ORIGINAL ARTICLE

Assessment on contamination vulnerability of Akaki well fields using GIS and DRASTICA methods

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Abstract

Groundwater vulnerability to contamination is becoming a major issue in urban settlement territories due to multiple anthropogenic activities. Akaki well fields supply 30% of the domestic water for Addis Ababa city, However, these well fields are highly vulnerable to contamination as these well fields are located downstream of the city, and assessment of groundwater vulnerability to contamination is essential. The present study investigates the vulnerability of Akaki well fields to contamination using the GIS DRASTICA method. DRASTICA stands for depth to water level (D), recharge (R), aquifer (A), soil (S), topography (T), impact of vadose zone (I), hydraulic conductivity (C), and anthropogenic activities (A). To generate the groundwater vulnerability to contamination, the method considered these eight parameters. Groundwater samples were collected from twenty boreholes for laboratory analysis to determine the water quality index. This water quality index was used to validate the DRASTICA method besides nitrate concentration. The DRASTICA method identified five vulnerability zones such as very low, low, moderate, high, and very high. According to the result of the DRASTICA method, 7.68% of the study area has a very low class of groundwater vulnerability zone, 24.54% is low class, 28.91% is moderate class, 29.85% is high class, and 9.02% of the study area has a very high class of vulnerability zone. Sensitivity analysis reveals that the impact of a vadose zone is the most influential parameter of the vulnerability index. The correlation between the DRASTICA index and nitrate was $R^2 = 0.95$ which indicated that the DRASTICA method has the best relation with actual pollution substances found in the groundwater. Those well fields that have high water quality index were found in the very high vulnerability zone of the DRASTICA index. Thus, both water quality index and nitrate concentration were found to be correlated with the method.

Keywords Akaki well fields · Groundwater vulnerability · DRASTICA method · Water quality index

Introduction

Water is the greatest resource of humanity. It does not only help with survival but also helps in making life comfortable and luxurious. Most of the Earth's liquid freshwater is found not in lakes and rivers, but underground in aquifers (Morris et al. 2003). The Earth's hydrosphere contains a huge amount of water, about 1386 million cubic kilometers, and

of this, 97.5% is saline water, 2.5% is fresh water, and 29.9% of freshwater exists as groundwater and only 0.26% exists as surface water (Shiklomanov 1998).

Groundwater is freshwater located in the sub-surface pore space of soil and rocks (Subramanya 2008). It has been exploited for domestic use, development in most parts of the world, livestock, and irrigation since the earliest times (Chilton 1996; Tolera et al. 2020). The statistics gathered on the use of groundwater in Sub-Saharan Africa are sparse and not complete; although rural domestic water supply, small-scale livelihoods, and livestock rearing are highly dependent on it (Tuinhof et al. 2011). Over the last 25–30 years, there has been a massive anthropogenic change in the hydrological cycle of rivers and lakes all over the world (Shiklomanov 1998; Subramanya 2008; Chilton 1996; Tolera et al. 2020; Tuinhof et al. 2011). Groundwater can be contaminated by localized releases from sources such as hazardous waste

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disposal sites, municipal landfills, and substances released at or near the soil surface (National Research Council 1993).

Groundwater vulnerability assessments are important components of groundwater protection and management (Oke and Fourie 2017). This concept was first introduced by Margat (1968) about the potential for groundwater contamination by surface pollutant sources (Qian et al. 2011). Vulnerability is the possibility of percolation and diffusion of contaminants from the ground surface into the groundwater system (Kumar et al. 2013). Many methods are used for estimating groundwater vulnerability to contamination. The subjective rating method, the statistical method, and the process-based method are ways of assessing groundwater vulnerability (Maria 2018). The DRASTIC model is one of the overlay index methods which was developed for groundwater vulnerability assessment(Kumar et al. 2013). It provides the user with a measure of relative groundwater vulnerability to pollution and is used to identify data gaps that affect pollution potential assessment (Aller et al. 1987). DRASTICA is a modified DRASTIC model that incorporates the overlay and index methods and takes into account anthropogenic influence in urbanized environments. The chemical substances which are disposed of on or near the ground surface influence groundwater quality (Villumsen et al. 1983; Nagaraju et al. 2016; Mohamed et al. 2019; Honarbakhsh et al. 2019).

Water quality is a major concern for humanity because it is directly related to human health, environmental protection, plant growth, and long-term development (Nagaraju et al. 2016). The water quality index (WQI) is one of the most efficient techniques to evaluate groundwater quality (Mohamed et al. 2019). It is a mathematical instrument used to convert large amounts of water quality data into a single number that indicates the level of water quality (Patel and Vadoria 2018). The Groundwater Quality Index (GWQI) is an indicator of water quality and suitability for drinking (Honarbakhsh et al. 2019).

In the present study, the Akaki well fields were conducted to assess their vulnerability to contamination, and the risk zone area has been identified. The main objective of the present research work is to assess the Akaki groundwater vulnerability to contamination using the GIS DRASTICA method and determine the water quality index of the study area.

Materials and methods

Geographically, Akaki well fields are located between the latitudes 8° 45′ 48″ N and 8° 53′ 46″ N, and longitudes 38° 41′ 16″ E and 38° 49′ 32″ E. Akaki well fields are found in Akaki catchment which is located in Awash River basin with a total area of 127 square kilometers. It is located in

the southern part of Addis Ababa city and is 22 km far from the city's center. The topography of the study area includes both gentle and sloppy. The elevation around the Akaki well fields area ranges from 1980 to 2380 m above sea level. The maximum temperature around Akaki station is 32 °C during March and the minimum temperature drops to 3.4 °C during December. The annual average rainfall of the study area is 988.86 mm.

DRASTICA is the popular modified DRASTIC method for the development of vulnerability maps in the groundwater vulnerability assessment. ArcGIS 10.4.1 was used for preparing the spatial distribution of the groundwater quality map and the overlay of the DRASTICA map. Strater5 software was used in this study to visualize the strata of the study area. Digital elevation model data with 12.5×12.5 m resolution has been downloaded from the Alaska satellite facility.

The depth of water level in this study was obtained from the Addis Ababa Water and Sewerage Authority Head Office. It has been interpolated using an interpolation algorithm with the help of the inverse distance weighted (IDW) interpolation tool in ArcGIS 10.4.1 because the best results from IDW are obtained when sampling is sufficiently dense or evenly distributed and a depth to groundwater map was generated. Year of September 2021 Landsat8 OLS/TRS image was downloaded from the USGS website and ArcGIS 10.4.1 software was used for the classification of land use land cover in the study area using the maximum likelihood algorithm. Groundwater recharge has been estimated using the modified Chaturvedi formula method because it applies to the tropical zones and is derived from water table fluctuation.

$$R = 0.621(P - 1.019)^{0.814}, \tag{1}$$

where R is groundwater recharge due to precipitation within a year (mm) and P is annual rainfall given by mm.

Then, groundwater recharge map was delineated using IDW tools in ArcGIS 10.4.1 for its spatial interpolation. The transmissivity of the study area was collected from Addis Ababa Water and Sewerage Authority and the hydraulic conductivity was calculated from it using:

$$T = K * H, \tag{2}$$

where T is transmissivity in m²/day, K is the hydraulic conductivity of the aquifer in m/day and H is the thickness of the aquifer below the water level in m.

Then, with the help of IDW tools, they were interpolated and the hydraulic conductivity map was generated. A total of 20 groundwater samples were collected from the well fields to determine the water quality index from laboratory analysis and for validation of the DRASTICA method.

The soil media and vadose zone of the study area were obtained from Addis Ababa Water and Sewerage Authority and their map was delineated using ArcGIS 10.4.1 software. To calculate the water quality index, the next procedures were followed:

First step: selection of parameters

In the assessment of groundwater quality for drinking, the greatest parameters that impact human health were considered for laboratory conductance (WHO 2008). Based on this, twelve sample parameters such as PH, turbidity, total dissolved substance (TDS), sulfate ($SO4^{2-}$), chloride (Cl^{-}), nitrate (NO_3^{-}), fluoride (F^{-}), calcium ion (Ca^{2+}), magnesium ion (Mg^{2+}), manganese (Mn), total iron (Fe) and total alkalinity were taken for laboratory purpose.

Second step: assigning unit weight for each parameter.

The unit weight (W_i) of different water quality parameters is inversely proportional to the recommended standard value for the related parameters.

$$W_i = \frac{K}{S_i}, \tag{3}$$

where W_i is the relative weight or unit weight of ith parameters, S_i is the standard value of ith parameters and K is the relative constant.

The value of K is calculated using,

$$K = \frac{1}{\sum \left(\frac{1}{S_i}\right)}. \tag{4}$$

Third step: rating scale calculation for each parameter selected.

The rating scale of the water quality index was calculated using

$$Q_i = \frac{C_i - I_i}{S_i}, \tag{5}$$

where Q_i is the rating scale; C_i is the ith parameters concentration; I_i is the ideal value of the ith parameter in pure water and zero for other parameters but it is equal to 7 for the PH parameter, S_i is the drinking water standard for ith parameter in mg/L or other units according to the Ethiopian and WHO standard.

Fourth step: developing water quality index

$$WQI = \frac{\sum Q_i W_i}{\sum W_i}. \tag{6}$$

The DRASTICA Index indicates the groundwater's vulnerability to contamination and is classified based on its calculated index value. Eight parameters have been considered for the calculation of its index. To calculate this index, the next procedures were used:

The weight of DRASTICA was assigned concerning each other (i.e., from 1 to 5); each of its parameters has been divided into ranges and was assigned associated ratings (the rating was assigned from 1 to 10), then DRASTICA Index was calculated by multiplying weight and rating of each parameter for which it was assigned. Next, the results were added after multiplying the rating and weight of each parameter and the DRASTICA index has been classified (i.e., very low, low, moderate, high, and very high groundwater vulnerability to pollution).

DRASTICA index (DI) was computed using the formula:

$$DI = Dw * Dr + Rw * Rr + Aw * Ar + Sw * Sr + Tw * Tr + Iw * Ir + Cw * Cr + Aw * Ar, \tag{7}$$

where D, R, A, S, T, I, C, A represent the 8 parameters, r is rating, and w is the weight assigned to the respective 8 parameters. Finally, the overall vulnerability index has been calculated by combining the eight raster data with the help of the weighted sum method in ArcGIS 10.4.1, and the contamination potential of the study area has been identified. A very high DRASTICA index number indicates a high risk of groundwater vulnerability to contamination.

Sensitivity analysis of the DRASTICA model and groundwater contamination analysis is carried out to make a common consensus because different scientists have different ideas on the requirements of parameters used in the model (Krishna et al. 2015) and it measures the model output with input variables (Thapa et al. 2018).

There are two types of sensitivity analysis: single parameter and map removal sensitivity analysis.

Single parameter sensitivity analysis has been used in this study because it provides information on the rating and weighting assigned to each parameter of the DRASTICA model, and it compares the theoretical and effective weight assigned to each parameter in the model.

$$Sp = \frac{Pr * Pw}{V}, \tag{8}$$

where

Sp is sensitivity,
Pr is assigned rate to each parameter,
Pw is assigned a weight to each parameter and
V is the total vulnerability index.

Results and discussion

Depth to groundwater

Depth to groundwater is the distance from the land surface to the water table beneath the ground. It determines the depth

of material through which a contaminant must travel before reaching the aquifer and the contact time with the surrounding media. The deeper the water level, the lower the possibility of contaminants entering into groundwater because deeper water levels imply longer travel times for pollutants. This does mean that if the soil, vadose zone, and aquifer of the study area do not permit the movement of water inside of it easily, the arrival time of contaminants with the movement of water to the groundwater table is longer. The other definition of this statement is when the depth to water level are compared with each other in a study area the one which has a greater depth gets contaminants after the shallow depth of groundwater becomes contaminated. For example, in a highly fractured or karstified system, more rainfall enters the sub-surface in the form of recharge(large volumes of water), and different pollutants enter the groundwater over a short time scale. But the pollutants first arrive at shallow depth and later at the deep depth of the groundwater table.

Here, both shallow and deep depth of groundwater is compared to each other and the rate of the rapid possibility of the arrival of contaminants to the groundwater table for greater depth is low and for shallow depth is high.

The depth to groundwater in the study area was classified into five categories: (8–9.1) m, (9.1–15.2) m, (15.2–22.9) m, (22.9–30.5) m, and (30.5–132.4) m. These classifications are based on Aller et al 1987. It has five rating classes (1, 2, 3, 5, and 7) and a total weightage of 5, 10, 15, 25, and 35, respectively, as shown in Table 1 (Figs. 1, 2, 3).
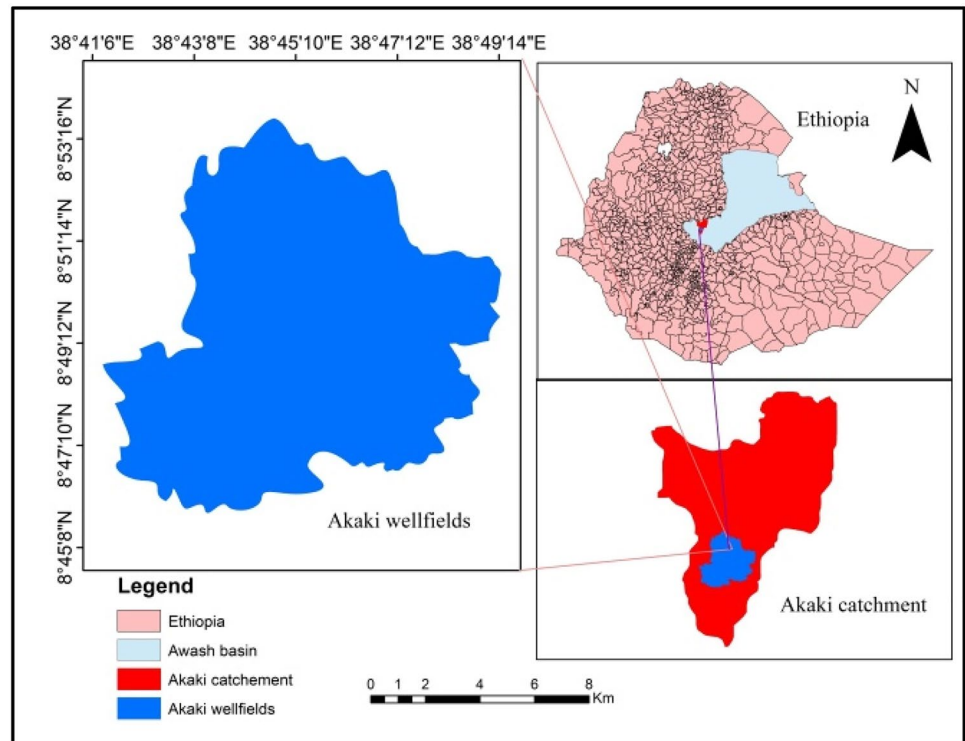
Net recharge

Recharge is the amount of water that reaches the groundwater, and it is a principal vehicle for leaching and transporting solid or liquid contaminants to the water table. The greater the recharge of the area, the greater the pollution potential

Table 1 Range and rating of DRASTICA for the various hydrogeological settings in the study area based on Aller et al. 1987 classification

Parameters	Range	Rating	Weight
Depth to water level (m)	4.6–9.1	7	5
	9.1–15.2	5	
	15.2–22.9	3	
	22.9–30.5	2	
	>30.5	1	
Net recharge (mm)	101.6–177.8	6	4
	177.8–254	8	
Aquifer media	Basalt	9	3
	Fractured igneous rock	3	
Soil media	Shrinking Clay/black cotton	7	2
	Clay soil	3	
Topography (slope in %)	0–2	10	1
	2–6	9	
	6–12	5	
	12–18	3	
	>18	1	
Impact of vadose zone	Basalt	9	5
	Clay	3	
	Black cotton	7	
Hydraulic conductivity (m/day)	0.05–4	1	3
	4–12.3	2	
	12.3–28.7	4	
	28.7–41	6	
	41–82	8	
	>82	10	
Land use land cover/Anthropogenic impact	Built-up area	7	5
	Agriculture	5	
	Forest	2	
	Bare land	5	
	Shrubland	2	
	Waterbody	1	

Fig. 1 Location map of the study area

of the groundwater in the study area. The maximum and minimum recharge of the study area/Akaki well fields were 136.78 mm/year and 213.41 mm/year, respectively (Fig. 4).

Aquifer media

Aquifer media refer to the consolidated or unconsolidated rock which serves as an aquifer (such as sand and gravel or limestone). Basalt and different fractured igneous rock are the primary aquifer media at the prospective site of the study area (Fig. 5).

The sub-surface strata are illustrated in Fig. 6 using strater5 software. As illustrated in Fig. 6, the thickness of black cotton soil varies from 0 to 8 m in both WF02-PW-16 and WF01-PW-1 boreholes. The thickness of the clay soil varies from 0 to 14 m in WF01-PW-11 and 0 to 8 m in the WF02-PW-13 borehole. The thickness of the black cotton soil varies from 0 to 2 m in SL-PW-04 and from 0 to 8 m in the SL-PW-05 borehole. The aquifer was dominated by basalt and fractured igneous rock (Figs. 7, 8, 9).

Soil media

Soil is the uppermost part of the vadose zone. In the DRASTICA method, the soil is commonly considered the upper weathered zone of the earth which averages a depth of 2 m or less from the ground surface (Aller et al. 1987).

It has a significant impact on the amount of recharge which percolates into the water table and determines the ability of the vertical movement of contaminants into the vadose zone. The soil media of the study area was considered up to 2 m beneath the ground surface based on the criteria proposed by Aller et al 1987 and is dominated by the black cotton and clay soil type.

Topography

Topography refers to the slope and slope variability of the land surface. It helps to control pollutants that runoff or remain on the surface in one area. It is a significant parameter because the movement of groundwater is directed by the slope of the land surface. The higher the slope, the greater the runoff and the lesser the infiltration rate of the area. The slope of the study area was expressed in percentages. It ranges from 0 to 71.06% and has been classified into five categories. A 20 square kilometers of the study area have a slope of 0–2%, which has a high rating scale of 10, which covers 15.77% of the study area. A minimum rating scale was assigned to an area of 3.09 square kilometers, covering 2.44% of the study area. A low slope percent value indicates that pollutants spend more time on the ground, allowing for greater seepage of contaminant-rich water tables. The greater area of well fields is occupied by a 2–6% slope, which covers 46.36% of the study area, and
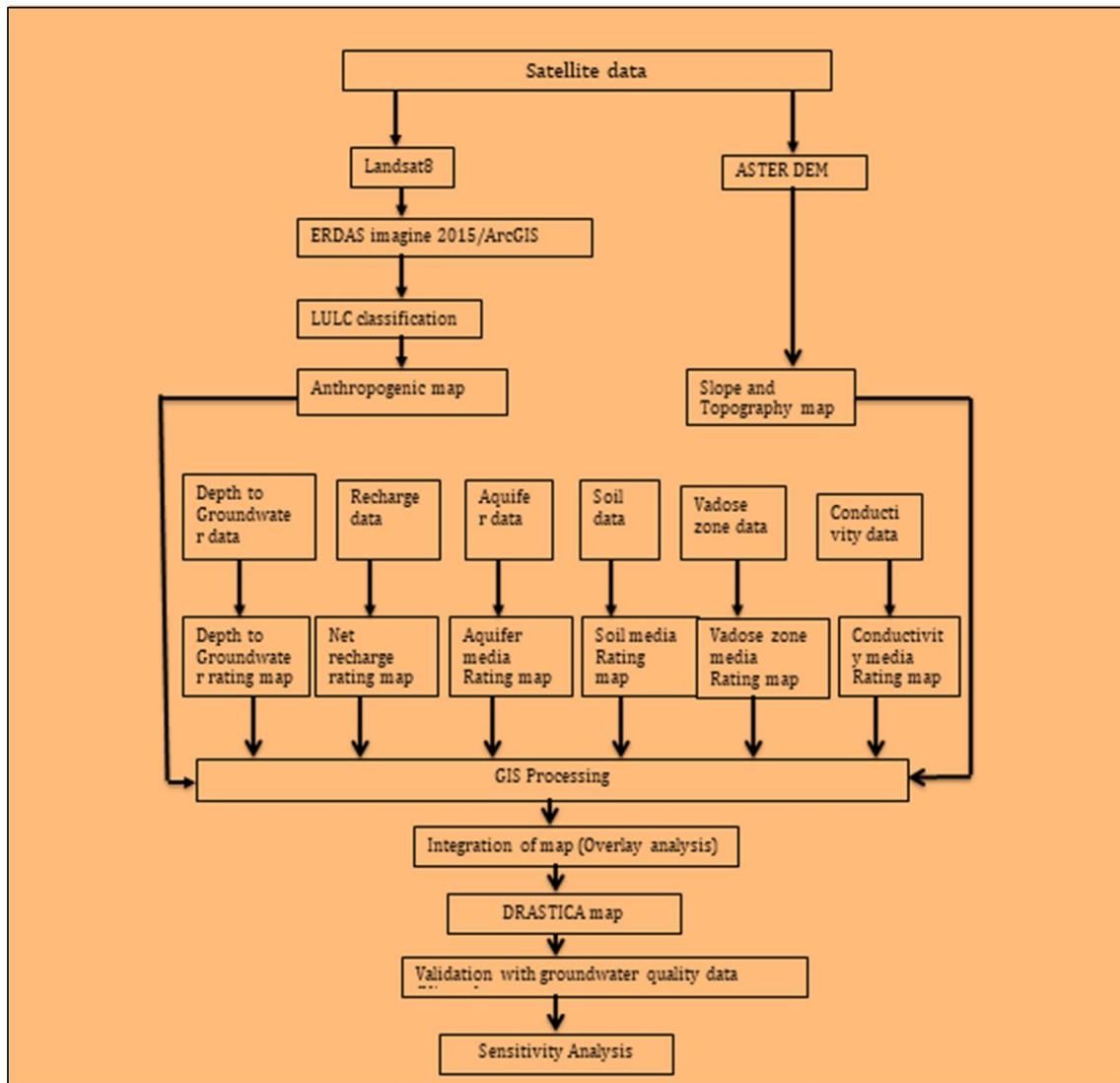
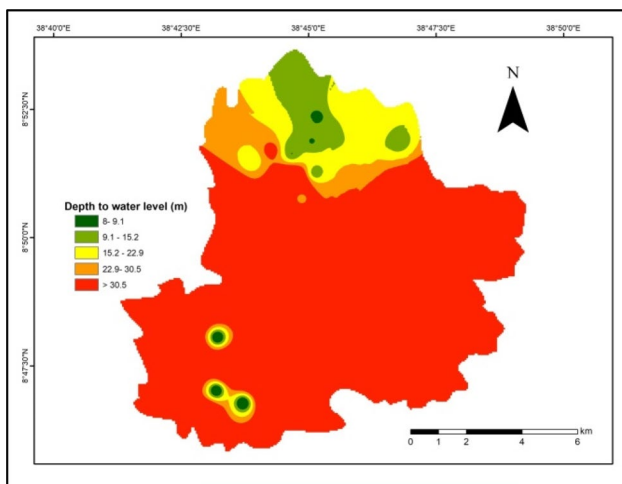**Fig. 2** Methodology of the DRASTICA model method

Fig. 3 Depth to water table map

from 6 to 12% slope is the second level, covering 30.13% of the study area.

Impact of vadose zone

The vadose zone is defined as the zone above the water table which is unsaturated. This vadose zone is not the same as the depth to water level because the depth to water level starts from ground level but that of the vadose zone starts from 2 m below the ground level according to the DRASTICA method. The other difference between them is their rating also different. The depth of the vadose zone of the study area varied from 2 to 132 m, and it was almost dominated by basalt. But, in some percent there are clay and black cotton/shrinking clay presented. The basalt covered 72.4% of the study area; black cotton and clay
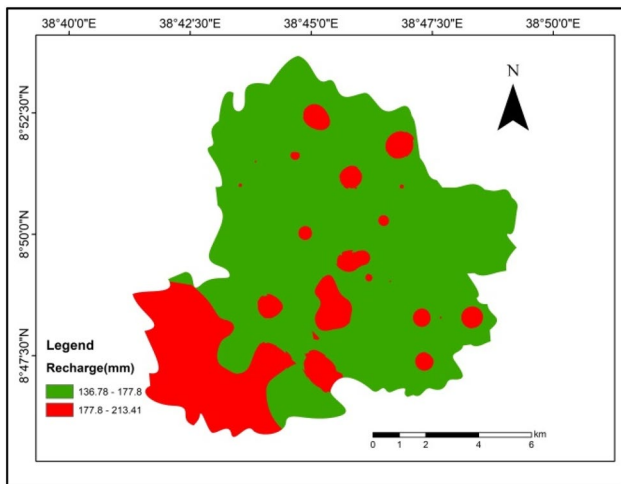
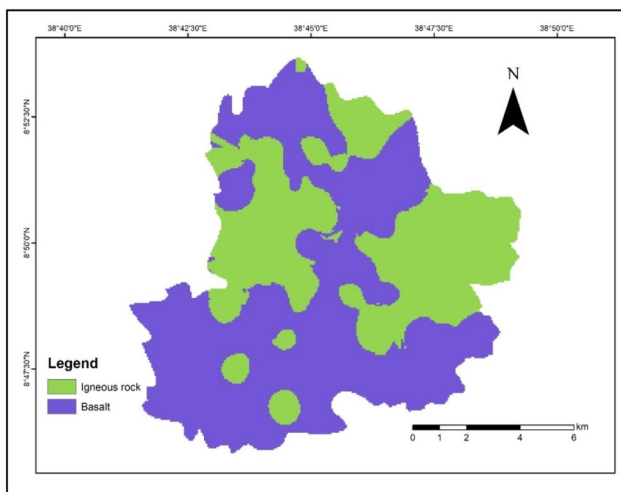**Fig. 4** Recharge map of the study area

Fig. 5 Map of aquifer media

covered 21% and 6.6%, respectively. The deeper vadose zone influences the natural recharge of groundwater, as well as contaminant transport. The weightage of the vadose zone was 5 and basalt, clay and black cotton ratings will be 9, 3, and 7, respectively.

Hydraulic conductivity

Hydraulic conductivity refers to the ability of aquifer materials to transmit water to saturated parts. The hydraulic conductivity values are calculated from aquifer pumping tests. The hydraulic conductivity of the study area ranges from 0.054 to 273.27 m/day and is categorized into six classes as explained in Fig. 10. High hydraulic conductivities are

associated with higher pollution potential. Figure 10 indicated that 60.37% of the study area has greater than 82 m/day of conductivity and 0.45% has 0.054 to 4 m/day of hydraulic conductivity. The lowest hydraulic conductivity was found in the East and North of the well fields (Fig. 11).

Land use land cover

Land use land cover map of the study area includes the water body, forest, agriculture, bare land, shrub, and urban areas. The built-up area occupies 5.35 square kilometers, the bare land area is 0.11 square kilometers, the agricultural area is 77.12 square kilometers, the forest is 16.57 square kilometers, the shrub is 23.69 square kilometers, and the water body has 3.69 square kilometers. Agricultural land has the highest area and the bare land has the smallest area in the study area.

Groundwater vulnerable zone

The groundwater vulnerability of Akaki well fields has been calculated using the DRASTICA index (DI) equation with the help of eight thematic layers integration. The DRASTICA index ranges from 75 to 212 and the spatial distribution of groundwater contamination has been classified into five classes. The final map of groundwater vulnerability to contamination is shown in Fig. 12, which is categorized into very low, low, moderate, high, and very high. The result of the finding revealed that 9.02% of the area is covered by the very high vulnerable zone, 29.85% under the high vulnerable zone, 28.91% under the moderate vulnerable zone, and 24.54% under the low vulnerable zone, and 7.68% under the very low vulnerable zone. The North–East portion of the Akaki well fields, around the Abasamuel reservoir well fields, and the Abasamuel reservoir itself, indicated a very high vulnerable zone to contamination (Table 2).

The DRASTICA index of Fig. 12 indicated that the urban areas showed high vulnerability to pollution, and the groundwater samples were taken around urban areas for laboratory analysis also showed high nitrate concentrations. This is because the source of nitrate has arisen from anthropogenic activities (Fig. 13).

Water quality index

For the calculation of the water quality index, both physical and chemical parameters of water quality were analyzed in the laboratory. The water quality index (WQI) values are classified into five categories (Ibrahim 2019) which are illustrated in Table 3 as follows: excellent, good, poor, very poor, and unfit water for drinking purposes. The lower values of the water quality index show that the water is very clean,

Fig. 6 Cross section of sub-
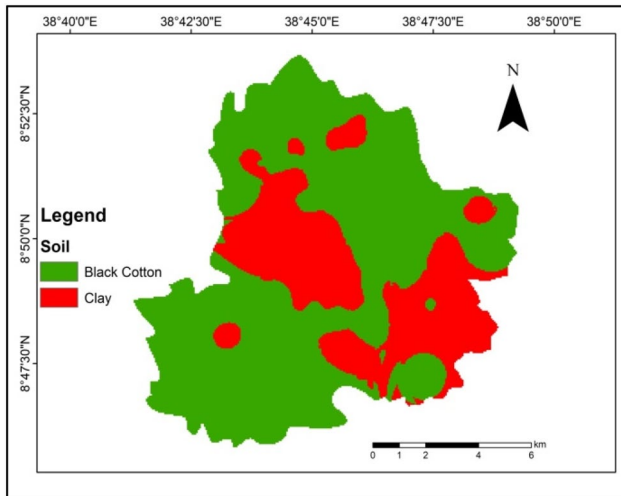surface of the study area
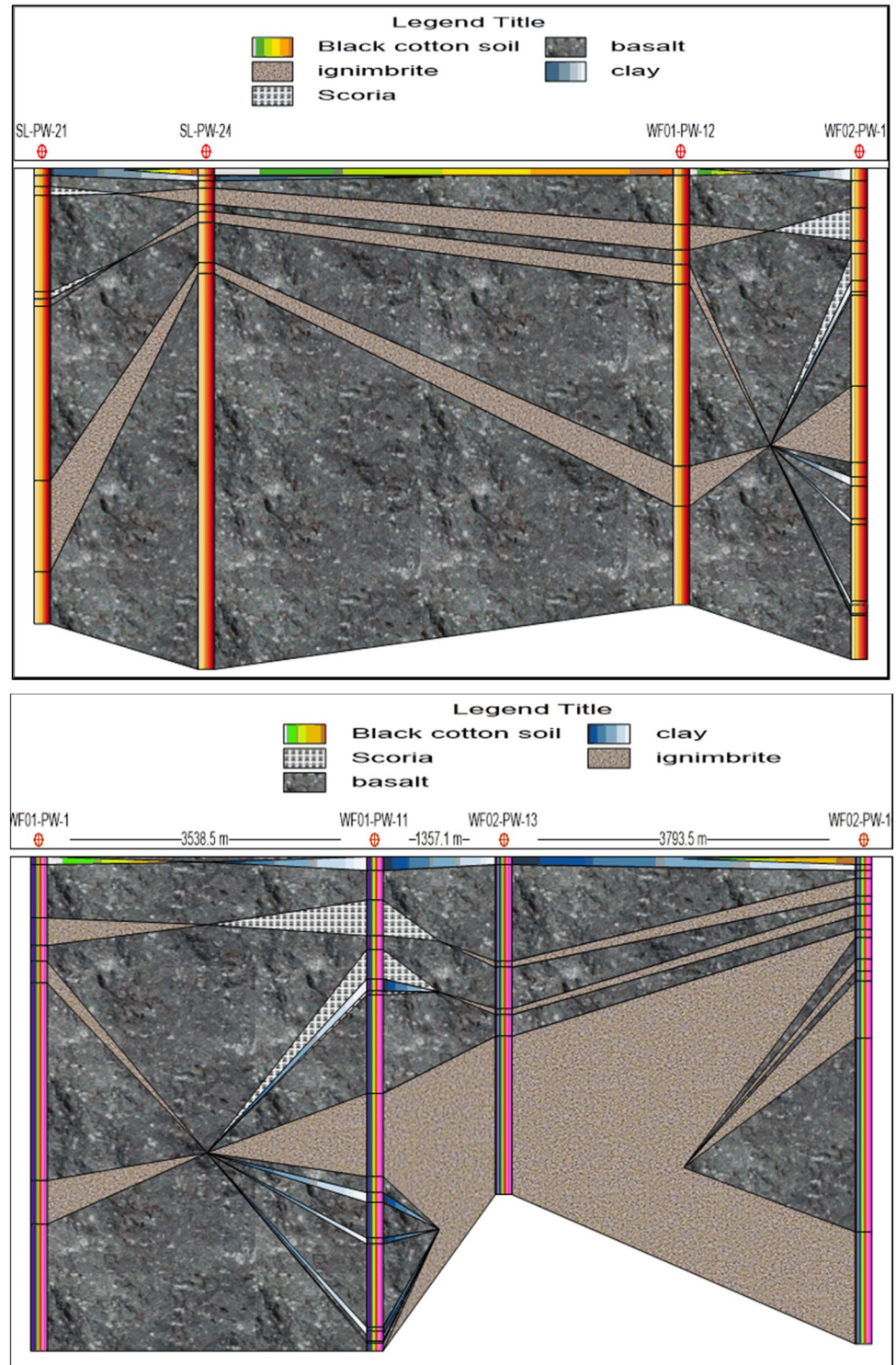
Fig. 7 Soil map of the study area
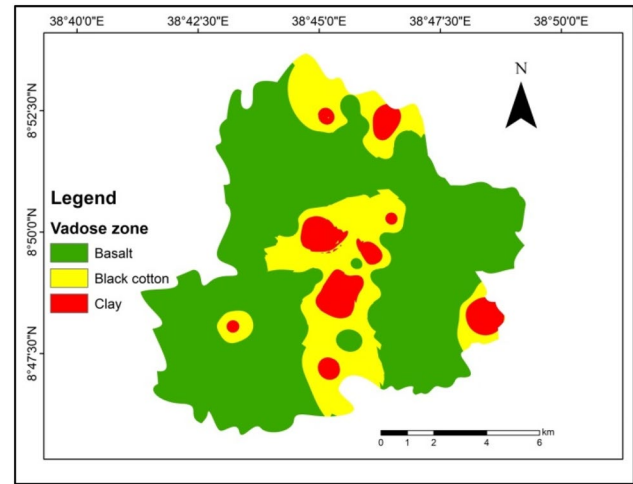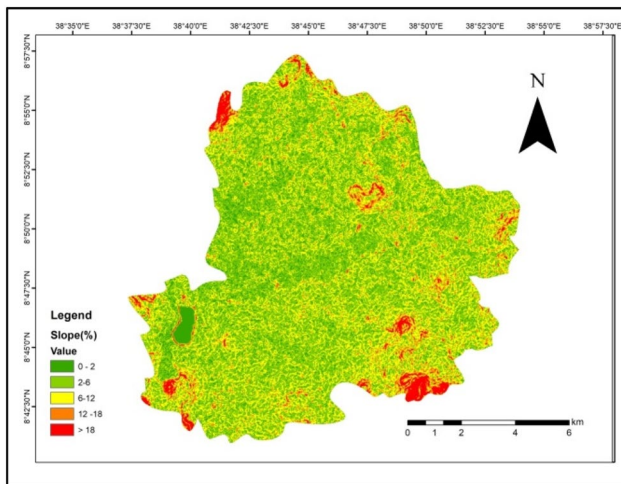

Fig. 9 Vadose zone coverage map

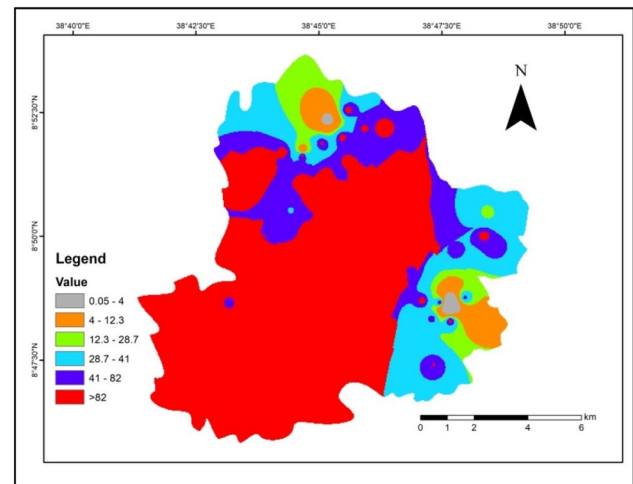**Fig. 8** Slope map of the study are

Fig. 10 Hydraulic conductivity spatial map

that is, it is free of any impurities throughout the study area (Tables 4, 5).

The four‑groundwater sample of the well fields in the study area indicated good class water quality for drinking purposes; two well fields are on the transition boundary between excellent and good in water quality index classification, and fourteen groundwater samples showed an excellent class water quality for drinking purposes. The minimum and maximum values of the water quality index of the study area were 6 and 67, respectively.

Validation of the DRASTICA method

To validate the DRASTICA method, the water quality parameter of nitrate and water quality index was used. The nitrate concentration in groundwater was determined by collecting samples of water from 20 wells and tested in the laboratory. The nitrate concentration was used to associate and correlate the pollution in the groundwater with the DRASTICA index method. The squared correlation coefficient between the vulnerability index and the observed nitrate concentration was 0.95. In the present study, the nitrate concentrations were correlated with the DRASTICA index values. The water quality was used again to validate the method and high values of the water quality index were found in the class of very high vulnerability to contamination.

The squared correlation coefficient between the vulnerability index and the water quality index is 0.89 (Fig. 14). Both nitrate concentration and water quality index are
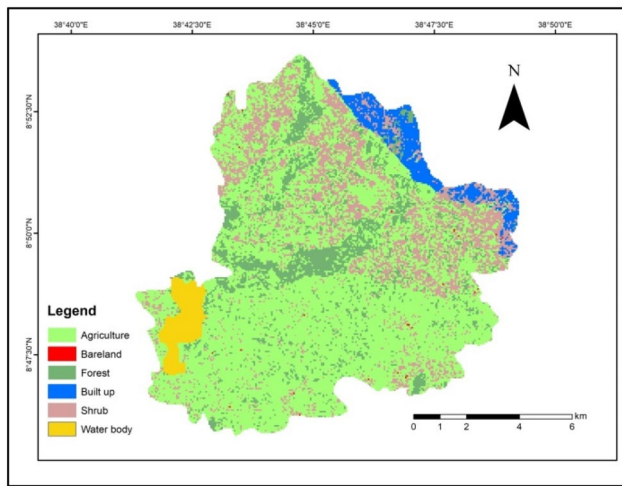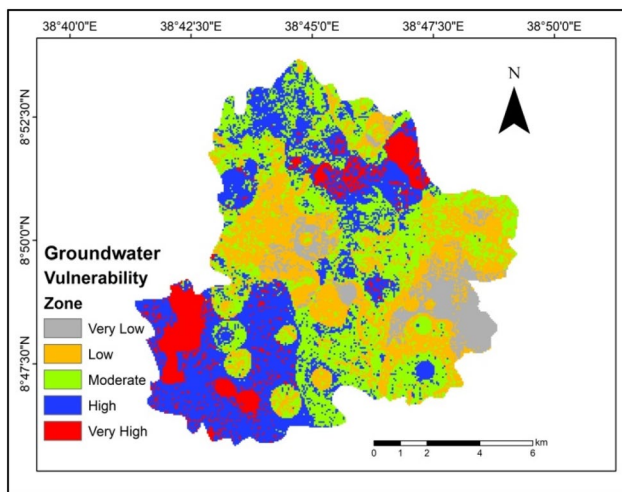
Fig. 11 Land use and land cover map

Fig.12 Groundwater vulnerable to the contamination zone of the Akaki well fields

Table 2 DRASTICA index areas vulnerable to groundwater contamination

Classes	Range of index	No of count (pixel)	Area km^2	Area %
Very Low	75–122	2895	9.678	7.68
Low	122–139	9252	30.930	24.54
Moderate	139–154	10,901	36.443	28.91
High	154–172	11,255	37.626	29.85
Very High	172–212	3401	11.370	9.02

correlated with the DRASTICA method. But, the correlation of nitrate is more than that of the water quality index.

Sensitivity analysis

A sensitivity analysis was carried out in this study to evaluate the accuracy of the prepared vulnerability maps using the DRASTICA method. It helps to know the influence of individual input parameters on the output of the model (Thapa et al. 2018). The single parameter sensitivity test has been performed to check the influence of the eight DRASTICA parameters on the vulnerability index. This test has been carried out by comparing the effective and assigned theoretical weight of each parameter of each sub-area. If the mean effective weight (actual weight) of a parameter is greater than its theoretical weight, then the parameter is more significant for encouraging groundwater contamination (Rao et al. 2018). Higher values of single parameter sensitivity analysis indicate higher importance of the parameters in the model (Barbulescu 2020).

The highest mean value was associated with the impact of the vadose zone, whose value was 33.54%, whereas the topography showed the lowest sensitive value (6.9). The effective weight factor results indicate that parameter I dominates the vulnerability index with an average weight of 33.54% against the theoretical weight of 17.86%. All the calculated effective weight of parameters was greater than their theoretical weight. This indicated that all parameters are very important.

Conclusion

The DRASTICA method was used to compute the vulnerability of Akaki well fields to contamination using ArcGIS. Its index was divided into five zones (very low, low, moderate, high, and very high) based on the index of groundwater vulnerability to contamination. This method was validated by nitrate concentration and water quality index obtained from twenty well fields laboratory analyses. The correlation of nitrate with DRASTICA is $R^2 = 0.95$ and that of water quality and the DRASTICA method is $R^2 = 0.89$. The higher value of the vulnerability index indicated that the risk of groundwater contamination is higher and its lower value indicated a lower risk of groundwater contamination. The results revealed that the very highly vulnerable
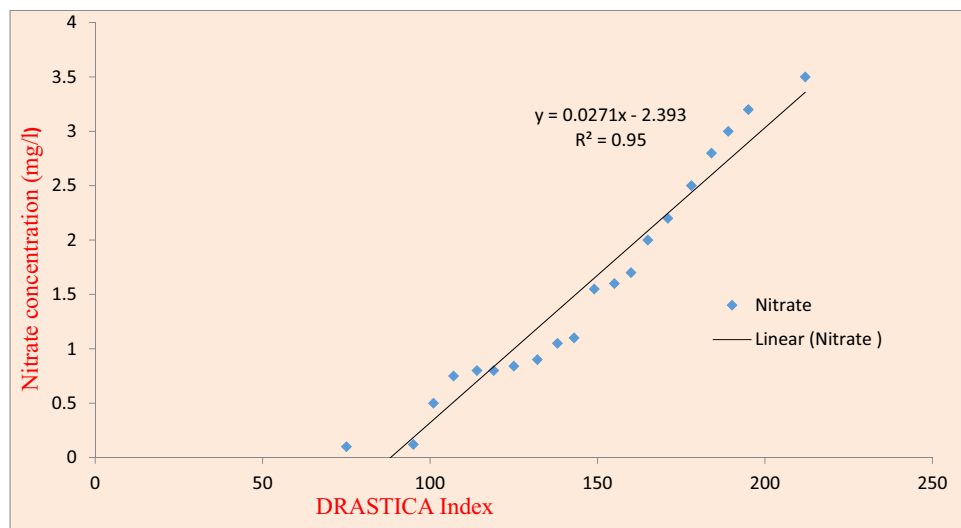
Fig. 13 Nitrate and DRASTICA index correlation

Table 3 Water quality index classification

No	Water quality index range	Type of water
1	< 50	Excellent
2	50.1–100	Good
3	100.1–200	Poor
4	–300	Very poor
5	> 300	Not recommended

Table 4 Water quality index

Well fields	WQI
SWAWF2	67
SWAWF5	51
SWAWF4A	51
SWAWF4B	55
WF01-PW1	17
WF01-PW2	19
WF01-PW3	10
WF01-PW4	12
WF01-PW6	47
WF01-PW7	44
WF01-PW18	11
WF02-PW6	18
WF02-PW17	24
WF02-PW18	26
WF03-PW10	6
SL-PW-03	25
SL-PW-05	6
SL-PW-12	8
SL-PW-15	22
SL-PW-22	7

Table 5 Statistics of single parameter sensitivity analysis

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (%)		
			Mean	Min	Max
D	5	17.86	24.51	2.36	46.67
R	4	14.29	27.00	11.32	42.67
A	3	10.71	20.12	4.24	36.00
S	2	7.14	10.75	2.83	18.67
T	1	3.57	6.9	0.47	13.33
I	5	17.86	33.54	7.08	60.00
C	3	10.71	20.71	1.42	40.00
A	5	17.86	24.51	2.36	46.67

to contamination class covered a percentage of 9.02% of the total study area. Sensitivity analysis results indicated that the effective weight of all parameters is greater than the theoretical weight assigned in the DRASTICA method and this revealed that all parameters are important in the groundwater vulnerability assessment. Sensitivity analysis reveals that the impact of the vadose zone is the most influential parameter of the vulnerability index in the study area. The result obtained from the water quality index indicated that the area which has higher values of the DRASTICA index has a higher water quality index.

Fig. 14 Water quality index and DRASTICA index correlation
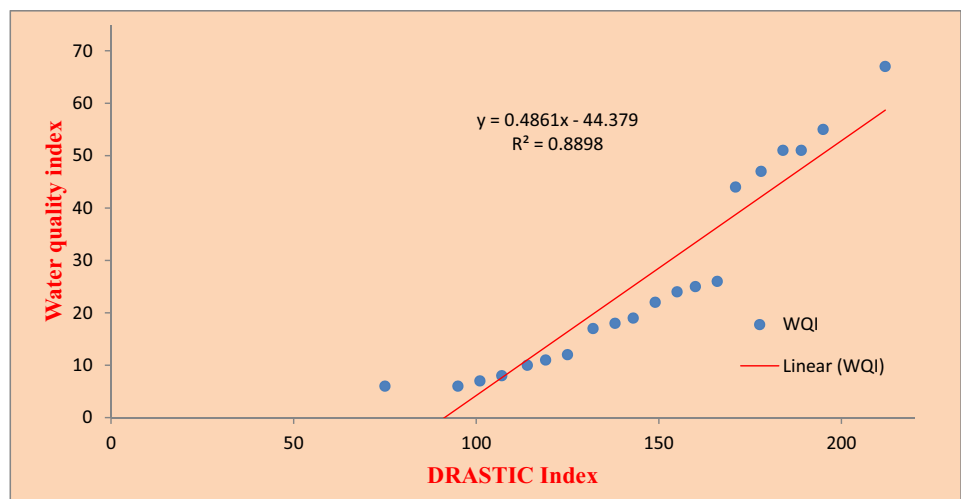
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