Spatial assessment and appraisal of groundwater suitability for drinking consumption in Andasa watershed using water quality index (WQI) and GIS techniques: Blue Nile Basin, Northwestern Ethiopia

Getnet Taye Bawoke1* and Zelalem Leyew Anteneh1

Abstract: This study aimed to evaluate the overall groundwater hydrogeochemical evolution and suitability for drinking in Andasa watershed (Northwestern Ethiopia). To achieve this, analyses of hydrogeochemical, multivariate (PCA, HCA), correlation matrix, and Water Quality Index (WQI) methodologies were employed. A total of 64 groundwater samples which had been collected during winter season (February–April, 2018) were assessed for ionic and composite variables (major physicochemical and composite parameters). The samples have been gathered from deep wells, shallow wells, hand dug wells and springs which are spatially distributed throughout the watershed. The study results revealed that major ions dominating are Ca>Mg>Na>K and HCO3>Cl>SO4>N03>P04>F for cations and anions, respectively. Computed WQI portray "good water type" mainly distributed in southern and western parts of the area.

About the Authors

Getnet Taye Bawoke obtained his BSc. (in Applied Geology) as well as MSc. (in Hydrogeology) degree from Mekelle University, Ethiopia. Now, he is working as an assistant professor in Bahir Dar University, Ethiopia. His research works include hydrogeochemistry, isotope hydrology, rainfall variability, groundwater recharge, modeling, managed aquifer recharge and redox conditions for petroleum exploration. His research interest focuses mainly on topics of groundwater including: Hydrogeochemistry, Isotope, Water Quality, Recharge, Geochemistry, Management, Modeling and Managed Aquifer Recharge.

Zelalem Leyew Anteneh obtained his BSc. degree in Applied Geology from Mekelle University, Ethiopia and MSc degree in Hydrogeology from Addis Ababa University, Ethiopia. Currently, he is working in Bahir Dar University (as assistant professor) with ample teaching and field experiences. His research work includes hydrogeochemistry and isotope hydrology, groundwater potential and redox potentials of petroleum explorations. His research interest includes groundwater potential, recharge and hydrogeochemistry, hydrogeophysics, water quality, groundwater modeling and management.

Public Interest Statement

Natural resources are degraded continuously due to rapid population growth, global climate change, poor management and misunderstanding. Among all, water is the one which is basic for wholesome functioning of any ecosystem. This natural resource is limited in nature spatially and temporarily. Hence, the issue of groundwater quality becomes more sensitive in global context which can be affected by anthropogenic and geogenic pollutants. This study aimed to evaluate the overall groundwater hydrogeochemical facies evolution and its suitability for domestic use in Andasa watershed (northwestern Ethiopia) through integrated methods (hydrogeochemical, multivariate, GIS, Water Quality Index (WQI)). The study results revealed that the major ionic dominancy as: Ca>Mg>Na>K and HCO3>Cl>SO4>N03>P04>F for cations and anions, respectively. The corresponding water types are Ca-HCO3, Mg-Ca-HCO3-CI, Mg-Ca-Na-HCO3-SO4, Mg-HCO3-SO4, Mixed CaMgHCO3, Mixed CaNaHCO3 and Na-HCO3, where Ca-HCO3 recognized as dominant. Computed WQI portray “good water type” mainly distributed in southern and western parts of the area.
Ca-HCO$_3$, Mg-Ca-HCO$_3$-Cl, Mg-Ca-Na-HCO$_3$-SO$_4$, Mg-HCO$_3$-SO$_4$, Mixed CaMgHCO$_3$, Mixed CaNaHCO$_3$ and Na-HCO$_3$ were recognized as water types where Ca-HCO$_3$ (59.69%) was identified as dominant. Ionic ratio plots are indications for groundwater enrichment by Na$^+$, Ca$^{2+}$ and Mg$^{2+}$ cations (silicate minerals hydrolysis). Chloro-alkaline indices resulted for CAI-I (96.88%) and CAI-II (84.48%), showed Ca$^{2+}$+Mg$^{2+}$ exchange in groundwater with Na$^+$+K$^+$ in an aquifer, confirmed for cation exchanging. Four factor loadings (PCA analysis) explained for the existence of geogenic and anthropogenic pollutions. WQI values showed the majority of the samples comprised “good water” (57.81%), distributed in southern and western parts, followed by “excellent water” (20.31%). Additionally, WQI maps portrayed “Good” to “poor water” types in northern portions (waste disposal landfill, urban centers, irrigated areas), while “very poor” to “unsuitable” types are dispersed to northeastern tips. Generally, the study result is believed to give directions for groundwater management options.

Subjects: Earth Systems Science; Engineering Technology; Environmental Geology; Geomorphology - Geochemistry; Geostatistics; Hydrogeology & Groundwater; Water Quality; Water Engineering; Water Science; Pollution

Keywords: water quality index (WQI); multivariate analysis; Andasa watershed; spatial mapping; hydrogeochemical facies; geogenic effects; anthropogenic pollution

1. Introduction

Natural resources are degraded continuously due to rapid population explosion, global climate change, poor management and misunderstanding of the nature of resources which is resulted from lack of coordination and integrated approaches. Among all, water is the prime natural resource which is basic for healthful functioning of any ecosystem. This natural resource is limited in its nature (Ravikumar et al., 2011), spatially and temporally and all humankind always competes for usage leaving behind sustainability issues. Ground and surface waters are the principal components on earth where life began around, and the issue of quality and quantity become more sensitive in global context. The issue of water quality deterioration is more pronounced in surface waters (e.g., Khan & Tian, 2018; Nemaxwi et al., 2019; Khan et al., 2016, 2017; Khan, Khan et al., 2016) through anthropogenic pollutants such as use of fertilizers in agricultural practices, industry effluents, sewerages from urban centers, etc.

Groundwater, found filling interstices within geological materials (rock and soil particles) and needs permeable media for its economical exploitability, is very challenging since it is invisible. Any water resource planning and management options should start from resource quantification and suitability assessment. Physico-chemical characteristics of groundwater can be affected by anthropogenic impacts (Alemayehu, 2006; Ayenew, 2005; Freeze & Cherry, 1979; Kalaivanan et al., 2017; Kebede, 2013; Şener et al., 2017) rock-water interaction (Appelo & Postma, 2005; Domenico & Schwartz, 1990; Freeze & Cherry, 1979; Hem, 1970; Redwan & Abdel Moneim, 2016; Srinivasamoorthy et al., 2008; Todd & Mays, 2005) and over pumping/drafting (Deepa & Venkateswaran, 2018).

A country like Ethiopia in which most of the lithological composition is complex (Alemayehu, 2006; Demlie & Wohnlich, 2006; Kieffer et al., 2004) and affected by continuous tectonic setting, denudation and sedimentation by uplifting and subsidence (Kebede, 2013). Characterizing surface and groundwater are very difficult in terms of quantity and quality in which these are the standpoint for water resource planning and management in ensuring sustainability (Ayenew et al., 2008; Kebede et al., 2017). The Andasa watershed (study area), which is situated in the upper Blue Nile Basin (Abay Basin), has 828.26 km$^2$ areal coverage and prominently dominated with flow
basaltic geological units with their residual black cotton clay soils. The rugged topographic setting ranging from 1585 to 3209 m a.m.s.l dominated by monomodal rainfall pattern (Figure 1).

Regional studies in upper Blue Nile (Alemayehu, 2006; Asrat, 2017; Ayenew et al., 2008; Demlie et al., 2007; Kebede, 2005; Kebede et al., 2017) and neighboring basins, specifically Tana sub basin level are undertaken for water resource potential assessment (Abiy et al., 2016; Mamo, 2014; Nigate et al., 2016) and water quality (Enku et al., 2017; Mamo, 2014) issues. A recent study conducted by (Bawoke et al., 2019) in the area, reported that the overall evolution of both surface and groundwater indicated the incidence of pollution by geogenic and anthropogenic effects. The
authors have tried to compare individual water quality parameters with WHO (2011) standards yet the composite (combined) variables effect and their suitability for domestic purposes are not explored. Regardless of the various studies by different water-related organizations and researchers in the area and adjacent watersheds, none of them has evaluated the groundwater quality using WQI approach. As directions observed from local and federal water offices, depth increments can bring substantial amount of water without giving emphasis to depth wise adverse hydrogeochemical change of the area (SMEC, 2010; SOGREAH, 2013).

The area under consideration, Andasa watershed, is not well known for its groundwater resource potential and potability conditions (domestic, irrigation, industrial, livestock) despite its multipurpose use and sustaining life including peculiar urban expansion in the watershed (Bawoke et al., 2019). Irrigation use of water from Blue Nile river through open canal and the big river, Andasa river, are not assessed for their hydrogeochemical loads that affect suitability of domestic water supply and irrigation. Moreover, Bahir Dar metropolitan city is dominantly found in the watershed in which a lot of groundwater wells are drilled, and groundwater extraction is substantial for domestic use (Bawoke et al., 2019). In the upper part of the watershed, floriculture and immense agricultural activities are held yet their impact is not considered in relation to domestic water appraisal. Open landfill waste disposal site situated in the area wherein its effect in the groundwater is not deciphered well considering its use for domestic consumption purpose is also a case in point.

As studies conducted by (Asrat, 2017; Ayenew et al., 2008; Kebede, 2013; Kieffer et al., 2004; Zewdie & Yoseph, 2012), the geology of the area is composed of Oligocene—Miocene flood basalts, quaternary basalts, scoria cones and fall outs and recent quaternary deposits. Taking into consideration the litho-facies found in the area, the upper most quaternary flow basalt which is highly permeable and weatherable (Nigate et al., 2016), can inject wastes from agricultural activities, industries, and landfills to the groundwater so that the chemical property of groundwater is altered beyond its natural constituents (Bawoke et al., 2019).

Studies centering on urban areas like Addis Ababa (capital of Ethiopia) and Bahir Dar city, showed evidence of anthropogenic pollution of groundwater (Ayenew, 2005; Demlie & Wohnich, 2006; Demlie et al., 2008, 2007; Kebede, 2013; Kebede & Travi, 2012). Most parts of Bahir Dar metropolitan city (capital of Amhara Regional State) are included in the study area and this study is the first in its kind to assess groundwater quality based on WQI, GIS and spatial variability of groundwater hydrogeochemical parameters appraisal for domestic consumption.

Water quality index (WQI), effective method in determining the potability of water use for specific purpose, is utilized by various researchers worldwide (e.g., Deepa & Venkateswaran, 2018; Gebrehiwot et al., 2011; Kalaivanan et al., 2017; Kao & Karuppannan, 2018; Naga et al., 2017; Nair et al., 2018; Ponsadalakshmi et al., 2018; Kumar et al., 2009; Saleem et al., 2016; Šener et al., 2017; Tiwari et al., 2017). WQI has been employed by assigning relative weights and quality rating scales and aggregating large number of water quality data into a single WQI value so that it can be easily understood in disseminating information to water users and policy makers (Bodrud-Doza et al., 2016; Saleem et al., 2016). Multivariate statistical and GIS techniques are also prominent for detecting and presenting the spatial (Elubid et al., 2019; Bodrud-Doza et al., 2016; Deepa & Venkateswaran, 2018; Kao & Karuppannan, 2018; Singhal & Gupta, 2010) as well as temporal (Dhanasekarapandian et al., 2016; Sadat-Noori et al., 2014) variability of hydrogeochemical variables in groundwater.

As a concluding remark, principal aim of the research is to assess the hydrogeochemical compositional loads of groundwater in the study area using water quality index (WQI), GIS and multivariate statistical analysis techniques via evaluating major ions (cations, anions) and composite ionic quantities (e.g., EC and TDS). Specifically, the study tried to investigate hydrogeochemical facies, rock-water interaction, anthropogenic groundwater pollution effects (irrigation, agriculture, and waste landfill site), groundwater evolution and spatial mapping of ions found in the Andasa watershed where the study is conducted (Figure 1).
2. Study area scope and description

The Andasa watershed is located within geographic coordinates of 37.257° to 37.605°E longitude and 11.151° to 11.601 N latitude in the upper Blue Nile Basin, Northwestern Ethiopia. It is about 560 km from Addis Ababa (Capital of Ethiopia). Most parts of Bahir Dar metropolitan City (capital of Amhara National Regional State) are included whereby rapid urbanization, fast growing of industries, floriculture activities and agriculture as well as irrigation through diverted hydraulic structures are practiced well (Figure 1).

The total area of the watershed is 828.26 km² consist parts of three administrative districts (woredas): Bahir Dar Zuria, Yilmana Densa and Mecha. There are a number of small towns which are entirely dependent on groundwater for their domestic use and livestock intakes. Andasa is the main river found in the area. Following the topographic advantage of the river, people of the area are practicing irrigation agriculture by diverting the river. There are also huge yield springs the can feed the river system and ensuring its perennial condition. Upper Blue Nile River is also diverted in the northern part of the area and used as irrigation water in which its effect on the groundwater system is not deciphered well.

As a general trend, the area follows dominantly monomodal rainfall pattern with maximum rainfall season during summer (June–September). Black cotton and clayey soils are representative for the area. Clayey silt, sandy silt and silty clay materials originated from fluvial sediments found mixed with pebbles, cobbles and boulders of basalt. Sand, silt and clay bearing clasts of basalt, rhyolite and scoriaceous materials are responsible for the formation of thick black, brown and reddish-brown soils (Asrat, 2017; Beshawered et al., 2010; Kebede, 2013; Kieffer et al., 2004; Mamo, 2014; Nigate et al., 2016; Zewdie & Yoseph, 2012). The geomorphological make up is ranging from relatively gentle to rugged sloppy areas. Southern, southeastern and southwestern parts of the area are elevated in elevation and rugged terrains whereas northern, northeastern and northwestern portions are gently slopped with some pockets of river incised and structurally collapsed grabbens occupied with quaternary deposits.

3. Geological and hydrogeological settings

The Ethiopian flood basalts stratigraphy has been described by many researchers as Ashengie, Albo, Alaj and Tarmaber Formations (BECOM, 1998; Chernet, 1985, 1993; Mohr, 1971, 1983) in the former times. Currently, lower basalt (Tv1), middle basalt (Tv2), upper basalt (Tv3) and uppermost basalt (Tv4) units have been coined with extensive studies (Asrat, 2017; Hailemariam et al., 2012; Haro et al., 2010). In the study area, there are six lithological units: TV1, TV2, TV3, Quaternary flow basalts, scoria cones and Quaternary deposits (Figure 2). TV1 is composed of porphyritic with pyroxene, plagioclase and olivine with phenocrysts. In the Andasa watershed, TV2 behaved with phryic basalts of pyroxene-plagioclase, plagioclase, and occasional olivine-pyroxene-plagioclase, and olivine commonly forming gentle slope geomorphology (Asrat, 2017). The thickness of TV3 is up to 650 m in the area exhibiting pyroclastic nature towards the top and confined by columnar basaltic units (Asrat, 2017). Quaternary flow basalts are comprising olivine phyric, pyroxene-plagioclase phyric, zeolite-rich strongly vesiculated basalts; basalt lava flows separated by basaltic agglomerate and basaltic breccia. Scoria cones are vesicular to scoriaceous olivine, pyroxene-plagioclase phyric basaltic cones; commonly horizontally stratified scoria falls. The remaining unit, Quaternary deposit, is situated mostly in depression portions, incised-bottom valleys, foot of hills, marshy as well as flood plains of the study area (Asrat, 2017; Beshawered et al., 2010).

Volcanic terrains found in highland, central Ethiopia and in the rift are the main groundwater sources along fractures and flow contacts and weathering profiles together with their stratigraphic superimposing which are essential water supply sources for rural and urban societies (Alemayehu, 2006; Demlie et al., 2008; Kebede, 2013).
Miocene to Quaternary sediments, in spite of their limited areal coverage, they have higher primary porosity through the formation of loose sediments which leads them to be the largest groundwater storage in Ethiopia (Alemayehu, 2006; Demlie et al., 2008; Kebede, 2013).

Two most groups of aquifers systems characterizing the study area are extensive aquifers of intergranular permeability and extensive aquifers with fracture permeability. Therefore, north, northeast, and some faulted localized pocket areas ranked moderate to high productive aquifers. In the contrary, southern, central and southwestern parts have low to poor groundwater productivity (ADSWE, 2015).
Moreover, high discharge springs are existed in the area. These springs are highly controlled with structures dominantly affiliated in the northern and northeastern directions.

4. Methodology

4.1. Sampling and Data Collections
The method applied during the collection of the samples is systematic where lithological differences at most occur for interpretation and comparison study. The sampling device (plastic bottles) cleaned very well before use by the water to be sampled to prevent mixing up of water if remained in the bottle prior to sampling and to remove other unwanted ordinary materials. Total number of (N = 64) water samples were collected from groundwater sources (hand dug wells, deep and shallow wells and springs) during winter season (February–April, 2018). These representative samples have been analyzed in situ for their pH, total dissolved solids (TDS), electrical conductivity (EC). The material used was portable water analyzer kits (HANNA) which was calibrated appropriately before use and checked each day with a standard solution. For further chemical analysis, the samples were sealed tightly and taken to Amhara Design and Supervision Works Enterprise (ADSWE) water, soil and geotechnics laboratory following and using guidelines with reference to American Public Health Association (APHA) (2005).

4.2. Data analysis
Anions and cations of the samples are identified in the ADSWE Geochemistry laboratory. Atomic absorption spectrophotometry (AAS) was used to measure Ca$^{2+}$, Mg$^{2+}$, Fe, B$^{-}$ and Mn. Flame photometer emission and absorption methods were employed for Na$^{+}$ and K$^{+}$ concentration measurement. Titration techniques were applied to measure HCO$_3^-$, CO$_3^{2-}$, SO$_4^{2-}$ ions despite the absence of CO$_3^{2-}$ in all samples. By means of colorimetric methods, Total Alkalinity (TA), Total Hardness (TH), PO$_4^{3-}$, F$^{-}$, NO$_3^{2-}$ and Cl$^{-}$ ionic concentrations were analyzed. Turbidity meter was employed for measuring turbidity of each groundwater samples. The quality assurance and quality control (QA/QC) mechanisms of the data has been done in the following ways. Duplicated samples were collected in the field and checked in laboratory for their data to ensure QA/QC mechanisms. Before statistical analysis of the hydrogeochemical sample data analysis and interpretation, the accuracy of laboratory results was checked using ion balance error relationship empirically in meq/liter using the following equation (Equation (1)):

\[
\text{Charge Balance Error (CBE)}(\%) = \frac{\sum (\text{cations} - \text{anions})}{\sum \text{cations} + \text{anions}}
\]

If the CBE is less than 5%, it is good and acceptable and some samples up to 10% CBE could be considered for analysis and interpretation in different studies (Ravikumar et al., 2011; Piña et al., 2018; Singhal & Gupta, 2010). Figure 3 is also supporting the above equation by showing a good relationship between the total sum of cations and anions (meq/l) almost equal in the 64 groundwater samples. Therefore, of the 69 groundwater samples collected from primary and some secondary raw data, only five samples showed CBE beyond 10% and rejected.

The samples minimum, maximum and mean (statistical analyses) of hydrogeochemical parameters have been done by different statistical softwares. Moreover, multivariate statistical analyses were utilized for the preparations of Q-mode and R-mode groundwater samples which in turn provides Hierarchical clustering analysis (HCA) and principal components analysis (PCA) for recognizing eigenvalues and total variance. In addition to this, correlation matrix to observe the association between the hydrogeochemical variables has been done by this statistical software. For identification of water types and groundwater evolution detection, AquaChem (version 4.0) software was used for plotting Piper and Gibbs diagrams (Gibbs, 1970; Piper, 1944). Ionic ratio plots employed for determining hydrogeochemical facies evolution. Arc GIS version 5.1 was employed for spatial mapping of the variables through interpolation technique (kriging) with spatial analysis tool extension.
4.3. Water Quality Index (WQI) Calculation for Domestic use

WQI is defined as a rating reflecting the composite influence of different water quality parameters (Ramakrishnalah et al., 2009). WQI method together with different data representing techniques (tables, graphs and pictures) applied to evaluate the suitability of groundwater quality for drinking consumption in Andasa watershed. Fourteen parameters (pH, EC, TDS, Ca, Mg, Na, K, HCO₃, Cl, SO₄, NO₃, F, Total hardness (TH), PO₄) have been used for the calculation purpose. Computation of WQI needs four steps and these stages description is clearly defined as follows:

Step—1 each of the 14 parameters have been assigned a weight (wi) according to its relative importance in the overall quality of water for drinking purposes (Table 1). The maximum weight of 5 has been assigned to parameters like total dissolved solids (TDS) and nitrate (NO₃) due to their major importance in water quality assessment (Srinivasamoorthy et al., 2008). Phosphate (PO₄) gives the minimum weight of 1 as it plays an insignificant role in the water quality assessment especially in the study area. The remaining other parameters were assigned a weight between 1 and 5 depending on their importance in the overall quality of water for drinking purposes.

Step—2, the relative weight (W_i) is computed using a weighted arithmetic index method given below (Brown et al., 1972; Tiwari & Manzoor, 1988) using formula (Equation (2)):

\[ W_i = \frac{w_i}{\sum_{i=1}^{n} W_i} \]  

where \( W_i \) is the relative weight, \( w_i \) is the weight of each parameter and \( n \) is the number of parameters.

Step—3, a quality rating scale (Q_i) for each parameter is assigned by dividing its concentration in each water sample by its respective standard according to the guidelines of WHO (2011) and then multiplied by 100 (Equation (3)):

\[ Q_i = \left( \frac{C_i}{S_i} \right) \times 100 \]  

Figure 3. Relationship between total sum of Cations (TSC) and Anions (TSA) to check CBE.
where $Q_i$ is the quality rating, $C_i$ is the concentration of each chemical parameter in each water sample in mg/l, and $S_i$ is the WHO (2011) drinking water standard for each chemical parameter in mg/l according to the guidelines of Table 1.

Step—4, the sub index ($S_i$) is first determined for each chemical parameter, which is then used to determine the WQI as per the following equation (Equation (4)):

$$S_i = W_i \times Q_i$$ (4)

$S_i$ is the sub index of $i^{th}$ parameter and $Q_i$ is the rating based on concentration of $i^{th}$ parameter. The overall water quality index (WQI) was calculated by adding together each sub index values ($S_i$) of each groundwater samples as follows:

$$WQI = \sum S_i$$ (5)

Finally, the computed WQI values are usually classified into five categories (as a flow chart).

(Table 2) as excellent water, good water, poor water, very poor water and unfit water for drinking purposes (Sahu & Sikdar, 2008). The overall and summarized methodological approach of the study is presented in Figure 4 as a flow chart.

| Physicochemical Parameters (mg/l) except pH (unit less) and EC (µS/cm) | WHO standards (World Health Organization (WHO), 2011) | Weight (wi) | Relative weight (Wi) |
|---|---|---|---|
| pH | 6.5–8.5 | 4 | 0.091 |
| EC | 1000 | 4 | 0.091 |
| TDS | 500 | 5 | 0.114 |
| Ca | 75 | 3 | 0.068 |
| Mg | 50 | 3 | 0.068 |
| Na | 200 | 2 | 0.045 |
| K | 12 | 2 | 0.045 |
| HCO$_3$ | 120 | 3 | 0.068 |
| Cl | 250 | 3 | 0.068 |
| SO$_4$ | 250 | 3 | 0.068 |
| NO$_3$ | 50 | 5 | 0.114 |
| F | 1.5 | 3 | 0.068 |
| TH | 300* | 3 | 0.068 |
| PO$_4$ | 10 | 1 | 0.023 |

$\sum wi = 44$  $\sum Wi = 1$

*Taken from Saleem et al. (2016) and WHO (1984) standard (as cited in Dhanasekarapandian et al., 2016).

| WQI Ranges | Type of water |
|---|---|
| <50 | Excellent water |
| 50.1–100 | Good water |
| 100.1–200 | Poor water |
| 200.1–300 | Very poor water |
| >300.1 | Unfit for drinking |
5. Results and discussion

5.1. Physicochemical variables statistical and spatial distribution analysis

The descriptive summarized physicochemical variables with field measured and laboratory analyses results (N = 64) are presented in Table 3. For TA (N = 46) and PO$_4$ (N = 45), sample observations are considered.

5.2. 5.1.1 pH, EC, TH, TA and TDS

Hydrogeochemical concentration variations of groundwater can be expressed in different ways. One of the plots that can give highlight and easiest clarification is, box plot, especially for major ionic variables and non-ionic/composite parameters (Deepa & Venkateswaran, 2018). Box plots were used to show major cations, anions and composite groundwater parameters (pH, EC, TDS, TA, and TH). According to the plots in Figure 5, cations and anions dominancy were identified in the orders of Ca>Mg>Na>K and HCO$_3$> Cl$>$SO$_4$ $>$ NO$_3$ $>$ PO$_4$ > F, respectively (Figure 5).

There are outlier values that can augment parameters variability of the study area in hydrogeochemical variables due to groundwater table depth variation, groundwater evolution from recharge to discharge areas, and anthropogenic pollution effects around agricultural, waste disposal landfill and urban centers.

The minimum, maximum and mean pH values of the study area are 5.77, 8.45 and 7.08, respectively. The values indicated that the pH classification falls in the low acid water to low alkaline water with a mean pH value of neutral water (Tables 3 and 4) and is the mean pH value is within the permissible range of WHO (2011). As it can be understood from the spatial distribution map of pH (Figure 6(a)), low acidic waters are found in southwestern direction while those neutral to low alkaline waters are located in the central and northern to northeastern portions, respectively. Elevated pH values are related with deep groundwater circulation system and sluggish groundwater recharge mechanisms (Kawo & Karuppannan, 2018).
As revealed in Figure 6(b), the spatial interpolation of EC is higher in the northeastern direction of the area where groundwater evolved to elevated concentrations of dissolved salts. Table 3 portrays that the existence of wide variations of EC values minimum, maximum and mean of 137, 5610 and 627.55 µS/cm in their respective order. WHO is not recommended EC values greater
than 1000 µS/cm and the mean of EC in the area is within the desirable limit though elevated values are recorded in the groundwater discharge direction and depth increment (GD = deep groundwater). Similar trend is observed for TDS and this is assured by their very high linear association/correlation (R = 0.99**) with statistically significant condition (Figure 6(c) and Table 6).

As depicted from Figure 6(d), the total Alkalinity (TA) spatial variation is high at the northeastern parts and low in the entire portion of southern direction. 55, 1950 and 251.85 mg/l are the minimum, maximum and mean values of TA. Water hardness is an expression of Ca^{2+} and Mg^{2+} total concentrations (mg/l) and can be done by substituting the concentrations of Ca^{2+} and Mg^{2+}. (Freeze & Cherry, 1979). Using the following equation hardness can be easily calculated (Equation (6)):

| pH Variation Range | Specification      | TDS Range (mg/l) | Quality Classification |
|--------------------|--------------------|------------------|------------------------|
| 3–3.5              | High acid water    | <200             | Fresh water            |
| 3.5–5.5            | Acid water         | 200–500          | Brackish water         |
| 5.5–6.8            | Low acid water     | 500–1500         | Saline water           |
| 6.8–7.2            | Neutral water      | >1500            | Brine water            |
| 7.2–8.5            | Low alkaline water |                  |                        |
| >8.5               | Alkaline water     |                  |                        |

Table 4. pH (left side) and TDS (mg/l) (right side) classifications (Sen, 2015)

Figure 6. Groundwater spatial variation maps of non-ionic variables: pH (A), EC (B), TDS (C) Total alkalinity—TA (D) and Total hardness—TH of Andasa watershed. N.B. “Boundary”, in the legend of all of the figures refers to the demarcation of the watershed under study.

Bawoke & Anteneh, Cogent Engineering (2020), 7: 1748950
https://doi.org/10.1080/23311916.2020.1748950
Page 12 of 30
Total Hardness (TH) = 2.5(Ca$^{2+}$) + 4.1(Mg$^{2+}$)  

Scale formation (carbonate mineral precipitation) during boiler feed of water can be produced if the hardness is usually above 60–80 mg/l (Freeze & Cherry, 1979). In the study area, high values of TH were noted in the northeastern parts and relatively low concentrations recorded in the southern and southeastern directions (Figure 6(e)).

5.2.1. Major cations

Major cations spatial distribution maps are presented in Figure 7(a–d). Calcium variations explained as the minimum, maximum and mean values are found to be 8.7, 198 and 30.18 mg/l, respectively.

Figure 7. Groundwater spatial variation maps of major Cations: Calcium (a), Magnesium (b), Sodium (c) and Potassium (d) of Andasa watershed.
The elevated values are found in the northern and northeastern parts of the area (Figure 7(a)). The mean value of Ca is within the permissible limit of WHO standards which is 75 mg/l. The Mg distribution map is also shown in Figure 7(b) with a mean value of 20.72 mg/l which is within WHO standards (50 mg/l). The maximum value found in the northeastern tip part is extremely beyond WHO standards. The Na and K concentrations are also shown in Figure 7(c,d) respectively. Both these ions are increased in the north and northeastern trends related with depth and deep groundwater evolution prominently cation exchanging conditions. But, K interpolation map is also displayed in urban and agricultural-related areas and might be threatened with anthropogenic effects.

5.2.2. Major anions
Bicarbonate which is the major anion is spatially distributed from higher values in the northeastern direction to low concentrations in the south, central, northwest, southeastern and southwestern...
parts (Figure 8(a)). The minimum, maximum and mean documented values of HCO₃ are 70, 3550 and 273.48 mg/l, respectively. Except the minimum value and a few samples (N = 9) mostly hand dug wells, most samples (86%) are out of the range of WHO desirable limits which is 120 mg/l.

The chloride concentrations are focused around northern, northeastern and some pocket areas of agricultural-dominated practices. From the spatial Cl map indicated (Figure 8(b)), it is found in the permissible thresholds. But, the pronounced elevated values are highly related with landfill sites, urban centers and irrigation agricultural areas since it is rare to get Cl bearing minerals in silicate dominating terrains (Srinivasamoorthy et al., 2008). Spatial concentration map of nitrate is shown in Figure 8(c) and the mean value is found to be 4.64 mg/l which is within the recommended limit. Similar concentration trend distribution is perceived like Cl in spatial maps and this is related to anthropogenic pollution effects. Although sulfate concentrations are met within WHO standard, larger values are revealed in agricultural land use types especially in the eastern and northeastern directions where diverted irrigation is visible (Figure 8(d)). Phosphate is the other anion which is important to be considered in the drinking water suitability analysis where more than 10 mg/l concentrations are not recommended. The minimum, maximum and mean values existed in the area are 0.10, 98.80 and 5.72 mg/l, respectively. The maximum value is seen in the hand dug well wherein agricultural practices are immense, specific local area called Yisala. This might be coined with the use of phosphatic fertilizers. The other elevated values seen (>10 mg/l) are in a spring sample (Gw53) around waste landfill site and hand dug well a local name called Koti (agricultural area). The spatial interpolated map of PO₄ is presented in Figure 9(a). Raised fluoride values are spatially distributed in the western and northwestern parts related with mostly in hand dug wells (Gw38, Gw24, Gw29, Gw34) and spring samples (Gw52, gw55, Gw36 (waste landfill)) and a few increased depths of deep boreholes (Gw1, Gw2, Gw3, gw19, Gw21) (Figure 9(b)). The maximum is recognized in the hand dug well (1.07 mg/l) at Gw38 sample location. Higher values of fluoride look like related with anthropogenic pollutions.

5.3. Hydrogeochemical facies
Hydrogeochemical facies are distinguishable genetically interrelated distinct zones that possess major cation and anion concentration classes which aids to understand and detect the different water compositions in different assemblages (Ravikumar et al., 2011). Based on Piper (1944) diagram, the water types have been classified mainly as Ca-HCO₃ type, Mg-Ca-HCO₃-Cl, Mg-Ca-Na-HCO₃-SO₄, Mg-
Figure 10. Hydrogeochemical facies shown on Piper diagram along with dominant anions and cations and classification of water samples (GD = Deep borehole, HD = hand dug well, SB = Shallow borehole, SP = spring).

| Sample ID | Main Water Types | Sample ID | Main Water Types | Sample ID | Main Water Types |
|-----------|------------------|-----------|------------------|-----------|------------------|
| GW1       | Ca-HCO₃ type     | GW23      | Ca-HCO₃ type     | GW44      | Ca-HCO₃ type     |
| GW2       | Ca-HCO₃ type     | GW24      | Ca-HCO₃ type     | GW45      | Ca-HCO₃ type     |
| GW3       | Ca-HCO₃ type     | GW25      | Ca-HCO₃ type     | GW46      | Ca-HCO₃ type     |
| GW4       | Ca-HCO₃ type     | GW26      | Mg-HCO₃SO₄       | GW47      | Ca-HCO₃ type     |
| GW5       | Mixed CaNaHCO₃   | GW27      | Ca-HCO₃ type     | GW48      | Ca-HCO₃ type     |
| GW6       | Na-HCO₃ type     | GW28      | Ca-HCO₃ type     | GW49      | Ca-HCO₃ type     |
| GW7       | Ca-HCO₃ type     | GW29      | Ca-HCO₃ type     | GW50      | Ca-HCO₃ type     |
| GW8       | Ca-HCO₃ type     | GW30      | Ca-HCO₃ type     | GW51      | Ca-HCO₃ type     |
| GW9       | Na-HCO₃ type     | GW31      | Ca-HCO₃ type     | GW52      | Ca-HCO₃ type     |
| GW10      | Ca-HCO₃ type     | GW32      | Ca-HCO₃ type     | GW53      | Mg-Ca-HCO₃Cl     |
| GW11      | Na-HCO₃ type     | GW33      | Ca-HCO₃ type     | GW54      | Ca-HCO₃ type     |
| GW12      | Ca-HCO₃ type     | GW34      | Ca-HCO₃ type     | GW55      | Ca-HCO₃ type     |
| GW13      | Na-HCO₃ type     | GW35      | Ca-HCO₃ type     | GW56      | Ca-HCO₃ type     |
| GW14      | Ca-HCO₃ type     | GW36      | Mg-Ca-HCO₃Cl     | GW57      | Ca-HCO₃ type     |
| GW15      | Ca-HCO₃ type     | GW37      | Mg-Ca-Na-HCO₃SO₄ | GW58      | Ca-HCO₃ type     |
| GW16      | Na-HCO₃ type     | GW38      | Ca-HCO₃ type     | GW59      | Ca-HCO₃ type     |
| GW17      | Mixed CaNaHCO₃   | GW39      | Ca-HCO₃ type     | GW60      | Ca-HCO₃ type     |
| GW18      | Ca-HCO₃ type     | GW40      | Ca-HCO₃ type     | GW61      | Ca-HCO₃ type     |
| GW19      | Ca-HCO₃ type     | GW41      | Ca-HCO₃ type     | GW62      | Ca-HCO₃ type     |
| GW20      | Mixed CaNaHCO₃   | GW42      | Ca-HCO₃ type     | GW63      | Ca-HCO₃ type     |
| GW21      | Ca-HCO₃ type     | GW43      | Ca-HCO₃ type     | GW64      | Ca-HCO₃ type     |
| GW22      | Mixed CaMgHCO₃   |           |                  |           |                  |
HCO₃⁻SO₄, Mixed CaMgHCO₃, Mixed CaNaHCO₃ and Na-HCO₃ Type (Table 5 and Figure 10). The dominant one was Ca-HCO₃ type water (59.69%) that accounts about fifty one (N = 51) samples. This is due to incongruently dissolution and weathering of silicate minerals that can be aggravated by dissolved CO₂ existed in the area, especially in most areas of the recharge zones. The next major water type identified was Na-HCO₃ type (7.81%) consisting of five samples (N = 5) and are entirely confined with deep groundwater boreholes. The issue is related with vertical depth variation that could give time for rock water interaction so that cation exchanging took place.

The next group of waters are mixed type (mixed CaNaHCO₃ type and mixed caMgHCO₃ type) comprising of three (N = 3) and one (N = 1) groundwater samples, respectively, and these are characterized by no dominant ions are presented in the samples. The samples are found in deep boreholes and are existed in the central parts of the study area. The last classification is holding three types of waters (Mg-Ca-HCO₃-Cl (N = 2), Mg-Ca-Na-HCO₃-SO₄ (N = 1) and Mg-HCO₃-SO₄ (N = 1)). These groundwater hydrogeochemical facies are near to the early stage of zone II (Figure 10) and highly related with anthropogenic pollution effects. The groundwater samples participated in this water types are from city waste landfill sites (Gw 36 and 53) and hand dug wells (Gw 22 and 26) around agricultural sites might be linked with fertilizers.

5.3.1. Groundwater evolution and chemistry controlling mechanisms

The most common and expected geochemical situation in groundwater evolution is probably to have bicarbonate type waters near to the surface with chloride type waters in the deeper portions of litho-stratigraphic formations which are used as groundwater reservoirs (aquifers) (Bowen, 1986). Groundwater chemistry can be determined based on rock-water interaction analysis, evaporation incidence and precipitation-related hydrogeochemical synthesis. Based on Gibbs (1970) diagram, one can understand the controlling mechanisms of groundwater chemistry either as rock-water interaction dominance (weathering), evaporation dominance and precipitation dominance (Figure 11(a,b)). Gibbs ratio plots have been done based on using the following two equations for cations and anions correspondingly (Equations (7) and (8)).

\[
\text{TDS versus } \frac{Na^+}{(Na^+ + Ca^{++})} \quad (7)
\]
\[
\text{TDS versus } \frac{Cl^-}{(Cl^- + HCO_3^-)} \quad (8)
\]
Figure 11(a,b) showed that there is dissolution of rock-forming minerals (rock weathering dominancy took place) for the hydrogeochemical facies evolution of the groundwater system in the study area. Ionic ratio plots can also be evidence for the existence of silicate hydrolysis for determining hydrogeochemical facies. Thus, if the ionic ratio of sodium to chloride (Na/Cl)>1, it means that hydrolysis of silicates is the source of Na in the groundwater (Deepa & Venkateswaran, 2018; Kawo & Karuppannan, 2018; Srinivasamoorthy et al., 2008). In the study area, most samples (80%) showed Na/Cl>1 suggesting continuous supply of Na cation via hydrolysis in the groundwater regimes except very few samples (20%) disclosed Na/Cl<1. This ratio extremely allied with hand dug wells and springs which are exposed for anthropogenic pollutions. The same ionic ratio plot of Ca/Mg whenever higher than 2 is an indication of silicate minerals hydrolysis for Ca and Mg presence in groundwater. In the Andasa watershed most of the samples showed Ca/Mg>2 which magnifies the hydrolysis of silicate minerals produced Ca and Mg cations in the groundwater samples and become responsible for Ca-HCO₃ water types and other Mixed CaMgHCO₃ types. The other important condition in silicate minerals environment is the production of HCO₃⁻ with the involvement of dissolved CO₂.

From Figure 12(a), we can understand that there is excess supply of alkalis for enriching Ca+Mg in groundwater samples from silicate weathering (Srinivasamoorthy et al., 2008). The plots of SO₄²⁻+HCO₃ vs Ca+Mg (Figure 12(b)) can justify the occurrence of cation exchanges among cations. Hence, as Figure 12(b) showed, in the study area the plot of SO₄²⁻+HCO₃ versus Ca+Mg dropped along and below the equiline that manifests both cation exchange and reverse cation exchange with lots of samples falling below the equiline signifying silicate weathering dominancy which means carbonate weathering is insignificant (Deepa & Venkateswaran, 2018; Dehnavi et al., 2011; Srinivasamoorthy et al., 2008).

Moreover, the presence of cation exchange can be verified with the two chloro-alkaline indices (CAI) as suggested by (Schoeller, 1965) by using the following equations to reveal groundwater hydrogeochemical evolution:

\[
CAI - I = \frac{Cl^- - (Na^+ + K^+)}{Cl^-} 
\]

\[
CAI - II = \frac{Cl^- - (Na^+ + K^+)}{SO_4^{2-} + HCO_3^- + CO_3^{2-} + NO_3^-} 
\]

According to the above equations, either negative or positive indices results can be obtained. The collected groundwater samples are tested for chloro-alkaline indices: CAI-I about 96.88% samples (N = 62) and CAI-II about 84.48% samples (N = 54) showed negative indices which implied an exchange of Ca+Mg in groundwater with Na+K in an aquifer materials thereby increasing Na+K concentrations especially along groundwater flow direction and depth increment. This situation will be responsible for changing the spatial distribution of hydrogeochemical facies both along depth and flow direction (Figure 13) trajectories (Kawo & Karuppannan, 2018).
5.4. Multivariate statistical approaches

5.4.1. Correlation matrix analysis

This is done for identification of relationships or correlations among groundwater variables of the area. The correlation matrix gives the evaluation of the correlation coefficients “R” between groundwater hydrogeochemical variables. Positive and negative correlations are considered for observing how strong or weak linear relationship existed between groundwater parameters (Elubid et al., 2019) and in Table 6, fifteen (N = 15) hydrogeochemical variables have been presented in Pearson’s correlation matrix. The existence of extreme correlation (0.99) between EC and TDS is attributed to increment of dissolved constituents then increases electrical conductivity of the ions. Ca, Mg, Na, K, HCO₃, TH and TA have strong positive correlation coefficients with TDS and EC showing their contribution for the construction of dissolved ions in groundwater thereby increasing electrical conductivity of the ionized water. Good correlations of between Ca with HCO₃ (0.53), Mg with HCO₃ (0.96) and Na with HCO₃ (0.96) may be an indication of reaction of silicate minerals with water and CO₂ (Kawo & Karuppannan, 2018).

N = 45 for PO₄ and N = 46 for TA

Poor correlations are found among variables of major cations (e.g., Mg and Ca, Ca and Na, Na and K, Mg and K). Negative and poor correlation coefficients are observed among NO₃ and major cation and anions, SO₄ and major cations and anions and PO₄ and major ions in the study area. This might be their sources of origin are quite different, i.e. the NO₃, PO₄ and SO₄ are coined with
Table 6. Correlation matrix of the hydrogeochemical variables in the study area

|     | pH   | EC    | TDS  | Ca   | Mg   | Na   | K    | HCO₃ | Cl   | SO₄  | NO₃  | F   | TH   | TA   | PO₄  |
|-----|------|-------|------|------|------|------|------|------|------|------|------|-----|------|------|------|
| pH  | 1    |       |      |      |      |      |      |      |      |      |      |     |      |      |      |
| EC  | 0.06 | 1     |      |      |      |      |      |      |      |      |      |     |      |      |      |
| TDS | 0.06 | 0.99* | 1    |      |      |      |      |      |      |      |      |     |      |      |      |
| Ca  | 0.05 | 0.69* | 0.71*| 1    |      |      |      |      |      |      |      |     |      |      |      |
| Mg  | 0.05 | 0.77* | 0.75*| 0.32*| 1    |      |      |      |      |      |      |     |      |      |      |
| Na  | 0.07 | 0.76* | 0.74*| 0.36*| 0.94*| 1    |      |      |      |      |      |     |      |      |      |
| K   | 0.13 | 0.51* | 0.50*| 0.61*| 0.25*| 0.37*| 1    |      |      |      |      |     |      |      |      |
| HCO₃| 0.05 | 0.87* | 0.86*| 0.53*| 0.96*| 0.96*| 0.41*| 1    |      |      |      |     |      |      |      |
| Cl  | 0.04 | 0.48* | 0.69*| 0.49*| 0.41*| 0.36*| 0.35*| 0.42*| 1    |      |      |     |      |      |      |
| SO₄ | 0.05 | 0.34* | 0.33*| 0.35*| 0.49*| 0.41*| 0.18 | 0.46*| 0.41*| 1    |      |     |      |      |      |
| NO₃ | -0.13| -0.14 | -0.13| 0.04 | -0.12| -0.13| -0.01| -0.13| 0.13 | 0.25*| 1    |     |      |      |      |
| F   | 0.40*| -0.18 | -0.17| -0.06| -0.10| -0.16| -0.08| -0.16| 0.22 | 0.01 | 0.01 | 1    |     |      |      |      |
| TH  | 0.02 | 0.64* | 0.61*| 0.29*| 0.93*| 0.89*| 0.20 | 0.89*| 0.41*| 0.51*| 0.04 | -0.02| 1    |     |      |      |
| TA  | -0.01| 0.89* | 0.89*| 0.90*| 0.76*| 0.87*| 0.56*| 0.95*| 0.39*| 0.17 | -0.16| -0.28| 0.38*| 1    |     |      |
| PO₄ | -0.17| -0.07 | -0.07| 0.12 | -0.10| -0.07| -0.06| -0.02| 0.14 | 0.16 | 0.76*| 0.05 | 0.63*| -0.05| 1    |      |

**Correlation is significant at the 0.01 level; * Correlation is significant at the 0.05 level.
anthropogenic effects and the major ionic concentrations are related with geogenic (silicate mineral origin). An interesting correlation between NO$_3$ and PO$_4$ (0.76) is observed and can be related with anthropogenic effects.

5.4.2. Hierarchical Clustering and dendrogram synthesis
Grouping of observations based on their similarity and distinct characteristics can be done by clustering. In this study, two types of clustering techniques utilized: R-mode (Figure 14), for different water quality variables; and Q-mode (Figure 15), to group the samples based on the hydrogeochemical data similarity. On the bases of variable grouping mechanisms, three major clusters are formed in the study area. The first cluster consisting of EC, TDS, Na, HCO$_3$, Mg, Ca, TA and K signified principally rock-water interaction effects. Further sub clusters showing strong associations are observed. The second cluster is related chiefly with anthropogenic effects that consist of NO$_3$, PO$_4$, Cl, TH and SO$_4$. The last group is composed of pH and F which can be attributed by a combination of geogenic and anthropogenic signatures.

Considering Q-mode clustering, there are four major clusters forming mainly depicting rock-water interaction, anthropogenic effects and groundwater evolution from recharge to discharge areas. For example, taking in to account the minimum clustered sampling site consisting of (cluster-1 = Gw8 and 49), they show highly ionized water and found in the discharge area with typical water types of Ca-Na-HCO$_3$ and Mg-Na-Ca-HCO$_3$ respectively. Cluster-2 is highly related with hand dug wells along the recharge areas with mainly Ca-HCO$_3$ water types. The remaining groups of clusters are fall in between cluster 1 and 2.

5.4.3. Principal Component Analysis (PCA) and factor loadings
The principal objective of PCA is to build a set of new variables (principal components) from original variables thereby reducing the large data set of variables into a few factors that can be inferred to
reveal and understanding the data structure in a simple way (Dhanasekarapandian et al., 2016). With the involvement and actions of cation exchanges, weathering of silicate minerals, material leaching and anthropogenic pollution effects (agricultural fertilizer, waste landfills and domestic sewage), Principal component analysis (PCA) technique can display a complex hydrogeochemistry in the study as used by different authors (e.g., Bodrud-Doza et al., 2016). The use of eigenvalues greater than one is recommended and hence four factor loadings are verified for hydrogeochemical analysis. These total four principal components together explained 80.624% of the cumulative variance of the area (Table 7 and Figure 16). The factor loadings of F1, F2, F3 and F4 contributed 48.006%, 16.444%, 8.899% and 7.275% total variances respectively. EC, TDS, Ca, Mg and TA have strong positive loadings (>0.75) in the first principal component while K and TH have moderate positive loadings (0.5–0.75). The rest variables have weak (<0.5) loading factors in the first principal component (Table 7). These variables contribution is coming mainly from geogenic effects.

The second principal component (Factor-2) is strongly loaded positively with NO\textsubscript{3} and PO\textsubscript{4} (related with anthropogenic effects) and moderately positive loaded with TH. Fluoride positive loading (strong) and pH positive loading (moderate) are representing Factor-3. Principal component four is positively loaded strongly with SO\textsubscript{4} which might be related with anthropogenic activities.

5.5. Groundwater suitability analysis for domestic use

5.5.1. WQI spatial variation and interpretation in Andasa watershed

The overall cumulative effects of geogenic mineral weathering and hydrolysis (mainly rock-water interaction), cation exchange and anthropogenic pollution effects which shape the hydrogeochemical evolution facies can be synthesized using WQI analysis for specific use of domestic purposes.

The computed WQI values and water type classifications based on WQI ranges of the study area is presented in Table 8. As it can be seen from this table, the five WQI classes are obtained: Excellent water, good water, poor water, very poor water and unsuitable water for drinking purposes.

Table 9 presented the descriptive statistical analysis of WQI values for the study area. Accordingly, the majority of the samples (N = 37) comprised “good water” class which covers about 57.81% of the total samples. The next major WQI water type class fall under “excellent
Table 7. Factor loadings and eigenvalues matrix of each hydrogeochemical parameters

| Variables | Factor Loadings | Factor Loadings | Factor Loadings | Factor Loadings |
|-----------|-----------------|-----------------|-----------------|-----------------|
|           | Factor-1 | Factor-2 | Factor-3 | Factor-4 |
| pH        | -.061     | -.318     | .678     | .199     |
| EC        | .963      | -.133     | .028     | -.119    |
| TDS       | .962      | -.133     | .029     | -.120    |
| Ca        | .866      | .146      | .002     | .172     |
| Mg        | .857      | -.126     | .222     | -.103    |
| Na        | .940      | -.143     | -.111    | -.102    |
| K         | .687      | -.005     | -.133    | .335     |
| HCO3      | .986      | -.077     | .039     | -.060    |
| Cl        | .475      | .348      | .244     | .219     |
| SO4       | .205      | .416      | -.107    | .774     |
| NO3       | -.037     | .868      | -.076    | .053     |
| F         | -.336     | .071      | .812     | .076     |
| TH        | .502      | .641      | .231     | -.352    |
| TA        | .948      | -.104     | .013     | .054     |
| PO4       | .013      | .890      | .065     | -.272    |
| Total Eigenvalue | 7.201 | 2.467 | 1.335 | 1.091 |
| % of Variance | 48.006 | 16.444 | 8.899 | 7.275 |
| Cumulative % | 48.006 | 64.450 | 73.349 | 80.624 |

Figure 16. Scree plot showing eigenvalues for each principal components.
| Sample ID | WQI values | Water type | Sample ID | WQI values | Water type | Sample ID | WQI values | Water type |
|-----------|-------------|------------|-----------|-------------|------------|-----------|-------------|------------|
| GW1       | 82.46       | Good       | GW23      | 50.81       | Good       | GW44      | 95.52       | Good       |
| GW2       | 81.92       | Good       | GW24      | 59.03       | Good       | GW45      | 70.09       | Good       |
| GW3       | 123.35      | Poor       | GW25      | 110.20      | Poor       | GW46      | 162.41      | Poor       |
| GW4       | 74.29       | Good       | GW26      | 58.03       | Good       | GW47      | 35.73       | Excellent  |
| GW5       | 136.40      | Poor       | GW27      | 31.79       | Excellent  | GW48      | 64.93       | Good       |
| GW6       | 71.21       | Good       | GW28      | 160.92      | Poor water | GW49      | 755.45      | Unfit       |
| GW7       | 49.83       | Good       | GW29      | 54.10       | Good       | GW50      | 52.87       | Good       |
| GW8       | 417.84      | Poor water | GW30      | 60.29       | Good water | GW51      | 49.22       | Excellent  |
| GW9       | 82.19       | Good       | GW31      | 49.62       | Good water | GW52      | 55.83       | Good       |
| GW10      | 43.83       | Good       | GW32      | 97.17       | Good water | GW53      | 82.37       | Excellent  |
| GW11      | 62.94       | Good       | GW33      | 121.35      | Poor water | GW54      | 51.39       | Good water |
| GW12      | 53.83       | Good       | GW34      | 118.00      | Poor water | GW55      | 113.88      | Poor water |
| GW13      | 79.51       | Good       | GW35      | 86.14       | Good water | GW56      | 54.60       | Excellent  |
| GW14      | 79.26       | Good       | GW36      | 95.17       | Good water | GW57      | 46.28       | Excellent  |
| GW15      | 61.60       | Excellent  | GW37      | 47.77       | Good water | GW58      | 78.13       | Unfit       |
| GW16      | 214.36      | Very poor  | GW38      | 72.46       | Good water | GW59      | 65.24       | Good       |
| GW17      | 94.29       | Good       | GW39      | 40.75       | Good water | GW60      | 41.40       | Excellent  |
| GW18      | 61.21       | Good       | GW40      | 83.07       | Good water | GW61      | 45.50       | Excellent  |
| GW19      | 149.17      | Poor       | GW41      | 76.09       | Good water | GW62      | 41.24       | Good       |
| GW20      | 83.59       | Good       | GW42      | 83.12       | Good water | GW63      | 43.54       | Good       |
| GW21      | 44.33       | Excellent  | GW43      | 83.59       | Good       | GW64      | 44.33       | Excellent  |

Bawoke & Anteneh, Cogent Engineering (2020), 7: 1748950
https://doi.org/10.1080/23311916.2020.1748950

Page 24 of 30
water” covering about 20.31% of the samples (N = 13). “Unsuitable water” type class is exhibited on sample codes of Gw 8, 49 and 59 covering 4.69%. These samples are highly ionized and evolved water samples and found around the discharge zones as well as increased borehole depths. Gw8 and Gw49 have been clustered in a clear distinctive cluster-1 group in Q-mode clustering above (Figure 15). The spatial distribution map of WQI in Andasa area is displayed in Figure 17. Majority of the area is mapped as good water type distributed in the southern and western parts of the study area showing less groundwater evolution and confined with recharge highland areas with Ca-HCO₃ water type domination.

Good to poor water types is shown in the northern parts of the area by centering waste disposal landfill sites, urban centers and irrigated areas. Very poor to unsuitable water types are spatially distributed on the northeastern tips of the area representing highly evolved water types.

6. Conclusions
Based on the samples collected from groundwater, the following conclusions are made for Andasa watershed from integrated approaches of hydrogeochemical spatial mapping and WQI revealing groundwater hydrogeochemical facies evolution and suitability synthesis for domestic purposes. A total of 64 groundwater samples have been used and analyzed for their major ionic concentrations and composite parameters. Hydrogeochemical analyses (Piper and Gibbs plots, Chloro-Alkaline Indices), spatial interpolation techniques, ionic ratio plots and multivariate statistical analysis (PCA, HCA) were employed as a methodological approaches to determine and understand the overall groundwater evolution system. WQI is computed to evaluate suitability of groundwater for domestic use in the area.

The results of the study revealed that cation dominancy is in the order of Ca>Mg>Na>K and that of Anions were identified to be HCO₃⁻ > Cl>SO₄²⁻ > NO₃⁻ > PO₄ > F. Seven water types: Ca-HCO₃, Mg-Ca-HCO₃-CI, Mg-Ca-Na-HCO₃-SO₄, Mg-HCO₃-SO₄, Mixed CaMgHCO₃, Mixed CaNaHCO₃ and Na-HCO₃ were recognized. The dominant water type of the study area was found to be Ca-HCO₃ type which covers 59.69% resulted from incongruent dissolution and weathering of silicate minerals.
that can be aggravated by dissolved CO\textsubscript{2} and this water type is linked with groundwater recharge zones of the area. Ionic ratio plots (Na/Cl and Ca/Mg), are witnesses for the enrichment of groundwater of the area by Na\textsuperscript{+}, Ca\textsuperscript{2+} and Mg\textsuperscript{2+} cations via hydrolysis of silicate minerals regimes except very few samples which are extremely allied with hand dug wells and springs that are exposed for anthropogenic pollutions. The hydrolysis condition is responsible for Ca-HCO\textsubscript{3} and Mixed CaMgHCO\textsubscript{3} water types. The incidence of cation exchange is verified by chloro-alkaline indices and resulted for CAI-I (96.88%) and CAI-II (84.48%) samples implied an exchange of Ca\textsuperscript{2+} and Mg\textsuperscript{2+} in groundwater with Na\textsuperscript{+} and K\textsuperscript{+} in an aquifer materials thereby increasing Na\textsuperscript{+} and K\textsuperscript{+} concentrations especially along groundwater flow direction and borehole depth increment. Moreover, correlations matrix results discovered that the moderate to strong association between Ca\textsuperscript{2+} with HCO\textsubscript{3}\textsuperscript{−} (0.53), Mg with HCO\textsubscript{3} (0.96) and Na with HCO\textsubscript{3} (0.96) are indications of reaction of silicate minerals.
with water and CO₂. In addition to geogenic hydrogeochemical facies controlling mechanisms, anthropogenic pollution effects are justified in the correlation matrix which has been explained by strong correlation between NO₃⁻ and PO₄³⁻ (0.76). R-and Q-mode HCA methods are employed and produced three clusters based on variable distributions and four clusters based on sampling site variations, respectively. The first groundwater variable cluster holding EC, TDS, Na, HCO₃⁻, Mg, Ca, TA and K denoted predominantly rock-water interaction effects. The second cluster is related chiefly with anthropogenic effects consisting of NO₃, PO₄, Cl, TH and SO₄. Four major clusters are obtained from Q-mode clustering analysis indicating rock-water interaction, anthropogenic effects and groundwater evolution from recharge to discharge areas. Four factor loadings extracted from PCA in which geogenic (PCA-1), and anthropogenic effects (PCA-2 & 4) are clearly identified.

Excellent water, good water, poor water, very poor water and unsuitable water for drinking purposes are obtained from computed WQI. Accordingly, majority of the samples comprised “good water” class (57.81%) followed by “excellent water” (20.31%). Hence, WQI spatial variation map is showing principally “good water type” which is distributed in the southern and western parts demonstrating limited groundwater evolution. Good to poor water types are exposed in northern portions around waste disposal landfill sites, urban centers and irrigated areas while very poor to unsuitable water types are spatially distributed on the northeastern tips of the area representing highly evolved water types. The results of the study is believed to give directions for future groundwater management options to decision makers and laid foundation for establishment of groundwater monitoring stations to periodic monitoring and evaluation of groundwater quality in Bahir Dar metropolitan city.

**Funding**

This work was supported by Bahir Dar University, School of Earth Sciences, [Research Grant ID/Number: BDU/RCS/SOE/06/10].

**Author details**

Getnet Taye Bawoke¹
E-mail: getdestin@gmail.com
Zelalem Leyew Anteneh²
E-mail: zelalem4812@gmail.com

¹ Department of Geology, School of Earth Sciences, Bahir Dar University, Bahir Dar, Ethiopia.

**Citation information**

Cite this article as: Spatial assessment and appraisal of groundwater suitability for drinking consumption in Andasa watershed using water quality index (WQI) and GIS techniques: Blue Nile Basin, Northwestern Ethiopia, Getnet Taye Bawoke & Zelalem Leyew Anteneh, Cogent Engineering (2020), 7: 1748950.

**References**

Abiy, A. Z., Demissie, S. S., Macalister, C., Dessu, S. B., & Melesse, A. M. (2016). Groundwater recharge and contribution to the Tana Sub-basin, Upper Blue Nile Basin, Ethiopia. In A. M. Melesse & W. Abtew (Eds.), Landscape dynamics, soils and hydrological processes in varied climates. Springer International Publishing, (pp. 463–481). https://doi.org/10.1007/978-3-319-18789-7

ADSWE. (2015). Well completion report, drilling and construction of Fereswoga well, water supply project at West Gojam Zone, Amhara Design and Supervision Works Enterprise, Bahir Dar, Ethiopia [Unpublished Technical Report], p. 27.

Alemayehu, T. (2008). Groundwater occurrence in Ethiopia. UNESCO, American Public Health Association (APHA), (2005). Standard methods for the examination of water and wastewater (21st ed.). American Public Health Association.

Appelo, C. A. J., & Postma, D. (2005). Geochemistry, groundwater and pollution (2nd ed.). A.A. Balkema publishers.

Asrat, A. (2017). Groundwater potential assessment project in the north and south Gojjam Abay Sub Basins [unpublished]. Geological, geomorphological and structural study report (final, phase-1), Amhara Design and Supervision Works Enterprise (ADSWE), p. 101.

Ayenew, T. (2005). Major ions composition of the groundwater and surface water systems and their geological and geochemical controls in the Ethiopian volcanic terrain. SINET: Ethiop. Journal of Science, 28 (2), 171–188.

Ayenew, T., Demile, M., & Wohlneich, S. (2008). Hydrogeological framework and occurrence of groundwater in the Ethiopian aquifers. *Journal of African Earth Sciences*, 52(3), 97–113. https://doi.org/10.1016/j.jafrearsci.2008.06.006

Bawoke, G. T., Anteneh, Z. L., Kehali, A. T., Mohammeyasin, M. M., & Wudie, G. (2019). Hydrogeochmical and isotopic signatures of groundwater in the Andasa watershed, Upper Blue Nile basin, Northwestern Ethiopia. *Journal of African Earth Sciences*, 160, 103617. https://doi.org/10.1016/j.jafrearsci.2019.103617

BECOM. (1998). Abbey river basin master plan project - phase 2 - water resources - Hydrogeology, Addis Ababa Ethiopia. Ministry of Water Resources (MoWR), Addis Ababa, Ethiopia,[Unpublished Report]. pp. 3 – 27.

Beshawered, E., Ashenafi, S., Edris, M., Burusa, G., Zewede, T., Tesfaye, Y., … Wendant, M. (2010). *Geology, geochemistry and gravity survey of the Bahir Dar area* [unpublished]. Geological Survey of Ethiopia, Basic geoscience mapping core process, p. 69.

Bedrud-Dozo, M., Islam, A. R. M. T., Ahmed, F., Dos, S., Saha, N., & Rahman, M. S. (2016). Characterization of groundwater quality using water evaluation indices, multivariate statistics and geostatistics in central...
Bangladesh. Water Science, 30(1), 19–40. https://doi.org/10.1016/j.wsj.2016.05.001
Bowen, R. (1986). Groundwater (2nd ed.). Elsevier applied science publishers.
Brown, R. M., McClelland, N. J., Deininger, R. A., & O’Connor, M. F. (1972, June 18–24). A water quality index—crossing the psychological barrier. Proceedings of the International Conference on Water Pollution Research, 787–797.
Chernet, T. (1983). Hydrogeology of ethiopia (Explanation of the hydrogeological map of Ethiopia, 1:2,000,000). Ministry of Mines and Energy, Ethiopian Institute of Geological Surveys.
Chernet, T. (1993). Hydrogeology of Ethiopia and water resources development [unpublished]. Ministry of Mines and Energy, Geological survey of Ethiopia, p. 222.
Deepa, S., & Venkateswaran, S. (2018). Appraisal of ground water quality in upper Manimuktha sub basin, Vellar river, Tamil Nadu, India by using water quality index (WQI) and multivariate statistical techniques. Modeling Earth Systems and Environment, 4(3), 1165–1180. https://doi.org/10.1007/s40808-018-0468-3
Dehravi, A., Sarikhani, R., & Nagargue, D. (2011). Hydro geochemical and rock water interchange in, Karkheh river, East of Kurdistan, NW of Iran. International Journal of Environmental Science and Research, 1(1), 16–22.
Demlie, M., & Wohnilich, S. (2006). Soil and groundwater pollution of an urban catchment by trace metals: Case study of the Addis Ababa region, central Ethiopia. Environmental Geology, 51(3), 421–431. https://doi.org/10.1007/s00254-006-0337-7
Demlie, M., Wohnilich, S., & Ayenew, T. (2008). Major ion hydrogeochemistry and environmental isotope signatures as a tool in assessing groundswater occurrence and its dynamics in a fractured volcanic aquifer system located within a heavily urbanized catchment, central Ethiopia. Journal of Hydrology, 353(1–2), 175–188. https://doi.org/10.1016/j.jhydrol.2008.02.009
Demlie, M., Wohnilich, S., & Wisotzky, F. (2007). Groundwater recharge, flow and hydrogeochemical evolution in a complex volcanic aquifer system, central Ethiopia. Hydrogeology Journal, 15(6), 1169–1181. https://doi.org/10.1007/s10040-007-0163-3
Dhanasekarapandian, M., Chandran, S., Devi, D. S., & Kumar, V. (2016). Spatial and temporal variation of groundwater quality and its suitability for irrigation and drinking purpose using GIS and WQI in an urban fringe. Journal of African Earth Sciences, 124, 270–288. https://doi.org/10.1016/j.jafrearsci.2016.08.015
Domenico, P. A., & Schwart, F. W. (1990). Physical and chemical. John Wdey & Sons, Inc.
Elubid, B. A., Huang, T. H., Ahmed, E., Zhao, J. M., Elhag, K., Abbass, W. M., & Babiker, M. (2019). Geospatial Distributions of Groundwater Quality in Gedaref State Using Geospatial Information System (GIS) and Drinking Water Quality Index (DWQI). International Journal of Environmental Research and Public Health, 16(5), 731. https://doi.org/10.3390/ijerph16050731
Enku, T., Melesse, A. M., Ayana, E. K., Tilahun, S. A., Abate, M., & Steenhuis, T. S. (2017). Groundwater evaporation and recharge for a floodplain in a sub-humid monsoon climate in Ethiopia. Land Degrad. Develop. 184(1), 1831–1841. https://doi.org/10.1002ldr.2650
Freeze, R. A., & Cherry, J. A. (1979). Groundwater. Prentice-Hall, Inc. Englewood Cliffs, New Jersey 07632.
Gebrehiwot, A., Tadesse, N., & Jigar, E. (2011). Application of water quality index to assess suitability of groundwater quality for drinking purposes in Hantebet watershed, Tigray, Northern Ethiopia. ISABB Journal of Food and Agriculture Science, 1(1), 22–30.
Gibbs, R. J. (1970). Mechanisms controlling world water chemistry. Science, 170(5), 2–4. https://doi.org/10.1126/science.170.3962.1088
Haillemariam, D., Yismaw, A., Agonafir, M., Zenebe, B., Sewnet, R. M., Edris, M., ... Ashenafi, S. (2012). Geology, geochemistry and gravity survey of the Yifag area [unpublished report]. Ministry of Mines, Geological Survey of Ethiopia, Basic Geoscience Mapping Core Pocess.
Haro, W., Hailemariam, D., Getachew, I., Kassahun, T., Ashenafi, S., Buriso, G., & Edris, M. (2018). Geology, Geochemistry and gravity survey of the Debre Tabor area. Memoir 29, the Federal Democratic Republic of Ethiopia, Geological Survey of Ethiopia [unpublished report]. Basic geoscience mapping core process.
Hem, D. (1970). Study and interpretation of the chemical characteristics of natural waters. U.S. Geol. Surv. Water Supply Paper.
Kaloivanan, K., Gurugnanam, B., Pourghasemi, H. R., Suresh, M., & Kumaravel, S. (2017). Spatial assessment of groundwater quality using water quality index and hydrochemical indices in the Kodavaran sub-basin, Tamil Nadu, India. Sustainable Water Resources Management, 4(3), 627–641. https://doi.org/10.1007/s40899-017-0148-x
Kawo, N. S., & Karuppannan, S. (2018). Groundwater quality assessment using water quality index and GIS technique in Modjo River Basin, central Ethiopia. Journal of African Earth Sciences, 147(6), 300–311. https://doi.org/10.1016/j.jafrearsci.2018.06.034
Kebede, S. (2005). Groundwater recharge, circulation and geochemical evolution in the source region of the Blue Nile River, Ethiopia. Applied Geochemistry, 20 (20), 1658–1676. https://doi.org/10.1016/j.apgeochem.2005.04.016
Kebede, S. (2013). Groundwater in Ethiopia: Features, numbers, and opportunities. Springer-Verlag Berlin Heidelberg.
Kebede, S., Abdalla, O., Sefelinsr, A., & Tindimugaya, C. (2017). Interaction of surface water and groundwater in the Nile River basin: Isotopic and piezometric evidence. Hydrogeology Journal, 25(3), 707–726. https://doi.org/10.1007/s10040-016-1503-y
Kebede, S., & Travi, Y. (2012). Origin of the 618O and 62H composition of meteoric waters in Ethiopia. Quaternary International, 257, 4–12. https://doi.org/10.1016/j.quaint.2011.09.032
Khan, M. Y. A., Gani, K. M., & Chakrapani, G. J. (2016). Assessment of surface water quality and its spatial variation. A case study of Ramganga River, Ganga Basin, India. Arabian Journal of Geosciences, 9(1), 1–9. https://doi.org/10.1007/s12651-015-2134-7
Khan, M. Y. A., Gani, K. M., & Chakrapani, G. J. (2017). Spatial and temporal variations of physicochemical and heavy metal pollution in Ramganga River—a tributary of River Ganges, India. Environmental Earth Sciences, 76(9), 2233–2240. https://doi.org/10.1007/s12665-017-6547-3
Khan, M. Y. A., Khan, B., & Chakrapani, G. J. (2016). Assessment of surface water quality and its spatial variation. A case study of Ramganga River, Ganga Basin, India. Arabian Journal of Geosciences, 9(8), 516. https://doi.org/10.1007/s12651-016-2551-2
Khan, M. Y. A., & Tian, F. (2018). Understanding the potential sources and environmental impacts of dissolved and suspended organic carbon in the diversified Ramganga River, Ganges Basin, India. Proceedings of the International Association of Hydrological Sciences, 379(Dic), 61–66. https://doi.org/10.5194/iahs-379-61-2018
Kieffer, B., Arndt, N., Bastien, F., Bosch, D., Pecher, A., Yirgu, G., ... Meugniot, C. (2004). Flood and shield basalts from Ethiopia: Magmas from the African superswell. Journal of Petrology, 45(4), 793–834. https://doi.org/10.1017/pet.2003.102

Kumar, S.K., Ramamohan, V., Sahayam, J.D., & Jeevanandam, M. (2009). Assessment of groundwater quality and hydrochemistry of Manimuktha River basin, Tamil Nadu, India. Environmental Monitoring and Assessment, 159(1–4), 341–351. https://doi.org/10.1007/s10661-008-0633-7

Mamo, S. (2014). Integrated Hydrological and Hydrogeological System Analysis of the Lake Tana Basin, Northwestern Ethiopia. Addis Ababa University, Ethiopia (Unpublished PhD Dissertation).

Mohr, P. A. (1971). The geology of ethiopia, reprinted, haei sellasse i university press. University college of addis ababa Press.

Mohr, P. A. (1983). Ethiopian flood basalt province. Nature, 303(5918), 577. https://doi.org/10.1038/303577a0

Naga, C., Talnani, C., Honor, J., Ab, O., Bernard, Y. O., Guillaume, Z. S., & Henoc, A. (2017). Spatio-Temporal Analysis and Water Quality Indices (WQI): Case of the Ébrié Lagoon, Abidjan. Hydrology, 3(32), 1–12. https://doi.org/10.3390/hydrology3030032

Nair, H. C., Padmalal, D., Joseph, A., & Gopinathan, V. P. (2018). Hydrochemistry and water quality assessment of shallow aquifers in the western flanks of Southern Western Ghats, SW India. Arabian Journal of Geosciences, 11(6). https://doi.org/10.1007/s12517-018-3401-1

Nemawxi, P., Odioy, J. O., & Makungo, R. (2019). Estimation of groundwater recharge response from rainfall events in a semi-arid fractured aquifer: Case study of quaternary catchment A51H, Limpopo Province, South Africa. Cogent Engineering, 6(1), 1–19. https://doi.org/10.1080/23311916.2019.1635815

Nigante, F., Van Camp, M., Kebede, S., & Walvoordens, K. (2016). Hydrologic interconnection between the volcanic aquifer and springs, Lake Tana basin on the Upper Blue Nile. Journal of African Earth Sciences, 121, 154–167. https://doi.org/10.1016/j.jafrearsci.2016.05.015

Pinya, A., David, L., Blake, S., & Cramer, T. (2018). Applied Geochemistry: A compositional multivariate statistical analysis of the hydrogeochemical processes in a fractured massif: La Línea tunnel project, Colombia. Applied Geochemistry, 95(May), 1–18. https://doi.org/10.1016/j.apgeochem.2018.05.012

Piper, A. M. (1944). A graphic procedure in the chemical interpretation of water analysis. Transactions, American Geophysical Union, 25(6), 914–923. https://doi.org/10.1029/TR025i006p00914

Ponsadalakshmi, S., Sankari, S. G., Prasanna, S. M., & Madhurambal, G. (2018). Evaluation of groundwater suitability for drinking using drinking water quality index in Nagapattinam district, Tamil Nadu in Southern India. Groundwater for Sustainable Development, 6(October 2017), 43–49. https://doi.org/10.1016/j.gsd.2017.10.005

Ramakrishnahally, C. R., Sadas Hivalah, C., & Ranganna, G. (2020). Assessment of water quality index for the groundwater in Tumkur Taluk, Karnataka state, India. E-Journal of Chemistry, 6(2), 523–530. https://doi.org/10.1155/2009/757424

Ravikumar, P., Somashekar, R. K., & Angami, M. (2011). Hydrochemistry and evaluation of groundwater suitability for irrigation and drinking purposes in the Markandeya River basin, Belgum District, Karnataka State, India. Environmental Monitoring and Assessment, 173(1–4), 459–487. https://doi.org/10.1007/s10661-010-1399-2

Redwan, M., & Moniem, A. A. A. (2016). Factors controlling groundwater hydrochemistry in the area west of Tahta, Sohag, Upper Egypt. Journal of African Earth Sciences, 118, 328–338. https://doi.org/10.1016/j.jafrearsci.2016.05.015

Sadat-Noori, S. M., Ebrohami, K., & Lighat, A. M. (2014). Groundwater quality assessment using the Water Quality Index and GIS in Saveh-Nobaran aquifer, Iran. Environmental Earth Sciences, 71(9), 3827–3843. https://doi.org/10.1007/s12665-013-2770-8

Sahu, P., & Sikdar, P. (2008). Hydrochemical framework of the aquifer in and around East Kolkata wetlands, West Bengal, India. Environmental Geology, 55(4), 823–835. https://doi.org/10.1007/s00254-007-1034-x

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), 1–11. https://doi.org/10.1080/23311916.2016.1237927

Schoeller, H. (1965). Qualitative evaluation of groundwater resources. Methods and techniques of groundwater investigations and development (pp. 54–83). UNESCO.

Sen, A. K. (2015). Practical and applied hydrogeology. Elsevier Inc.

Şener, Ş., Şener, E., & Davraz, A. (2017). Evaluation of water quality using water quality water quality index (WQI) method and GIS in Aksu River (SW-Turkey). Science of the Total Environment, 584, 131–144. https://doi.org/10.1016/j.scitotenv.2017.01.102

Singhol, B.B.S., & Gupta, R.P. (2010). Applied hydrogeology of fractured rocks, second edition. Springer science + business media (pp. 408).

SOGERAH. (2013). Detailed groundwater investigations and monitoring in Tana and Beles sub-basins, Final stage 1 Report – Part: Hydrogeological Survey. Ministry of Water Resources (MoWR), Addis Ababa, Ethiopia. [Unpublished Report]. p. 85.

Srinivasamoorthi, K., Chidambaram, S., Prasanna, M. V., Vasanthavahar, 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, 17(1), 49–58. https://doi.org/10.1007/s12040-008-0012-3

Tiwari, A. K., Singh, A. K., & Mahato, M. K. (2017). Assessment of groundwater quality of Pratappurh district in India for suitability of drinking purpose using water quality index (WQI) and GIS technique. Sustainable Water Resources Management, 4(3), 601–616. https://doi.org/10.1007/s00899-017-0144-1

Tiwari, J. N., & Manzoora, A. (1988). Water quality index for Indian rivers. In R. K. Trivedy (Ed.), Ecology and pollution of Indian rivers (pp. 271–286). Aashish Publishing House.

Todd, D. K., & Mays, L. W. (2005). Groundwater Hydrology (3rd ed.). John Wiley & Sons, Inc.

Tropics Consulting Engineers PLC. (2009). Geology of Bahir Dar Area. Addis Ababa.

WHO. (2011). Guidelines for drinking-water quality. In Incorporating the first addendum (4th ed., pp. 38). WHO chronicle.

World Health Organization (WHO). (2011). Guidelines for drinking-water quality (4th ed.). Switzerland.

Zewdie, G., & Yoseph, Z. (2012). Integrated Hydrogeological Mapping of Bahir Dar Map Sheet (NC 37-1) [Unpublished]. Ministry of Mines, Geological Survey of Ethiopia, Groundwater resource assessment directorate, p. 77.
