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Assessment of groundwater vulnerability in Webuye Municipality, Kenya

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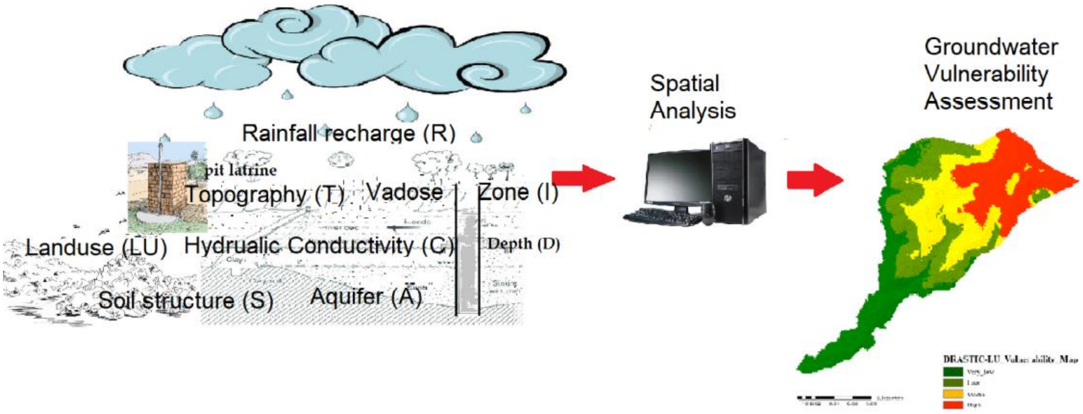
GRAPHICAL ABSTRACT



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ABSTRACT

Access to safe water and sanitation is a basic human right and is enshrined in the sustainable development goal 6. Consequently, resources have been channeled towards development and improvement of water sources. Unlike surface water, the demand for groundwater is increasing due to its preserved quality, affordable development capital and drought resilience. Population density has resulted into entry of pollutants into aquifers because of reduced distance between the pollutants and groundwater sources, human activities and hydrogeological conditions. The aim of this study was to carry out an assessment of groundwater vulnerability to contamination as a preventive approach. Webuye town is a service area of Nzoia Water Services which provides water and sewerage services. However, water and sanitation coverage in Webuye town still below 50%, a portion of residents rely on onsite sanitation systems and groundwater. This is due to costs of installation, topographical challenges and limited pipeline extensions. It was observed that areas where groundwater sources are predominantly used, human waste is managed onsite close to groundwater abstractions points. The methods used in this study included the application of DRASTIC model which was interfaced in ArcGIS version 10.3. Inverse distance weighted (IDW) interpolation technique was used to produce vulnerability maps. The model inputs were seven: depth, recharge, aquifer, soil properties, topography, impact of the vadose zone, hydraulic conductivity and Land use. The results show that North Eastern areas of the study area; Maraka (Township) and Muchi scored the highest DRASTIC-LU values, implying high chances of groundwater vulnerability to contamination. The shallow water table, groundwater recharge, the type of soil, slope and the land use activities in the study area resulted into increased vulnerability. The findings should inform the municipality management on water quality precautions to be undertaken while developing groundwater sources in the area and development of pollution control framework.

1. Introduction

Access to water and sanitation is a human right, acknowledged through various initiatives, including United Nation's 17 sustainable development goals (Spijkers, 2020). It is barely 19% of the global population that have access to basic drinking water services (Ohwo and Ndakara, 2022). Groundwater exploration has lately increased due to its preserved water quality status as compared to surface water.

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Groundwater is extensively available and highly reliable even in extreme climate change events (Amanambu *et al*., 2020). Groundwater usage is dependent of the region. Japan and Northern parts of Europe are highly humid and groundwater is mainly used for industrial and domestic purposes (Shaji *et al*., 2021). Countries that are away from humid inter-tropical zone, and other parts of the world; India, Pakistan, Saudi Arabia, USA, China, Iran and Mexico use groundwater mainly for irrigation (Sharma *et al.*, 2024). Efficiency in abstraction has increased groundwater usage risking overexploitation (Shaji *et al.*, 2021).

Groundwater usage in Africa supersedes surface water even in regions that are well-endowed in surface water (Siganga, Ong’or, and Kanda, 2023). South Africa receives rainfall approximately 450 mm/yr (Siganga, Ong’or, and Kanda, 2023), while Congo and Papua New Guinea are rich in freshwater resources, but they are classified as water stressed countries. Ethiopia is the water tower of East Africa. It is endowed with nine major river basins but it still has water shortages. This is due to the increased water demand and deteriorating water quality of surface sources. Utilization of groundwater in Africa is motivated by; its slower response to extreme weather variability and its convenience to develop within points of need (Amanambu *et al*., 2020).

In Kenya, approximately 17 million people live in Arid and Semi-Arid Lands (ASALs). Due to the scarcity of surface water and unpredictable rainfall in these areas, groundwater serves as the main sources of water (Fankhauser *et al*., 2022). Groundwater usage in Kenya is expected to grow further as a result of population growth and unreliable water quality of surface water resources (Fankhauser *et al*., 2022).

Groundwater has been the best alternative for poor surface water quality, unreliable rains and high costs of water treatment. However, human activities including waste generation and disposal has continuously resulted into groundwater quality degradation (Chakraborty *et al*., 2022).

Groundwater contamination is resulted from various components combining to contaminate or create an enabling environment for contaminants to reach the aquifers. These components are; distance of groundwater source from dumpsites, pit latrines, location of sources of contamination upstream or downstream of groundwater source, human activities around groundwater sources and groundwater design factors. Human activities, such as overexploitation, mechanized agriculture, urbanization, wastewater leakage, land use changes, climate change, and global warming are serious threat to groundwater therefore risking its existence (Kirlas *et al*., 2023).

Usage of on-site sanitation systems is growing as part of the wastewater facilities especially in Urban and peri-urban communities (Gwara *et al*., 2020). Defaults in installations and operation affect the treatment processes therefore discharging partially or untreated effluent into the environment (Preisner, Neverova-Dziopak, and Kowalewski, 2020). In urban setups, populations dwell in unplanned settlements while others have small portions of land where they tend to develop groundwater sources and onsite sanitation systems especially in areas not covered by municipal water network. The proximity of onsite sanitation systems to groundwater abstraction points is one challenges (Kanda *et al*., 2023).This environment increases the probability of groundwater pollution through leakages to the aquifer (Kanda *et al.,* 2023). It is therefore important to effectively manage groundwater and ensure it is free from contamination. This can be done by carrying out a periodical assessment of groundwater contamination vulnerability. Groundwater vulnerability mapping is actually an effective way to prevent groundwater pollution significantly (Oke, 2020). Similar studies have been carried out in Terjun Indonesia where DRASTIC model was applied in mapping groundwater vulnerability (Nurfahasdi *et al.*, 2023). In Hamadan–Bahar plain, Iran (Abdullah *et al*., 2020) also carried out assessment of groundwater vulnerability using DRASTIC model where all DRASTIC parameters were assessed to find the most intervening parameter in water groundwater contamination. In another study, (Abdullah *et al*., 2020). Carried out assessment of groundwater vulnerability by applying COP and the VLDA models in Halabja-Saidsadiq, Iraq.

Webuye municipality is one of the fast-growing areas in Western Kenya due to its population increase. the Municipality was declared as the industrial park for Bungoma County Government, therefore attracting people from various parts of the country. The living spaces are reduced within the municipality making people to settle on even smaller portions of land, where they still practice farming, installation of sanitation facilities and groundwater sources especially in areas not covered by the Municipal water services. This has greatly compromised with the standard distance between pit latrines, dumpsites and groundwater sources. According to Webuye District Hospital, the rate of water borne diseases is rising. Carrying out groundwater assessment to monitor contamination is an uphill task especially in extensive areas.

Various researchers have developed various models to assess groundwater vulnerability in various areas (Eftekhari, and Akbari, 2020; Talebi and Fatemi, 2020; Maleki *et al*., 2023, Ni *et al*., 2023, Nurfahasdi *et al*., 2023; Jamaa *et al*., 2024). SINTACS model, Multi-criteria Decision Analysis (MCDA) and DRASTIC model have been used to carry out groundwater vulnerability, however, DRASTIC model has been extensively applied in groundwater vulnerability assessment. It is the most popular, reliable and extensively applied empirical index method.

2. Research methodology

2.1. Study area

This study was carried out in Webuye West Sub-County in Bungoma County. The area is located at latitude 00 45’0” N and 00 30’0” N of the Equator and longitude 340 40’0” E and 340 45’0” E of the Greenwich meridian. Webuye municipality totals up to 95.48 Km^2. Webuye West is made up of five sub locations namely Malaha, Maraka, Matulo,Township and Mihuu. The Sub-County is comprised of both rural and semi-urban areas, with a population of 151,654 and approximately 32,839 households in 6 sub-locations (KNBS, 2019). The Webuye Local Physical Development Plan estimations that the current population of Webuye town is about 65,000, implying that 43% of the population in the study area live in the urban areas. Increased population in Webuye has resulted in the increase in waste generation. Currently, only 15% of the total population within the study area is served by the sewerage system while 85% rely on on-site sanitation as disposal methods. Webuye town, like other urban centers in Kenya, is experiencing rapid population growth largely due to rural-urban migration and natural rate of increase.

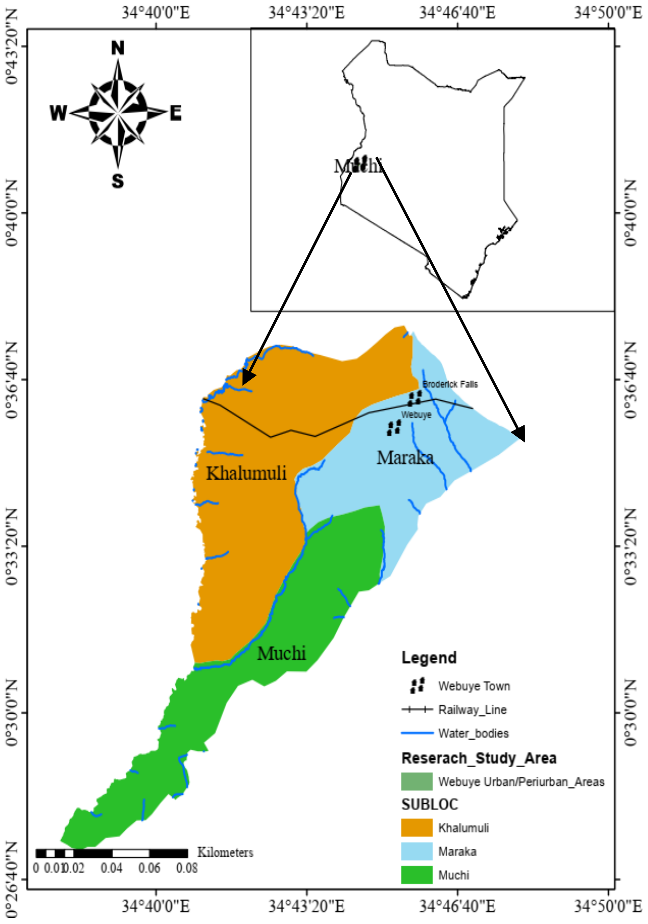


Fig. 1. Study area map.

2.4. Data source

Experimental research design was employed in this study to enable the researcher carry out assessment of groundwater vulnerability in Webuye. DRASTIC-LU model used eight environmental parameters to describe the hydrogeological attributes and evaluate groundwater vulnerability to contamination. The eight hydrogeological parameters that were used to come up with DRASTIC-LU vulnerability Index were entered into ArcGIS and distance weighted interpolation carried out under spatial analysis, to create scenarios of groundwater vulnerability to extreme DRASTIC parameters which cause contamination.

2.4.1. GPS Coordinates

Geographical points of groundwater, onsite sanitation systems and solid wastes disposal sites were collected during field data and water samples collection. This data was collected using M-water application which was installed on a smart mobile phone. The app was able to collect GPS points using phone's location. This enabled faster data collection, real time submission and easy precise data analysis.

2.4.2. DRASTIC-LU

This section shows how the sources of data for DRASTIC-LU parameters;

a. Depth of water

Depth of water level was measured using Solinst Model 102M P4 Probe Water Level Meter. The water level was determined by direct reading from the graduated cable at the top of the well casing or borehole. The meter has a probe that when it makes contact with water, a light and buzzer are activated. For accurate water level depth, the measurement was conducted very early in the morning before water is drawn from the wells. Water depths in wells was measured in meters (m). Water level of all wells was collected except for the wells that had no water.

b. Net recharge (R):

The Webuye net recharge was generated from rainfall data which was overlaid on land use map and allocation of values based on the anthropogenic activities and geological occurrence with regard to infiltration potential. The net recharge was classified in 5 classes >200, 150- 200, 100- 150, 50- 100 and 0- 50 mm/yr, and was weighted 4. This implied that the higher the rate of net recharge, the higher the chances of groundwater pollution.

c. Aquifer media (A):

The aquifer information was found from the geological maps and geophysical reports of boreholes done in the around Webuye township areas. The weight value allocated for this parameter was 3. The aquifer was classified in two classes Sandy and Clayey. The formation was converted to raster, and reclassified under spatial analysis in ArcGIS.

d. Soil (S):

The soil media was used in the model to assess its type and how it affects the rate of infiltration. Soil data was derived from the soil maps which was overlaid on the study area to be able to identify the soil category. The soil composition in Webuye is: Clay soils, Loam Clay and Nitisols. Soil data was collected from the soil maps downloaded from the ICPAC geoportal and overlaid into ArcGIS 10.7, clipped into the study area to classify soil layers. Through this data it was possible to get the;
i. type of the soil
ii. soil classifications
iii. hydraulic conductivity
iv. soil depth and permeability

e. Topography (slope) (S):

The slope of Webuye was sourced from the Digital Elevation Model (DEM). Slope values were calculated from the DEM which was overlayed on the map of the study area in ArcGIS 10.7, then spatial analysis technique used to categorize and interpolate. The slope values were rated based on the criteria of DRASTIC model with 10 being the lowest slope. The slope was divided into four classes ranging from 0-2, 2-6, 6-18 and >18. The slope was rate 1-10 with 10 representing the highest slope and 1 representing lowest slope.

f. Impact of vadose zone (I):

The information about the vadose zone was found from geological map and geophysical reports for the study area. Webuye's main aquifer in is a semi-confined aquifer which occupies 72% of the study area and the 28% unconfined part. Therefore, the vadose zone of the confined and unconfined parts was rated 1, 6 and 8 in classes of; clay, medium and fine weighted 5.

g. Hydraulic conductivity (C):

The data on hydraulic conductivity was derived from standard conductivity provided for the type of soil composing the subsurface aquifer system. The values for hydraulic conductivity used in the study were 15.21 and 0.11 for clayey and sandy aquifer respectively. Hydraulic conductivity was rated 3 and 1, and it was weighted 3.

Table 1. Standard hydraulic conductivity ranges for various soil type (Usowicz and Lipiec, 2021).

So. No.	Soil texture	Hydraulic conductivity, m/s
1	Sand	1.7×10^{-4}
2	Loamy	1.56×10^{-4}
3	Sand loam	1.13×10^{-5}
4	Silt loam	7.19×10^{-6}
5	Loamy	6.94×10^{-6}
6	Sandy clayey loam	6.31×10^{-6}
7	Silty clayey loam	1.70×10^{-6}
8	Clay loam	2.45×10^{-6}
9	Sandy clayey loam	2.17×10^{-6}
10	Silty clay	1.02×10^{-6}
11	Clay	1.2×10^{-6}

h. LU:

The land sat map was prepared using land sat image of Webuye for the year 2021 downloaded from earth explorer. Land use is important in DRASTIC modelling as it's the source of primary information and also helps in understanding the behavior of a parameters like net recharge.

2.5. Model description

DRASTIC model has been widely used in groundwater vulnerability assessment. The model was developed by the US Environmental Protection Agency (USEPA) with an aim to standardize and evaluate the probability of groundwater contamination (Wang *et al*., 2023). It is empirical based method which undertakes assessment of groundwater vulnerability through numerical ranking hydrogeological parameters which influence groundwater movement. The term DRASTIC-LU is an abbreviation for hydrological and geological parameters: depth of groundwater (D), net recharge (R), aquifer type (A), soil type (S), topography (T), impact of the unsaturated zone (I), hydraulic conductivity (C) and in this study, land use (LU) was included as the eight parameters, to assess the impact of land use activities on groundwater quality. DRASTIC model has been widely applied in groundwater vulnerability assessment; (Murmu *et al*., 2019, Rama *et al*., 2022). The model was interfaced with ArcGIS 10.3 to carry out spatial interpolation of DRASTIC-LU values. The parameters were then assigned weights depending on the hydrogeological conditions of Webuye urban and peri-urban areas. Weight factors of the DRASTIC-LU parameters ranged between 1 and 5 based on probability to cause contamination. In the end, the linear equation of the total impact criterion score as the DRASTIC index or vulnerability rating has the following formula:

$$\text{Vulnerability Index} = \sum_{i=1}^{8} \mathrm{W_i}\ \mathrm{R_i} \qquad \text{(i)}$$

W is weight
r is rank.

This formula however, works best based on four accounts, i.e.
i. the contaminant is introducing at the ground surface;
ii. the contaminant is leached into the groundwater by precipitation;
iii. the contaminant is soluble; and
iv. the evaluated area is ≥40 ha

To establish the parameter contribution to high environmental sensitivity to contamination, parameters were organized into rating relative scale (r) ranging from 1 to 10; the highest value represent the most significant sensitive environment to contamination while lower values indicate less significant sensitive environment to groundwater contamination. A sum of all of these parameters defines the groundwater vulnerability of an area. Individual maps per each parameter were classified and designated ratings and weighted according to DRASTIC standards (Wang *et al*., 2023) as shown in Eq. (ii) was rewritten as follows:

2.6. Model inputs

The model input parameters included each of the parameters in DRASTIC-LU equation, so were organized into weight factors and rating values and organized as shown in Table 3 below. Each of the parameters was entered to generate a map ad finally a vulnerability map developed combining all DRASTIC -LU values;

Table 2. DRASTIC standard weight.

Parameter	Criteria Weight
Depth to groundwater (D)	5
Recharge (R)	4
Aquifer (A)	3
Soil properties (S)	2
Topography (T)	1
Vadose zone (I)	5
Hydraulic conductivity (C)	3
Land Use (LU)	4

Table 3. Rating and weight values of DRASTIC-LU model

Parameters	Range	Rating	Weight
D (Groundwater depth)	>21	1	5
	10–20	3	
	5–10	8	
	<5	10	
R (Net recharge (mm/yr)	>200	9	4
	150- 200	7	
	100- 150	5	
	50- 100	3	
	0- 50	1	
A (Aquifer media)	Sandy	9	3
	Clayey	1	
S (Soil group)	Clay soils	1	2
	Loam Clay	3	
	Nitisols	5	
T Topography (Slope, %)	0-2	10	1
	2-6	9	
	6-18	3	
	>18	1	
(Impact of Vadose Zone)	Medium sand	8	5
	Clay	1	
	Fine sand	6	
C (Hydraulic conductivity), (m/d)	>16	10	3
	5-15	3	
	0-5	1	
Lu	Agricultural	9	4
	Built-up area	8	
	Water body	3	
	Tree-clad area	1	

The model was interfaced with ArcGIS 10.3 to carry out spatial interpolation of DRASTIC-LU values, from points using an inverse distance weighted (IDW) technique, which was based on assumption that things that are close to one another are more alike than those that are farther apart. To predict a value for any unmeasured location, IDW uses the measured values of parameters surrounding the predicted location. The IDW method is also referred to as "Shepard's method" (Malvić *et al*., 2020). The equation used is as follows:

$$F(x,y)=\sum_{i=2}^{n} w_i f_i \qquad (ii)$$

where, n< is the number of scatter points in the set, f_i is the prescribed function values at the scatter points (e.g., the dataset values), w_i is the weight functions assigned to each scatter point.

3. Results and discussion

3.1. DRASTIC-LU values and vulnerability maps

The results of this study were drawn from the assessment of 8 environmental factors defining the vulnerability of the environment around the groundwater formation. The results were presented in 8 maps, each map representing a DRASTIC- LU parameter stated in Equation (i). These maps represent spatial distribution of DRASTIC-LU values in the study area. Each DRASTIC-LU value was assessed based on its the environmental properties to prevent or influence groundwater contamination. The results presented in Fig. 2 and Fig. 3 explains the measure of each DRASTIC-LU value and its ability to influence groundwater contamination. The spatial distribution of these values was used to develop a vulnerability map.

3.2. DRASTIC-LU values

a. Depth of water in wells (D):

The study indicates that 77 % of the water wells measured a groundwater depth less than 5 m. It is important to note that 86% of the study area has wells with depth < 5m. Water wells in Muchi and Khamululi areas are mainly below 5m, Maraka area which is the North east part of the study area has wells within 5-10m, 10-20m and >21m in depth which represents 14% coverage however, the wells below 5m deep were still predominant as shown in Fig. 2(a) above. The findings show that Webuye urban and peri-urban area has a high-water table and this could be the reason why many residents construct their wells with shallow depths. Areas around the town and peri-urban areas in the study area are likely to have contaminated water wells because of the shallow depth, because of the reduced media through which contaminants infiltrates. Well depth of water is used to refer to the vertical distance in which the pollutants travel through the soil media before reaching the water table. Well depth is a well design factor that explains the extent to which a medium by which the water infiltrating, or percolating moves before reaching the water that is soaked (Jat Baloch et al., 2021). It's important to note that the shallow water table zone, the higher the chances of vulnerability to pollutants.

b. Net recharge (R):

The net recharge was classified in 5 classes >200, 150-200, 100- 150, 50-100 and 0-50 mm/yr. The results show that areas with the highest rate of recharge are Muchi and some parts of Khalumuli which recharge more 170 mm/yr. Other areas in the study area have an average groundwater recharge ranging between 75mm/year o 110 mm/year. Areas with the lowest recharge are majorly in town areas where most surfaces are lined; buildings, roads, pavements and roofs. This prevents infiltration thus affecting groundwater recharge. Groundwater recharge plays a big role in contaminant movement. Webuye town is located along River Nzoia, which is the main supply for raw water for treatment and also source of industrial water. This river is the main aquifer recharge in the study area. High net recharge helps in dilution of pollutants, however, recharge from polluted areas onsite sanitation systems, sewer bursts and urban drainage can facilitate migration of pollutants to spread in the water table. The results are shown in Fig. 2(b).

c. Aquifer media (A):

The aquifer was classified in two classes Sandy and Clayey. The results indicate that the study area has two main types of aquifer formation. The central part of the study area, especially the town areas have sandy aquifer. Clayey aquifer occupies areas such as Muchi and some parts of Khalumuli. The formation of the aquifer determines the flow rate and contaminant transport in the aquifer. The aquifer that contains larger grain size, high void ratio, and more fractures have higher permeability. This leads to lower pollutant attenuation capacity that, being so, leads to greater contamination potential (Shah *et al*., 2021). The main aquifer in Webuye, is mainly comprised of mixture of gravel and sand with significant amount of clay, therefore the rating value of this media is 3. The results are as shown in Fig. 2 (c).

d. Soil (S):

The results in the Fig. 2 (d) show that there are three categories of soil in the study area; Clay, Loam and nitisols. Clay soil is fairly distributed in Khamululi, Muchi and Maraka areas covering 48% of the study area. Loam soils are majorly concentrated in Muchi and Khamululi areas of the study area covering 21% of the study area, while nitisols are covering 31%. Soil has an impact on the quantity of recharge and transport of contaminants to groundwater. Silt and clay soils have lower soil permeability with a reduced contaminant transport (Siganga, Ong'or, and Kanda, 2023). Soil data was derived from the soil maps which was overlaid on the study area to be able to identify the soil category.

e. Topography (slope) (S):

The slope was divided into four classes ranging from 0-2, 2-6, 6-18 and >18. The slope was rated 0-18 with 18 representing the highest slope and 1 representing lowest slope. The slope was allocated the weight of 1. The results in Fig. 3 a. show that the study area is largely comprised of fair slopes between 0 to 6, this is in all parts of the study area; Muchi, Khamululi and Maraka. Less infiltration Water on steeply slope surface of earth creates surface runoff and infiltrates less than water falling on flat land surface. This implies that Muchi, Khamululi and Maraka have high vulnerability of groundwater to contamination due to level ground surfaces which increase the rate of infiltration. The far North Eastern parts of the study area the boundary of maraka area which is around the foot of Chetambe hills have steep slopes (>18) meaning that there is low vulnerability of the groundwater to contamination because of steep slopes which do not allow enough time for maximum infiltration. The results show that the northern and eastern parts of the study area have reduced chances of contamination because of reduced rates of infiltration. The topography determines contaminant movement, areas with gentle slopes have reduced surface runoff rates, therefore increased infiltration which in turn increases the aquifer vulnerability. Studies have been carried out to link slope to contamination of groundwater. A study carried out by (Xiong *et al*., 2022) revealed that the runoff on uneven topography increases the rate of infiltration. The study is confirmed by the experimental findings of (Yi *et al*., 2022) who reported that velocity of water, runoff rate and erosion were greater in less slopes than on three steep slopes especially those that are conically shaped.

f. Impact of vadose zone (I):

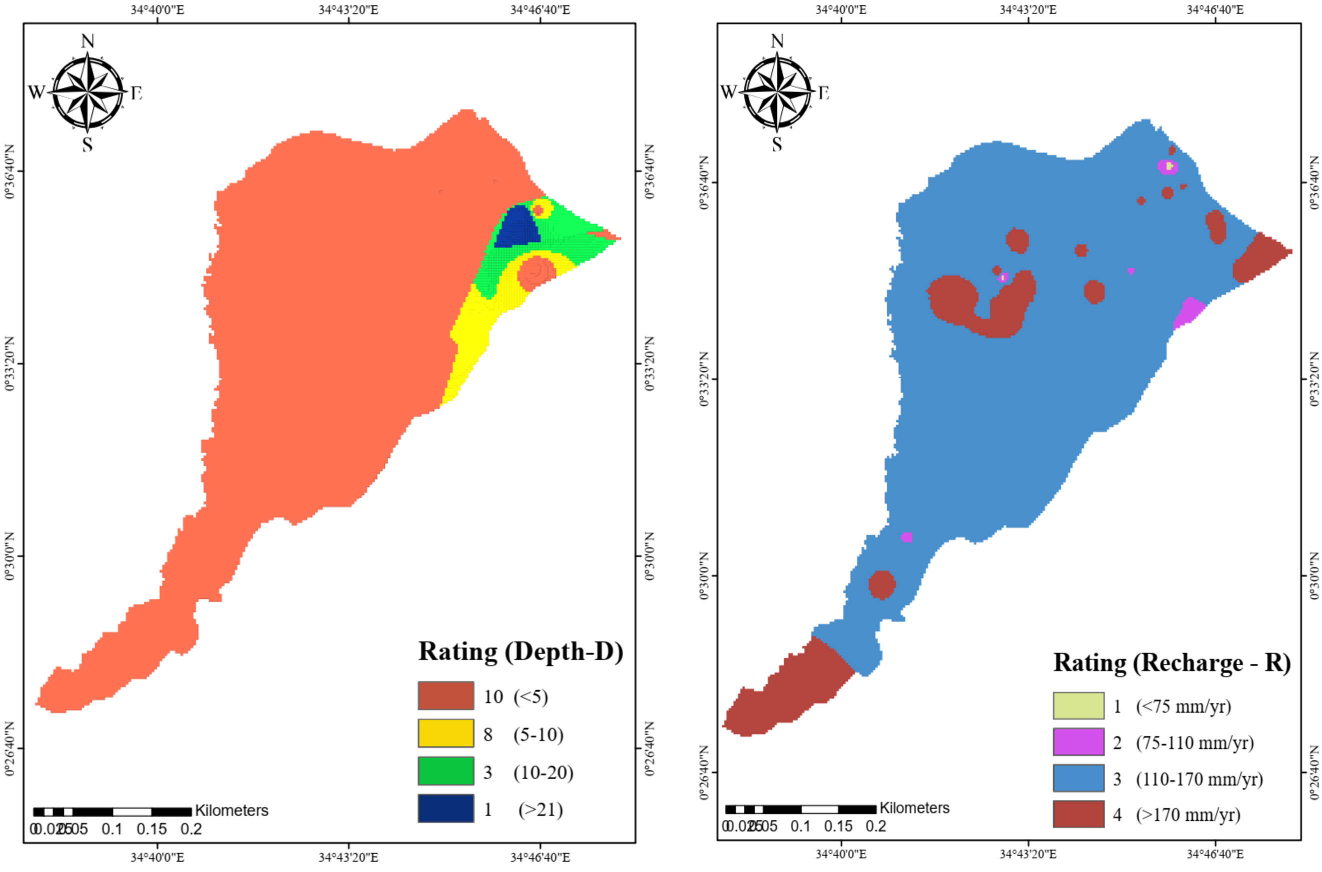
The results in Fig. 3 b show that the study area is mainly composed of clay soil in the vadose zone found which covers 59% of the study area in Muchi and khamululi, fine sand is distributed in Maraka area and occupies 44% of the study area while medium sand composition of the vadose zone is mainly found in the northern part of the study area, specifically in the upper parts of Khamululi. Properties of vadose Zone plays a key role in groundwater protection, and it is therefore, important to combine the pollution and vadose zone characteristics in assessment of groundwater pollution (Xin *et al.*, 2019). Vadose zone is basically a natural filter against contaminants dissolved in water before reaching the water table (Amin *et al.,* 2021). Therefore, soil media characteristics of the vadose zones are important in controlling the level of pollution through the vadose zone to the water table. Yang *et al*. (2020) found out that there is a physical relationship between fertilizers and soil which is predominantly in granular where high-permeable media can facilitate transport. The permeability of soils can decrease as a result of reduction of effective porosity caused by an increase of contaminant concentration (Liu *et al*., 2020).

g. Hydraulic conductivity (C):

The results in Fig. 3 c show that 61% of the study area has hydraulic conductivity of 0.11m^3/d distributed in whole of urban and peri urban areas of Webuye, while 39% of study area has hydraulic conductivity of 15.21 m^3/d which is mainly concentrated in Maraka in Khamululi areas. Maraka and Khamululi areas have high hydraulic conductivity values implying that vulnerability of aquifers in these areas are high. It is also important to note that the areas are highly concentrated in loam and nitisols soils which have high hydraulic gradient as compared to Muchi area which has mainly clay soils. Hydraulic conductivity is a soil geological property which is used to determine soil’s ability to drain (Petryk *et al.,* 2023). Hydraulic conductivity of soil is determined by type of soil, void ratio, pore size distribution, grain size distribution, viscosity of a fluid, and degree of saturation determine the (Petryk *et al.,* 2023).

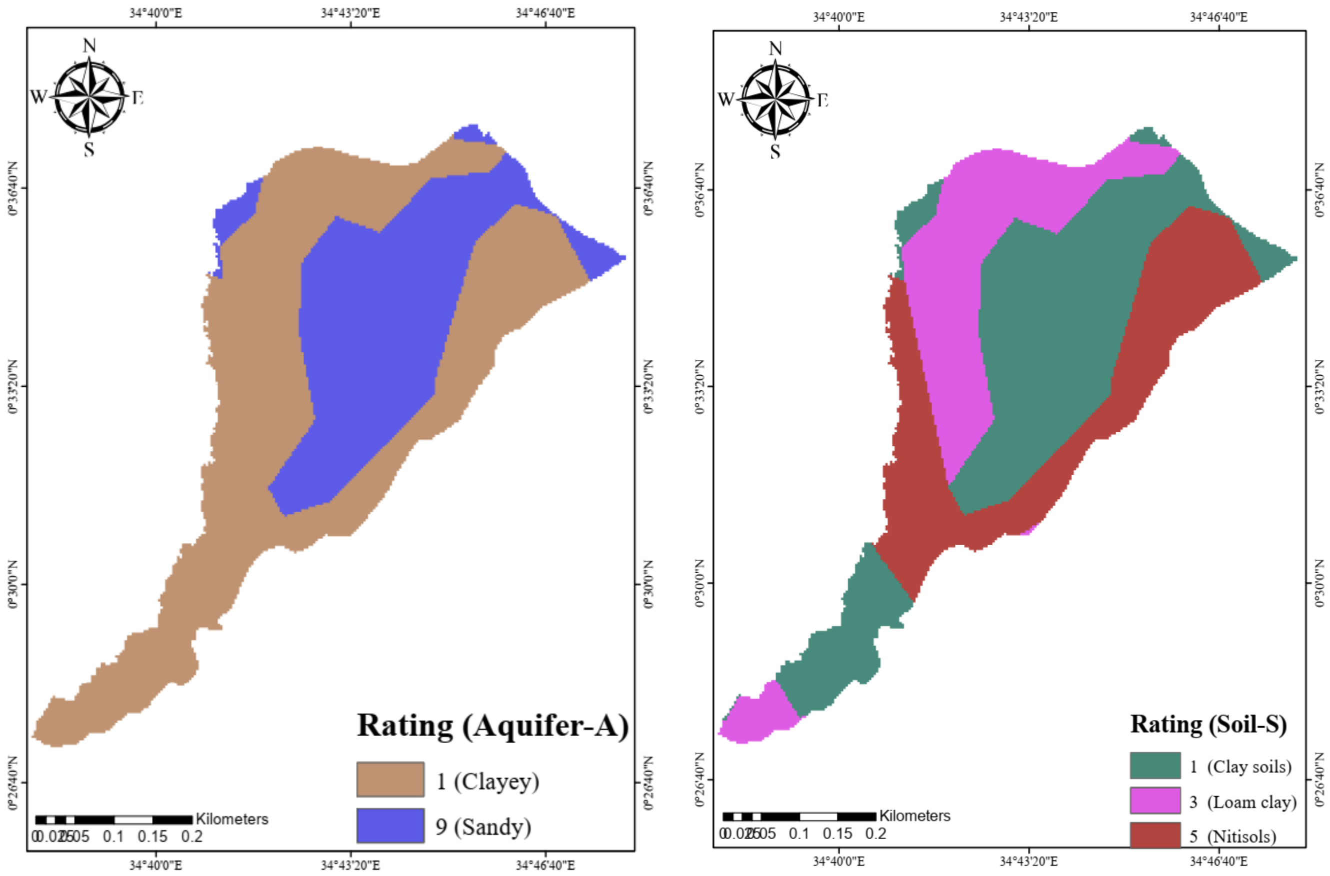
h. Land Use (LU):

The study area has been affected by human activities through agricultural activities which occupy 44%, 41% is occupied by built up areas, water bodies occupy 9% of the study area while 6% of the area is occupied by trees. Land use activities inform spatially about nitrate and phosphates generation in the study area. Land use plays a role in determining the generation and transport of nitrate pollution, caused by anthropogenic activities (Salomó-Coll *et al*., 2021). Land use is important in DRASTIC modelling as it’s the description of human activity influence on DEASTIC parameters. The land sat map was prepared using land sat image of Webuye for the year 2021 as shown in the Fig. 3 d.



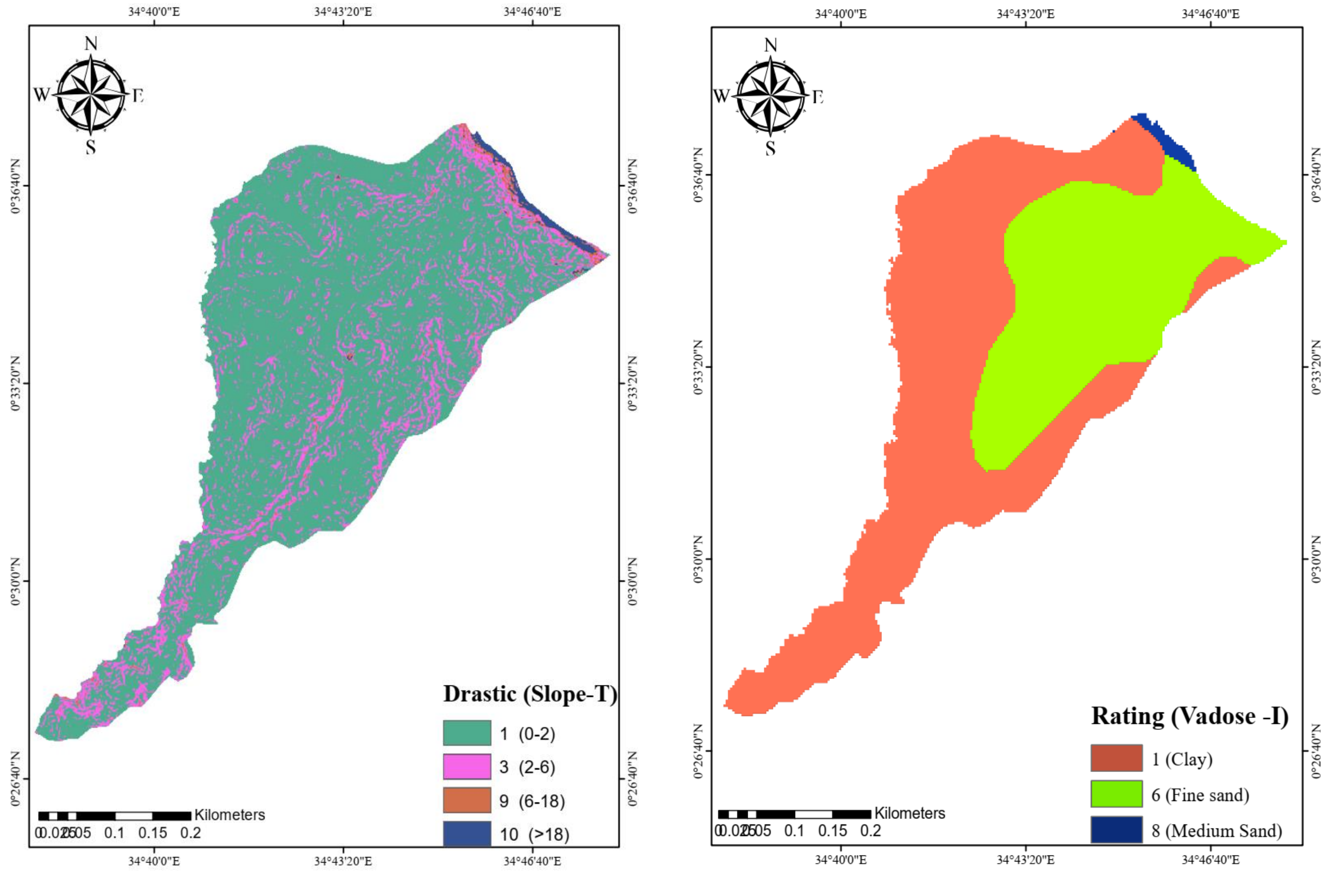
(a)

(b)

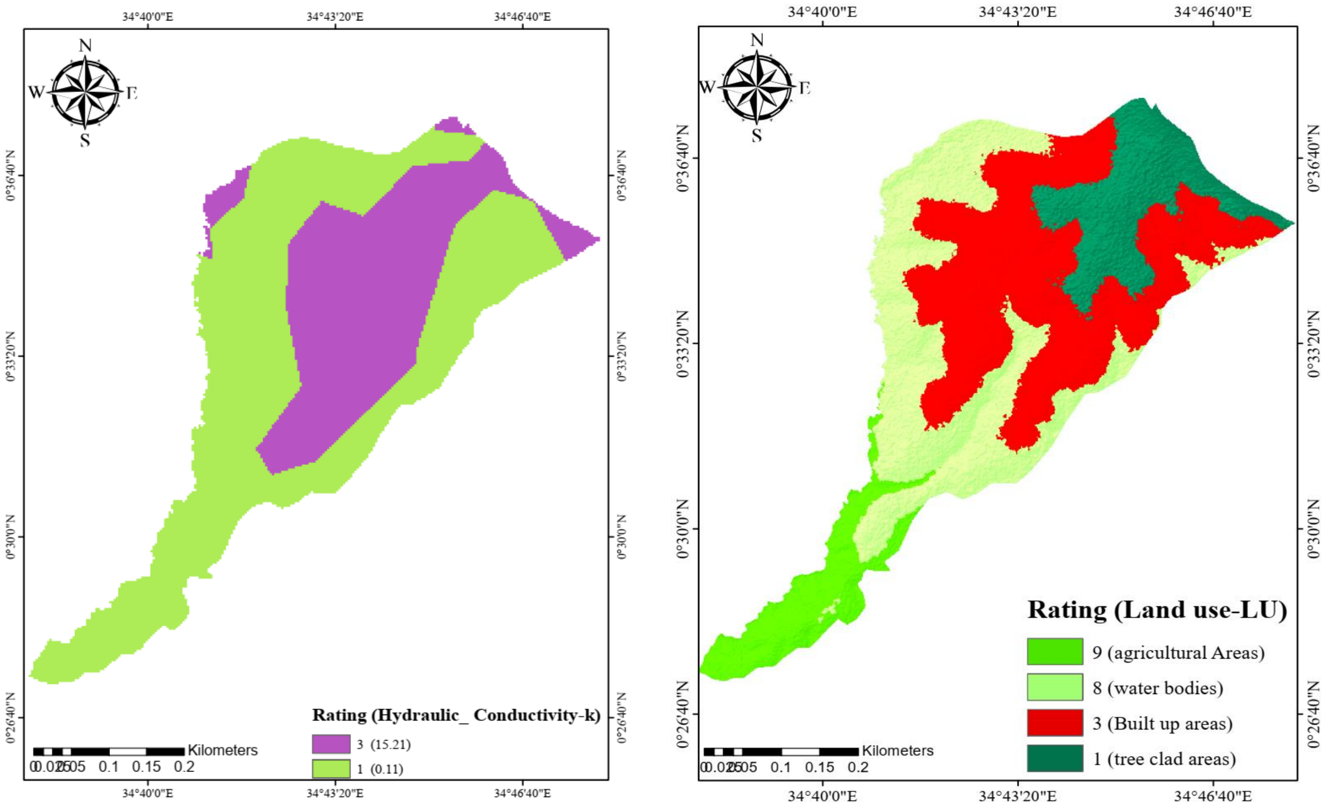


(c) (d)

Fig. 2. Spatial distribution of the parameters: (a) depth, (b) recharge, (c) aquifer and (d) soil media.



(a) (b)



(c) (d)

Fig. 3. Spatial distribution of parameters, (a) Slope, (b) Impact of vadose (c) Hydraulic conductivity and (d) Land use.

3.3. Groundwater vulnerability map

The DRASTIC-LU index map was presented in four general classes as Shown in the Fig. 4 below. The classes include; very low, low, high and very high, to describe the level of vulnerability of groundwater to pollution. The four classes were based on DRASTIC-LU values. This therefore implies that areas that scored low DRASTIC-LU values have low vulnerability and those that scored high values have highest chances of ground water vulnerability. The results show that the North Eastern areas of Webuye have high scored the highest DRASTIC-LU values and therefore have the highest chances of groundwater vulnerability to contamination. The North eastern areas are comprised of the urban and peri-urban areas of Webuye. The area is densely populated and has water and sewerage coverage; however, it is characterized by frequent sewer bursts, limited spaced for development of groundwater sources and onsite sanitation systems. The results indicated that there is possible higher generation of human and industrial wastes which end up setting a vulnerable environment to groundwater in North Eastern parts of Webuye. The area also shows prevalence in DRASTIC-LU parameters such as the highest recharge in the area above 110mm/yr as seen in Fig. 2(b). The area is partly consisted of sandy aquifers as seen in Fig. 2 (c) which are porous and permeable making it easy for transmission of water and contaminants. Fig. 2 (d) also shows the area is partly composed of nitisols which are weathered soil material and well drained. Such soils can fairly support contaminant movement from the surface to groundwater zones (RagaPriya *et al*., 2020). The results agree with a study carried out in Terjun Indonesia where DRASTIC model was applied in mapping groundwater vulnerability topography, aquifer depth and soil media showed highest influence on groundwater vulnerability (Nurfahasdi *et al*., 2023).

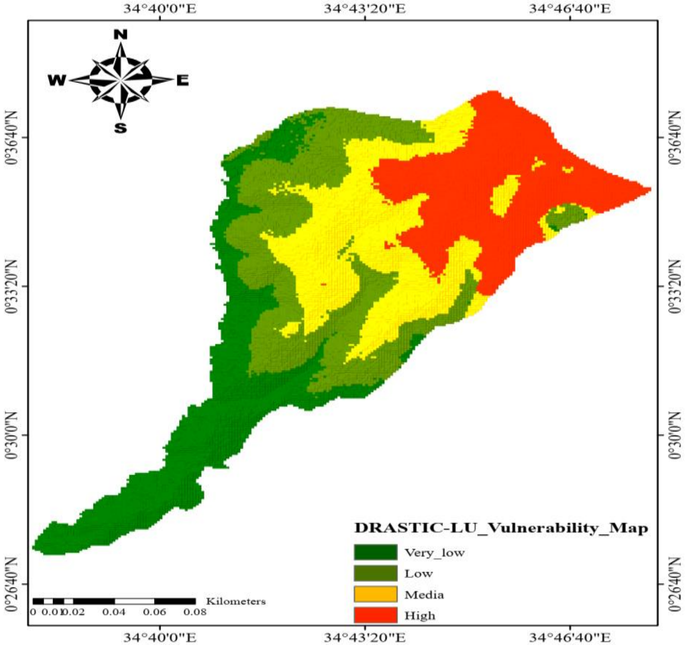


Fig. 4. DRASTIC-LU index map.

Similar results were reported in Hamadan–Bahar plain in Iran where water depth was found to be the most contributing factor to groundwater vulnerability (Novinpour, Moghimi, and Kaki, 2022). Additionally, a comparative study carried out in Halabja-Saidsadiq in Iraq using COP and the VLDA models confirms the findings of this study by indicating that areas with recent recharge are more vulnerable to groundwater contamination (Abdullah *et al.*, 2020).

Further, the findings in Fig. 3 a show that the north east part of Webuye has the steepest slopes >18 as compared to all other zones in the study area, sandy soils in zone as seen in Fig. 3 (b) and hydraulic conductivity in Fig. 3 c have collective contribution to contaminant infiltration and movement. Findings by (Alasbahi and Al-Hawshabi, 2021) show that when slope is combined with soils of higher infiltration capacity greatly reduces runoff than soils having lower infiltration therefore, steeper slopes contribute to pollutant transport across land surfaces to surface water sources and less time for infiltration to groundwater sources. Hydraulic conductivity ranges between 0.11 and 15.21 m^3/d with the highest levels in north east parts of the study area. Higher hydraulic conductivity values contribute to more vulnerability of groundwater sources. Findings by (Das, Dhorde, and Mitra, (2022) show that higher hydraulic conductivity results in a wider cone of depression and therefore extended contamination. The north east part has some areas of good tree cover, but its majorly composed of built-up areas of Webuye town. Das, Dhorde, and Mitra, (2022) also reported that urbanized areas affect groundwater quality through solute composition, by altering the natural surface conditions. This inhibits groundwater circulation system thus affect the dilution and transport of groundwater.

4. Conclusions

DRASTIC-LU model was used to carry out assessment of groundwater vulnerability using ArcGIS approach. Where interpolation was carried out using Distance Weighted Interpolation carried out under spatial analysis (IDW) in spatial analysis. The results show groundwater vulnerability based on DRASTIC-LU parameters. The results show that groundwater is more vulnerable due to shallow water depth <5, predominance of sandy soils in high recharge areas, steep slopes >18 and anthropogenic activities. These factors form an environment for contaminate generation and transport to the aquifers. DRASTIC model is the best way of assessing the vulnerability of groundwater towards pollution. This information is critical to stakeholders in policy formulation, legislations, water source development and to the County Water and Sanitation department for planning purposes.

Author Contributions

Collins Akhonya Siganga: Conceptualization, investigation, methodology, and writing- original draft.
Basil T. Iro Ong'or: Supervision, methodology and review.
Edwin K. Kanda: Supervision, methodology and review.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability Statement

The datasets used in the current study are available on request.

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