollution" (1.0 < NPI < 2.0), "High pollution" (2.0 < NPI < 3.0), and "Very high pollution" (NPI > 3.0), as outlined by Al-Aizari *et al.*[18] Analysis of the NPI values (Table 6) reveals that samples from sites Y2, Y4, and D1 exhibited values of 1.97, 1.93, and 1.95, respectively, categorizing them as experiencing Moderate Pollution, which accounts for 30% of the total samples. Five sites (Y3, E1, E2, S1, and S2), representing 50% of the total, were classified as "Clean (unpolluted)". The D2 site was categorized as having "Low pollution". Notably, the Y1 site was classified as experiencing "Very high pollution", indicating a significant and concerning level of nitrate contamination at this location.

3.4. WQI

The WQI offers a detailed assessment of the quality of surface and groundwater for a wide range of domestic uses.[47] As a rule, the WQI is utilized to appraise the suitability of groundwater for drinking purposes in accordance with established the WHO standards.[13]

The WQI values are classified as follows: "Unsuitable for drinking" (WQI ≥300), "Very poor" (200 < WQI < 300), "Poor" (100 < WQI < 200), "Good" (50 < WQI < 100), and "Excellent" (WQI < 50). These classifications are based on the work of Elssaidi *et al.*[3] Table 6 presents the WQI values for all groundwater samples analyzed, as calculated using Equations I, VI, VII, and VIII. The WQI values, as shown in Table 6, ranged from 19.4 to 143.6 across the 10 sampling sites, with an average value

Table 7. Correlation matrix among the various water quality parameters

Parameter	T	Turbidity	EC	TDS	pH	HCO_3^-	TA	K^+	Mg^{2+}	Ca^{2+}	TH	SO_4^{2-}	NO_3^-	Cr^{6+}	Total Fe	WQI
T	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Turbidity	0.265	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-	-
EC	0.526	0.470	**1**	-	-	-	-	-	-	-	-	-	-	-	-	-
TDS	0.526	0.471	**1**	**1**	-	-	-	-	-	-	-	-	-	-	-	-
pH	0.239	0.159	0.195	0.195	**1**	-	-	-	-	-	-	-	-	-	-	-
HCO_3^-	0.419	0.246	**0.720**	**0.720**	0.084	**1**	-	-	-	-	-	-	-	-	-	-
TA	0.419	0.246	**0.720**	**0.720**	0.084	**1**	**1**	-	-	-	-	-	-	-	-	-
K^+	**0.699**	0.287	**0.945**	**0.945**	−0.170	**0.814**	**0.815**	**1**	-	-	-	-	-	-	-	-
Mg^{2+}	0.353	0.374	**0.866**	**0.866**	−0.360	**0.652**	**0.652**	**0.836**	**1**	-	-	-	-	-	-	-
Ca^{2+}	0.446	0.551	**0.956**	**0.956**	−0.270	0.566	0.566	**0.834**	**0.776**	**1**	-	-	-	-	-	-
TH	0.448	0.510	**0.976**	**0.976**	−0.310	**0.666**	**0.666**	**0.892**	**0.912**	**0.962**	**1**	-	-	-	-	-
SO_4^{2-}	0.470	0.541	**0.961**	**0.961**	−0.240	0.580	0.580	**0.851**	**0.806**	**0.969**	**0.963**	**1**	-	-	-	-
NO_3^-	0.120	0.573	0.504	0.504	−0.170	−0.050	−0.050	0.214	0.376	**0.670**	0.569	**0.681**	**1**	-	-	-
Cr^{6+}	0.042	0.217	0.044	0.044	**0.801**	0.425	0.425	0.168	−0.090	0.159	−0.120	−0.090	−0.370	**1**	-	-
Total Fe	0.478	**0.766**	0.128	0.128	−0.350	−0.060	0.062	0.011	0.036	0.185	−0.080	−0.120	−0.280	−0.160	**1**	-
WQI	0.452	0.447	**0.972**	**0.972**	−0.200	0.621	0.621	**0.865**	**0.850**	**0.964**	**0.975**	**0.981**	**0.651**	0.026	0.026	**1**

Note: The coefficients in bold indicate a statistically significant positive correlation at the 0.05 level (two-tailed).
Abbreviations: EC: Electrical conductivity; T: Temperature; TH: Total hardness; TA: Total alkalinity; TDS: Total dissolved solids; WQI: Water quality index.

of 69.01. Based on the calculated WQI values (Table 6), the groundwater sources investigated were classified into three categories for drinking purposes: “Excellent”, “Good”, and “Poor”. Accordingly, 20% of the Dubuluk (D1 and D2) groundwater samples were rated as “Poor” quality for intended human consumption. On the contrary, 30% of the Yabello (Y1, Y2, and Y4) sampling sites were found to have “Good” water quality. Conversely, 50% of the water samples collected from the present study, namely, those fetched from Yabello (Y3), Eleways (E1 and E2), and Surupa (S1 and S2), exhibited “Excellent” water quality for human consumption. Notably, none of the water samples analyzed in this study were classified as “Very poor” or “Unsuitable for drinking” based on the WQI values. In a related study conducted in the Kombolcha town area of Ethiopia by Berhe,[12] the WQI values for groundwater samples ranged from 23.47 to 81.22, with an average of 42.14. Based on these values, the groundwater was categorized into two groups: excellent water and good water for drinking. In addition, findings by Mengstie *et al.*[43] indicated that WQI analysis classified the water samples from the source, reservoir, and taps in Hawassa town, Ethiopia, as being of good quality for drinking purposes.

3.5. Correlation coefficient matrix analysis

As reported by Sanad *et al.*,[13] a correlation coefficient (r) close to +1 or −1 indicates a strong positive or negative correlation, respectively, between two variables.

The results of the Pearson correlation matrix (r), obtained from the statistical analysis of 20 selected variables, are presented in Table 7, with bolded coefficients indicating very strong correlations.

In this study, the water temperature showed a significant positive correlation only with K^+ ($r = 0.699$). Meanwhile, turbidity exhibited a significant positive correlation only with total Fe ($r = 0.766$). In addition, TDS and EC demonstrated a perfect positive correlation ($r = 1$). It is important to note that TDS and EC are closely related and can often be used interchangeably.[16]

Variations in TDS as a function of HCO_3^-, TA, K^+, Mg^{2+}, Ca^{2+}, TH, SO_4^{2-}, and the WQI exhibited strong positive associations, with r values ranging from 0.720 to 0.976. The pH of the water samples showed a positive significant correlation only with Cr^{6+} ($r = 0.801$).

Furthermore, HCO_3^- demonstrated significant positive correlations with several parameters, including K^+ ($r = 0.814$), Mg^{2+} ($r = 0.652$), TH ($r = 0.666$), EC ($r = 0.720$), and TDS ($r = 0.720$). TA showed a perfect positive correlation with HCO_3^- levels ($r = 1$). TH displayed a strong positive correlation with HCO_3^- ($r = 0.666$), EC ($r = 0.976$), TDS ($r = 0.976$), K^+ ($r = 0.892$), Mg^{2+} ($r = 0.912$), Ca^{2+} ($r = 0.962$), SO_4^{2-} ($r = 0.963$), and WQI ($r = 0.975$). These correlations indicate the mineralization of the investigated water samples. The results were also consistent with the findings of Adamou *et al.*[16] Strong correlations were observed between Mg^{2+} ($r = 0.912$), Ca^{2+} ($r = 0.962$), and SO_4^{2-} ($r = 0.963$), suggesting that the water samples exhibit permanent hardness, likely caused by the presence of magnesium and calcium sulfates. The WQI of the water samples exhibited significant positive correlations with several parameters, including NO_3^- ($r = 0.651$), EC ($r = 0.972$), TDS ($r = 0.972$), K^+ ($r = 0.865$), Mg^{2+} ($r = 0.8502$), Ca^{2+} ($r = 0.964$), TH ($r = 0.975$), and SO_4^{2-} ($r = 0.981$), indicating their influence on overall water quality.

4. Conclusion

This study aimed to assess groundwater quality for drinking using indices such as GPI, NPI, and WQI. All groundwater samples analyzed exhibited turbidity, pH, HCO_3^-, NO_2^-, and Cu^{2+} concentrations within or below the threshold values set by the WHO. However, some parameters exceeded the recommended limits. All groundwater sources investigated were classified as hard water.

The GPI values ranged from 0.190 to 1.44, with the majority (80%) of the ground drinking water sources categorized as “Insignificant pollution” (GPI < 1), indicating their suitability for human consumption. In contrast, 20% of the sources were classified as having “Low pollution” (1 < GPI < 1.5). The NPI values ranged from −0.89 to 4.04, with 50% of the groundwater drinking source classified as “Clean (unpolluted)”. Three sources (30%) were classified as experiencing “Moderate pollution”. The D2 groundwater drinking source was categorized as “Low pollution”. Notably, the Y1 groundwater drinking source was identified as experiencing “Very high pollution”, indicating a significant and concerning level of nitrate contamination likely linked to anthropogenic activities, such as fertilizer use and sewage intrusion. The WQI analysis revealed that 50% of the groundwater sources are classified as “Excellent” quality for drinking, while 30% are rated as “Very good” and 20% as “Good” quality for human consumption. The findings of this study provide valuable insights for policymakers and relevant authorities, supporting informed decision-making and effective management strategies.

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Conflict of interest

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Author contributions

Conceptualization: All authors
Investigation: Dereje Diriba
Methodology: Dereje Diriba
Writing – original draft: Dereje Diriba
Writing – review & editing: All authors

Availability of data

Data are available from the corresponding author upon reasonable request.

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