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Groundwater vulnerability assessment using GIS based DRASTIC model in Aksum area, central Tigray, Northern Ethiopia

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ABSTRACT

The study area is located 220 km northwest of Mekelle, the capital of the Tigray Regional State in Ethiopia. The objective of this research is to produce a groundwater vulnerability map for Aksum and its surroundings using the GIS-based DRASTIC model to protect the groundwater quality of the area. The DRASTIC model uses seven parameters that influence and control movement of the contaminants from the surface to the subsurface. These are Depth to aquifer (D), net Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I), and Hydraulic conductivity (C). These factors were rated, weighted and overlaid to create vulnerability maps showing areas affected by varying levels of groundwater contamination. The ArcGIS 10.7 software was used to create the groundwater vulnerability map by overlaying the seven layers. The DRASTIC vulnerability index was calculated as the sum of the products of ratings and weights assigned to each parameter on scales of 1 to 10 and 1 to 5, respectively. The vulnerability index ranged from 79 to 165 and reclassified into three classes using the quantile classification method: low (79–120), moderate (120–130) and highly (130–165) vulnerable zone, and cover about 78.3 km^2 (33.9%), 83.1 km^2 (36%), and 69.5 km^2 (30.1%) of the study area, respectively. The resulting DRASTIC index indicated a relative degree of vulnerability of the aquifer to pollution. The results were validated using nitrate concentrations in groundwater and the observed nitrate concentrations in wells are in accordance with the vulnerability map in most parts of the study area. The groundwater vulnerability map can be used as an initial tool at the planning, policy, and operational levels of the decision-making process concerning sustainable groundwater management and protection.

Keywords: Groundwater; Vulnerability; DRASTIC Model; GIS; Aksum

INTRODUCTION

Groundwater is one of the most important natural resources and is the main source of freshwater for different purposes in most parts of the world (Al-Madhlom et al., 2016). It is essential to meet domestic, industrial and agricultural water needs, especially in arid and semi-arid areas where surface water is scarce and seasonal (Jhariya et al., 2019). According to Shakoor et al. (2020), more than two billion people worldwide depend on groundwater to ensure their drinking water supply. In the case of Ethiopia, groundwater is the main source of drinking water and more than 80% of the country's drinking water supply comes from groundwater (Shiferaw et al., 2005: Mengistu et al, 2021).

However, groundwater pollution is one of the serious and increasing potential problems in the largest urban and agricultural areas because aquifers are inherently vulnerable to contamination from land use and anthropogenic influences such as urbanization development, population growth, increase in agricultural activities, and lack of proper sewage and municipal landfill leachate (Saidi et al., 2011). Unlike surface water, groundwater pollution is more difficult to detect and control, and can last for many years (Bhuvaneswaran and Ganesh, 2019; Moges and Dinka, 2021). Once polluted, it is very expensive, takes a long time and is very difficult to remediate, and sometimes restore impractical (Yin et al., 2012; Moges and Dinka, 2021).

In Ethiopia, concern about groundwater pollution were not considered a major problem until recently (Tilahun and Merkel, 2010). However, the development of settlements and industries mostly occurs without proper installation of sewers and poor waste disposal practices (Tilahun and Merkel, 2010). In the study area, water quality is poor due to natural processes (geogenic), consequently many wells have been abandoned. Besides the geogenic process there is increasing deterioration in water quality at several water points due to anthropogenic sources (Abay Engineering 2006; Alemayehu, 2011).

To solve this problem, one way to protect groundwater from pollution is to assess its vulnerability to contamination. The groundwater vulnerability map is a key element for prediction and a prevention tool, recognized for its ability to delineate vulnerable areas due to anthropogenic and geogenic activities (Ahirwar et al., 2020). Moreover, the groundwater vulnerability map shows the relative degree of vulnerability of an area and is an effective tool to support water managers at regional to local levels. According to the National Research Council (1993), groundwater vulnerability to contamination is defined as "the tendency or probability that pollutants will reach the water table after discharging at the ground surface". A groundwater vulnerability assessment is not directly measured but rather "a relative, immeasurable, dimensionless property that indicates where contamination is most likely to occur" in the area (Oke, 2020).

There are many methods or approaches used to map vulnerable zones, such as overlay and index methods process-based, and statistical methods (Mkumbo et al., 2022). Overlay and indexing methods, among others things, are comparatively common and popular and are based on the geological, and hydrogeological settings of the area. The most common overlay and index methods include: GOD (Foster 1987), DRASTIC (Aller et al., 1987), SINTACS (Civita, 1994), SEEPAGE (Moore and John, 1990). In this research, DRASTIC model is adopted because it is simple, cost effective, less time consuming and flexibility, (Zenebe et al., 2020; Patel et al., 2022; Gonçalves et al., 2023).

Therefore, this study classified areas where groundwater is possible to pollute and is used to attract the attention of decision-makers and policymakers, water managers and other stakeholders to particular vulnerable areas to protect and preserve groundwater resources from future contamination.

MATERIAL AND METHOD

Study area

The study area is located in north of Ethiopia, Tigray regional state, in the central zone, in the Aksum area. Geographically, it lies in UTM Zone 37, bounded by coordinates between 462361 and 478130 mE, and 1550260 and 156510mN, covering a total area of 234.5 km² (Fig. 1). The climatic data of the study area were taken from the Ethiopian Meteorological Agency (EMA) for the years 2005-2018. The area's average annual rainfall calculated using arithmetic mean is 734.4 mm, with peaks occurring in July and August. The mean monthly minimum and maximum temperatures are 8.5 ^{0}C and 29.5 ^{0}C, respectively.

The study area is characterized by both flat area and mountainous terrain with an elevation range from 1900 to 2500 m a.s.l. The area has mountainous and hills to the north, northwest, southwest and gentle topography in southern and south eastern parts of the study area. The slope gradient varies from gentle slopes to steep hill slopes. These streams originated from the surrounding highlands. The streams are dense at the area of higher slops and sparse where the slop is relatively flat. Dendritic drainage is mainly defined the drainage pattern of the study area. Many of the tributaries are flowing from the northeastern and northwestern towards southern and south western parts of the study area.

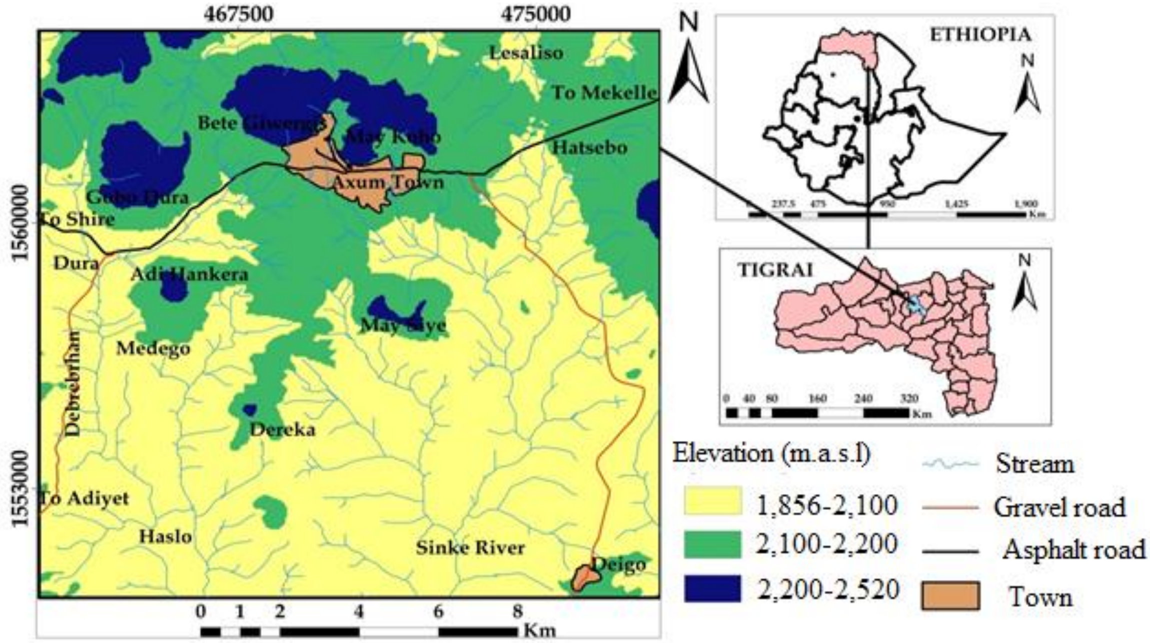

Figure 1. Location map of the study area

The geology of the study area is composed of different types rock type and geological structures. It includes the Precambrian (basement complex), Mesozoic sedimentary rocks (undifferentiated clastic sedimentary rocks, dominantly reddish sandstone), basaltic rocks, and trachyte and phonolite plugs from the oldest to the youngest.

The Precambrian basement contains low-grade metamorphic rocks characterized by highly weathered, fractured, sheared, and showing a range of colors such as light grey, dark grey and light green. It exhibits a general trend of NE-SW strike direction (Tadesse et al., 1999). The sandstone in the area is characterized by reddish color, high degree of weathering and fracturing, and covers 18.1% of the study area. In addition, the dominant rock found exposed in this area is the basaltic flow characterized by textural and compositional variation along with the presence of horizons of thin red Paleo-soils within the succession (Tadesse, 1997). At places, the basalts are characterized by black fresh color and light brownish weathered color, fine grain size, massive and in places, highly fractured and extensively weathered and columnar jointing basalt is well observed. The trachyte and phonolite rock units are found exposed as independent irregular dome shaped bodies forming an elevated area. The trachyte is characterized by being bright white, whitish-gray in fresh color, moderately weathered, relatively hard, compact, and massive while the phonolite is characterized by being dark gray to pink in color, coarse grained, extensively weathered and fractured due to jointing. Closely spaced vertical joints and exfoliation weathering are common in the phonelite (Fig. 2).

Hydrogeologically, the area is characterized by a higher degree of weathering and fracture of the rocks. The main aquifer in the area is the highly weathered and fractured part of the basaltic formation (Alemayehu, 2011).

Sampling

A total of twenty four (24) water samples have been collected from different water points (12 shallow wells, 3 Deep wells, 7 hand dug wells, 1 spring and 1 surface water) for nitrate concentration analysis and Garmin GPS was used to locate water sampling points (Fig. 3). The water samples for nitrate analysis were collected in properly cleaned, labeled, and sealed one-liter plastic bottles. Before sampling, the wells were pumped for an average of four to five minutes in order to remove stagnant water, and each sample bottle was washed three times by the water to be sampled. The collected water samples were transported to the Mekelle University hydrogeochemistry laboratory and stored in refrigerator at 4^{o}C until the analysis was done, using UV-Spectrophotometer (model UV-VIS) to analyze the nitrate concentration.

Twenty soil samples (10 for texture classification and 10 undisturbed soil samples for soil permeability analysis) were randomly collected from 10 locations (Fig. 3). Soil texture (Sand, slit and clay ratio in soils) and soil permeability were analyzed using the hydrometer method and a constant head hydraulic conductivity meter respectively, at soil physics laboratory, Mekelle University. The textural soil classification was done based on the United State Department of Agriculture (USDA) (1994) soil textural classification method

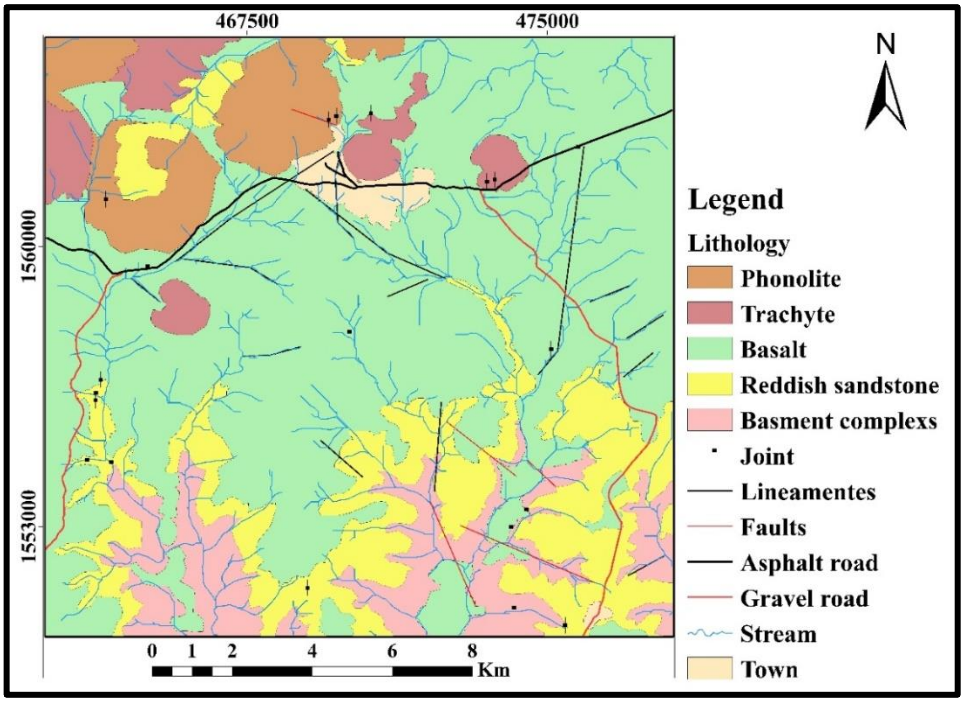

Figure 2. Geological map of the study area .

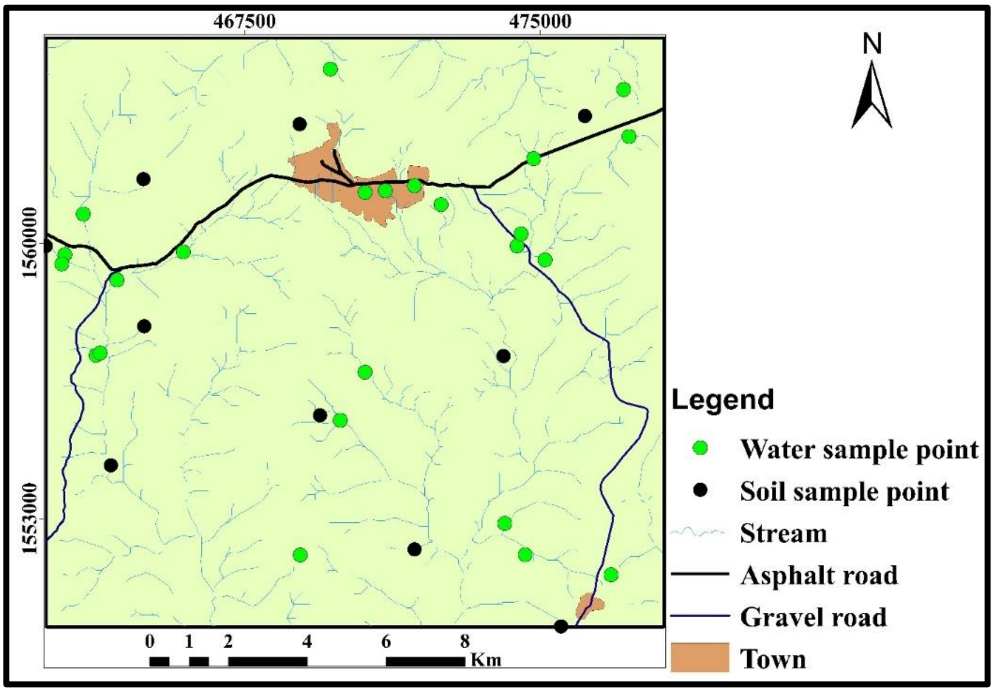

Figure 3. Water points and soil sample distribution

DRASTIC approach

The DRASTIC model is a GIS based overlay and indexing method originally developed by the U.S. Environmental Protection Agency (EPA) to assess groundwater susceptibility to contamination (Aller et al., 1987). According to Aller et al. (1987), the DRASTIC model is based on the principle of environmental hydrogeological setting which depends on "the main geological and hydrological factors that influence and control groundwater movement into, through and out of an area". This model considers seven parameters or factors which are abbreviated as DRASTIC, namely (1) depth to aquifer (**D**), (2) net recharge (**R**), (3) aquifer media (**A**), (4) soil media (**S**), (5) topography (**T**), (6) impact of vadose zone (**I**), and (7) hydraulic conductivity (**C**). All of these parameters were applied as input layers to determine the relative degree or sensitivity of groundwater to pollution in the area.

Each of the parameters was assigned a DRASTIC rate from 1 to 10 based on relative susceptibility to pollution, with 1 representing the lowest vulenerability and 10 representing the highest vulenerability to contamination (Table 1). Each parameter is then weighted based on its relative contribution to potential contamination, with the weighting range from 1 to 5 (Aller et al., 1987). 1 indicates the least significant parameter and 5 indicates the most significant parameter (Table 1). The rate was multiplied by its weight, giving the weighted rate of the individual parameter. Finally, the weighted rate of each parameter was added to obtained the final DRASTIC index using Eq 1. The resulting index is a relative measure of vulnerability to contamination, i.e., areas with a higher index value are more vulnerable to contaminant than those with a lower index.

DRASTIC index is calculated by Eq.1 (Aller et al., 1987):

$$\boldsymbol{DRASTIC\ index = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \cdots Eq.1}$$

Where suffixes r and w indicate the assigned rates and weight, respectively.

Once a DRASTIC index has been calculated, it is likely to classify areas that are more susceptible to groundwater contamination relative to each another (Aller et al., 1987). Quantile classification was applied to divide the study area into three zones namely low, moderate, and high vulnerability, thereby classifying data into a certain number of categories with an equal number (Sener et al., 2009). Each class contains an equal number of features. A quantile classification is well suited to linearly (i.e., evenly) distributed data. Because features are grouped by the number in each class, the resulting map can be misleading. Similar features can be placed in adjacent classes, or features with widely different values can be put in the same class (ESRI, 1996). Arc GIS 10.7 was used to develope the weighted rate map of the individual parameters and the combination of the seven parameter maps. The depth to water level was measured with deep meter which is Solinst 101 model. pumping test well data were collected from Tigray Water Resource Bureau (TWRB) and AQTESOLV pro4.0 was used to calculate the hydraulic conductivity of the aquifer.

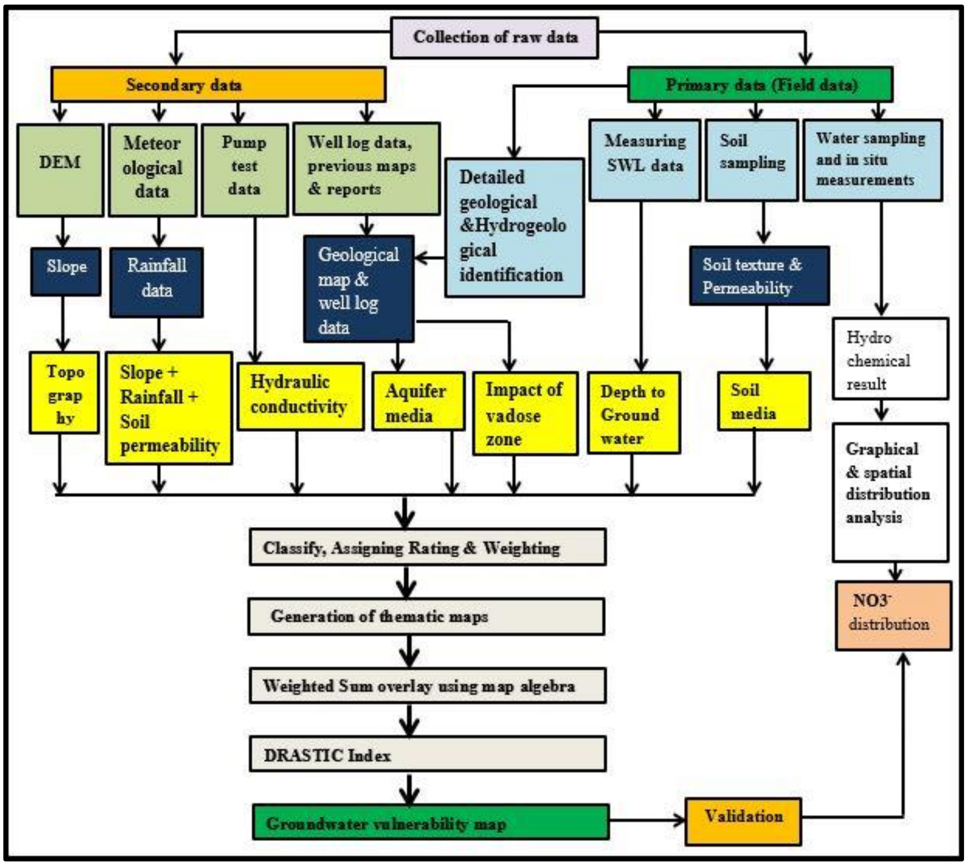

Figure 4. Methodological flow chart of the study

Table 1 The ranges, ratings and weight of the DRASTIC parameters (Aller et al., 1987)

DRASTIC parameters	Ranges	Ratings	Relative weight
Depth to water level (m)	0 - 1.5	10	**5**
	1.5 - 4.6	9	
	4.6 - 9.1	7	
	9.1 - 15.2	5	
	15.2 - 22.8	3	
	22.8 - 30.4	2	
	>30.4	1	
Aquifer media	Karst Limestone	10	**3**
	Basalt	9	
	Sand and Gravel	8	
	Massive Limestone	8	
	Massive Sandstone	6	
	Bedded Sandstone, Limestone	6	
	Weathered Metamorphic/Igneous	4	
	Metamorphic/Igneous	3	
	Massive Shale	2	
Soil media	Thin or absent	10	**2**
	Gravel	10	
	Sand	9	
	Peat	8	
	Shrinking Clay	7	
	Sandy Loam	6	
	Loam	5	
	Sandy Clay Loam	4	
	Clay Loam	3	
	Silty Clay Loam	3	
	Sandy Clay	2	
	Muck	2	
	Clay	1	
Topography (slope %)	0 - 2	10	**1**
	2 - 6	9	
	6 - 12	5	
	12 - 18	3	
	>18	1	
Impact of vadose zone	Karst Limestone	10	**5**
	Basalt	9	
	Sand and Gravel	8	
	Metamorphic/Igneous	4	
	Sand and Gravel with significant Silt	6	
	Bedded Sandstone, Limestone & Shale	6	
	Sandstone	6	
	Limestone	6	
	Shale	3	
	Silt/Clay	3	
Hydraulic conductivity(m/d)	<0.5	1	**3**
	0.5 - 1	3	
	1 - 1.5	6	
	>1.5	10	
To estimate recharge value the following three parameters has been used.		Relative weight of Recharge=	**4**

Slope (%)		**Rainfall (mm)**		**Soil permeability**		**Recharge value**	
Range	Factor	Range	Factor	Range	Factor	Range	Rating
<2	4	>850	4	High	5	11 - 13	10
2 - 10	3	700 - 850	3	Mod-high	4	9 - 11	8
10 - 33	2	500 - 700	2	Moderate	3	7 - 9	5
>33	1	<500	1	Slow	2	5 - 7	3
				Very slow	1	3 - 5	1

Assumptions of DRASTIC method

This model holds the following basic assumptions:

- "The potential sources contamination are introduced at the ground surface;
- The contaminant is flushed into the groundwater by precipitation;
- The pollutant has mobility similar to that of water; and
- The area evaluated using DRASTIC should be greater than100 acres/0.4sq.km" (Aller et al., 1987; Saidi et al., 2011).

VALIDATION

The model result was validated by comparing the model output (vulnerability index) with the observed nitrate concentration. The high levels of nitrates comes mainly from surface sources like agricultural activities such as fertilizers, pesticides, manure, sewage discharges, septic tanks and landfills.

The reason for selecting nitrate is that the main sources of nitrate in groundwater are anthropogenic in nature (Freeze and Cherry, 1979). For this reason the distribution of NO_3^- concentration maps is preferred as a good water-quality parameter for validating groundwater vulnerability maps (Saidi et al., 2011). If the nitrate concentration in groundwater is above 10 mg/L, this indicates anthropogenic contamination (Sener et al., 2009). The spatial distribution of nitrate (NO_3^-) concentration was prepared and finally correlated with the vulnerability index map (Fig. 4).

RESULTS AND DISCUSSION

Depth to water level

The minimum and maximum depths of water level measured in the study area were 1.5 m and 20 m below the ground level, respectively. Based on the result, flat areas mainly in the north, east (local name Hatsebo), and some parts of the south of the study area have shallow groundwater depths. In terms of area coverage, it was found that the four classes such as 1.5-4.6 m, 4.6-9.1 m, 9.1-15.2 m and 15.2-22.8 m are about 16.8%, 69.5%, 12.9%, and 0.8%, of the total study area, respectively (Fig. 6a).

Shallow groundwater is more vulnerable to pollution than deeper groundwater due to the short travel time, and distance to reach contaminants in the saturated zone. Accordingly, 1 is assigned for the groundwater depth > 30.4 m and 10 is assigned for groundwater depth < 1.5 m (Malik and Shukla, 2019; Zenebe et al., 2020; Mkumbo et al., 2022).

Net recharge

Net recharge map was calculated using an equation that integrates available features that are supposed to act as recharge zones relative to other areas.

Based on the result, the slope factor (value in percent) was assigned rating values of 1 for >33% (steep slope), 2 for 10-33%, 3 for a range between 2 and 10%, 4 for 0-2% (gentle slope), and accounts for an area of approximately 3.2%, 30.7%, 52.3%, and 13.8% of the study area, respectively (Table 2 and Fig. 5a). Rainfall is expected to be uniform throughout the study area and ranging from 704 to 766mm. According to Piscopo (2001), a uniform rating of 3 which signifies rainfall of 700 - 850 mm was adopted (Fig. 5b). The soil permeability of the study area was classified into two classes: slow and moderate, where the slow soil permeability was rated 2 and covered an area of about 51.3%, and the moderate soil permeability was rated 3 and covered 48.7% of the study area (Table 2 and Fig. 5c).

Table 2. Parameters used to calculate recharge value and their range and ratings

Slope (%)		**Rainfall (mm)**		**Soil Permeability**		**Recharge Value**	
Range	**Factor**	**Range**	**Factor**	**Range**	**Factor**	**Range**	**Factor**
<2	4			slow	2	5-7	3
2-10	3	700-850	3	Moderate	3	7-9	5
10-33	2					9-11	8
>33	1						

The net recharge map was then prepared by overlaying the three parameters (Fig. 5a, b, c) in Arc GIS using map algebra and classified according to the criteria given in (Table 2). The recharge value rating in the study area has three values: 3, 5, 8 and covering about 15.6%, 79%, and 5.4% of the area, respectively, with the rating 3 reflecting the minimum recharge rate due to its minimum rainfall amount, high slope percent, and slow permeability. The high value of 8 shows higher recharge ability (Fig. 6b).

Aquifer media

The aquifer media of the study area is dominated by weathered and fractured basalt, weathered sandstone (mudstone) and fractured metamorphic (meta sediment and meta volcanic) (Fig. 6c). The central north, east and west parts of the study area are mainly weathered and fractured basalt and covering 72.4% (169.3 sq.km). The sandstone (mudstone) aquifer mainly covers the south, south central and south east of the study area and occupies about 17.8% (41.7sq.km) whereas, the weathered and fractured metamorphic covers the south western part of the area and covers 9.8% of the study area (23 sq.km). Aquifer media controls pollutant attenuation processes based on the permeability. This means that the larger the grain size and the greater the number of fractures or openings within the aquifer, the higher the permeability or the higher vulnerability potential (Mkumbo et al., 2022).

The corresponding ratings assigned for each aquifer media is given in (Table 3) (Aller et al., 1987). As stated by Tilahun and Merkel, (2010), "all vulnerability concepts consider the upper most aquifer, and do not take into account stacked aquifer systems".

Table 3. Range and Rating for aquifer media in the study area

Aquifer Media Type	Rating
Weathered and Fractured basalt	9
Weathered and Fractured metamorphic	4
Sandstone (Mudstone)	6

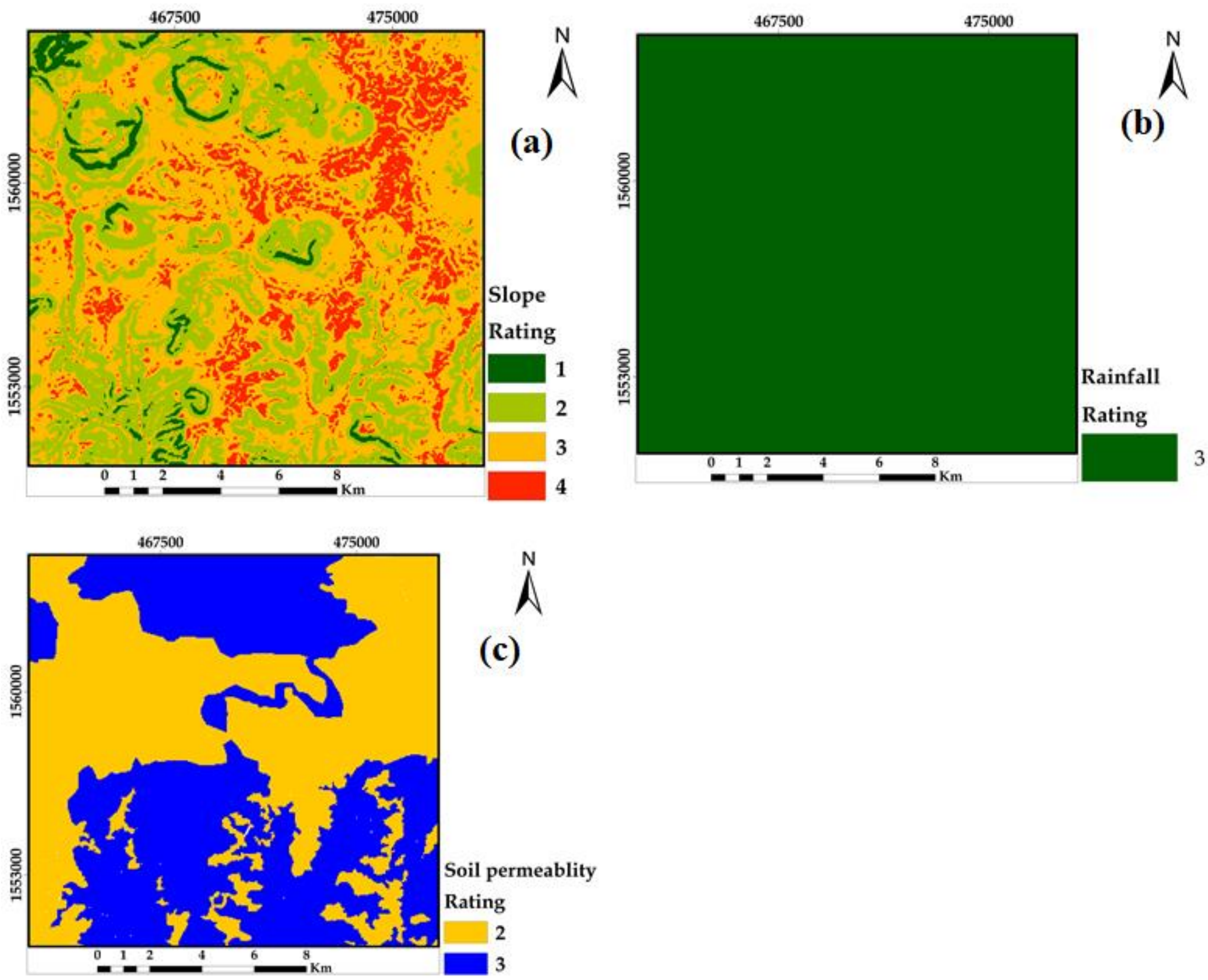

Figure 5. Parameters used to calculate recharge value: (a) Rated slope range, (b) Rated Rainfall range, and (c) Rated soil permeability range

Soil media

Based on the results, different soil types exist in different parts of the study area such as: The southern and southwestern parts of the areas are covered by silt clay loam and sandy clay loam soil types, while the north and northwestern are dominated by silt loam and silt clay and clay and clay loam exposed in central, eastern and some parts of western of the study area (Fig. 6d). Clay and clay loam are the two dominant soil types in the study area, covering about 26.8% and 23.2% of the total study area, respectively. The other soil types are silt clay, sandy clay loam, silt loam, silt clay loam, and area covered by thin or absent soil, representing about 17.1%, 13.4%, 10.5%, 2.5%, and 6.5% of the total study area, respectively. The soil parameters are evaluated based on their permeability and texture. The texture of soil determines the amount of recharge and attenuation characteristics of contaminants, and the presence of a coarse texture class increases infiltration whereas a fine texture reduces infiltration (Ghosh et al., 2015; Mkumbo et al., 2022).

As shown in Table 4 and Fig. 5d a rating 10 has been given to areas with thin soil surface coverage or areas with bedrock. Rating 4 has been given to medium texture such as sandy clay loam and silt loam. Rating 3 has been given to moderately fine texture such as silt clay loam and clay loam. Rating 2 has been given to fine texture such as silt clay and finally rating 1 has been given to very fine texture such as clay (Table 4).

Table 4. Range and Rating for soil media in the study area

Soil Media (Texture)	Rating
Absent	10
Sandy clay loam	4
Silt clay loam	3
Clay loam	3
Silt clay	2
Silt loam	4
Clay	1

Topography

The topography was expressed in terms of slope percentage (%) of the study area. Based on the result, it was categorized in to five ranges or classes: (0-2%), (2-6%), (6-12%), (12-18%), and (>18%) and covers an area of about 13.8%, 35.3%, 23.8%, 12.6% and 14.5%, respectively. According to Aller et al. (1987), flat or gentle areas are assigned maximum rating values, whereas steeper areas are given low ratings (Table 5 and Fig. 6e).

The north (Bet Giwergis and May Koho), the northestern (Gobo Dura and Adi Hankera) and the southwest have relatively steep topography (>18%) and are relatively less vulnerable zones, whereas the north in the center (Axum town), eastern (Hatsebo), western (Medego, Debrebrhan), south central (Derka) and southern (Mehabre selam), have relatively gentle topography (0-6%) and those zones are relatively more vulnerable to pollution. Areas having a flat or gentle slope are more vulnerable to groundwater pollution due to less runoff and a high infiltration rate. This encourages more time for contaminants to percolate down to the saturated zone, where higher topographic areas are less vulnerable to groundwater pollution due to a steep slope that allows high runoff and low infiltration (Aller et al., 1987; Sener et al., 2009; Mkumbo et al., 2022; Gonçalves et al., 2023).

Table 5. Range and Rating for topography in the study area

Slope (%) range	0-2%	2-6%	6-12%	12-18%	>18%
Rating	10	9	5	3	1

Impact of vadose zone

The vadose zone media comprises clay or silt, trachyte, sandstone, highly weathered and fractured phonolite , and weathered metamorphic.

Based on field observation and well log data, most of the basalt flow is covered by unconsolidated sediments formed by weathering processes from the underlying basalts. The sediments are mainly black cotton soil that is rich in clay, and their thickness varies from place to place, especially in Tabiya Hastsebo, Lesaliso, Medego and Dura the thickness of the clay is about 9 m. This impermeable clay clogs the fractures and prohibits the infiltration of surface water. This condition reduces the entry of contaminants to the aquifer. Trachyte is relatively hard, compact and massive, producing a zone of runoff rather than infiltration, whereas phonolite is relatively highly weathered and jointed, and it encourages infiltration rather than surface runoff. The rating given for this parameter was ranges from 3 to 6 (Table 6). A rating of 3 was assigned to very low permeability classes such as: clay/silt, and trachyte with areal coverage (64.7%), a rating of 4 was assigned to phonolite and metamorphic occupies (17.5%) whereas sandstone was rated 6 and covered (17.8%) of the study area (Table 6 and Fig. 6f).

Table 6. Range and Rating for vadose zone in the study area

Vadose Zone Media	Rating
Trachyte, clay/silt	3
Weathered and Fractured Phonolite metamorphic (Weathered and Fractured)	4
Sandstone	6

Hydraulic conductivity

The value of hydraulic conductivity in the study area ranged between 0.03 and 10.04 m/d and has been divided into four zones as shown in (Table 7). According to Yin et al. (2012), the hydraulic conductivity result was reclassified in to four classes such as: <0.5m/day, 0.5-1 m/day, 1-1.5 and >1.5 m/day, with an aerial coverage of, 16.7%, 27.3%, 33.9% and 22.1%, respectively (Table 7 and Fig. 6g). Those with hydraulic conductivity value of <0.5 m/day are geologic materials such as metamorphic rocks, Rhyolite and massive phonolites: geologic materials. With hydraulic conductivity value between 0.5m/day and 1m/day are the intercalated sand stone, mudstone and silt stone rocks. The moderately fractured and weathered basalts and phonollites are with hydraulic conductivity ranges from 1m/day to 1.5 m/day. However, highly fractured basalts and phonelites result with hydraulic conductivity value of greater than 1.5 m/day.

In the southern, southwestern and eastern parts of the study area, the hydraulic conductivity is relatively low, indicating zones of low vulnerability, whereas in the northern, western and northwestern areas the high hydraulic conductivity is relatively high, which indicates high vulnerability zones to groundwater pollution. Low hydraulic conductivity indicates high resistance to contamination or less vulnerable to contamination and high hydraulic conductivity indicates more susceptible to contamination (Bera et al., 2021; Mkumbo et al., 2022).

Table 7. Range and rating of hydraulic conductivity

Range of Hydraulic conductivity (m/d)	Rating
0.5	1
0.5-1	3
1-1.5	6
> 1.5	10

Groundwater Vulnerability map

The groundwater vulnerability map of the study area was computed using the weighted sum method by multiplying the weight of each parameter by the corresponding rate in the raster calculator tool of the ArcGIS spatial analysis software. Equation (1) was used to generate the index map. The range of the DRASTIC vulnerability index value was between 79 and 165 and the resulting DRASTIC index represents a relative degree of vulnerability to pollution.

The higher the DRASTIC index value indicates the greater the vulnerability of the groundwater to pollution, whereas the lower the DRASTIC index value shows the lower the relative groundwater contamination potential of the area. The vulnerability index values were reclassified into three classes using the quantile classification method: low (79–120), moderate (120–130) and highly (130–165) vulnerable zone, as presented in Table 8 and is the most suitable method for this kind of classification (Sener et al. 2009).

The generated aquifer vulnerability map (Fig. 6) shows that large portion of the study area is dominated by moderately vulnerable areas. The highest class of vulnerability (130–165) covers about 69.5 km² (30.1%) of the study area mainly in the east, central, west, north, northwest, and a small portion of southern part of the study area. This is due to the gentle slope (this condition facilitates more infiltration), shallow groundwater depth, relatively high recharge, and higher hydraulic conductivity. This results in a low capacity to attenuate the contaminants from entering the saturation zone.

According to the final vulnerability map, about 83.1 km² (36%) of the study area is classified as moderately vulnerable (120-130); this area a covers large part northern, north eastern, south central and some part of the eastern. This vulnerable zone is dominantly found in the silt clay dominated soils.

The low groundwater vulnerability class, which is ranged between 79 and 120 occupies an area of about 78.3km² (33.9%) as showun in Table 8 and covers mainly southern, south western, south eastern and some portions of the west and east direction of the study area (Fig. 7). The low vulnerability in these zones are probably related to the deeper water table, relatively low hydraulic conductivity, and relatively steep slope, which encourages runoff instead of infiltration. Moreover, the presence of low permeable soils such as clay, clay loam and silty clay clogs the fractures and prohibits the infiltration of surface water. Hence, all these factors make the aquifer more protected or less vulnerable to pollution.

Table 8. DRASTIC vulnerability classes and their areal coverage of the study area

DRASTIC Index value	Vulnerability class	Area (in km^2)	Area (in %)
79 - 120	Low	78.3	33.9
120 - 130	Moderate	83.1	36.0
130 – 165	High	69.5	30.1

Validation of the model using nitrate concentrations

The nitrate concentration in the study area ranged from 0.8 to 96.63 mg/l. Nitrate concentrations observed at 24 water sampling points were overlaid on the vulnerability map to identify the correlation between different vulnerable zones. The range of observed nitrate concentrations was classified into three levels (Zenebe et al., 2020): < 20 mg/l; 20–50 mg/l and > 50 mg/l, as shown in Fig. 7 and compared with the corresponding groundwater vulnerability class.

From the special distribution map of nitrate, it was found that 75% (6 samples out of 8), 33% (2 samples out of 6) and 30% (3 samples out of 10) with >50mg/l, 20-50mg/l and 0.8-20mg/l, respectively, fall into the high vulnerability class. About 25% (2 samples out of 8), 50% (3 samples of 6) and 30% (3 samples of 10) with >50mg/l, 20-50mg/l and 0.8-20mg/l, respectively, fall into the moderate vulnerability class (Fig. 8).

Furthermore, 0% (0 sample of 8), 33% (2 samples of 6) and 60% (6 samples of 10) with >50mg/l, 20-50mg/l and 0.8-20mg/l, respectively, fall under the low vulnerability class, as shown in (Fig. 8). Generally, the trends of nitrate concentration and vulnerability class agreed well in most parts of the study area, except for some parts of the area (Fig. 8).

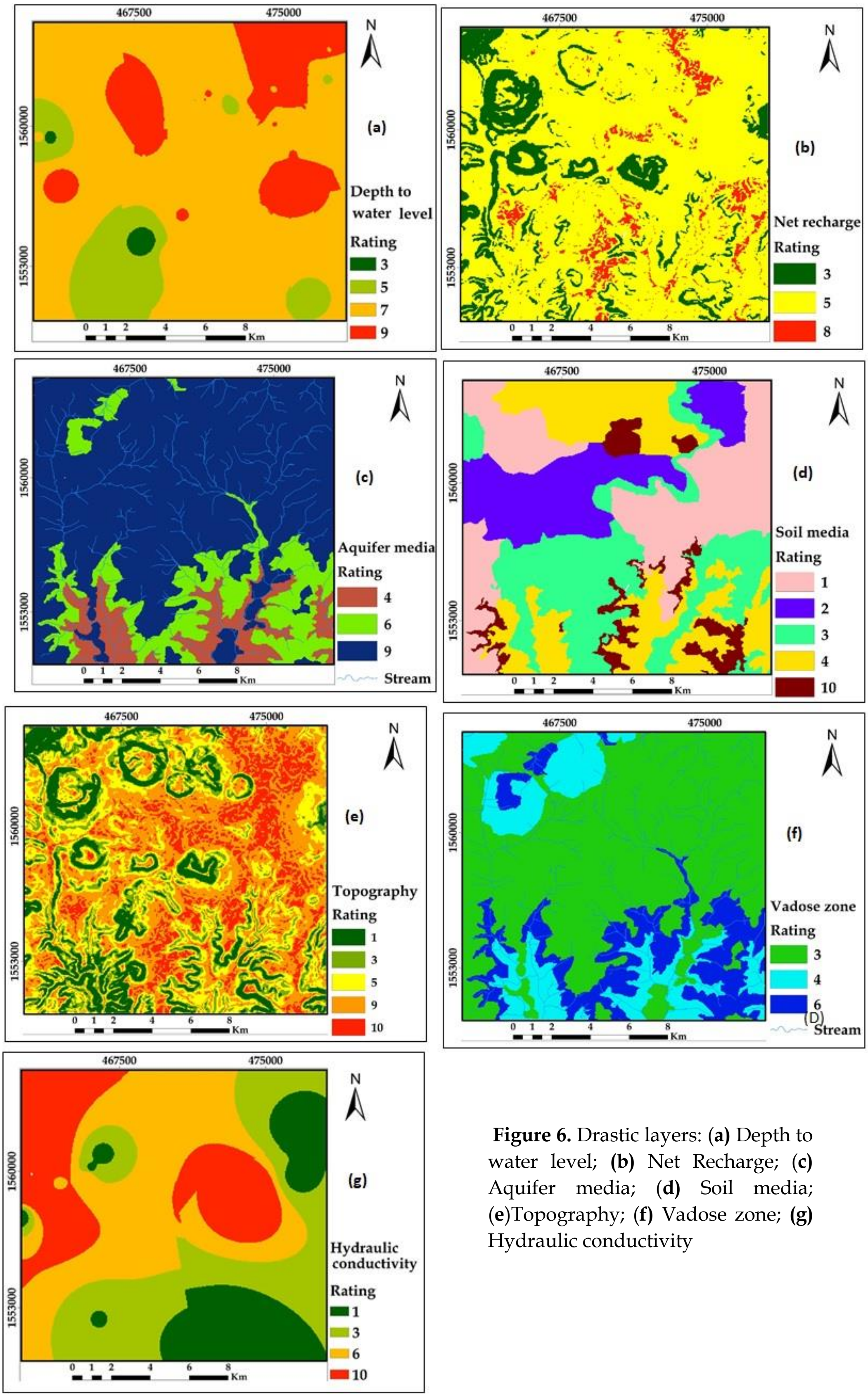

Figure 6. Drastic layers: (**a)** Depth to water level; **(b)** Net Recharge; (**c)** Aquifer media; (**d)** Soil media; (**e**)Topography; (**f)** Vadose zone; **(g)** Hydraulic conductivity

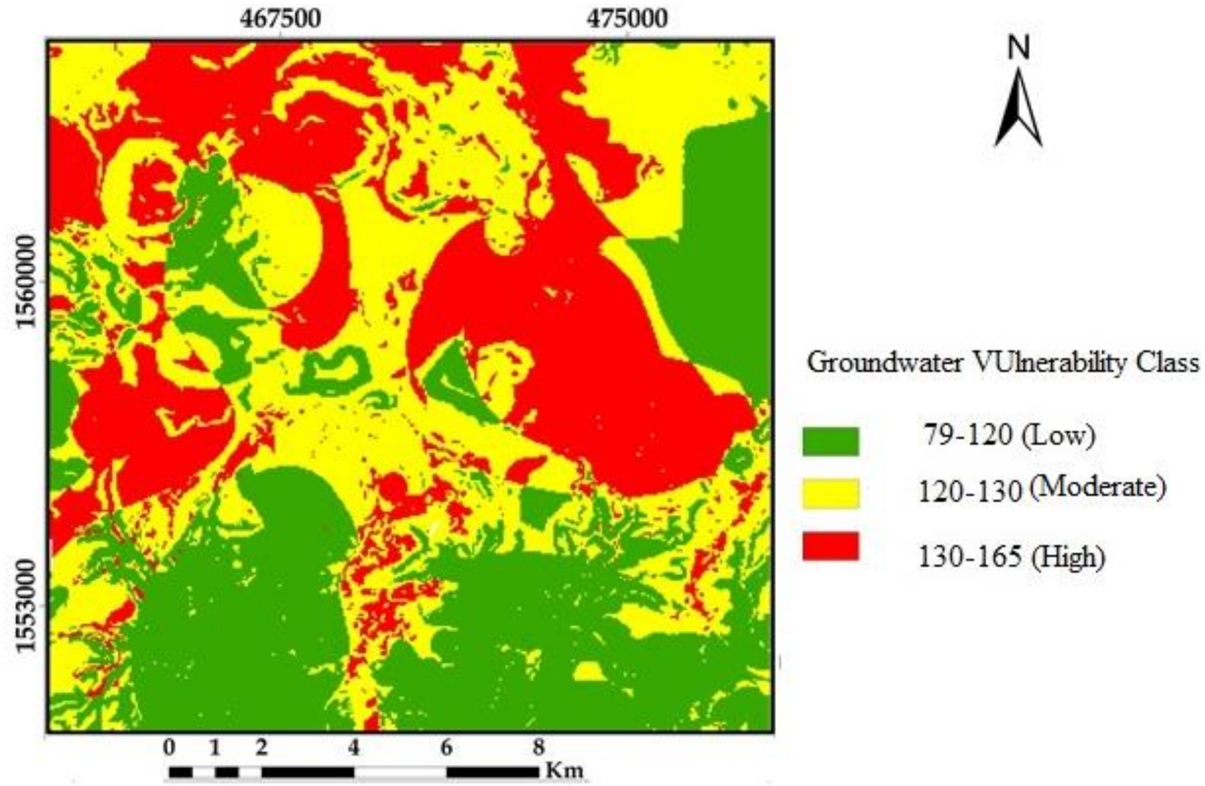

Figure 7. Groundwater vulnerability map of the study area

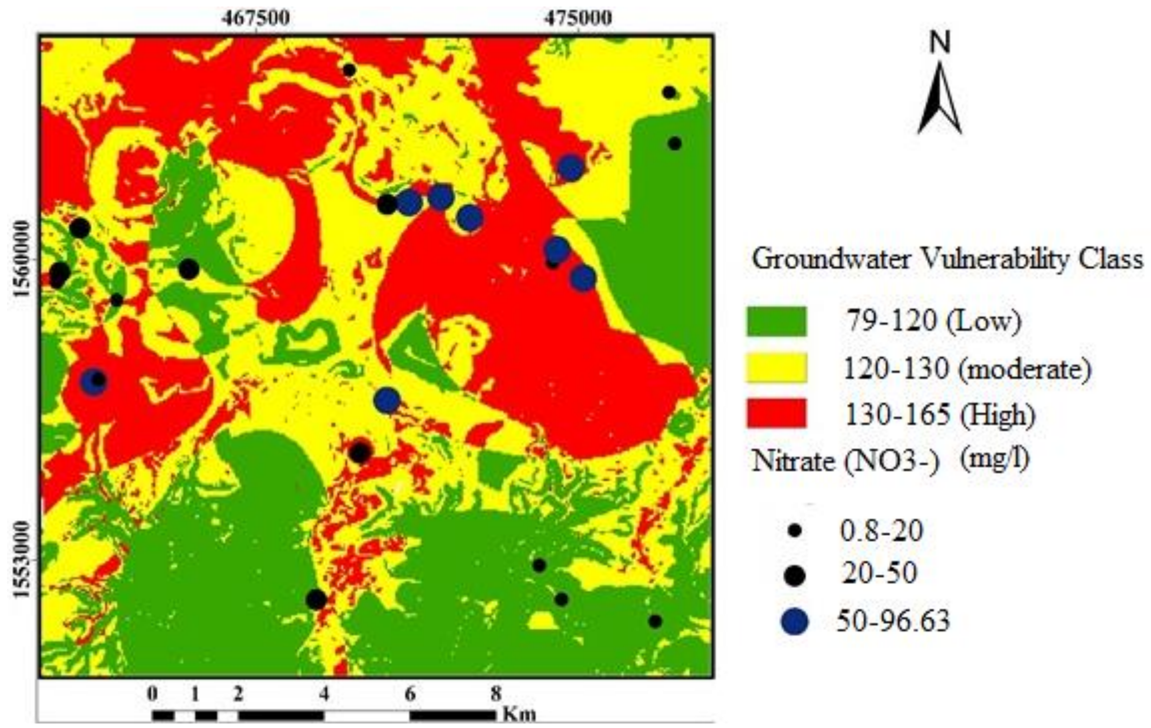

Figure 8. Groundwater vulnerability index and corresponding nitrate concentration

CONCLUSTION

Groundwater vulnerability assessment is a useful tool for groundwater resource management and protection zoning. Therefore, a GIS-based DRASTIC model was employed to produce a groundwater vulnerability map of the study area. Seven different hydrogeological input layers were used to identify vulnerable zones. The DRASTIC vulnerability index ranged from 79 to 165 further reclassified into three zones using the quantile classification method, such as low (79–120), moderate (120–130) and high (130–165) vulnerable.

The result of groundwater vulnerability shows that 30.1 % of the area has high vulnerability, which is mainly due to the gentle slope, shallow groundwater depth, high recharge and relatively higher hydraulic conductivity. It covers the eastern, central, western, northern, northwestern direction and a small part of the southern direction of the study area. About 36 % of the area is classified as moderately vulnerable and includes the northern, northeastern, south- central and some parts of the eastern direction. This vulnerable zone is dominantly found in the cultivated lands of the area and 33.9 % of the area is under the low vulnerability, which covers mainly the south, southwest, southeast and some parts of the west and east directions of the study area.

The groundwater vulnerability map was validated using nitrate concentrations in groundwater. The results indicate agreement between the obtained vulnerability map and the observed nitrate concentrations. However, it should be noted that, in principle, all groundwater resources are exposed to pollution, though the degree differs. DRASTIC vulnerability maps show only the relative vulnerability of areas within the same map, and do not represent absolute values that can be compared between maps.

Based on the conclusions and findings, the medium to high vulnerability area would require careful planning and monitoring of groundwater as well as restrictions of an activity that increases the vulnerability of groundwater to pollution such as dumping domestic and municipal waste in the highly vulnerable zones.

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