



GIS-based evaluation of shallow aquifer vulnerability to pollution using DRASTIC model: a case study on Abakaliki, southeastern, Nigeria

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Abstract

Groundwater is prone and most vulnerable to pollution from several human-mediated activities. Several measures have been taken to appraise the vulnerability of groundwater in order to manage it effectively. The current study uses the DRASTIC framework in a geographic information system (GIS) platform to evaluate groundwater vulnerability. For this study, a total of seven hydrogeological factors were investigated, and the resulting groundwater vulnerability map was created using an overlay weighted process and the DRASTIC index, which is divided into three vulnerable groups (high, moderate, and low). In the south and eastern provinces of the study area like Aghameghu, Obeagu, Ezzeagu, Ndiechi, Obusia Amachi, Odagateda, Okpuitumo Umuhu, Ugbuloke, and Ofe Iyioku, high groundwater contamination is been ascertained. The water quality indicators—nitrate and TDS—were adopted to validate the model, with a precision of 75% and 70%, correspondingly. GIS application of the DRASTIC model was proven to be an effective technique for evaluating the groundwater vulnerability in urban and semi-urban environments. This map can be used primarily for groundwater preservation and planning in a given area, as well as a necessary backdrop for management and land use decisions.

Keywords Groundwater vulnerability · DRASTIC · Hydrological criteria · GIS · Sensibility examination

Introduction

In both developed and less developed nations, respectively, groundwater and surface water are primary determinants of water for human consumption, commercial, and agricultural purposes (Rahmn 2008). However, surface water is utilized oftentimes as source of drinking water more especially in the rural areas because of its volume, cohesion, and as a result of limited access to groundwater. Consequently, groundwater remains a major source of drinking water in most urban cities particularly in developing nations

due to its quality for water requirement. Problem associated with groundwater primarily direct to environmental pollution, acidification, and over-abstraction (Khemiri et al. 2013; Abdeslam et al. 2017). Groundwater degradation is ambiguous in Nigeria; for instance, in Abakaliki, 38% of groundwater is formerly tainted by bacteriological parameters because of its shallowness to the surface. Pollution originated from both point and non-point has an impact on water quality (Woszcyk et al. 2018; Basheer 2018b). Non-point source pollution from farming activities and point source pollution from wastewater discharges, mineral extraction, and industrial discharges are the principal contaminant sources (Ahluwalia and Patel 2018; Basheer 2018b). Agrochemicals and chemical fertilizer are the most common agricultural contaminants. One of the most widespread and recurring issues of water pollution is involved with non-point pollution generated via the intensification of farming practices over the past years, with rising usage of pesticides and fertilizers and higher populations of livestock in smaller areas. High nutritional contents can create a range of issues, including biodiversity

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loss, such as algal blooms of water bodies, and human health issues (Basheer 2018a; Basheer and Ali 2018). Several factors influenced the transport and concentrations of contaminants in groundwater, including the rate and dissemination of fertilizer and manure use, land-use practices, and other human activities, as well as geogenic factors, like soil and aquifer attributes, hydrology, and the chemical composition of the nutrients compounds themselves (Suthar et al. 2009; Ali et al. 2005; Ali and Jain, 1998).

In recent decades, the demand for fresh water in most urban cities in Nigeria has escalated owing to the increased deterioration of surface water, industrial, and population growth. The key successful way of tackling groundwater pollution is early mitigation (Evans and Myers, 1990). Preservation of groundwater from pollution is important for successful groundwater budgeting and planning. Due to the vulnerability of surface water to contamination, inhabitants in different urban cities especially in Abakaliki rely primarily on groundwater for multiple uses. For effective groundwater budget planning, maintenance, and long-term development, determining the vulnerability of groundwater to pollution is critical. The environment is thought to shield groundwater from pollutants infiltrating the lithology underneath the soil (Saidi et al. 2011). A sluggish but dangerous phenomenon that can lead to adverse health effect is pollution of groundwater by human activities.

Since 1968, when Margat (1968) initially developed the theory of aquifer vulnerability, many frameworks have been proposed. For instance, Hirata and Bertolo (2020) outlined the aquifer vulnerability as “the attribute of an aquifer system that is based on the responsiveness of the material in authorizing the deterioration of the saturated region by contaminants substances arising from man-made sources,” while the National Research Council (National Research Council (NRC), 2019) described it as the relative ease by which a pollutant utilized on or in the earth surface can penetrate to the aquifer within a given set of agricultural management exercise, pesticide characteristics, and hydrogeological sensitivity environments.

The intrinsic susceptibility of aquifers to several contaminants resulting from activities of human is connected to the hydrological, geological, and hydrogeological components of the aquifer. Because aquifers have multiple reactions to a certain pollutant due to their physico-chemical properties, the specialized vulnerability exemplifies the aquifer’s vulnerability to a contaminant (or a class of contaminants) as defined by the contaminant’s attributes, considering the time of impact, the severity of the impact, and the interplay between the intrinsic vulnerability aspects and the pollutant (Doerflinger et al. 1999; Gogu and Dassargues, 2000). As part of the groundwater protection act, Gogu and Dassargues (2000) classified

the methodologies for assessing groundwater vulnerability into three categories. The soil and unsaturated zone were considered in the first class, groundwater flow and pollutant transport were considered in the second class to some extent (Derouane and Dassargue, 1998), and the soil, unsaturated medium, and aquifer were considered in the third class.

Voudouris (2009) created several strategies to estimate groundwater vulnerability, namely index, overlay, statistical, and simulation procedures. The advantage of index-based techniques is that they do not rely on data availability or similarity (Kumar et al. 2015). Rating-based methods perform by categorizing water vulnerability using a variety of ratings based on the physical parameters of the study material. Statistical analysis or regression models are used to investigate the vulnerability of the aquifer (Eckhardt and Stackelberg, 1995; Masetti et al. 2009; Yen et al. 1996). The simulation method, which make use of simulation approaches to identify pollution transport pathways (Neukum et al. 2008; Pineros Garcet et al. 2006; Singhal and Goyal, 2011; Fusco et al. 2020). Overlay and index approaches are the generally accepted methods for mapping groundwater vulnerability, as they overcome all of the aforementioned constraints. The overlay and index model integrates features that track the spread of pollutants from the vadose zone to the phreatic zone, leading in pollution of the groundwater. Some common overlay and index methods are DRASTIC (Aller et al. 1987); GOD (Foster and Hirata, 1988); AVI (Van Stempvoort et al. 1992); SINTACS (Civita, 1994; Ifediegwu et al. 2021), EPIK (Doerflinger and Zwahlen, 1997); GALDIT (Chachadi and Lobo-Ferreira, 2001); and SAI method (Heredia and Cirelli, 2007). Any of these approaches can be used depending on data availability, geochemical parameters, contaminant type, and sources (Twarakavi and Kaluarachchi, 2006).

The DRASTIC technique is the most often used for assessing groundwater vulnerability. In the USA, it is most commonly used to estimate water susceptibility. Its application is based on the hypothesis that some well-known essential factors have an impact on groundwater vulnerability and can be weighted. Appraising groundwater vulnerability for a specific location is both costly and time-consuming, whereas DRASTIC approach is a more cost-effective and time-efficient way to assess a wide range of regional groundwater risk while avoiding sloppy, uncontrolled land development and undesired activities. The DRASTIC model was developed by the Environmental Protection Agency (EPA) to analyze groundwater vulnerability in hydrogeologic situations (Aller et al. 1987; Babiker et al. 2005; Al Hallaq and Elaish, 2012). The acronym DRASTIC means depth to water, net recharge, aquifer media, soil media, topography, vadose zone impact, and hydraulic conductivity. The

DRASTIC parameters, according to Aller et al. (1987), are important in transporting contaminants into groundwater. It has been used in a wide variety of an areas across the globe, including North America, the Middle East, Europe, Asia, and Africa, as demonstrated by the research of Lynch et al. (1993); Navlur and Engel (1997); Fritch et al. (2000); Ettazarini (2006); Pathak et al. (2009); Anane et al. (2013); Edet (2013); Ekwere and Edet (2015); and Ifediegwu et al. (2021). For any sustainable development plan, regulating the risk of groundwater deterioration due to rapid urbanization, industrial revolution, and agricultural production becomes a necessity. As a result, the primary goal of this study was to use the DRASTIC model to outline the aquifer’s contamination risk using a GIS platform. By creating a risk appraisal map of the Abakaliki area, the hydrogeologic criterion was developed and plotted to detect locations susceptible to contamination. The findings of this study will aid

policymakers and planners in developing a groundwater management strategy in the years to come.

Study area

Present research took place in Abakaliki, the capital of Ebonyi State in southeastern Nigeria (Fig. 1). Geographically, Abakaliki is stationed between latitudes 6° 5' N to 6° 20' N and longitude 8° 5' E to 8° 20' E. Abakaliki covers eastern part of Ebonyi State, occupying a total landmass of about 584 sq.km (Aja et al. 2019). The study area reveals two prevalent topography which comprises of a vast lowland and undulating hills. The area is drained by Ebonyi river and many its tributaries which traverses southward and connect Cross. The region is marked by two distinct seasons: the dry season, which rouse from November to March, and the rainy season, which initiated from April and cease in October, with a brief period of abated rainfall in August, known as

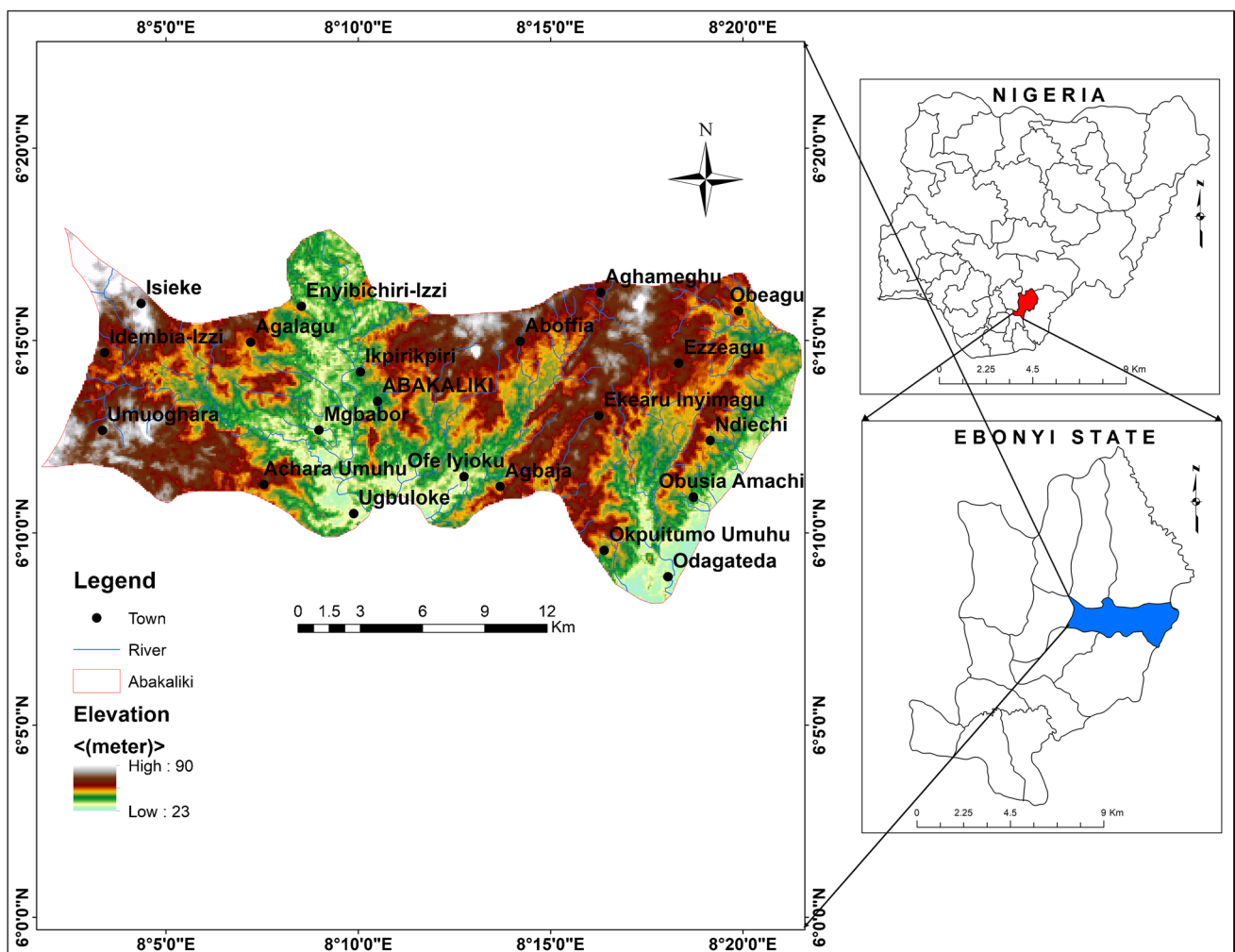


Fig. 1 Location map of the study area

August break. The average yearly rainfall documented in the area is 1,500 mm. Temperature ranges from 20 to 38 °C.

The study area is one of the Abakaliki Formations that occur in the Albian Asu River Group. The Asu River Group is largely described by very loosely bedded shale and scattered intercalations of sandstone, siltstone, and limestone strata (Ofoegbu and Amajor, 1987). The sandstone, siltstone, and limestone strata are heavily jointed and cracked. In the mid-Albian age, this was generally assumed to have begun depositing and was deposited within the lower Benue Trough. Intermediates to basic intrusives, extrusives, and pyroclastics are found within the sediments of Asu River Group (Murat 1972; Tijani et al. 1996).

The Abakaliki Formation is mainly shale, dark grey in color, blocky, and non-micaceous in most places, with a total diameter of about 500 m. The sequence of tectonic processes that have worked on the rocks is heavily folded, faulted, and broken (Ezeh and Anike, 2009). These have provided the shales with the capacity in certain places to store groundwater at a reasonable volume, while other sections still remain in its existence as aquiclude, and cracking is not prevalent. Mostly in broader part of the formation, it is calcareous and profoundly weathered into reddish brown clay.

Abakaliki area is generally characterized by aquiclude, unless in areas or zones where syn- and post-depositional effects have created secondary porosity conditions accessible. The syn-depositional condition is the emergence of sandstone or siltstone bed fragments, whereas weathering,

cracking or shearing, and volcanic intrusions are included in the post-depositional conditions.

Materials and methods

The groundwater vulnerability to pollution in the Abakaliki region is explored employing the DRASTIC model, which is built on a geographic information system (GIS). Aller et al. (1987) created the DRASTIC model for the US Environmental Protection Agency (USEPA) with the aim of enabling a standardized study of possible groundwater contamination in all hydrological environments. Depth to groundwater, net recharge, aquifer properties, soil properties, topography, vadose zone effect, and hydraulic conductivity are the seven hydrological layers used in the DRASTIC model. The model produces a mathematical index which is extracted from the rankings and weights allocated to individual criterion. Each criterion is further divided into groups or substantial categories that are classified between 1 and 10 in proportions to its corresponding influence on the contamination potential. The seven hydrological layers are allocated weights varying between 1 and 5 according to their corresponding influence. The DRASTIC index (Eq. 1) is further calculated by using a linear composite of the seven hydrological layers as shown in the calculation below (Machdar et al. 2018).

$$\text{DRASTIC Vulnerability Index (DVI)} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (1)$$

The seven hydrological layers are denoted by the letters D, R, A, S, T, I, and C, and the subscripts r and w signify ranking and weights. The DRASTIC index is calculated by multiplying each layer's ranking by its weight and adding the resulting values together. Subsequently, the seven hydrological layers were weighted to show their corresponding influence as regards each other. Additionally, two categories of sensibility analysis were also conducted. Spatial data investigation and digital mapping are executed in the GIS platform.

Preparation of thematic maps

The seven hydrological criteria were created as thematic layers from a variety of data and references. The depth of groundwater (D) refers to the distance between the surface of the earth and the water table. Deeper water table impose slighter casualty for pollution to take place. Depth to groundwater criteria has been ascribed with a corresponding weight of 5. Depth to groundwater influences the duration for a pollution to experience physicochemical and biological responses. With a decline in depth of groundwater, the

possibility of groundwater pollution upsurges. This criterion was obtained from well log data of 13 boreholes drilled within the study area. The borehole position vector map was produced appertaining to GPS examination and spatial dissemination map of groundwater was generated by interpolation via IDW approach.

The volume of water that percolates the earth's surface and gets to the saturated areas is known as net recharge (R). On a yearly basis, it is the overall volume of water (in mm) that percolates into saturated areas. The amount of recharge varies from 0.012 to 0.12 cm/year in the research region. It functions as a substantial conduit for conveying the pollutants. It conveys the pollutants to the aquifer vertically. The study area's net recharge was computed using the Piscopo method (Kaliraj et al. 2015), which is a best field-based approach. The corresponding weight of 4 was given to net recharge.

The groundwater zone is a significant property that governs the contaminant attrition process, and it is known as aquifer properties (A). For the aquifer media, analogue hydrogeological map acquired from Nigeria Geological

Table 1 Range and ranking of the DRASTIC criterion for Abakaliki area

Depth to water table (D)		Net recharge (R)		Aquifer properties (A)		Soil properties (S)		Topography (T)		Impact of vadose zone (I)		Hydraulic conductivity (C)																
Range (m)	Ranking (D _r)	Index	Weight (D _w)	Range (cm/year)	Ranking (R _r)	Index	Weight (R _w)	Geology	Ranking (A _r)	Index	Weight (A _w)	Soil type	Ranking (S _r)	Index	Weight (S _w)	Topography (m)	Ranking (T _r)	Index	Weight (T _w)	Lithology	Ranking (I _r)	Index	Weight (I _w)	Soil type	Ranking (C _r)	Index	Weight (C _w)	
21.01–26.61	8	60	4	0.012–0.034	2	22	5	Pyroclastic rock	3	20	2	Clay	2	4	23–39	10	10	10	10	10	Clay	1	8	0.00106–0.01185	1	2		
26.62–32.21	7	50	4	0.035–0.055	4	38	5	Shale	5	10	4	Clay loamy	4	6	39.01–50	8	8	8	8	8	Silt	2	13	0.01186–0.02263	2	4		
32.22–37.8	6	40	6	0.056–0.077	6	42	7		6	6	7	Silt clay	7	8	50.01–61	6	6	6	6	6	Gravel	3	18	0.02264–0.03342	3	6		
37.81–43.4	4	30	7	0.078–0.098	7	58	8		8	10	8	Sandy clay	8	10	61.01–90	4	4	4	4	4								
43.41–49	2	20	8	0.099–0.12	8	62																						
Weight (D _w)	5	Weight (R _w)	4	Weight (S _w)	2	Weight (I _w)	5	Weight (T _w)	1	Weight (C _w)	3																	

Survey Agency (NGSA) with a scale of 1:250,000 have been converted to digital format by scanning in Tiff Format and geo-referenced into Universal Transverse Mercator (UTM-Zone 32 N) and datum WGS-1984 to generate aquifer media map. This map was further modernized using satellite data. Aquifer media has the possibility of accumulating water. The movement of the pollutant thru the aquifer material reflects the attrition properties of the aquifer media. The water is hold in the void spaces and joints of the media. A longer migration period would result in additional contamination attrition. Its corresponding weight is ascribed as 3.

The topmost eroded zone of the vadose zone is known as the soil media (S), which governs the quantity of recharge that can penetrate beneath it. It conveys pollutants and water from the topsoil surface to the saturated region. Contaminant transport is sped up in soils of clay and silts (Sinan and Razack, 2009). Analogue soil map of southeastern Nigeria obtained from the Land and Water Development Division/FAO was used to create a computerized soil layer. The ranking ratings of soils are assigned based on their permeability. Its corresponding weight is ascribed as 2.

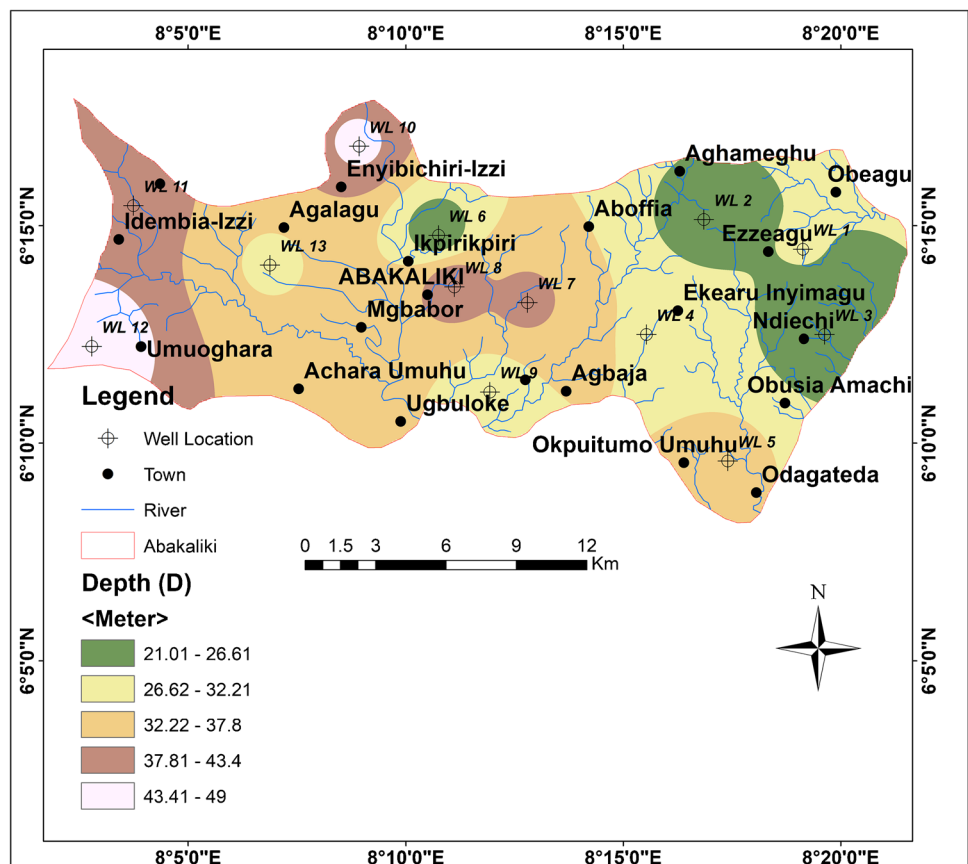
The landscape, which is an input in the DRASTIC model, is classified as topography (T). This criterion displays the rate of surface runoff that regulates biodegradation and

attrition. The topography decides whether water will stay on the ground surface lengthy period for pollutants to reach the aquifer. In a lowland topography, standing water improves penetration and provides a greater opportunity for pollutant transportation. The SRTM DEM (Shuttle Radar Topographic Mission-Digital Elevation Model) data was used to construct the topographic map. It is depicted in meter and its corresponding weight is 1.

Impact of vadose zone (I) refers to as the discontinuously saturated zone material underlying the normal soil profile and overlies the water table. The mobility of the pollutant to the groundwater zone is governed by this criterion. Different mechanisms that affect the possibility of contamination occur in unsaturated zones and govern the movement and attrition of the polluted substance to the saturated zone (Yin et al. 2012). The thematic layer was extracted from 21 borehole lithology information acquired from study area. The corresponding weight of impact of vadose zone is 5.

Hydraulic conductivity (C) shows the capability of saturated zone to transfer water which controls the rate of flow of pollutant substance into the aquifer media. Pumping test data from the study area was used to obtain hydraulic conductivity information. The layers corresponding weight in DRASTIC model is 3.

Fig. 2 Depth to groundwater map



Sensibility examination

The sensibility examination of the DRASTIC criteria was conducted to analyze the sensibility of each criterion in examining the intrinsic vulnerability of groundwater. The values of the vulnerability index are calculated using the weights of the DRASTIC criteria. In order to define the intrinsic vulnerability, it is required to analyze the prerequisites for using all seven DRASTIC criteria. Two sensibility analyses carried out are the map ouster and individual criteria sensibility examination. The map ouster sensibility examination portrays the sensibility related to eliminating one or two parameters during the period of model accomplishment. In the present investigation, the map ouster sensibility examination is carried out by the following arithmetic.

$$S = \frac{V/N - V'/n}{V} * 100 \tag{2}$$

Where *S* denotes the computation of individual criteria' sensibility, *V* denotes the total vulnerability index, *V'* denotes the vulnerability index of each criterion, *N* denotes the total number of criteria utilized to determine *V*, and *n* denotes the number of criteria employed to estimate *V'*.

The composed and agitated vulnerability indices are represented by *V* and *V'*, respectively. As a composed

vulnerability, the factual vulnerability index derived from the use of all seven thematic layers was investigated. The agitated vulnerability is determined by a decrease in the number of data layers. The model shows the affinities between composed and agitated vulnerability levels. Individual criterion sensibility analysis was introduced to ascertain and examine the influence of seven thematic layers of DRASTIC technique on the vulnerability index. It calculates the level of impact of single criteria for the vulnerability of groundwater. The efficient weight of individual attribute class is established by the following arithmetic.

$$W = \frac{P_r P_w}{V} * 100 \tag{3}$$

where *W* is the efficient weight of individual criteria, *P_r*, *P_w* is the ranking and weight of individual criteria, and *V* is the total vulnerability index.

Finally, the study took place during the dry season (December). In total, 13 borehole locations have been chosen around the area to measure nitrate and TDS concentrations. The American Public Health Association's standard techniques were used to quantify nitrate and TDS (APHA 2005). The spatial distribution map of nitrate and TDS was created with the help of the ArcGIS 10.5 spatial analysis tool and the IDW

Fig. 3 Net recharge map

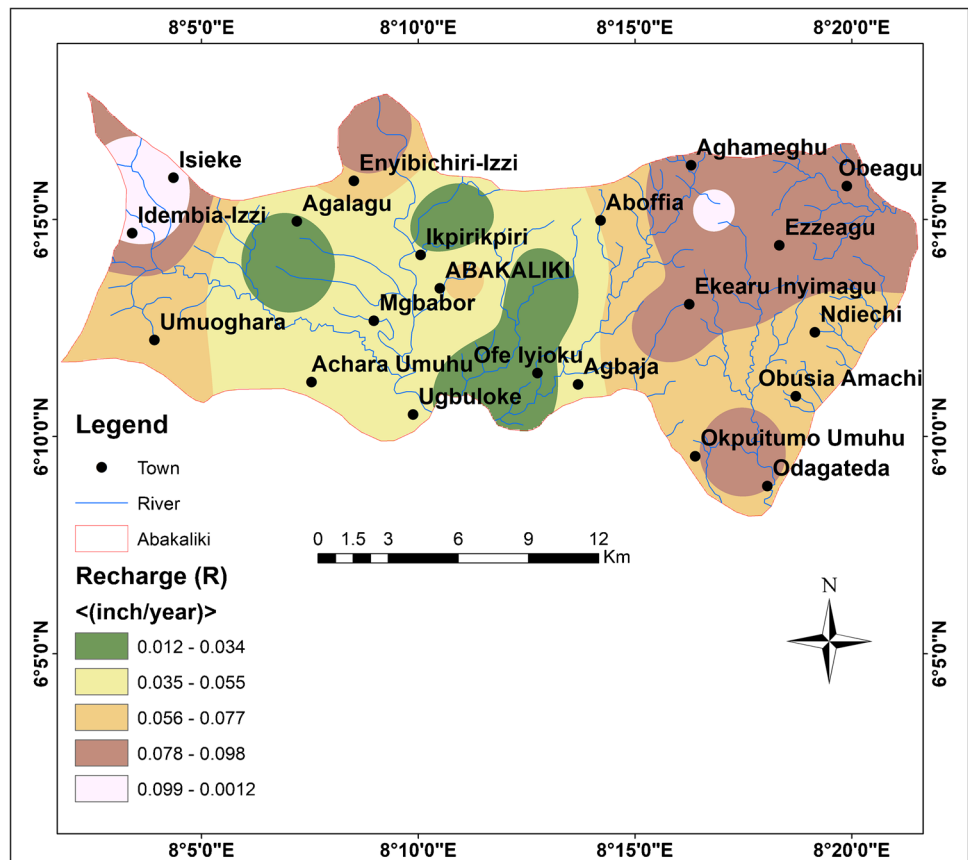
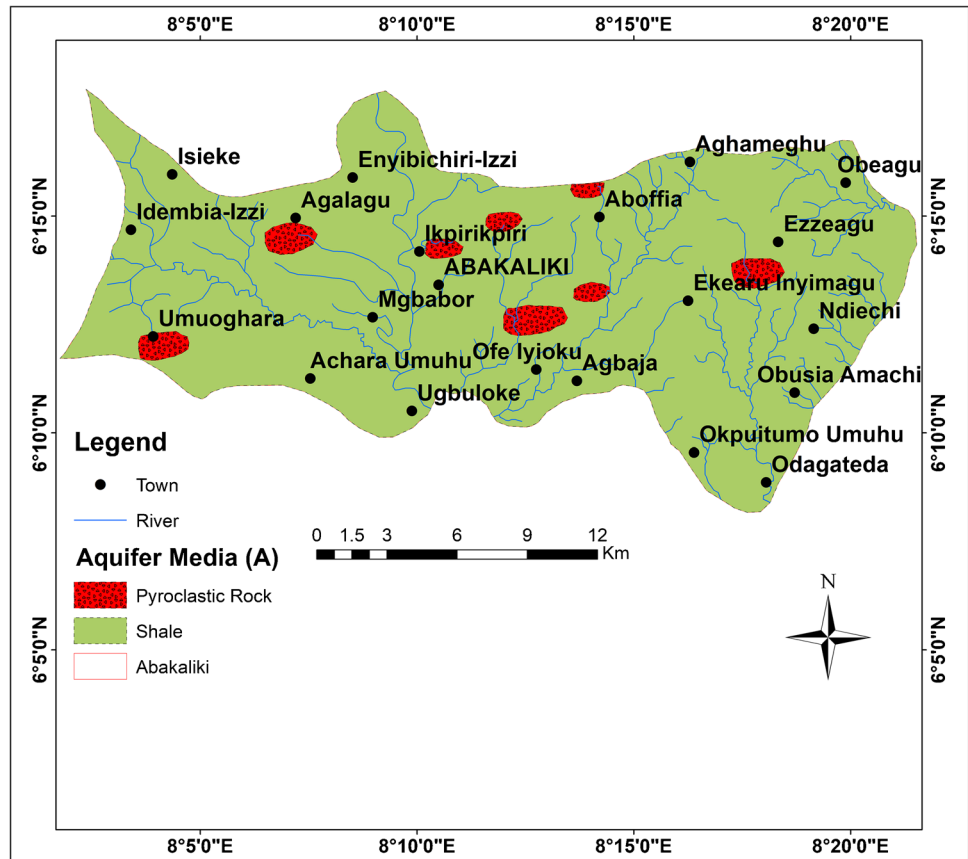


Fig. 4 Aquifer property map



Interpolation method. These data were adopted for the purpose of confirmation of the groundwater vulnerability map, as an appropriate guide for a quick appraisal of groundwater vulnerability in both urban and semi urban environments.

Results and discussion

The vulnerability index map is categorized into three groups according the DRASTIC model, such as high, moderate, and low vulnerability areas. Table 1 provides the range and rankings for the study area.

Depth to groundwater (D)

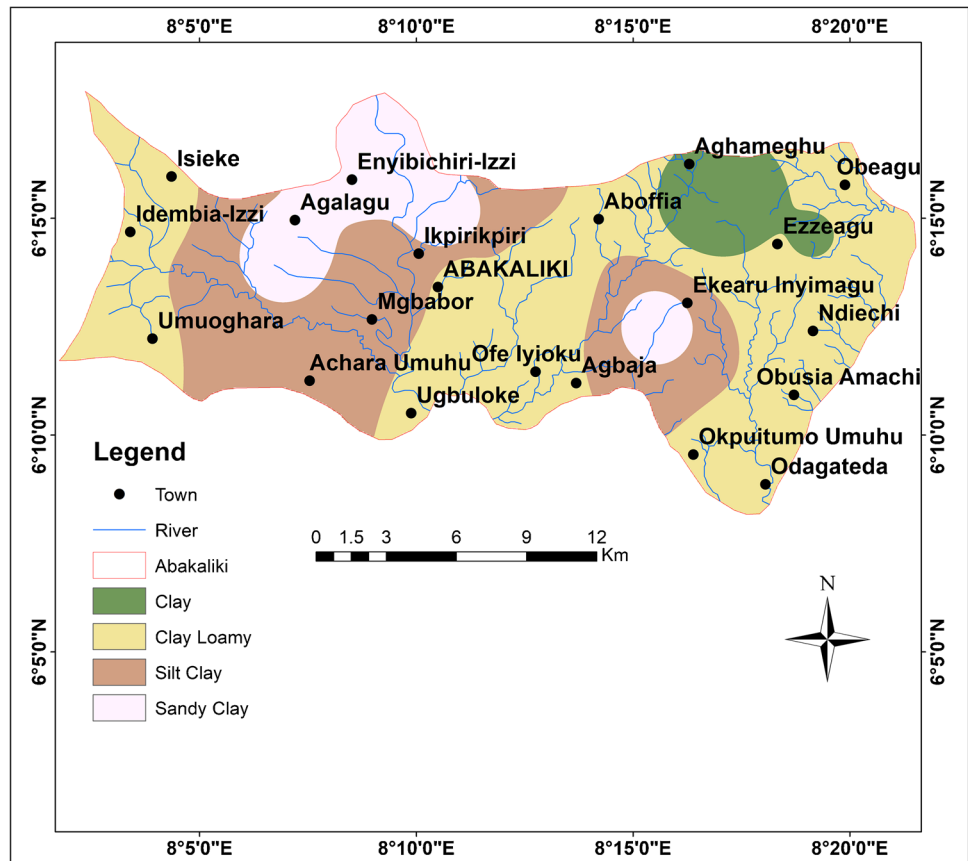
In the research area, the depth to the water table ranges from 21.01 to 49 m (Fig. 2). The depth to water table in the research area is divided into 5 groups ranging from 21.01–26.61 m, 26.62–32.21 m, 32.22–37.8 m, 37.81–43.4 m to 43.1–49 m having index weightages of 60, 50, 40, 30, 20, respectively. The depth to water level data is gathered from 13 shallow boreholes at various sites across the area. In the eastern district

(Ndiechi, Ezzeagu, Obusia Amachi, Obeagu, Aghameghu) and tiny pockets of the northern segment of the basin (Ikpirikpiri), the groundwater depth is low, ranging from 21.01 to 32.21 m, thus posing a high danger of contamination. While groundwater depths are substantially deeper in the south western and middle catchment regions, the areas of Abakaliki, Idembia-Izzi, Enyibichiri-Izzi, Isieke, and Umuoghara in that region are not as prone to contamination. Deeper groundwater is less susceptible than shallow groundwater (Machdar et al. 2018). Hence, low rankings are given to the regions with deeper groundwater.

Net recharge (R)

The net recharge of the research area fluctuates between 0.012 and 0.12 inch/year (Fig. 3). Total of 1.03% of the area has been allocated an index weightage of 62 and highest ranking of 10 for possessing a net recharge of 0.099–0.12 inch/year. The net recharge rate is very high in the upper catchments of the area. Specifically, the regions Ekearu Inyimagu, Ezzeagu, Obeagu, Aghameghu, and Odagateda possess moderately high net recharge rate fluctuating between 0.078 to 0.098 inch/year. In the southern and central parts of the catchment encompassing the

Fig. 5 Soil property map



areas Agalagu, Ofe Iyoku, Ikpirikpiri, Mgbabor, Agbaja, Ugbuloke, and Achara Umuhu, the net recharge rate is moderately low to very low. As a result, the risk of contamination is minimal.

Aquifer media (A)

Two important lithological formations in the research area are shale and pyroclastic rock which have been ascribed weightage based on their impact on groundwater quality (Fig. 4). Shale covers about 98.62% of the research area; just 1.38% of the area is encompassed by pyroclastic rock. The predominant aquifer material layers in the area are weathered/fractured/jointed shale. The layer was assigned ranking value of 5 and influenced by a weight of 10. A higher aquifer layer ranking score shows that the aquifer media is more permeable and has a higher prone potential.

Soil media (S)

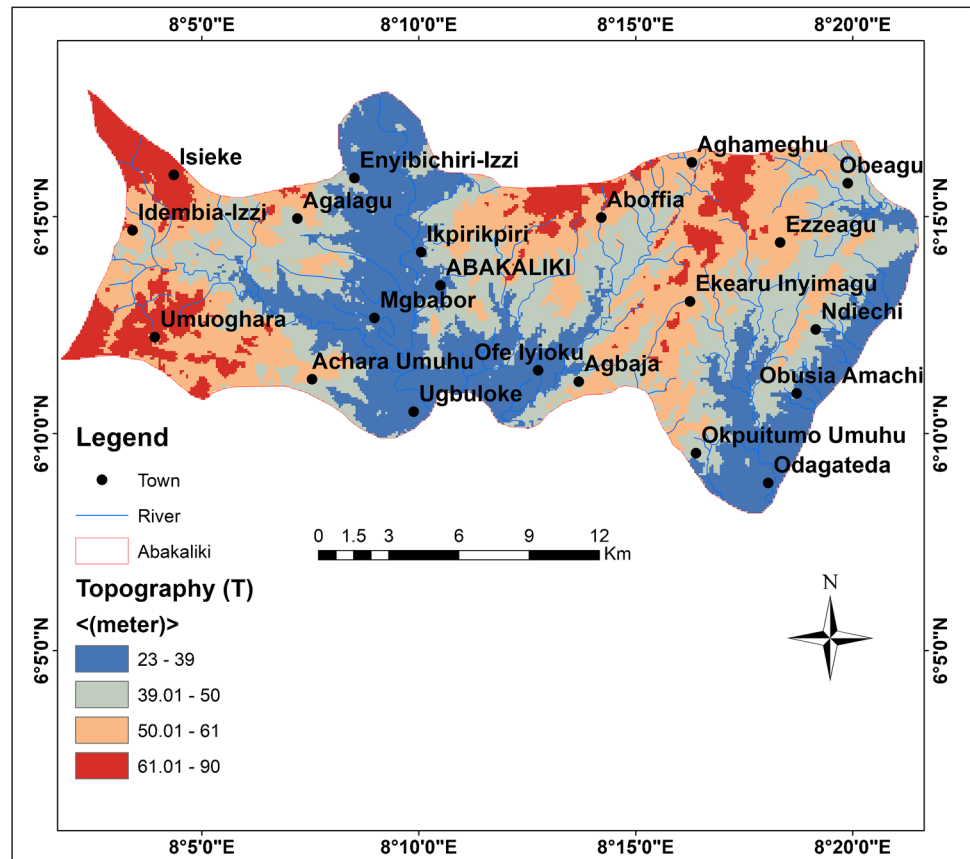
Clay, clay loamy, silt clay, and sandy clay are the four principal soil types found in the study area. The most common soils in the region are mixed clay loamy and silt clay (Fig. 5). Individual soil types have been classified as per their relative

importance. Clay loamy, which occupies 58% of the land area, has been graded 4 and given an index weightage of 6. Silt clay makes up only 31% of the total research area. In the southern, eastern, and few areas in the western sides (Idembia-Izzi, Umuoghara, Ugbuloke, Ofe Iyioku, Ndiechi, Obeagu, Okpuitumo Umuhu, Aboffia), clay loamy is found, and in the central portions of the study area (Achara Umuhu, Mgbabor, Ekearu Inyimagu, Ikpirikpiri), silt clay soil is ascertained. These soils have a moderate penetration rate, making them less susceptible to pollution. However, the upper catchment of the northern districts of the area (Ekearu Inyimagu, Agalagu and Enyibichiri-Izzi) has sandy clay soil. Because of their high penetration rate, sandy clay soils are more prone to pollution. Clay soil is found in the upper catchments in the north eastern section, with a lower penetration rate.

Topography (T)

The research area’s topography varies between 23 and 90 m and has been divided into four categories: 23–39 m (lowland), 39.01–50 m (plain), 50.01–61 m (plateau), and 61.01–90 m (inselbergs) (Fig. 6). 48.91% of the area possesses topographic values varying from 23 to 39 m, and the allocated index weightage is 10 with a ranking

Fig. 6 Topography map



of 10. For having a topography ranging from 61.01 to 90 m, an area of 121.03 sq km comprising 15.11% of the area was given an index weightage of 4. Low slope m value reveals higher domicile time and aids in greater infiltration of pollutant affluent water. The topography is quite high (inselberg) on the northwestern portion (Isieke, Umuoghara) of the upper catchment of the area, fluctuating between 61.01 and 90 m, and the danger of pollution is minor in these locations since the runoff is above the seepage rate. Similarly, in the lower catchment areas (Ugbuloke, Ofe Iyioku, Okpuitumo Umuhu, Odagateda, Obusia Amachi, Ndiechi), the lowlands and plain lands occupies most of the entire area, therefore indicating high danger of contamination.

Impact of the vadose zone (I)

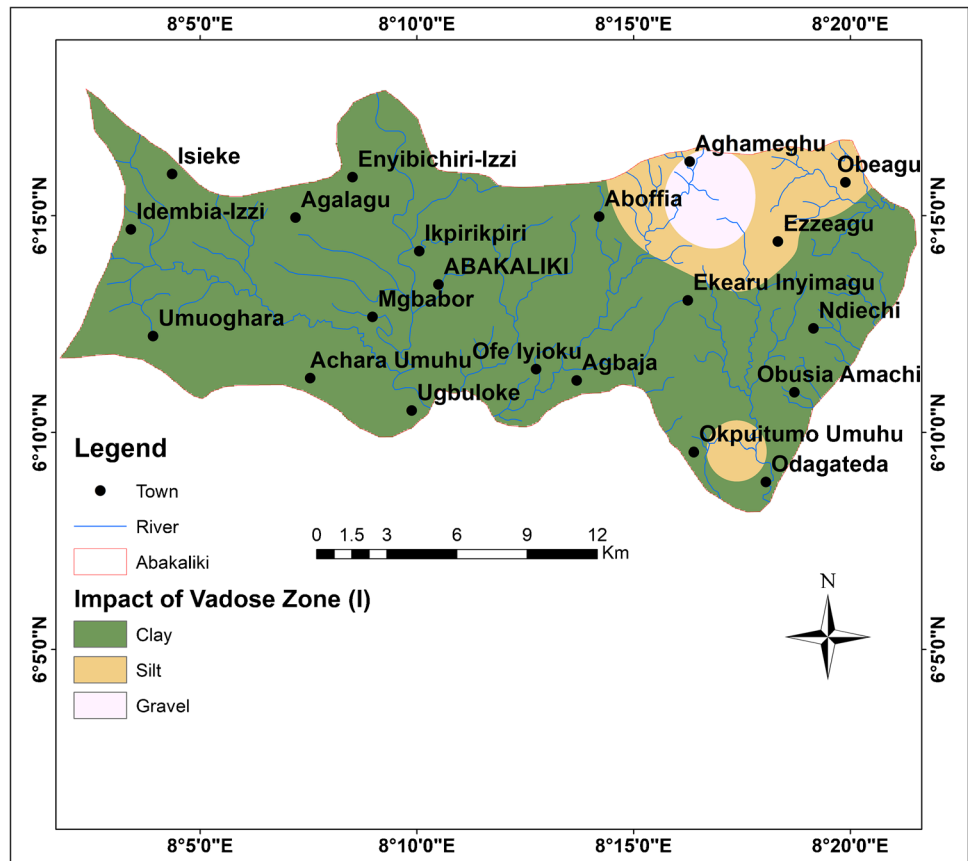
The vadose zone of the research area comprised of clay, silt, and gravel (Fig. 7). Clay occupies about 95.8% of the research area, and the minimum index weightage of 8 with ranking of 1 has been ascribed to the zone. An elevated index weightage of 18 with ranking of 3 has been ascribed to the gravel encompassing 0.82% of the research area. The northern, north western, central, and southern segments (Abakaliki, Ofe Iyioku, Ikpirikpiri, Agalagu, Umuoghara, Idembia Izzi, Agbaja, Ugbuloke,

Achara Umuhu, Ndiechi, Obusia Amachi) of the area comprises of clay type vadose media with moderate rate of pollution. Besides, the north eastern and small pocket in the south eastern portions (Aghameghu, Obeagu, Ezzeagu) can be described by silt and gravel vadose media, with high seepage rate and greater danger of contamination.

Hydraulic conductivity (C)

Hydraulic conductivity values in the research region range from 0.00106 to 0.05499 m/day and are divided into five categories (Fig. 8). Total 79.58% of the research area possesses hydraulic conductivity values varying from 0.00106 to 0.01185 m/day, with the ascribed index weightage 2 and ranking of 1. Hydraulic conductivity values ranging from 0.04421 to 0.05499 m/day, covering 0.57% of the research area, were given a higher index weightage of 10 with a ranking of 5. The northern, southern, western, and south eastern regions largely Enyibichiri-Izzi, Agalagu, Umuoghara, Mgbabor, Abakaliki, Agbaja, Ugbuloke, Ofe Iyioku, Achara Umuhu, and Abofia show relatively lower hydraulic conductivity. So, the contamination risk is lesser in these areas. However, the hydraulic conductivity in the north eastern regions (Obeagu, Ezzeagu, Aghameghu) is relatively higher

Fig. 7 Impact of vadose zone map



varying from 0.03343 to 0.05499 m/day; thus the danger of contamination is higher in these zones.

DRASTIC vulnerability index (DVI)

The groundwater vulnerability of the Abakaliki basin was determined using the DRASTIC vulnerability index (DVI) method, which included the addition of seven thematic layers. The DVI varies from 22 to 81 in the research area. The DVI of groundwater contamination of the area has been split into three categories: high, moderate, and low contamination (Fig. 9). The eastern and southern portions of the study area reveal high contamination. Approximately, 12% of the area covering the regions Aghameghu, Obeagu, Ezzeagu, Ndiechi, Obusia Amachi, Odagateda, Okpuitumo Umuhu, Ugbuloke, and Ofe Iyioku are found in this zone. Because agriculture is the most common land use in this zone, gravel and silt are the most common soil types, and hydraulic conductivity ranges from high to moderate; groundwater seepage is also relatively high. Moreover, because the aquifer level is shallow, therefore agriculture pollutants interact readily with recharge water, damaging the groundwater even more. However, the western and northern regions of the study area reveal low groundwater

pollution encompassing 5.4% of the area. In this region, the areas Enyibichiri-Izzi, Isieke, and Umuoghara are located (Table 2). Due to low hydraulic conductivity and a moderate recharge rate, these districts have a relatively low groundwater seepage rate. Additionally, because the groundwater depth is deep, contaminants mixed with recharge water require a long time to enter the groundwater level via the vadose zone; the longer the duration of attrition, the lower the pollution danger. The north-central and western districts including Abakaliki, Idembia-Izzi, Achara Umuhu, Ekearu Inyimagu, Agbaja, Ikipirikpiri, Agalagu, and Aboffia have moderate risk of contamination.

Sensibility of the DRASTIC model

The DRASTIC parameters are summarized statistically in Table 3. The topography parameter triggers the maximum level of contamination with an elevated rating of 7.0. With average values of 5.4, 5.4, 4, and 5.3, the depth to water table, net recharge, aquifer media, and soil properties are all impacted with a considerable danger of pollution. The impact of vadose and hydraulic conductivity inflicted a minor danger of contamination with an average rating of 2.0 each. The impact of the vadose zone parameter is

Fig. 8 Hydraulic conductivity map

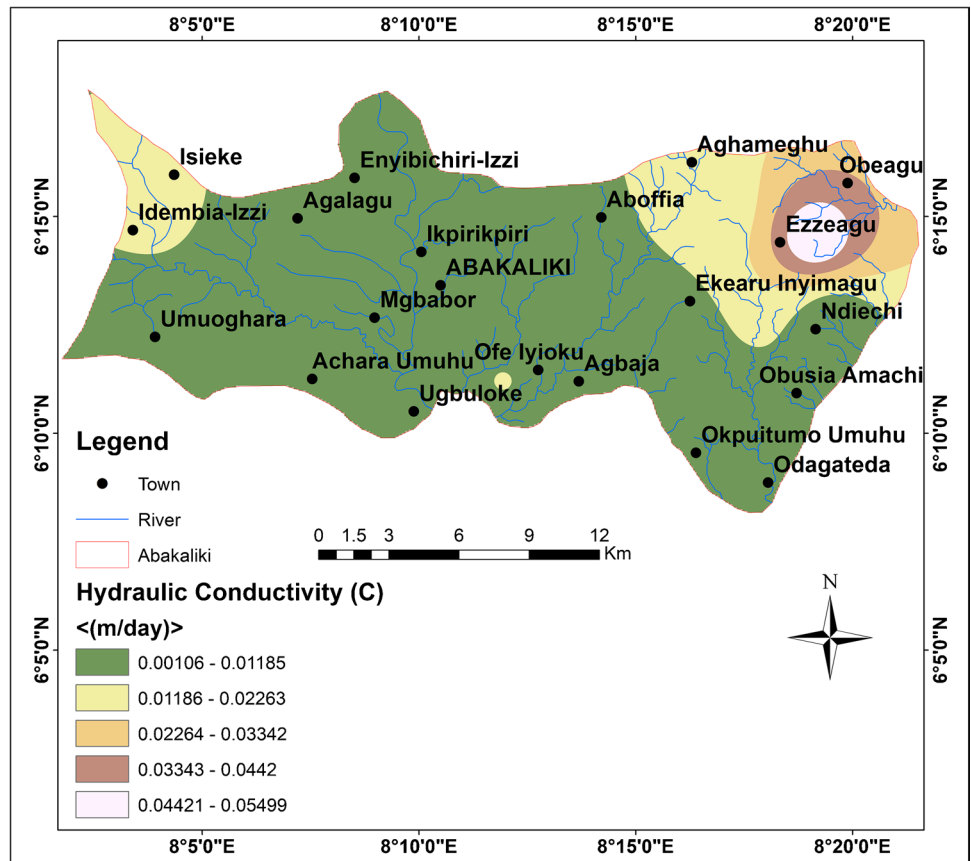


Fig. 9 DRASTIC vulnerability map

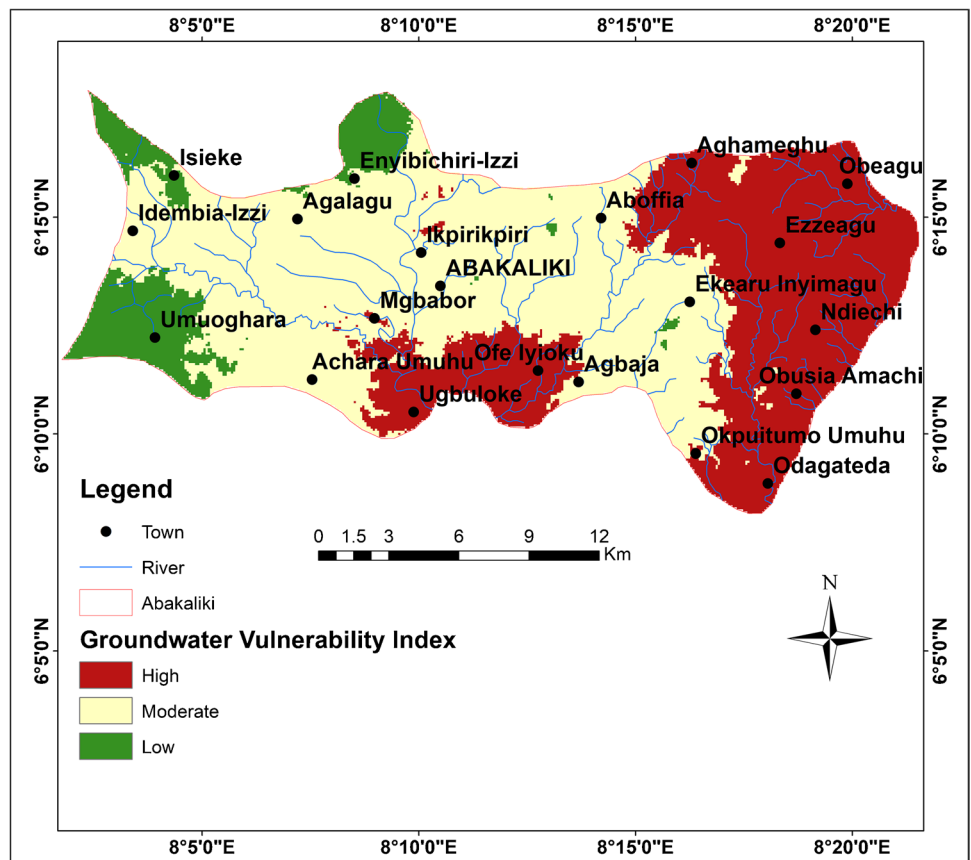


Table 2 DRASTIC susceptibility index for Abakaliki area

S/N	DRASTIC index	Area occupied (%)	Intensity of susceptibility
1	22–41	5.4	Low
2	42–61	82.6	Moderate
3	62–81	12	High

Table 3 A brief statistical analysis of DRASTIC criterion

Criteria	D	R	A	S	T	I	C
Min	2	2	3	2	4	1	1
Max	8	8	5	8	10	3	5
Mean	5.4	5.4	4	5.3	7.0	2.0	2.0
SD	2.2	2.2	1.7	2.4	2.0	2.4	1.4
CV	40.7	40.7	42.5	45.3	28.6	120	70

Min minimum, *Max* maximum, *SD* standard deviation, *CV* coefficient of variation.

Table 4 Statistics of map removal sensibility evaluation

Criteria removal	Fluctuation index (%)			
	Mean	Minimum	Maximum	SD
D	10.08	9	12.18	0.41
R	9.21	4.33	10.46	0.58
A	7.47	4.0	9.86	0.64
S	7.18	3.97	9.12	0.45
T	8.88	5.74	10.23	0.52
I	8.01	5.11	10.0	0.66
C	8.46	3.39	10.89	0.68

Table 5 Statistics of map ouster sensibility evaluation

Criteria utilized	Fluctuation index (%)			
	Minimum	Maximum	Mean	SD
D, R, A, S, T, I, C	6.27	14.79	12.15	1.89
D, R, A, S, T, I	4.89	14.28	10.61	1.66
D, R, A, S, T	3.16	14.00	10.38	1.43
D, R, S, T	2.11	13.87	10.17	1.66
D, R, T	0	14.14	8.49	3.18
D, R	0	12.62	8.56	3.01
D	0	10.73	7.72	2.24

highly varied, with a CV of 120%. The hydraulic conductivity, soil properties, aquifer media, depth to water, and net recharge are moderately varied with CV values 70%, 45.3%, 42.5%, 40.7%, and 40.7% respectively. The topography parameter is lowest variable parameter (CV = 28.6%). The sensitivity is calculated according to the rating and weights ascribed to the layer classes of individual parameter. The purpose of sensitivity analysis is to investigate

the sensitivity of seven criteria in establishing groundwater vulnerability.

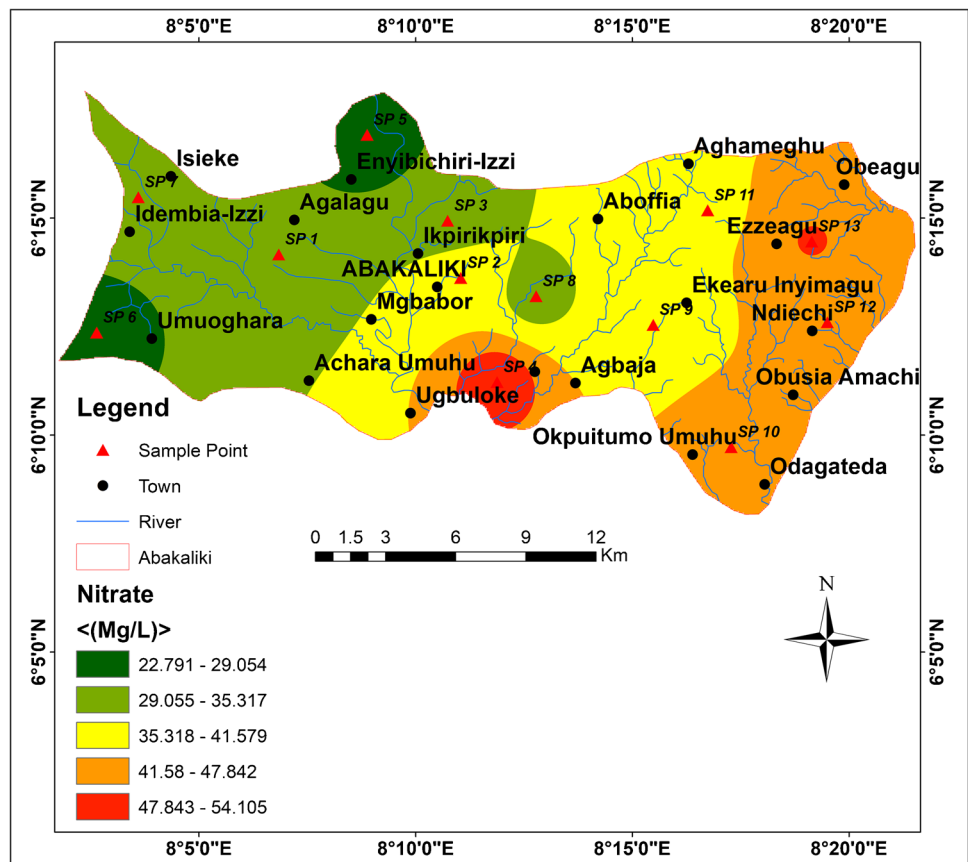
Map removal sensibility evaluation

As shown in Tables 4 and 5, the map elimination sensitivity evaluation is carried out by deleting one or more thematic layers at a time. The removal of the depth to water

Table 6 Statistics of individual criteria sensitivity examination

Criteria	Hypothetical weight	Hypothetical weight (%)	Efficient weight (%)			
			Mean	Minimum	Maximum	SD
D	5	20.5	20.18	10.56	26.02	20.73
R	4	17	28.96	22.22	31.93	18.46
A	3	13	9.87	8.48	11.61	10.22
S	2	11	8.13	6.17	6.85	8.55
T	1	5	8.01	4.23	6.23	3.49
I	5	20.5	11.29	10.16	10.34	15.60
C	3	13	6.33	5.44	7.01	4.31

Fig. 10 Spatial distribution of nitrate in the study area



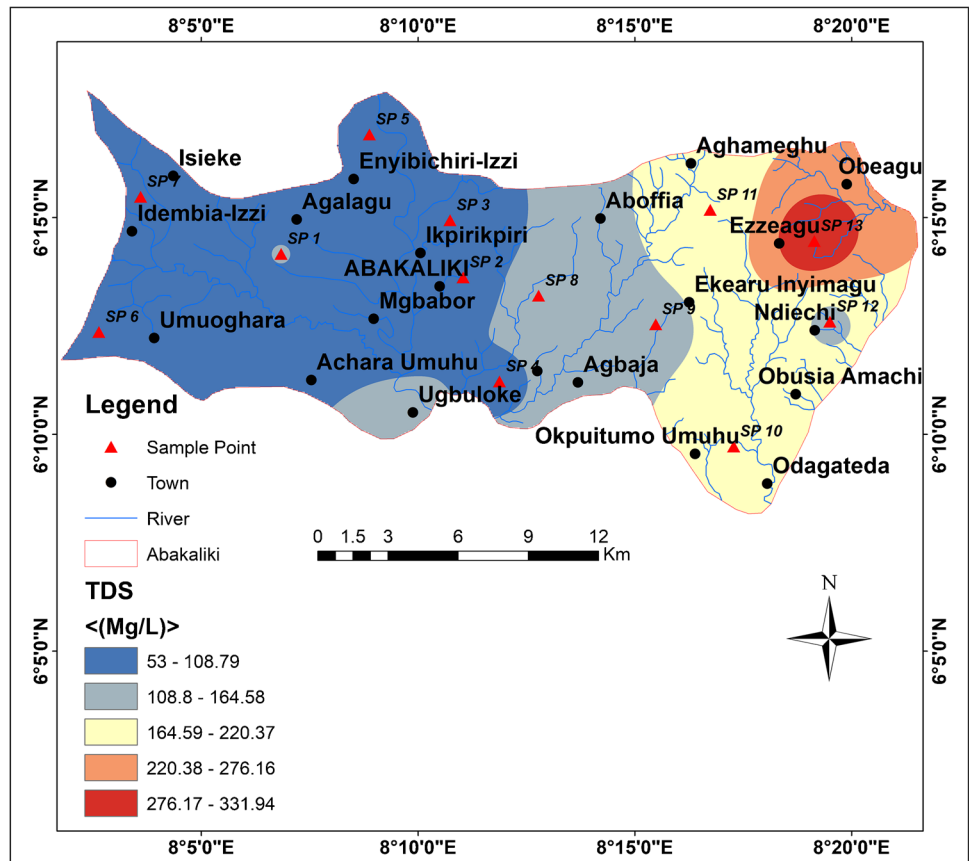
parameter, whose mean fluctuation indexes are 10.08% and 6.27%, respectively, is certain to result in a substantial fluctuation in vulnerability index. This may be as a result of the high hypothetical weight allocated to this parameter. On the removal of net recharge, topography, hydraulic conductivity, and the impact of the vadose zone, the vulnerability index appears to be somewhat sensitive. The map was removed in accordance with the map elimination sensitivity analysis, as shown in Table 4. Table 5 shows the variation in groundwater vulnerability due to the removal of one or more components at a time. After removing the impact of the vadose zone, the

lowest mean fluctuation index was determined (8.01%). Calculation of vulnerability index fluctuation provides sufficient information on the most active parameter concerned.

Individual criteria sensitivity examination

The individual criteria sensitivity examination is used to assess the impact of specific criteria on groundwater vulnerability. Table 6 shows the statistical summary of the individual criterion sensitivity examination. The efficient weights and hypothetical weights are compared in the individual criteria

Fig. 11 Spatial distribution of total dissolved solids (TDS) in the study area



sensitivity analysis. The efficient weight of the net recharge parameter is 28.96% on average, while its hypothetical weight is 17%. This indicates that this criterion is more active while assessing vulnerability. The impact of the vadose zone and the depth to water level have significant hypothetical weights (20.5%). They were assigned an efficient weight of 20.18% and 11.29%, respectively. Aquifer media, soil properties, topography, and hydraulic conductivity all have effective weights of 9.87% 8.13%, 8.01%, and 6.33%, respectively. The hypothetical weights ascribed to the criteria like aquifer media, hydraulic conductivity, soil properties, and topography are not in accord with the efficient weight. In the vulnerability analysis, net recharge is the most important factor, followed by depth to water level, impact of the vadoze zone, aquifer media, and topography and soil properties.

Validation

The accuracy of the DRASTIC model, which was used to generate the final groundwater vulnerability map, was tested using the nitrate and TDS parameters. Nitrate and TDS levels were measured in shallow boreholes drilled in 13 different places throughout the research area. The values of nitrate and TDS in the study region vary between 0.50 and 50 mg/l and 108.12–1125.64 mg/l, respectively

(Figs. 10 and 11). The spatial distribution of the parameters in the southern and eastern regions, specifically Obeagu, Ezeagu, Ndiechi, Obusia Amachi, Odagateda, Okpuitumo Umuhu, Ugbuloke, and Ofe Iyioku, show high nitrate concentrations ranging from 41.58 to 54.105 mg/l and correspondingly high TDS concentrations ranging from 220.38 to 331.94 mg/l. These areas have a high level of groundwater vulnerability. Agricultural pollutants mix with recharge water, polluting the groundwater further. TDS and nitrate concentrations in the western and north central parts of the research region are also very low, ranging from 53 to 108.79 mg/l and 22.791–35.317 mg/l, respectively. These areas such as Umuoghara, Idembia-Izzi, Isieke, and Agalagu demonstrate relatively lower groundwater vulnerability.

Conclusions

The DRASTIC model was used in conjunction with GIS unification to assess the groundwater vulnerability of the Abakaliki area, and seven hydrogeological criteria were investigated. The DRASTIC vulnerability index value spans from 22 to 81 in the current study, and the research region can be divided into three susceptible categories. The high

and moderate vulnerable categories cover around 12% and 82.6% of the study area, respectively, while the low vulnerable category covers only 5.4%. According to the statistical analysis of DRASTIC parameters, the topographical parameter, with a high mean value of 7.0, produces a high probability of contamination. The study area's eastern and southern regions are more susceptible to pollution. The groundwater table is shallow here, and the soil is predominantly clay loamy. Agriculture and mining are the two principal land uses in this area. The usage of fertilizers and agrochemicals for high yielding of various crop productions has resulted in a high nitrate concentration in this area. During precipitation, chemically laden inebriated water infiltrates the vadose zone, penetrating the water table and polluting it. If consumed in large quantities, this nitrate-rich water can have a negative impact on human health. As a result, protecting groundwater from pollution is both a critical and challenging responsibility. To mitigate this, reasonable land use practices must be combined with suitable basin management. Farmers near high groundwater vulnerable areas with elevated nitrate and TDS concentrations should start using organic agriculture systems and replace chemical fertilizers with bio fertilizers to reduce groundwater pollution, while abandoned mine pits might be used as recreation facilities. The DRASTIC vulnerability, as well as the nitrate and TDS values of 54.105 mg/l and 133.94 mg/l, respectively, indicates that the model's verification precision is extremely high. In conclusion, the GIS-based DRASTIC technique utilized in this study yielded a satisfactory result that can be used elsewhere to assess groundwater risk, particularly in basement and sedimentary terrains.

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Declarations

Competing interests The authors declare no competing interests.

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