A SINTACS GIS-based method for assessing groundwater vulnerability in sedimentary aquifers, South-Eastern, Nigeria

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Abstract

Groundwater vulnerability is an ardent problem all over the globe owing to the degradation of groundwater level and rising pollution which presents grievous adverse threat to the ecosystem. To determine this threat, comprehensive research has been conducted to examine the groundwater vulnerability by using several approaches. Broadly, the process-based approach, statistical analysis, and overlay index approaches are utilized in this regard. SINTACS method is one type of process-based and overlay index methods for vulnerability appraisal. This research represents a SINTACS model using applications of the Geographic Information System (GIS) techniques for groundwater vulnerability appraisal. According to the present SINTACS model, the study area surrounded high, moderate, and low zones of potential contamination with area occupy 20.41%, 71.6%, and 7.99%, respectively. The high potential contamination is majorly impacted by combined contributions of thematic layers viz., impact of the vadose zone, aquifer media, topography and net recharge. Nitrate concentrations analysis in some selected boreholes were compared with the SINTACS model to examine its accuracy. The validation rate of the present SINTACS model attains more than 65%, which is an evidence of a satisfactory modeling method. The SINTACS approach demonstrated its versatility even in this complicated hydrogeological setting.

Keywords Enugu State · SINTACS model · Vulnerability · Groundwater resources · Contamination

Introduction

Groundwater contamination can be boycotted by defining and tracking the vulnerable zones. Ascertaining the spatial expansion of regions vulnerable to contamination is hard given the various parameters influencing groundwater contamination (Jarray et al. 2017; Azubuike and Edet 2015). Indeed, groundwater vulnerability cannot be calculated directly in the field. It is a network function of a large number of variables associated with depth to water table, hydraulic conductivity, net recharge, topography, soil properties, impact of the vadose zone

and the aquifer media (Nury et al. 2009; Jarray et al. 2017; Kansoh et al. 2020). In France, Margat (1968) established the theory of groundwater vulnerability to contamination. It can be referred to as potentiality of infiltration and diffusion of contaminants from ground surface into the aquifer (Ahmed et al. 2018).

Difference procedures have been developed globally for groundwater vulnerability appraisal. They comprise of statistical methods, based on parameters affiliated contaminant accumulation or to contamination possibility (Al-Salamah et al. 2011), indices approach based on weighting between different parameters influencing the vulnerability (Aller et al. 2004) and model considering the biological, physical, and chemical mechanisms in the vadose zone (Civita and De Miao 2004). The indexes approach viz., DRASTIC (Aller et al. 2004), GOD (Abdelmadjid and Omar 2013), AVI (Van Stempvoort et al. 1993), SINTACS (Civita and De Maio 2000), DRISTPI (Jiménez-Madrid et al. 2013), EPIK (Doerfliger and Zwahlen 1997), PI (Goldscheider et al. 2000), and COP were according to European procedure (COST 2003). They are well recognized globally as cost-effective and the most suitable in terms of field authenticity due to the importance of the corresponding

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influence of individual parameters involved in groundwater vulnerability (Aller et al. 2004; Van Stempvoort et al. 1993; Al Adamat et al. 2003; Panagopoulos et al. 2005; Rahman 2008; Umar et al. 2009; Hussain et al. 2006). However, the preference of utilization of any of these approaches rely on the availability of information, nature of pollutant, origin and geochemical properties (Twarakavi and Kaluarachchi 2006; Azubuike and Edet 2015). A common and appreciative method may include the usage of statistical analysis via correlating descriptive criteria that control groundwater vulnerability to pollution.

The most broadly utilized vulnerability evaluation approaches is the SINTACS and this was initiated by Margat (1968). This approach has been utilized in different countries of the world—Italy, Algeria, India, France, Jordan, Iraq, Nepal, and many other countries—which is evident in the works of (Margat 1968; Civita and De Maio 1997; Corniello et al. 2004; Khemmoudj et al. 2014; Kumar et al. 2013; Kuisi et al. 2006; Shrestha et al. 2016; Al-Qurnawi et al. 2019).

According to Kumar et al. (2013), the SINTACS approach is anticipated on particular presumptions: (a) pollutant is initiated at earth surface, (b) the pollutant is penetrated down to aquifer system by precipitation, (c) the pollutant has the movement of water, and (d) the region examined is not less than 0.4 sq.km or bigger. Al-Qurnawi et al. (2019) further said that the SINTACS method consists of two major parts: (a) the classification of mappable features identified as hydrological environments and (b) the utilization of arithmetical systems of related rating of hydrological characteristics.

This technique requires a configuration of indexing by examining mathematical values to hydrological units or features depending on its quantity or subjective rating (Khemiri et al. 2013; Jarray et al. 2017). Individual feature was one after the other ascribed a corresponding significance ranks or weight contrast to the other features via professional evaluation (Sener et al. 2009).

Constraining the possibility of groundwater pollution related with urban development, industrialization and farming activities remain a requirement for any economic growth planning scheme (Fırat et al. 2006). This has entailed the attentiveness of this study aimed at (a) ascertaining and archiving the vulnerability of groundwater within the sedimentary basin and (b) demonstrating and delineating pollution vulnerability areas using the SINTACS GIS-based method. Finally, the SINTACS model is validated based on nitrated analysis of groundwater samples within the study area.
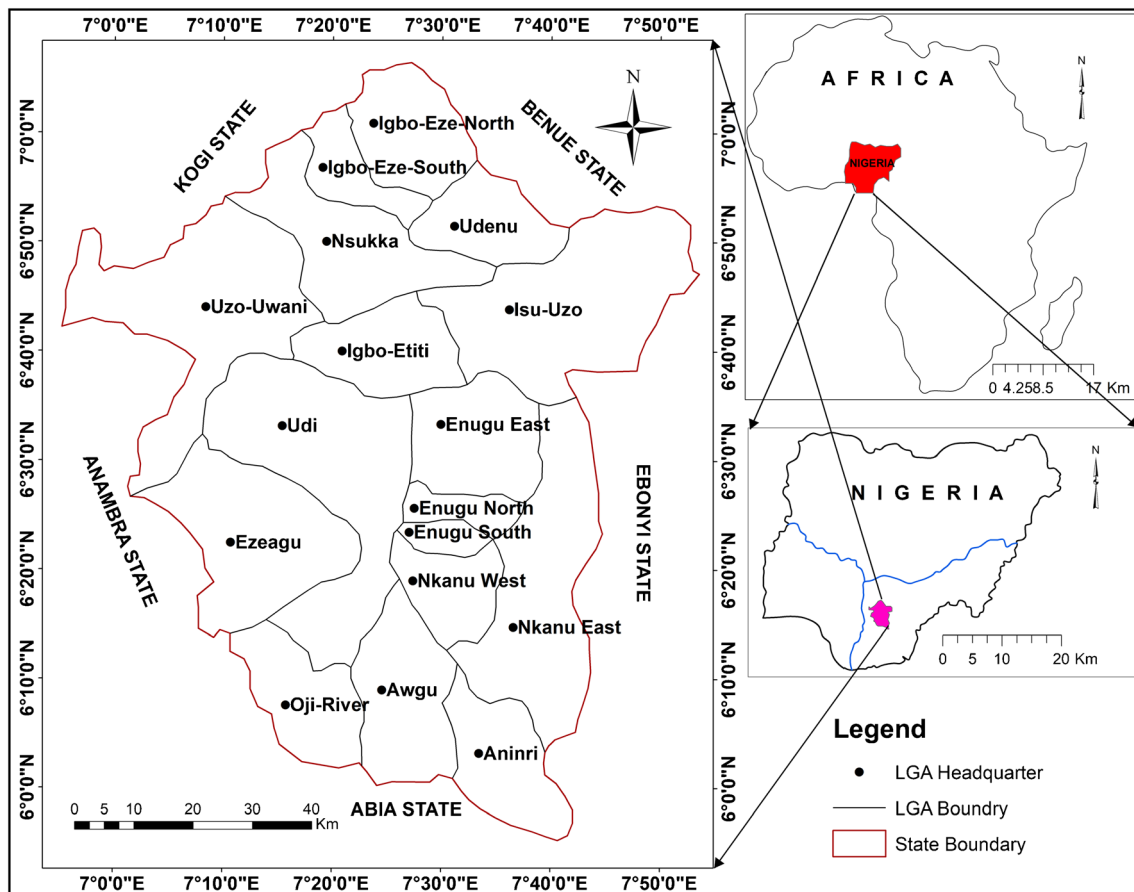

Fig. 1 Location map of the study area

Table 1 Sources of data used for preparation of hydrogeological parameters for the SINTACS model

Data category	Source	Format	Scale	Used to produce
Depth to water table data	Well log	Table		S
Rainfall data	NiMet	Table		I
Unsaturated zone data	Well log	Table		N
Lithological data	Geologic map of Nigeria	Analog	250,000	A
Soil data	Soil map of Nigeria	Analog	250,000	T
Topographic data	SRTM			S
Hydraulic conductivity	Geophysical survey	Table		C

Materials and methods

Study area

Enugu State is located between latitudes 6° 00′ and 7° 00′ N and longitudes 7° 00′ and 8° 00′ E. It occupies a total surface area of roughly 8231.9 km² with a population density of approximately 3,259,803 according to the 2006 census. In the early 50s during the colonial era, Enugu State used to be the headquarter of the Eastern Region of Nigeria. It has interstate borders with Kogi and Benue to the North, Abia in the South, Ebonyi to the East, and Anambra to the West (Fig. 1). The weather condition of the region is characterized by a wet and dry conditions. The wet season stretches between April to October with its maximum record in July. With storms of high intensity and brief period developing from 1200-1500m, precipitation is typically high. The dry season runs between October to March after which the harmattan winds typically void of moisture, reach most of the Northern part of Enugu. The temperature is fairly high all year round in Enugu State. The regular levels are generally higher than the monthly levels, specifically when temperatures can drop below 18 °C in the dry season. The peak temperatures, which are approximately 37 °C, are usually registered in February and March (NiMET 2016). The Cuesta elevation is the prevailing landscape aspect of the Enugu region. Inselbergs, plateaus, flat plains and river valleys are additional topographic characteristics. Thus, the cuesta is a lengthy period of drainage boundary between the plains of the Imo and the Anambra Valley in the west and the drainage basin of the Cross River in the east. Enugu State is drained by two lager river units. The first unit includes the Ekulu, Asu, Atafu, Aboine, and Nyaba rivers that originate from the base of the cuesta and drain into the

Table 2 Ranks and weights of the thematic maps of the SINTACS model (Civita and De Miao 2004)

Depth to water table (S)				Net recharge (I)			Impact of the vadose zone (N)			Soil cover (T)		
Range (m)	Ranking	Index		Range (m)	Ranking	Index	Range (m)	Ranking	Index	Range (m)	Ranking	Index
10.31–93.52	9	50		0–40	1	2	Clay	2	8	Lithosols	4	10
93.53–176.7	7	40		60–100	3	3	Sandstone	3	12	Young soil	1	8
176.8–259.9	5	30		> 100	6	4	Gravel	4	16	Ferrallitic	5	6
Weight = 5				Weight = 4			Weight = 5			Hydromorphic	2	4
										Weight = 4		

Aquifer media (A)			Hydraulic conductivity (C)			Topography (S)		
Range (m)	Ranking	Index	Range (m)	Ranking	Index	Range (m)	Ranking	Index
Imo	8	40	1.03–1.78	1	4	0–4	10	20
Nsukka	7	50	1.79–2.53	2	8	5–9	9	16
Ajali	6	60	2.54–3.29	3	12	10–14	6	12
Mamu	5	40	3.3–4.05	4	16	15–19	3	8
Nkporo	4	30	> 4.05	5	20	> 20	1	4
Awgu	3	50	Weight = 3			Weight = 2		
Ezeaku	2	20						
Abakiliki	1	10						
Weight = 3								

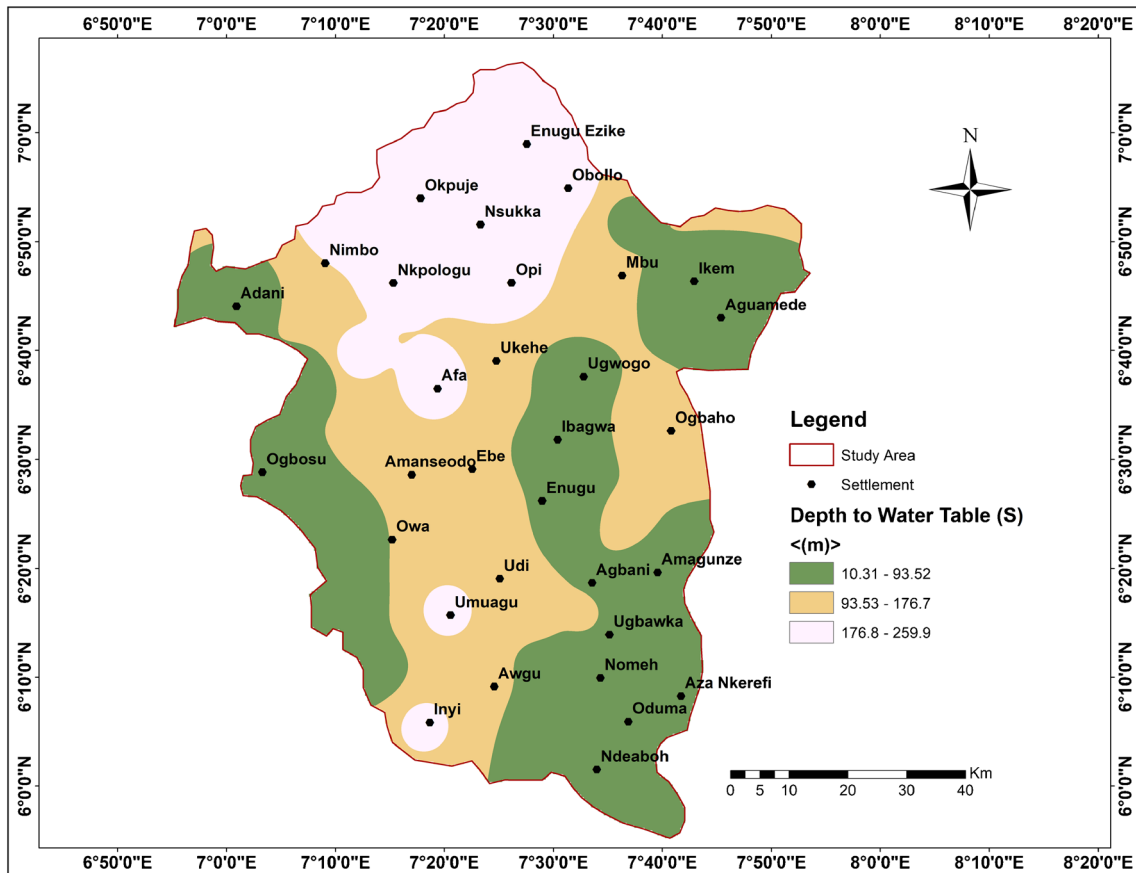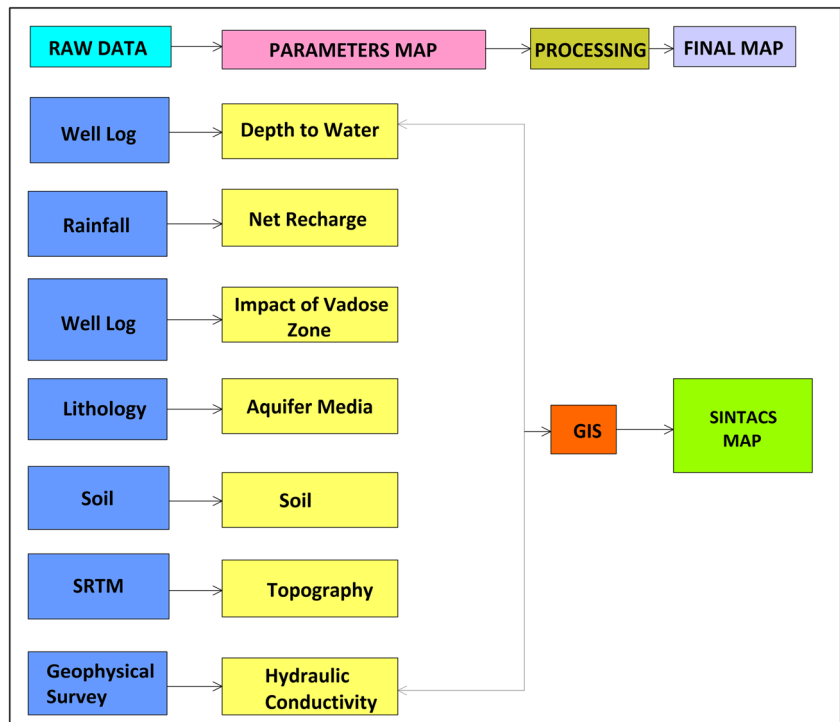**Fig. 2** Illustration of the flowchart of the study

Fig. 3 Depth to water table parameter map

Cross River Basin to the east while the second unit is made up of the rivers Adada, Mamu, Oji, and Ajalli, which emerge on the dip slope and drain west into the Anambra basin (Uma 2003).

Geology and hydrogeology

The various geological formations underlying the study area are chronologically arranged in the following order: Abakaliki Formation of Albian age rests uncomfortably on the crystalline rocks of the Precambrian basement, and overlain by the Ezeaku Formation of Turonian age followed by the Awgu Group which consists of Awgu Shale and Agbani Sandstone of Coniacian age, succeeded by the Nkporo Group comprising the Nkporo Shale, Owelli Sandstone, and Enugu Shale of Campanian age, overlain by Mamu Formation Lower Maarstrichtian age, followed by Ajali Formation of Upper Maarstrichtian age, overlain by Nsukka Formation of Danian age and succeeded by the Imo Group consisting the Imo Shale and Ebenebe Sandstone of Paleocene age ().

Groundwater is the primary source of drinking water in the study area, where shallow (10.31 m) and deep (259.9 m) wells draw water from sandstones and fractured, jointed, and weathered shale aquifers. At various districts, the sandstone aquifer of Ajali is predominately tapped at variable depths. Along the border with the Mamu Formatin in the northwest, the Ajali aquifer has extensive outcrop areas, where it gets several recharges that are higher than the volumes extracted from the aquifer. Apart from the Ajali aquifer, Agbani, Owelli and Ebenebe are other significant water source aquifers. Most water-supply wells are located within the areas underlain by Ajali, Agbani, Owelli, and Ebenebe Sandstones. These sandstone aquifers possess average hydraulic conductivity range from 2.54×10^{-3} m/s to above 4.06×10^{-3} m/s (Ezeh 2011).

The SINTACS model

There are various groundwater contamination vulnerability assessment models. Amidst these systems, the SINTACS approach employed in the present research was established by Civita and De Maio (2000) to assess comparative groundwater contamination vulnerability utilizing seven thematic layers (Kuisi et al. 2006).

To examine the groundwater vulnerability for the study area, the SINTACS model was chosen for several purposes
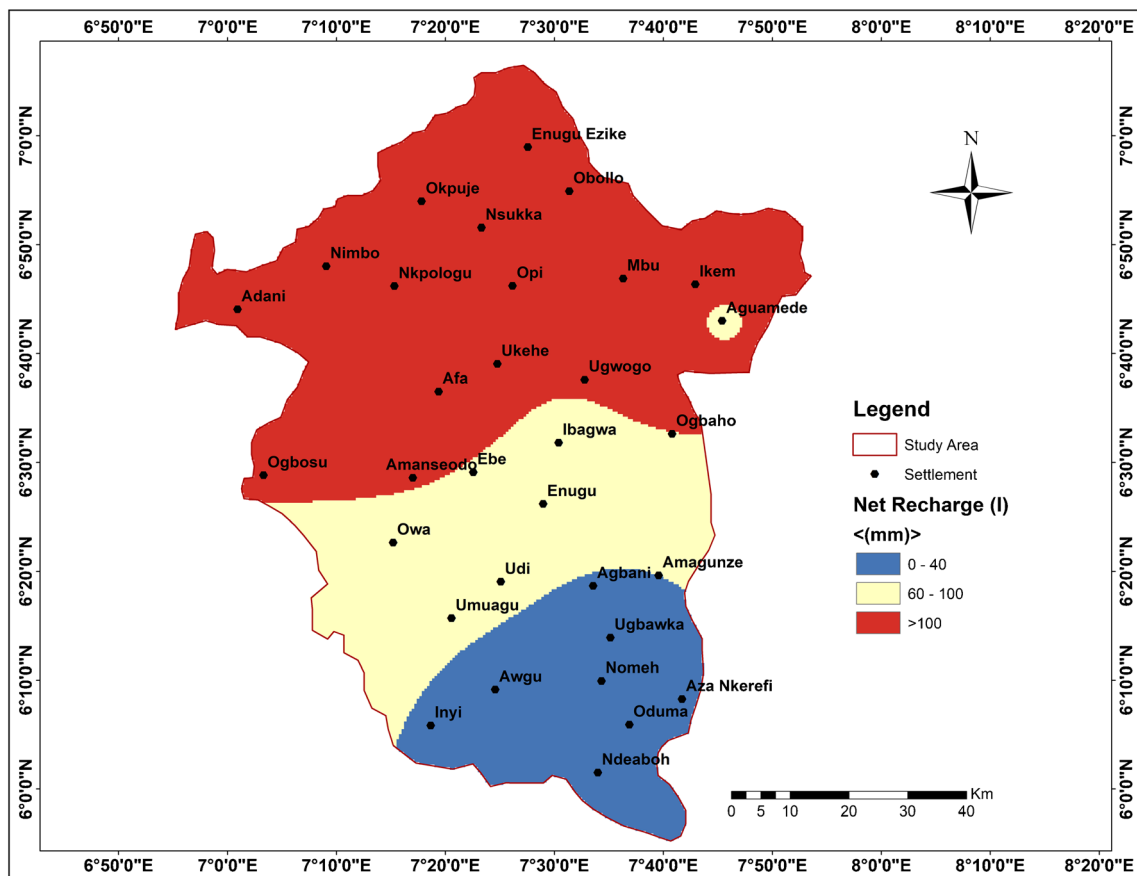

Fig. 4 Net recharge parameter map

viz., its appropriability for applying in tropical zones, its cost-effectiveness, its reliance on the availability of data, and the corresponding, dimensionless, and nonmeasurable characteristics that rely on the groundwater properties and properties of the regional hydrogeological settings.

The parametric method like SINTACS apply to the point count model class in which each component possesses not just its own score but also an extra weight to lower or higher its significance during the investigation. The additional weight is set in connection to ecological properties, like high distribution phenomena from surface water to groundwater or nonpoint contamination origins (Kumar et al. 2013). The word SINTACS represents the seven thematic layers utilized in the model which include the following: Depth to water table (S), Net recharge (I), Impact of the vadose zone (N), Soil properties (T), Aquifer media (A), Hydraulic conductivity (C), and Topographic (S). The aforementioned seven thematic layers are employed to delineate the hydrological environment of any region. Sources of data used for creation of hydrogeological parameter for the SINTACS method is shown in Table 1. These seven thematic layers are further recategorized into different zones, standing for different hydrological environments and are ascribed various ranking in a scale between 1 and 10 according to the ranking chart (Kuisi et al. 2006). The rankings allocated to every one of these zones reveal their corresponding significance within individual criteria, in influencing to groundwater vulnerability.

SINTACS intrinsic vulnerability index (SIVI)

The seven thematic layers are themselves not regarded to be proportionally significant in vulnerability appraisal. In order to show the corresponding significance of these criteria, weights in the scale between 1 and 5 were ascribed to every one of these criteria (Table 2). The SINTACS intrinsic vulnerability index (SIVI) is calculated adopting the following formular (Kuisi et al. 2006).

$$\text{SIVI} = \sum_{i-1}^{7} P_i \, x \, W_i \tag{1}$$

where the P_i represents the ranking of every one of the seven thematic layers that the approach regards and W_i represents the corresponding weight. The index is helpful at a broader
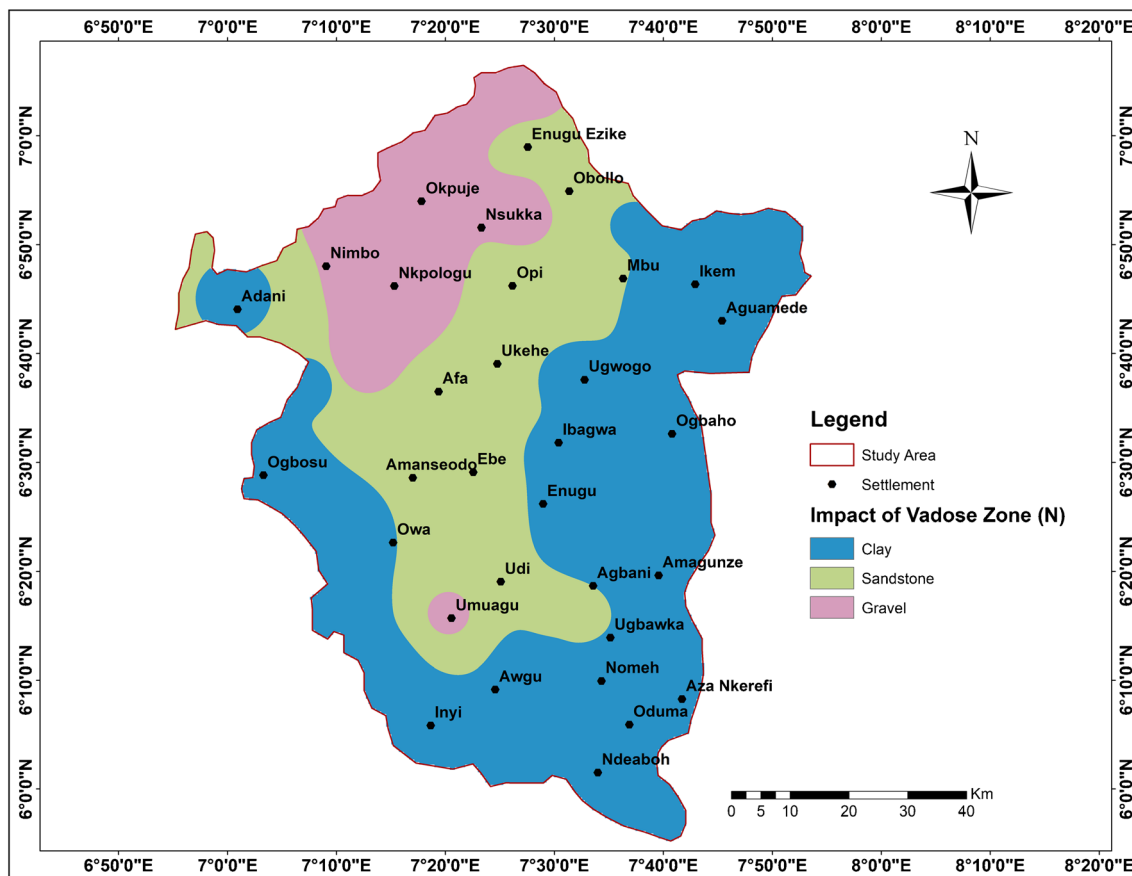

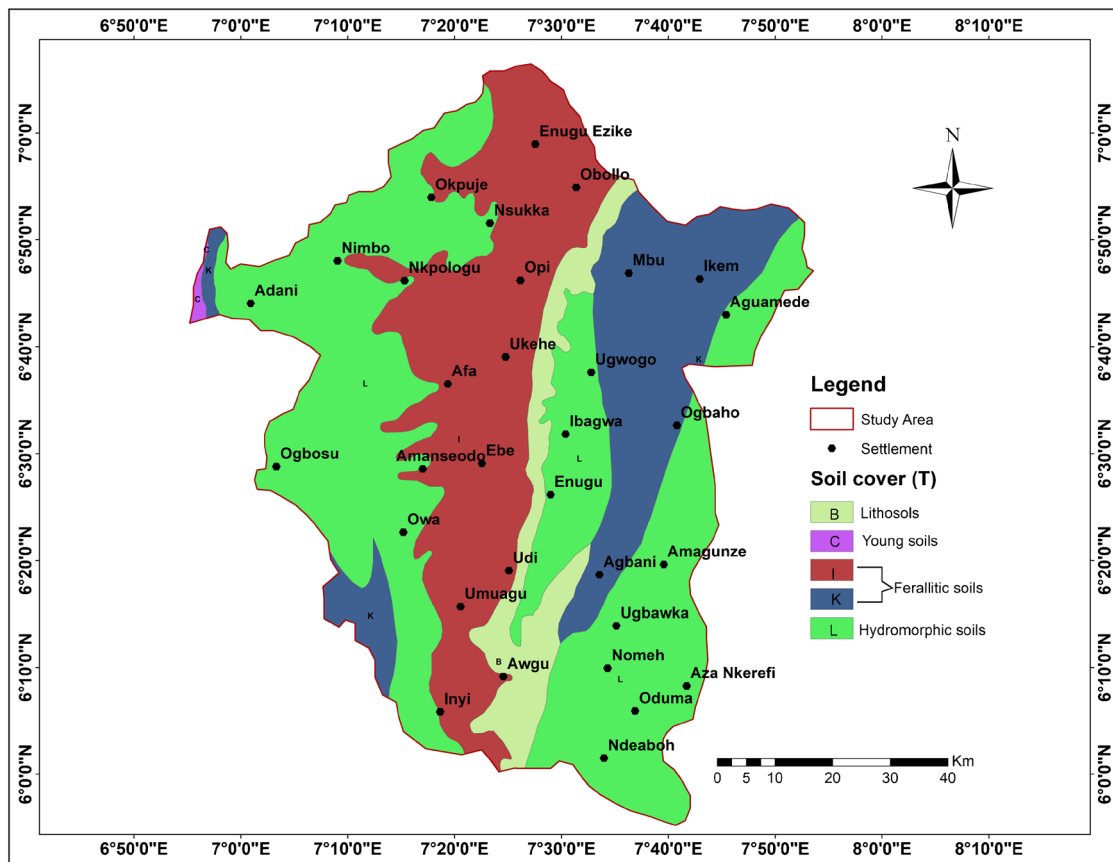Fig. 5 Impact of the vadose zone parameter map

Fig. 6 Soil cover parameter map

scale to classifies region into high, moderate, low, and very low vulnerability zones.

SINTACS single vulnerability index (SSVI)

In order to examine single vulnerability, the system is to be altered by including an extra criterion indicating the influence of human activities. The preference of the extra criterion relies on the kind of pollution for which the single vulnerable appraisal is to be produced. For studies including the nitrate as pollutant (Kumar et al. 2013; Azubuike and Edet 2015) is used as an alternative criterion. The nitrate criterion is further reclassified into groups as high, moderate, low and very low. Then these grades are allocated various ranking based on their potential of nitrate pollution from there various origins. This extra criterion is linearly joined additionally with SINTACS vulnerability index to compute the single SINTACS vulnerability index. The SINTACS single vulnerability index (SSVI) is computed adopting the following formular.

$$SSVI = SIVI + AI_r \times AI_w \qquad (2)$$

where AI represents human activity criteria, and the subscripts "r" and "w" show the relative ranking and weight. The region

has an elevated vulnerability index, revealing that it is more vulnerable to aquifer pollution compared to the region with less index value. The class of vulnerability index is classified into very low, low, moderate, and high vulnerability areas. Figure 2 shows the illustration of the flowchart of the study.

Statistical analysis

Multivariate statistical analysis was applied for the seven hydrogeological parameters utilizing correlation matrix to evaluate factors influencing the groundwater vulnerability and sources of pollution in the sedimentary aquifer. The relationships between different SINTACS variables were determined using Pearson's correlation coefficient.

Preparation of the thematic layers

Depth to water table (S)

The depth from the earth surface to the water table is regarded as the water table depth. This criterion was acquired from 50 well log data obtained from Enugu State Water Cooperation Authority. The water table depth from earth surface point dada was interpolated in GIS environment to produce water table

depth map. Then map was divided into classes based on the SINTACS model with ranking from 9 to 7 as indicated in Table 2. The 50 study wells utilized in the preparation of water table depth is revealed in Fig. 2.

Net recharge (I)

Net recharge is the quantity of water per unit area of earth which infiltrates the earth level and reaches the aquifer. This replenish water is therefore obtainable to convey pollutant vertically down to the aquifer and horizontally within the groundwater. The larger the recharge, the larger the possibility for aquifer contamination. In the current investigation, net recharge criteria were computed using annual rainfall data obtained from Nigeria Meteorological Agency (NiMet), which are according to the net recharge approach. The net recharge is calculated using the following formula:

$$R_r = \Delta_s + A_{ag} + A_{ip} + R_i \tag{3}$$

where Rr is net recharge, Δ_s is variation in aquifer storage, A_{ag} is aquifer exploitation for irrigation, A_{ip} is aquifer exploitation for human consumption and industrial uses, and R_i is reverted flow from irrigation.

Impact of the vadose zone (N)

The impact of the vadose zone is expressed as the zone beneath the normal soil horizon and above the continuous saturated zone. Impact of the vadose zone criteria is among the most important criteria in vulnerability evaluation and thus it is assigned a weight of 5. The ranking allocated to the impact of the vadose zone criterion, based on the SINTACS model, is shown in Table 2.

Soil properties (T)

This is defined as the topmost part of the discontinuous saturated zone (the vadose zone), and comprises the first strata of physical and chemical interaction between possible pollutants and the underlying soil. Hence, it performs a basic function in examining of groundwater intrinsic vulnerability. It has an importance influence on the quantity of recharge that will percolate in the earth and thus on the capability of a pollutant migrate vertically into the unsaturated zone. The aquifer intrinsic vulnerability is exceedingly governed by the grain size properties of the soil. The soil properties criteria were produced from analog map south-easter obtained from soil map southeastern Nigeria. The soil property varieties were
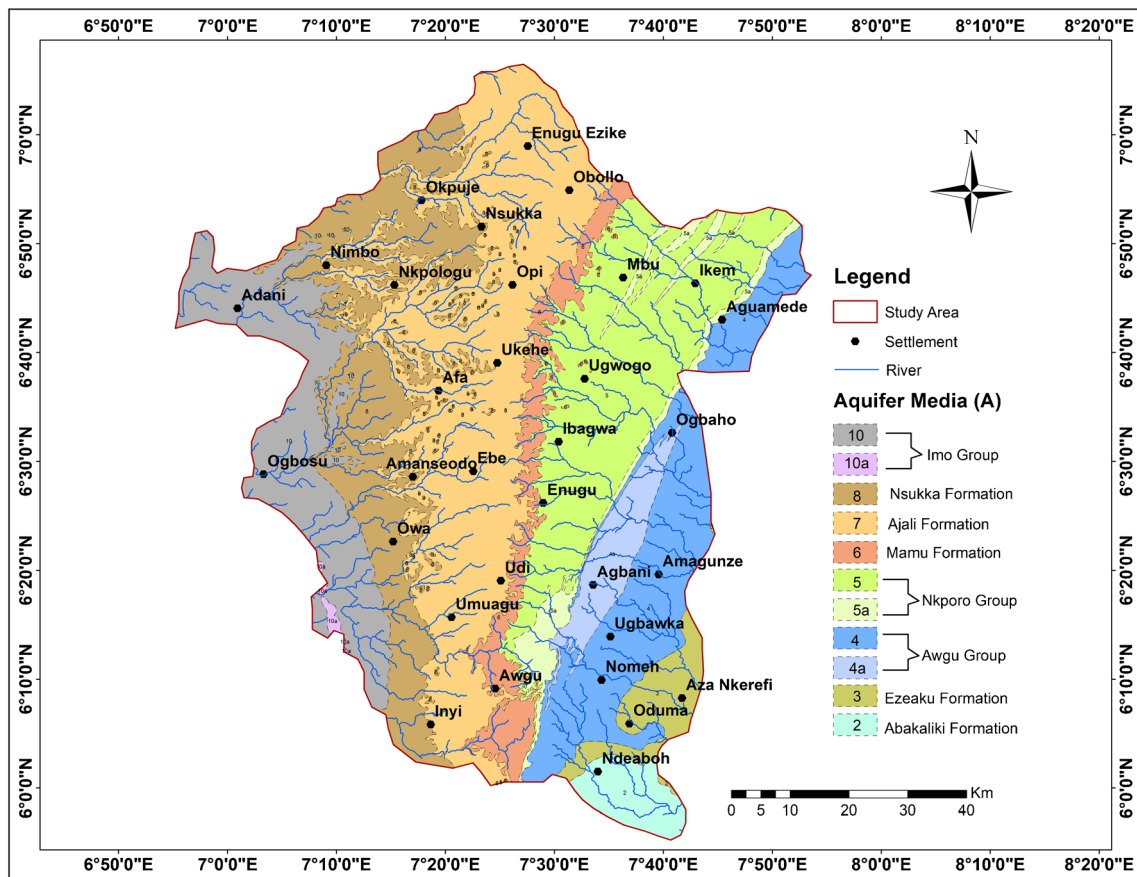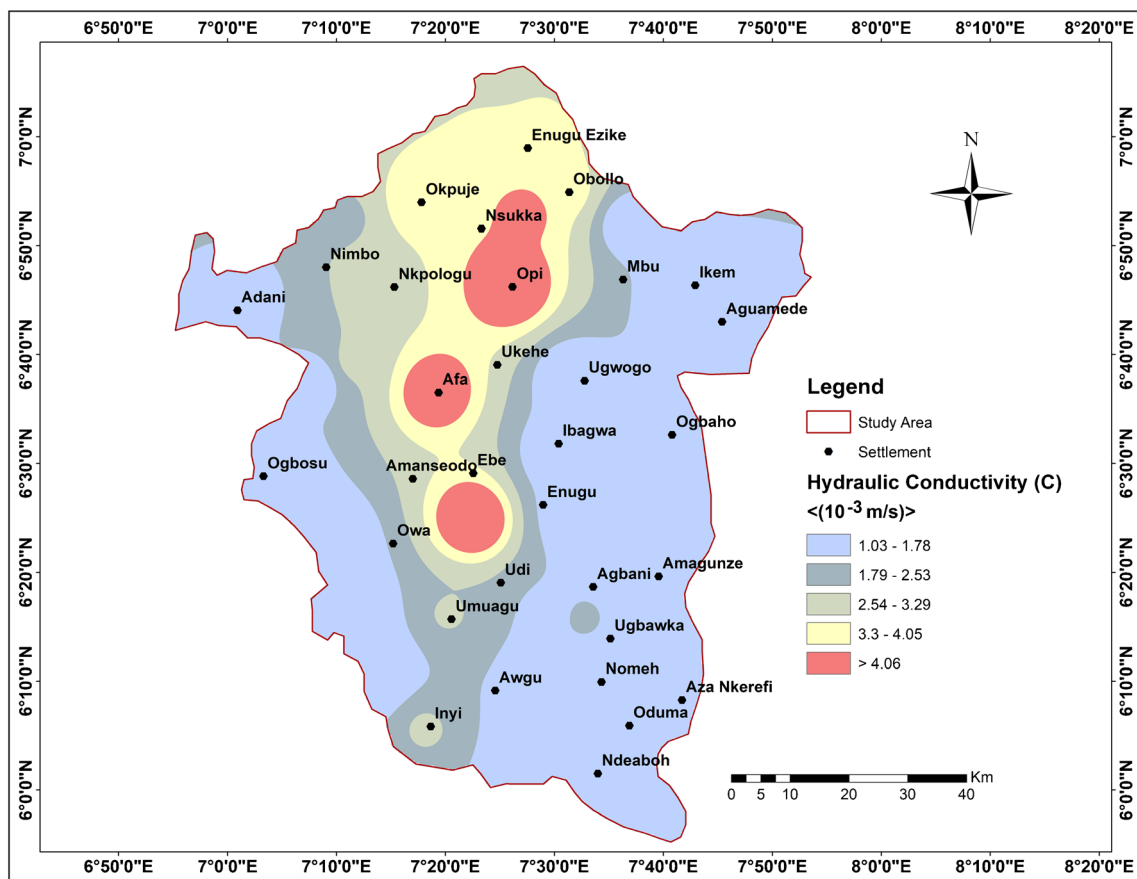

Fig. 7 Aquifer media parameter map

Fig. 8 Hydraulic conductivity parameter map

thereafter given rankings between 1 and 10 according to the SINTACS model (Table 2).

Aquifer media (A)

An aquifer is a continuous saturated zone where void spaces are filled with enough water to well or springs. The aquifer properties criteria were produced from geologic map of the study area obtained from Nigeria Geological Survey Agency (NGSA) sheet 72 at a scale of 1:250,000. The ranking ascribed according to the SINTACS model to the aquifer properties criteria are indicated in Table 2.

Topography (C)

Topography criteria refers to the slope variability of land surface and has an effect on vulnerability appraisal in terms of helping to govern the contaminant path that will runoff or remain on the surface long enough to infiltrate (Bazimenyera and Zhnoghua 2008). Higher slopes generate speedy runoff with lesser amount of infiltration and therefore a decline in the pollutant transportation into the aquifer. Slopes which produce a bigger chance for pollutants to infiltrate are related to higher potentiality of groundwater contamination (Anane et al.

2013). Topographic map was prepared from the SRTM (Shuttle Radar Topographic Mission) data. The map was created using the ArcGIS 10.5 software. The ranking ascribed to the topography criterion, according the SINTACS model, is shown in Table 2.

Hydraulic conductivity (S)

Hydraulic conductivity is a examines of capability of an aquifer to allow passage of water. Higher conductivity values generally relate to high vulnerability to pollutants, this criterion governs the amount at which aquifer will allow water passage under a particular hydraulic gradient (Kumar et al. 2013; Fazelabdolabadi and Golestan 2020). The amount at which aquifer transmit water also governs the amount at which pollutants passes away from the spot it entered the groundwater. The hydraulic conductivity data are obtained from 50 pumping well test data acquired from Enugu State Water Cooperation Authority. The values of hydraulic conductivity are utilized to produce the hydraulic conductivity map of the study area. The ranking ascribed to the hydraulic conductivity criterion, according to the SINTACS model, is shown in Table 2.
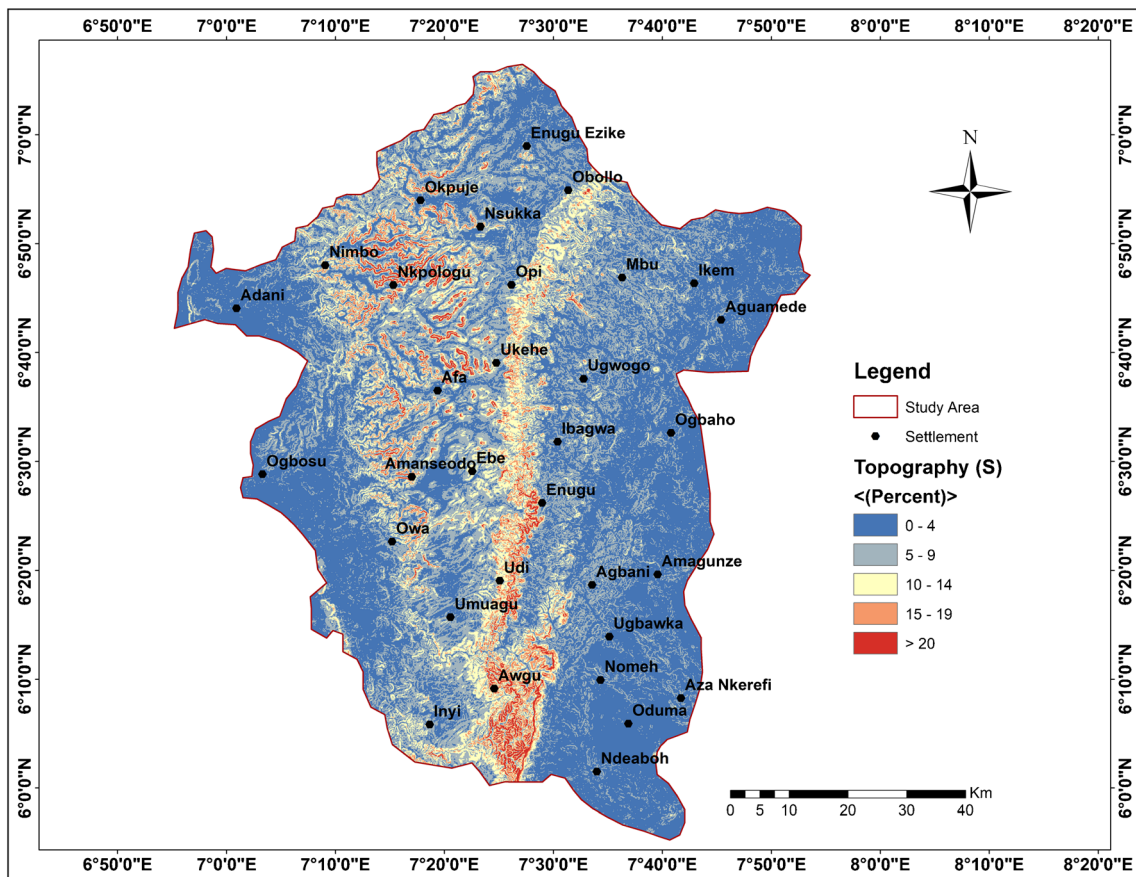
Fig. 9 Topographic slope parameter map

Nitrate sampling campaigns

Groundwater was sampled from 35 boreholes of the examined aquifer for nitrate analysis during February (dry season) and July (rainy season) 2019. The samples were well spread across the entire area. A volume of 5 mL of every sample was filtered at 0.2 μm and was preserved in 1litre plastic containers. The whole samples were reserved in an ice box at 4°C and conveyed to the laboratory where they were examined within 1

week of collection. The testes were done in the Laboratory of the Simuchi Analytical in Nsukka, Enugu State, Nigeria. Nitrate concentrations were measured by the titration method.

Results and discussion

The intentions formed for this current investigation comprises of conducting a particular vulnerability appraisal using the SINTACS model to demarcate area based on their vulnerability to pollution in sedimentary basins of Enugu State. The SINTACS model employed to execute a particular vulnerability appraisal is the product of seven thematic layers.

The depth to water table values from 50 observation wells were utilized to generate the depth to water map of the study area. The areas around Enugu, Ogbosu, Adani, Agbani, Ndeabor, and Oduma have the shallowest water table (10.31 m–93.52 m), while areas around Udi, Amanseodo, Ukehe, and Awgu have the moderate depth to water table (93.53 m–176.7 m), and the rest of the areas like Nsukka, Opi, Obollo, Enugu Ezike, and Okpuje have very high depth to water table (176.8 m–259.9 m). A high ranking of 9 was ascribed to the areas with low depth to water table. The depth to water table map is depicted in Fig. 3.

Table 3 Correlation analysis between SINTACS susceptibility index (SSI) and SINTACS criteria

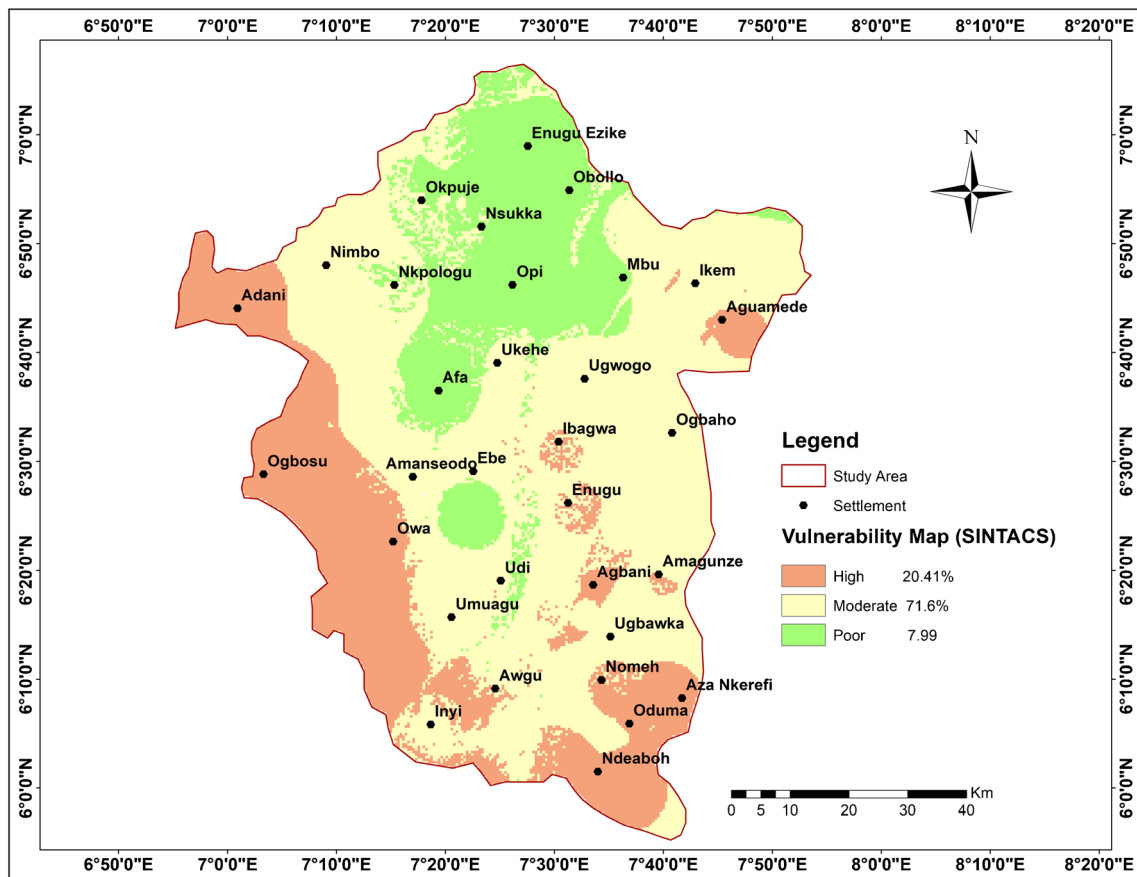|	S	I	A	T	SA	N	C	SSI
S	1.00							
I	0.21	1.00						
A	0.19	0.06	1.00					
T	0.39	−0.09	0.11	1.00				
SA	−0.72	−0.40	0.06	−0.73	1.00			
N	0.04	0.09	0.35	0.79	−0.33	1.00		
C	−0.60	−0.65	−0.40	0.06	−0.73	0.82	1.00	
SSI	0.93	0.29	0.88	0.31	−0.46	0.65	39	1.00

Fig. 10 Map of intrinsic aquifer vulnerability according to the modified SINTACS method

As per Eq. (3), the net recharge map was derived using the weighted Thiessen polygon method. Net recharge values are high in Nsukka, Obollo, Enugu Ezike, Mbu, Opi, Ukehe, Ugwogo, Afa, and Amanseodo areas. The areas of Ibagwa, Udi, Enugu, Owa, and Amagunze have moderate recharge (60–100 mm) and the rest of the areas have relatively low net recharge values. A high ranking of 6 was allocated to the high net recharge area. The net recharge map is revealed in Fig. 4. In the vadose zone parameter, the gravel was given a high-ranking value of 8; the area occupied by sandstone was allocated a moderate ranking value of 6 whereas the low-ranking values between 1 and 3 were ascribed to the areas surrounded by clay, respectively. The impact of the vadose zone criterion map is displayed in Fig. 5.

The available soil type in the study area was classified into four types viz., lithosols, young soils, ferallithic, and hydromorphic soils. Hydromorphic soil has occupied more than 70% of the total area. The ferallithic soil was assigned a high-ranking value of 6. The soil properties criterion is indicated in Fig. 6. In the study area, the main aquifers are the following (Fig. 7): Ajali Formation, Awgu, the Imo and Nkporo Groups, Ezeaku, Abakaliki, and Nsukka Formations. Information about every aquifer property was gathered from available geological information Nigeria Geological Survey Agency (NGSA) sheet 72 at a scale of 1:2500. The rating values of the aquifers were 4, 8, 9, and 7, respectively. The aquifers with rating values 8, and 9 represent about 40% of the total area. The Ajali aquifer (rating value 9) trend north to south and is the most viable aquifer in the study area.

The hydraulic conductivity criterion was characterized as regards to the pump test data obtained from 50 well locations in the study area. The areas with low hydraulic conductivity value vary from 1.03 to 1.78 (10^{-3}m/s), thus it is allocated low ranking values of 1 and 2. The resulting hydraulic conductivity map is exhibited in Fig. 8. The topographical map exhibited a gentle slope (0–4%) throughout most of the research area which has been given the SINTACS rankings of 9 and

Table 4 Vulnerability category of the SINTACS model

Vulnerability index (SI)	Rate of intrinsic vulnerability
7.99%	Low
71.6%	Moderate
20.41%	High

Table 5 Result of nitrate values from the water sampling stations

Sample locations	Longitude (E)	Latitude (N)	February 2019 Nitrate (mg/L)	July 2019
ESW 1	7.376	6.414	1.021	1.41
ESW 2	7.319	6.61	0.099	2.65
ESW 3	7.433	6.771	0.05	2.44
ESW 4	7.455	6.882	0.25	2.65
ESW 5	7.52	6.917	0.24	2.1
ESW 6	7.292	6.901	0.5	2.34
ESW 7	7.455	6.985	0.19	1.79
ESW 8	7.425	7.089	0.58	1.78
ESW 9	7.254	6.771	0.58	1.89
ESW 10	7.18	6.874	0.02	1.24
ESW 11	7.194	6.656	0.09	1.41
ESW 12	7.338	6.268	0.59	1.36
ESW 13	7.303	6.094	0.88	1.78
ESW 14	7.672	6.542	0.22	3.68
ESW 15	7.604	6.406	0.41	1.031
ESW 16	7.545	6.262	0.05	2.418
ESW 17	7.488	6.27	8.9	1.89
ESW 18	7.466	6.189	0.97	1.78
ESW 19	7.613	6.866	0.1	2.68
ESW 20	7.702	6.754	3.47	7.12
ESW 21	7.523	6.635	3.89	8.61
ESW 22	7.504	6.515	3.46	6.24
ESW 23	7.534	6.423	3.68	6.11
ESW 24	7.787	6.697	2.65	4.12
ESW 25	7.667	6.319	2.68	3.47
ESW 26	7.583	6.162	2.44	3.68
ESW 27	7.49	6.05	4.1	3.68
ESW 28	7.667	6.14	3.2	4
ESW 29	7.613	5.996	4.81	8.12
ESW 30	7.023	6.757	4.1	4.46
ESW 31	7.134	6.626	4.1	9.1
ESW 32	7.069	6.474	3.2	5
ESW 33	7.164	6.382	5.61	6
ESW 34	7.186	6.284	3.68	4.6
ESW 35	7.227	6.178	5.87	8.9

10. The rest of the areas were allocated a ranking of 1 (Table 1). The topography criterion map is revealed in Fig. 9.

Correlation analysis of rankings for SINTACS factors

Table 3 presents the correlation matrix between the seven SINTACS input variables and the SINTACS vulnerability index (SSI).

Correlation analysis demonstrate that the S ($r = 0.93$, $p < 0.01$), the N ($r = 0.65$, $p < 0.01$) and the A ($r = 0.88$, $p < 0.01$) are now the most relevant parameters for monitoring the surface and near-surface pollution vulnerability of groundwater within

the study area. SA ($r = -0.46$, $p < 0.01$) indicates a poor negative correlation with SSI. A poor correlation with SSI is observed in T ($r = 0.31$, $p < 0.01$). The poor or nonsignificant correlation between recharge ($r = 0.29$, $p < 0.01$) and C ($r = 0.39$, $p < 0.01$) and SSI can be due to a few computational datasets or origins.

SINTACS vulnerability map

The criterion maps extracted above were overlaid in the GIS environment, and the SSVI map of the study area was derived by using Eqs. (1) and (2). The obtained SSVI values were then reclassified into three categories of vulnerability including
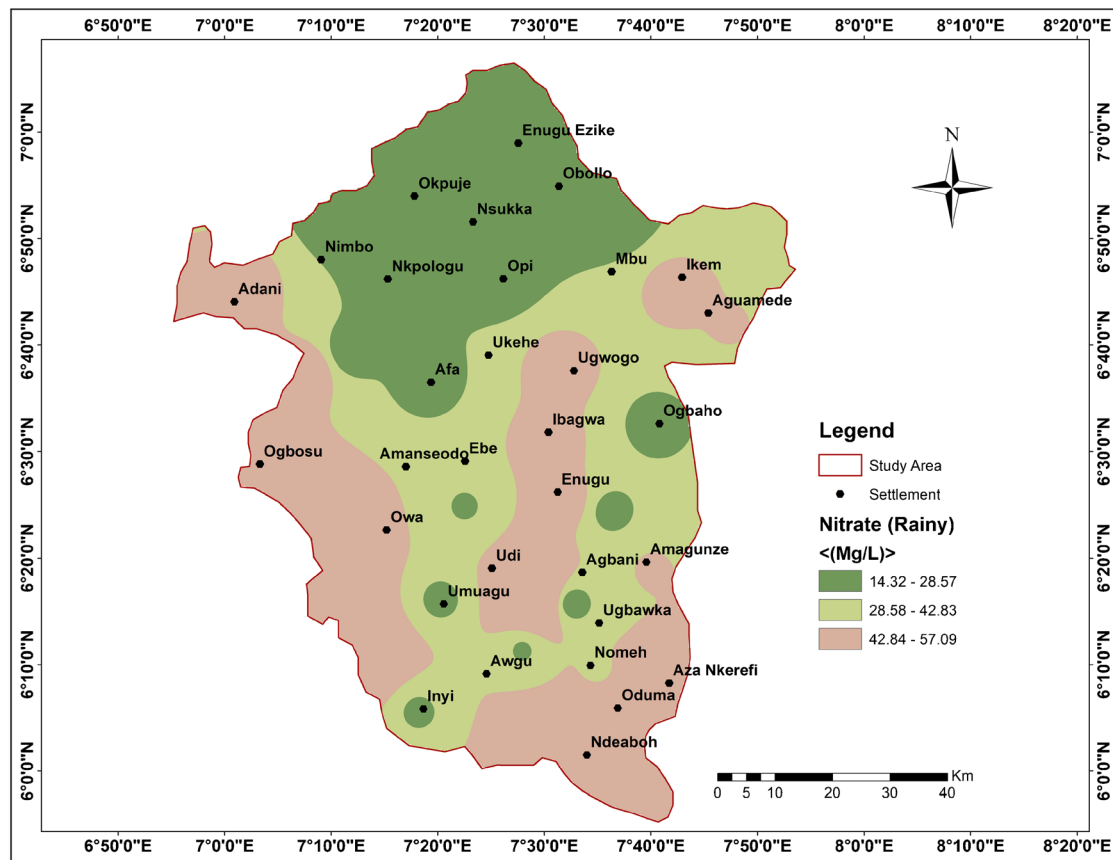
Fig. 11 Nitrate concentration dissemination in Enugu State groundwater in July 2019

low, moderate, and high groundwater vulnerability zones (Fig. 10). The categories delineate the relative potentiality to contamination within the examined area.

In terms of area of occupancy, 20.41%, 71.6%, and 7.99% of the study area are categorized as having high, moderate, and low potential to contamination, respectively (Table 4). The high and moderate vulnerability categories prevail the western and southeastern edges of the study area. The high contamination potential is majorly impacted by the combined contribution of the parameters: impact of the vadose zone (rating 9), aquifer media (rating 9), net recharge (rating 8), and topography (rating >7). On the other hand, soil media is acting as remediating component of the contamination, as majority of the study area is occupied by soil rating values of less than 5.

The vulnerability map indicates a high vulnerability of groundwater pollution where agricultural activities are majorly concentrated. The rest of the areas are placed in moderate and low vulnerability categories due to the absence of agricultural and other related activities.

Model validation

A complete groundwater vulnerability appraisal needs validating the model with field data. The most acceptable method is to compare the vulnerability map with the certain distribution of some usual contaminant in groundwater. The examined vulnerability of groundwater in the study area was compared with nitrate concentrations in the groundwater resources of the entire area. This is because nitrate is the most common human-mediated contaminant into aquifer, and it has become a global concern (Elisante and Muzuka 2016).

Nitrate pollution of groundwater is a worldwide problem because its hazardous effects on human lives and ecosystems (Buczko et al. 2010; Houria et al. 2020). Exceedance of the Nigeria Drinking Water Quality Standard (NDWQS) nitrate guideline value (50 mg/L) in drinking water may result to health issue, such as methemoglobinemia, thyroid disorder, and diarrhea (Almasri 2007; Hussain and Abed 2019). However, high nitrate values can result to eutrophication and hypoxia in surface water systems (Shrestha et al. 2016). Moreover, the detrimental health and environmental effects, nitrate contamination of water has adverse economic effects, due to the elevated costs of mitigation methods useful to reduce nitrate concentration (Babiker et al. 2004). Groundwater with nitrate concentration above the standard value (5–10 mg/L) is considered polluted owing to anthropogenic activities. Possible sources of nitrate include fertilizers, untreated industrial effluents, indiscriminate disposal of waste, sewage sites, and atmospheric deposition (Chroeder et al. 2004).
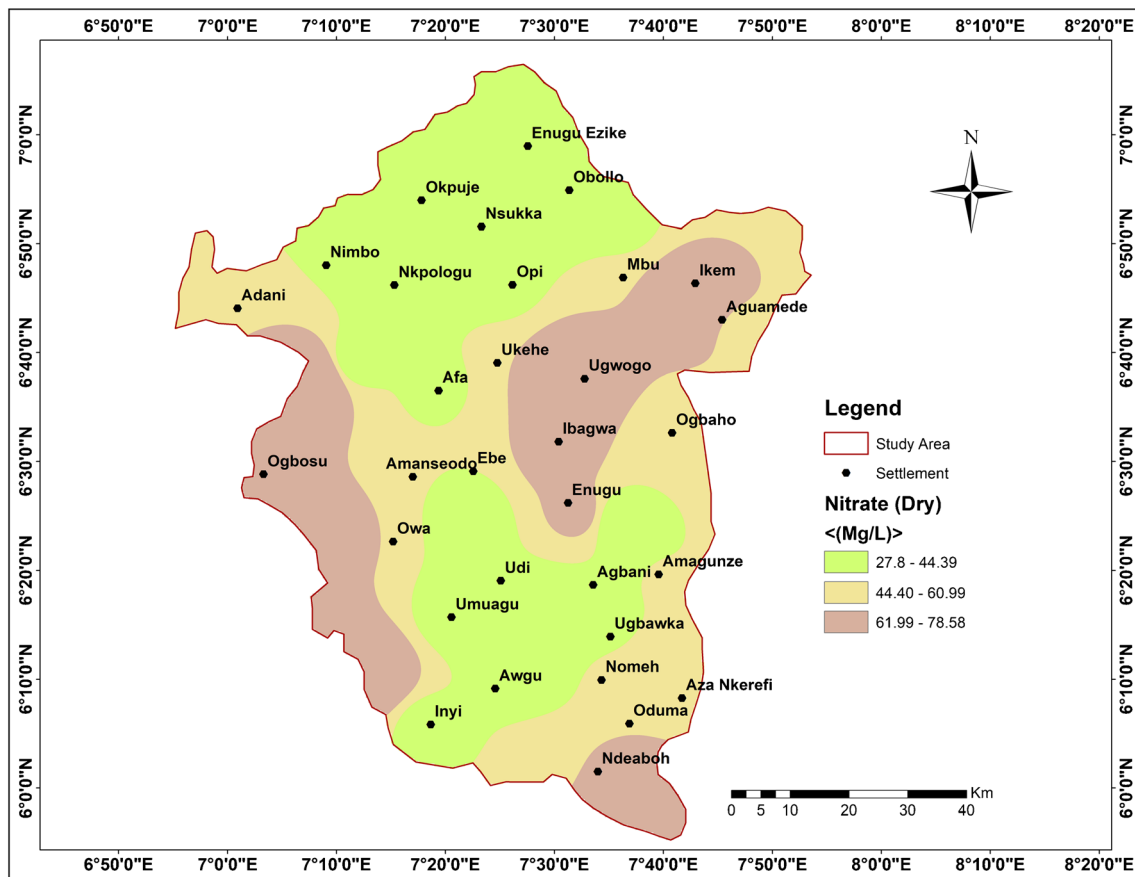
Fig. 12 Nitrate concentration dissemination in Enugu State groundwater in February 2019

Thirty-five samples were gathered from boreholes and examined for nitrate concentration (Table 5). The sampling campaign was conducted during the rainy and July seasons (February and July 2019). The procedures characterized by Clesceri et al. (1998) were adopted during fieldwork and laboratory examination.

Comparing the SINTACS vulnerability maps with nitrate concentrations is a universally used by various scholars (Civita and De Maio 2000; Kumar et al. 2013; Khemmoudj et al. 2014). Kumar et al. (2013) validated the SINTACS model with nitrate concentrations and discovered important correlation between them. Khemmoudj et al. (2014) compared the results of the SINTACS index map with groundwater nitrate values and found a positive relationship. Civita and De Maio (2000) noticed the increasing values of the nitrate value in groundwater in the Bologna region, which make them to outline the vulnerability of groundwater utilizing the SINTACS model.

The standard acceptable nitrate concentration (NO_3^-) for drinking water is 50 mg/L based on the NDWQS (2007). Hence, most of the water samples have nitrate concentration above the standard value set by the NDWQS (2007).

Nitrate concentrations in the study area are defined as low (14.32–28.57), moderate (28.58–42.83), and high (42.84–

57.09) in the rainy season (Fig. 11) while in the dry season, they are delineated as low (27.8–44.39), moderate (44.40–60.99), and high (61.99–78.58) compared with vulnerability categories of SINTACS (Fig. 12). The low category indicates samples with a low threat for anthropological or the ecosystem, and the moderate category shows samples with moderate nitrate is high enough to show the impact of anthropogenic activities. Nitrate concentrations in the high categories exceed the recommendations for drinking water set by NDWQS (2007).

Conclusion

The investigation has certainly exhibited that regional-scale evaluation of groundwater vulnerability using the SINTACS GIS-based method could be employed to delineate regions that are more possible to be polluted. The vulnerability map indicates the considerable impact of the rock units and geomorphological environments on the pollution vulnerability evaluation. The SINTACS GIS-based approach demonstrated its versatility even in this complicated hydrogeological setting. The standard of model validation over nitrate concentration

attained more than 65%, which is a good indicator of the satisfactory modeling method.

As thorough site-specific examination is costly, these evaluations can be adopted as an apparatus but not as a surrogative approach for thorough site-specific examination in areas of interest. Moreover, the vulnerability evaluation maps are important for the strategic water schemes in the study and in decision-making for the purpose of setting up contaminating companies in a particular area such as construction company, animal husbandry, mining company, and food processing company. In conclusion, the application of the SINTACS GIS-based method has proved to be a profitable tool in delineating groundwater vulnerability even in a greatly influenced area by hydrogeological processes.

Declarations

Competing interests   The authors declare that they have no competing interests.

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