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Characterizing groundwater vulnerability in developing urban settings using DRASTIC- L_uP_a approach: A case study of Aba City, Nigeria

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The impact of certain unregulated land-use activities harms the quality of water resources and reduces the sufficiency of drinking water in many developing countries. This study aimed to capture the impact of such activities and evaluate the specific groundwater vulnerability using a modified DRASTIC approach. The DRASTIC- L_uP_a was proposed and implemented for Aba City, Nigeria by incorporating land-use and the impact of pumping layers to the “intrinsic” DRASTIC parameters. The results of the analysis revealed that the area classified as “low” was 15 and 79.1% as “medium” and 5.9% as “high” vulnerability classes for the DRASTIC. Whereas for the DRASTIC- L_uP_a model 3.2% for “low”, 54.3% for “medium”, 41.8% for “high” and 0.7% for “very high” were found. The transitions in the vulnerability classes of areas displaying “high” and “very high” found in the DRASTIC- L_uP_a model represent the impact of urban hotspots observed in the area. This result implies that groundwater protection measures should be implemented in the area designated with “low” and “medium” vulnerability classes and used for abstracting clean water for drinking purposes. The proposed model enhances the predictability and guarantees better transferability of the approach in urban settings with similar urban trends.

Key words: Drinking water, DRASTIC, groundwater, groundwater vulnerability assessment, Nigeria.

INTRODUCTION

Groundwater remains the source of water for about half of the world's population (Kemper, 2004). Studies have shown that in developing countries groundwater is used mainly for domestic and agricultural purposes (DOUNGMANEE, 2016; FAO, 2020). With changing climate,

rapid economic and population rise observed in these countries, the groundwater has been under severe stress due to unregulated withdrawals. Again, further reduction in access to groundwater has continued due to anthropogenic contaminations resulting from poor urban

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implementation. Therefore, it is necessary to develop strategies to guarantee the sustainable use of this “invisible public good”. The management of groundwater resources can be performed either by planned physical monitoring or through computational modelling if sufficient data is available (Jang et al., 2017). The principle of digital risk management practices suggests identifying areas with high vulnerability potentials to reduce frequent monitoring and costs. This is because sampling and monitoring activities consume a lot of time and are expensive to execute over a large area.

The concept of groundwater vulnerability assessment is one of the management approaches that evaluate the physical properties of aquifers and ensure the sustainable use of the resource. Most vulnerability assessment methods bring natural (e.g., hydrogeological parameters) and/or human-induced activities that deteriorate groundwater qualities together to evaluate the contamination risk (Vrba and Zoporozec, 1994). When the vulnerability is influenced by only hydrogeological factors, it is described as “intrinsic vulnerability”. Whereas if it is caused by hydrogeological and human-induced components, then it is referred to as “specific vulnerability” (Frind et al., 2006). The knowledge of the vulnerability types helps to plan monitoring activities to protect the groundwater quality (Saatsaz et al., 2011; Jang et al., 2017).

In different parts of the world, several methods have been developed to evaluate the vulnerability of groundwater to contamination. The assessment method may be objective or subjective depending on the data requirement (Sorichetta, 2010). The objective methods use numerical data, while the subjective ones employ qualitative parameters that influence the hydrological complex (UNESCO, 2004; Sorichetta, 2010). The suitability of each approach depends on factors such as the study objectives, availability of the input data, financial budget, as well as, technical competence required to execute the method (Jang et al., 2017). Some examples of objective methods are process-based models such as SWAT, GLEAMS, HSPF, and MODFLOW (Jang et al., 2017). These models follow some numerical principles and require extended input data to predict groundwater vulnerability.

Again, some statistical methods have been used for groundwater vulnerability assessments. These assessment methods are objective just like the numerical process-based counterparts. Some examples of statistical approaches include the Bayesian theorem (Arthur et al., 2007; Sorichetta, 2010) or log-linear weight of evident (WofE) (Masseti et al., 2008; Sorichetta, 2010) and logistic regression methods (Mair and El-Kadi, 2013; Adiat et al., 2020).

Most groundwater vulnerability assessment studies in developing countries utilize subjective methods. These indexed-based methods are most commonly used because organizing the data is easier and the execution

is straightforward compared to the process-based and statistical methods. Some examples include the DRASTIC (Aller et al., 1987), GOD (Foster, 1987), SEEPAGE (Moore and John, 1990), SINTACS (Civita et al., 1991), AVI (Van Stempvoort et al., 1993), EPIK (Dörfliker and Zwahlen, 1998; Doerfliger et al., 1999), COP (Vias et al., 2006), etc.

The DRASTIC is the most widely applied subjective method and will be considered in this study. It has the main advantage of predicting precisely degrees of vulnerabilities in complex geological features, using intrinsic properties of the aquifer. The DRASTIC approach has been modified in many studies to improve its predictive capability and address specific vulnerability issues (Jasem, 2010; Moustafa, 2019; Jhariya et al., 2019). The modification in the method can be done to capture the impact of human activities on the groundwater quality. This can be achieved by incorporating additional human-induced settings that can influence the groundwater quality, besides the DRASTIC parameters (Secunda et al., 1998; Ijeh 2013; Amadi et al., 2014; Singh et al., 2015; Kumar and Krishna, 2019).

Most of Global South’s developing urban areas are described by increasing population and economic trends. Weak institutions, as well as the lack of maintenance and expanding existing infrastructures, have led to certain unregulated land-use activities and poor environmental practices that have been reported by Egboka et al. (1989) and Ljioma (2021b). These practices complicate urban hydrology (Wakode, 2016), and worsen the quality of the groundwater, as well as its management. This study aimed to characterize the vulnerability of groundwater in such developing urban settings, by enhancing the predictability of the DRASTIC approach. The specific objectives were (a) to identify appropriate anthropogenic layers that influence the hydrologic settings, (b) add these layers into the DRASTIC model, (c) evaluate the difference between the classical DRASTIC and the proposed modified model, as well as (d) recommend the applicability and transferability of the proposed method in the context of other developing urban settings.

MATERIAL AND METHODS

Study area

This study is focused on Aba City, a commercial hub in Abia State, southeast Nigeria (Figure 1a and b). The estimated number of people living in the area is over one million since the last population census of Nigeria was conducted in 2006 (baseline data source was obtained from the Department of Health in the local government areas making up Aba City). The area covers about 236 km² and it is situated in the rainforest agro-ecological zone of Nigeria. There are two main climate seasons, the rainy season between April and October and the dry between November and March, in the area. The average annual temperature is 27.6°C and the average annual rainfall between 1980 and 2019 is 2450 mm/annum. This amount of annual rainfall showed that the area is



Figure 1. Geographical location of the study area showing map of (a) Nigeria and (b) Abia State, (c) land-use distribution in Aba for 2017 and (d) a sketch showing some poor environmental practices within Aba City.

Source: (a) - (c) adopted from Ijioma (2021a), (d) modified from Agharanya and Dim (2018).

ultra-humid. The regional actual evapotranspiration lies between 800 and 1000 mm/annum (Hayward and Oguntuyinbo, 1987). The current water supply system in the area is privately controlled (Ijioma, 2021b). This is because the public supply system operated by state-owned water boards is dysfunctional in most urban parts of Nigeria (Macheve et al., 2015). Groundwater is obtained from private tube wells and it serves as the main source of water for domestic, commercial and industrial uses. However, the installation of these tube wells is poorly regulated, indiscriminate and takes place without licensing. Again, there is no central sewage system to manage the residential, municipal and industrial effluents. This has led to the use of cesspools, septic systems, and the discharge of effluents from both commercial and industrial facilities directly into the aquifer. These types of effluent disposal systems form alternative groundwater recharge sources that can harm the quality. A high chemical and poor bacteriological loading in the densest urbanized parts have been reported in Ijioma (2021b). With the growing population, economic and urbanization trends come with environmental challenges arising from poor handling of municipal wastes in the area. The waste management practices are crude and ineffective in handling tons of refuse generated. The wastes generated are not separated, and collection buckets are sporadically seen over-whelmed in different parts of the area (Figure 1d) and borrow pits are used as landfills. This type of developing urban scenario is not peculiar to Aba City alone, but it is common in many developing urban settings.

Hydrogeology and lithography of the area

The Benin formation constitutes the parent geology, which is composed of the coastal plain sand. The lithological characterization in this study was derived from three borehole hydrogeological investigations up to the first 100 m depths in different parts of the area (Figure 2). The borehole log hydrogeological investigation revealed the different layers and textures. The strata are made up of medium to coarse to very coarse sand, as well as very fine gravels fairly distributed throughout the area. The groundwater elevation tables range between 26.3 and 30 m in the tube wells. The results imply that the elevation of the water table is deep, and groundwater abstraction is facilitated with submersible motor (SUMO) pumps in the tube wells for the water supply. The average result of the pump test revealed an estimated aquifer yield at 4.5 l/s.

Groundwater vulnerability assessment based on the DRASTIC concept

The concept of groundwater vulnerability assessment assumes that the susceptibility of the aquifer depends on the extent of physical protection, which the groundwater gets from the covering layers. The DRASTIC method assumes that the contamination of groundwater begins at the surface, and it is conveyed by rainwater through the unsaturated zone to the groundwater in the saturated zone. The acronym DRASTIC represents seven hydrometeorological and geological parameters, which include depth to the water table [D], net recharge rate [R], aquifer media [A], soil media [S], topography [T], the impact of the vadose zone [I] and hydraulic conductivity [C]. The method addresses generally two sets of potential contamination sources: general and agriculture. However, this study deals with the general contamination potential since the aquifer in the area is minimally influenced by agricultural land use. The evaluation procedure assigns each parameter with a weight from 1 to 5. Parameters with higher contamination potentials are assigned higher values. Each parameter has a range, which is interpreted as the extent to which they can influence the quality of the groundwater. These ranges are assigned rating values from 1

to 10. The ranges, rating, and weights for each of the intrinsic aquifer parameters were predefined in Aller et al. (1987) for the DRASTIC (Table A-1 in Appendix 1). The DRASTIC index [DVI] is calculated as the sum of the products of the weight and rating for the DRASTIC parameters as expressed in Equation 1.

$$DVI = \sum_{i=1}^j w_i * r_i \quad (1)$$

where j = total number of hydrogeologic settings (parameters) considered, i = ith parameter, w = weight assigned to ith parameter, r = rating of the ith parameter.

Equation 1 can be rewritten in a simpler algebra expression as in (Equation 2).

$$DVI = D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r \quad (2)$$

Equation 2 expresses the intrinsic properties of the aquifer since only hydrogeological parameters were considered. To modify the expression, the influence of land use [L_u] and the impact of the active pumps [P_a] layers were introduced. These mappable layers were identified because they can influence the quality of groundwater in a poorly regulated environment. The modified expression addressed the specific groundwater vulnerability given by Equation 3.

$$DVI_m = DVI - R_w R_r + ([R_m]_w [R_m]_r + [L_u]_w * [L_u]_r + [P_a]_w * [P_a]_r) \quad (3)$$

where DVI_m = DRASTIC- $L_u P_a$.

For the modified model, the weight, range, and ratings of the land use map were adopted from Kumar and Krishna (2019). The calculated minimum and maximum indices of the DRASTIC and DRASTIC- $L_u P_a$ models lie between 24 - 220 and 34 - 340, respectively. The indices are categorized into five vulnerability classes by dividing them equally. The categorization of the classes has been summarized in Table 1. Each vulnerability class describes the susceptibility of the groundwater to contamination. This means the higher the index, the more vulnerable is the groundwater to contamination. The indices are dimensionless for both models.

The high rating suggests that the range make the aquifer more vulnerable to contamination. This makes the method less subjective and easy to implement with the ratings and ranges already predefined and provided for different scenarios. Then, adopting, reproducing and transferring the model becomes simple to apply in different local situations.

Creating thematic/rating maps

The sources and data types used to create the thematic maps for the groundwater vulnerability assessment models are summarized in Table 2. All the maps produced from vector data were converted into raster and the grid sizes resampled equally.

Rating maps for the intrinsic properties

The DRASTIC method utilizes intrinsic hydrogeologic properties as input data for its assessment. The combined impact of these properties contributes to the overall vulnerability of the groundwater. The creation of the thematic/rating maps is described in the following.

Depth to the water table [D]: The water-table elevation map of the

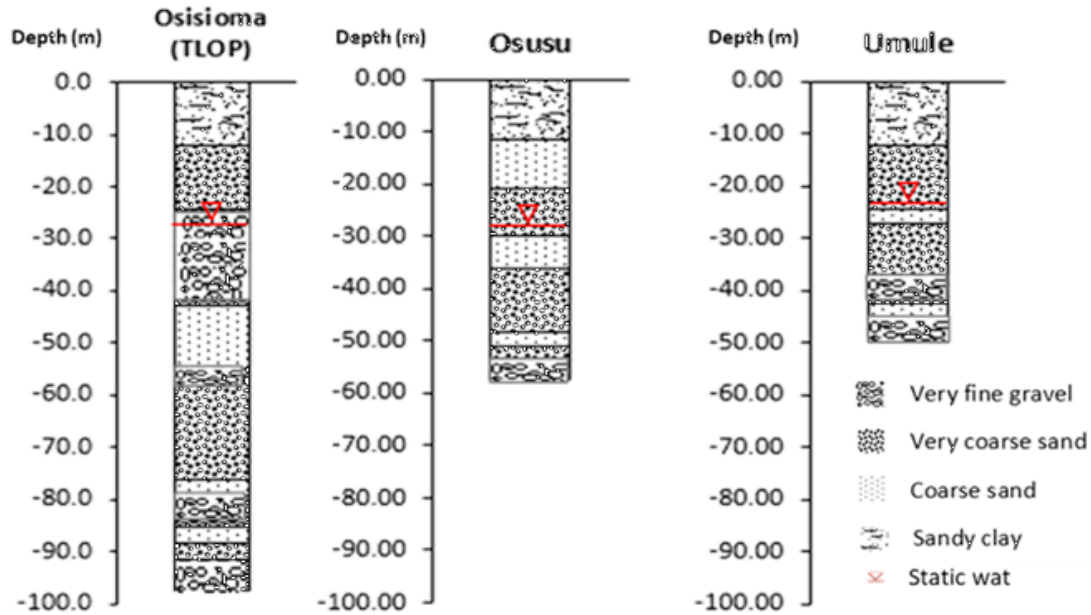


Figure 2. Hydrogeological investigations showing the lithography of three borehole sites in Aba City. Source: Ijioma (2021b).

Table 1. Vulnerability class designations for the DRASTIC and DRASTIC- L_uP_a indices.

Designation	Vulnerability indices	
	DRASTIC	DRASTIC- L_uP_a
Very low	24 - 60	34 - 95
Low	61 - 120	96 - 157
Medium	121 - 160	158 - 219
High	161 - 200	220 - 281
Very High	201 - 220	282 - 340

area was created from borehole dippings of selected wells based on availability. The data was augmented with records from local drillers in the area. The depth to the water table map was obtained by subtracting the water-table elevation map from the reference elevation map extracted, that is, SRTM DEM for the area (DEM resolution ≈ 30 m). The reference DEM served as a standard surface above sea level for the water table elevation map correction (Adams, 2013).

Net groundwater recharge rate [R]: The net groundwater recharge rating map was based on the effective groundwater infiltration rate described in Bazimenyera and Zhonghua (2008) and Sorichetta (2010). The concept employed the water balance method and utilized data from the hydrological parameters (e.g., rainfall, evapotranspiration and runoff coefficients). The land-use map identified four important classes, which include the built-up, barren-land, arable-land, and broadleaf vegetated land for this evaluation. The net recharge rate for each land-use class was calculated according to Equation 4:

$$N_r = (P_a - ET)(1 - R_r) \quad (4)$$

where N_r = Net infiltration rate; P_a = Average annual rainfall (mm/annum); ET = Average annual (upper and lower limits) evapotranspiration (mm/annum); R_r = Surface runoff coefficient for different ground surface; $(1 - R_r)$ = infiltration coefficient.

The surface run-off coefficients corresponding to the identified land use classes were adapted from Jinno et al. (2009) and used to calculate the net recharge in each land-use class. Intrinsically, the following assumptions were made in the estimation of the net recharge rating map.

- (1) The rainfall distribution was uniform throughout the area;
- (2) Groundwater recharge is only rainfed and all infiltrated rainwater constitute recharge;
- (3) Impervious land surface reduces the net recharge rate, and
- (4) The surface runoff coefficient is inversely proportional to the infiltration coefficient.

Aquifer media [A]: The lithographical information of the boreholes in Figure 2 was used to characterize the aquifer media in the area. The results revealed that the aquifer media consist mostly of medium-coarse-grained sand to very fine gravel. The geology of the area is simply coastal plain sand and the lithology confirmed the

Table 2. Hydrogeological settings and data types used for the groundwater vulnerability assessments (modified from Ijioma, 2021b).

Data output layer	Data type	Sources	Format
Depth to the water table	Borehole log, SRTM DEM	Field measurement, reports from AIRBA*, USGS Earth Explorer (https://earthexplorer.usgs.gov/)	Raster
Net recharge rate	Land use map, meteorological data, runoff coefficient	NRCRI meteorological station Umudike, Jinno et al. (2009)	Raster
Aquifer media	Shapefile, borehole lithograph	-	Vector
Soil media	Shapefile	-	Vector
Topography (Slope)	SRTM DEM	USGSA Earth explorer (https://earthexplorer.usgs.gov/)	Raster
Impact of vadose	Shapefile, borehole Lithograph	-	Vector
Hydraulic conductivity	Shapefile, point data pump test data, sieve analysis	Adamu et al. (2019); Agharanya and DIM (2018)	Vector
Impact of active pump surface	Shapefile, well abstraction rates (point data)	-	Raster
Land use map	Landsat 8 OLI/TIR imagery	USGSA Earth explorer (https://earthexplorer.usgs.gov/)	Raster

same. It was assumed that the aquifer is the same throughout the area and a uniform surface was created in this respect.

Soil media [S]: The soil media rating map was derived from documented field investigations that have characterized the soil in parts of the study area (Adindu et al., 2013; Adamu et al., 2019). The USDA classification of the soil texture at the sites of these studies revealed that the soil predominantly comprises sandy-silty-clay (sandy loam) sand type. When the study area was extracted from the soil map of Nigeria (ESDAC, 1990) a uniform distribution was observed throughout the area. The rating was assigned based on the recommendations of Aller et al. (1987) in Table A-1.

Topography/Slope [T]: The topography rating map was derived from the extracted filled SRTM DEM for the study area. The slopes of the filled DEM were generated in the GIS platform and distributions were reclassified. The outcome of the reclassification followed the recommendations of Aller et al. (1987) as described in the appendix (Table A-1).

Impact of the vadose zone [I]: The vadose zone is defined as the geological overburden above the saturated zone. It is part of the geological overburden under the soil, but on top of the saturated zone. It determines to what extent contaminants attenuation happen before they reach the saturated. The lithography information showed that the vadose consists of materials mostly sandy clay, as well as

medium to coarse-grain sand and very fine gravel with silty facies in the area.

Hydraulic conductivity [C]: The data used to create the rating map was collated from documented field experiments. These include laboratory methods - sieve analysis (Agharanya and Dim, 2018), pump test (Adamu et al., 2019) and analysis of soil texture or grain sizes (Ijioma, 2021b) conducted at sites in different local government areas that make up the study area.

Anthropogenic-based thematic/rating maps

It has been observed that unregulated human activities in urban settings of many developing countries harm groundwater quality (Ijioma, 2021a). Two additional rating maps were identified and integrated into the DRASTIC model to enhance the reliability of the vulnerability assessment for Aba City. The parameters captured the impact of poor land-use practices, which is common in many developing countries. The modification incorporates both the land-use (L_u) map with a special focus on some identified contamination hotspot activities and the impact of active pumps (P_a) as part of the rating maps to implement the proposed DRASTIC- L_uP_a model.

Land-use [L_u]: The land use map was derived from the Landsat imagery of the area for 2017 using remote sensing techniques. The supervised classification approach based on the maximum likelihood method was used for the characterization as described in Ijioma (2021b). Rasterized

polygons of the industrial zones were created and joined to the land map. One of the major urban land-use activities in the built-up parts that can influence groundwater quality is the use of septic drains. This is found in most built-up parts since the area has no central sewerage system to handle the municipal effluent. These two urban features characterize important potential contamination sources in the land-use rating map that harm the groundwater quality.

Impact of active pumps [P_a]: The active pumps can affect the lateral and vertical movements of the groundwater within the aquifer and this could harm the quality of the groundwater if poor environmental management practices prevail around the radius of influence of the pump. The impact of the active pump rating map was created using extraction data of pumps for domestic, industrial and commercial activities within the study area. The pump selection was based on availability and accessibility since these are not monitoring wells. Data for 234 pumps were collected and these pumps were categorized into subclasses according to their daily withdrawal rates. The impact of the active pump rating map was created using the ordinary kriging interpolation of the pumps points and their daily withdrawal rates.

Implementing the groundwater vulnerability assessment models

The implementation of the vulnerability models followed a GIS-based approach. The GIS platform serves as a

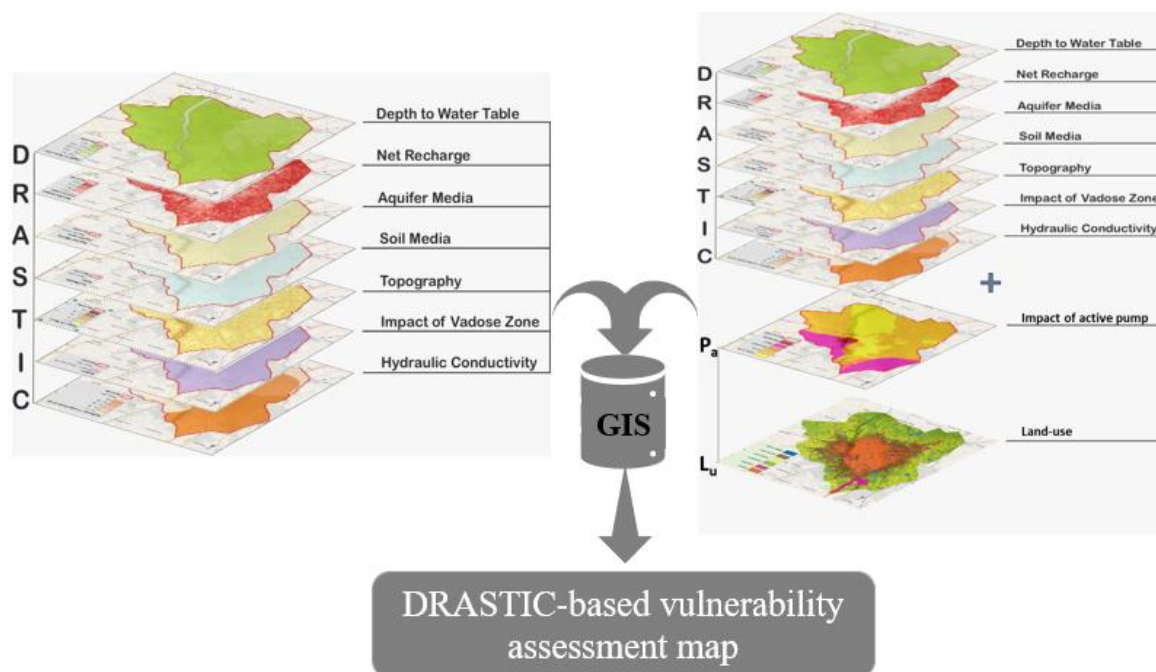


Figure 3. A schematic illustration showing different thematic layers used in implementing the DRASTIC and DRASTIC-LuPa models.

Source: Modified from Ijioma (2021b).

database to store and process the thematic/rating maps. Figure 3 schematically demonstrates the overlaying of the different rating maps required for each model. The weights and rates for each thematic parameter were appropriately assigned to the different raster pixels on the rating maps. The implementations of the models were executed with the raster calculator function in the spatial analyst toolbox of ArcGIS 10.7 following Equations 2 and 3 for DRASTIC and DRASTIC-LuPa respectively.

Validating the impact of active pumps on groundwater quality

Eight water quality indicators were used to develop a groundwater quality index distribution map (Figure 4a) using the geometric weighted sub-index aggregation method. The procedures for the water quality index map derivation are described in Ijioma (2021b).

The map revealed that the groundwater has been contaminated with petroleum products and unfit for drinking in the northwestern parts. This portion of the area was selected to validate the impact of pumping on the hydrogeologic setting since the quality of the groundwater in the remaining parts is evenly spread and acceptable for drinking. The influence of pumping activities caused a 2-dimensional flow (that is, lateral and perpendicular) of the groundwater and around the pump. During pumping, a cone of depression and zone of influence is formed (Figure 5). The empirical estimation of the radius of influence R for an unconfined aquifer was done according to Weber (1928) (equation 5).

$$R = 3 \sqrt{K_f h_o \frac{t}{n}} \quad (5)$$

where R = radius of influence (m), K_f = hydraulic conductivity (m/s), h_o = piezometric head before the pumping started (m), t = time of

pumping (s), and n = effective porosity (dimensionless ratio representing fractional volume).

Three tube wells were identified in the area where petroleum hydrocarbon product contamination has been observed in the groundwater (Figure 4c). The time (t) taken for the pumps to fill the overhead reservoir (V) and the depth to the water table elevation (h_o) were measured before pumping.

RESULTS AND DISCUSSION

The rating values used to create the thematic maps for the DRASTIC and DRASTIC-LuPa models are summarized in the Appendix (Table A-2). The results of the rating maps are discussed subsequently.

Intrinsic thematic maps

Depth to the water table [D]

The implication of the depth of the water table parameter to the overall DRASTIC vulnerability assessment shows that the deeper the water table, the lower the chances of the groundwater being contaminated or vice versa. The result of the derived rating map (Figure 6) showed that the rating in the area lies between 1 and 7. The dominant rating depth of the water table lies between classes 1 and 2 in most parts of the study area. Some parts in the southwestern corridor were shallower with a rating of 3, making this part more vulnerable.

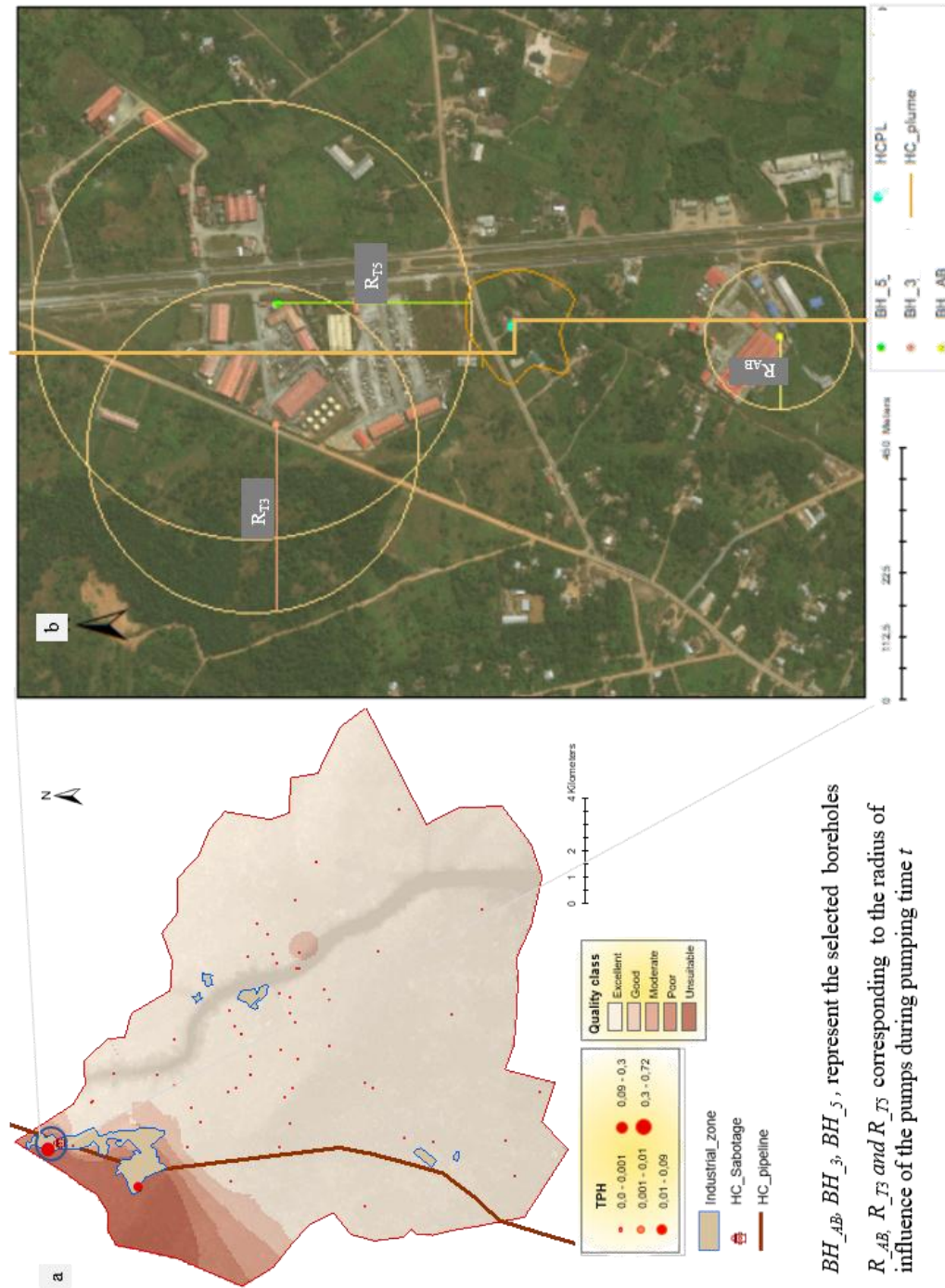


Figure 4. Illustration to validate the impact of active pumps on groundwater quality. (a) Quality index map distribution and a selected contaminated site in one of the industrial estates where petroleum hydrocarbon pipeline was vandalized. (b) Satellite image of the selected boreholes pumps estimating their zone of influence from a contamination plume. Source: Modified from Ijioma (2021b).

Net groundwater recharge rate [R]

The net groundwater recharge rate indicates the ease with which contaminants can be transported vertically

from the surface to the groundwater. The result of the net recharge distribution in the rating maps is summarized in Table 3. The DRASTIC approach suggests that the higher the net recharge rate, the more likely is that

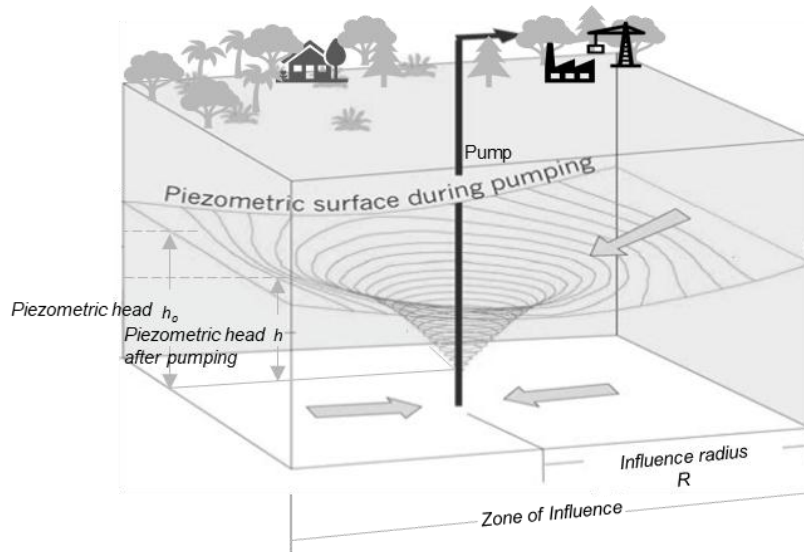


Figure 5. Illustration of cone of depression and a pump's zone of influence in a homogenous aquifer.

Source: Modified from Fileccia (2015).

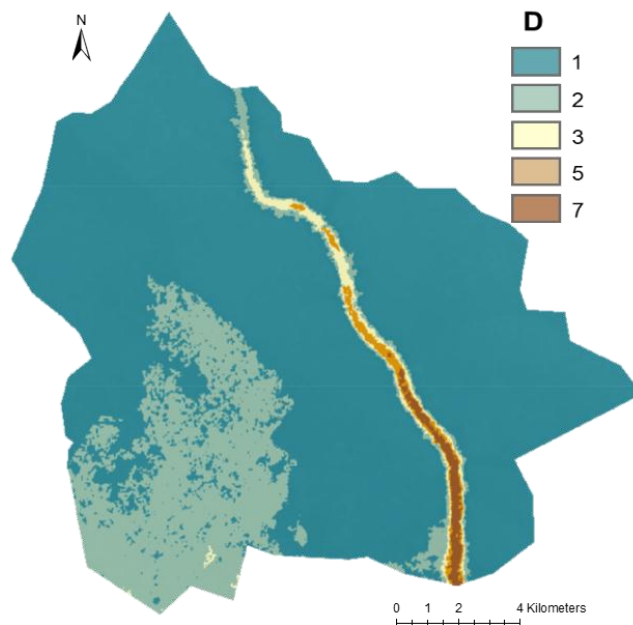


Figure 6. Depth to the water table rating map [D].

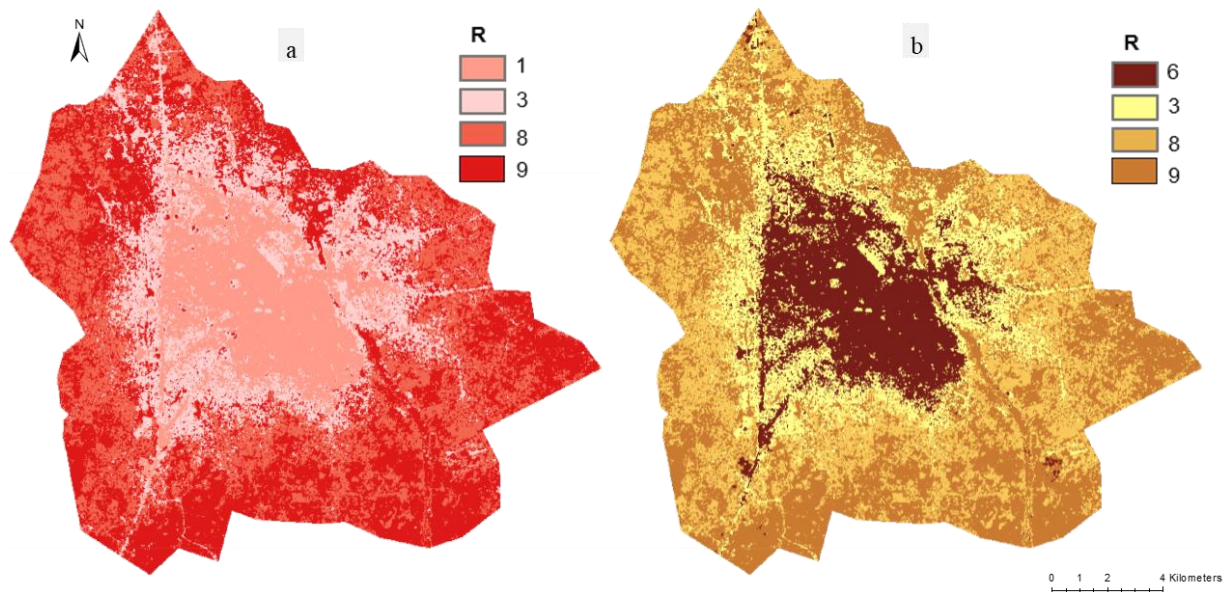
contamination at the surface reaches the groundwater table faster. The land-use classes influence the ratings in the area. The order according to contamination susceptibility of the aquifer based on the land-use class is as follow: vegetated > arable > built-up > barren land as summarized in Table 3. Considering the impact of some practices in the built-up parts which contribute to groundwater recharge in the area, the rating of the net

recharge map was modified [R_m] to account for these practices. The rating map illustrations (Figure 7a and b), revealed that groundwater recharge occurred mostly within the vegetated and arable land classes. This makes these parts the most susceptible in the area with ratings of 9 and 8 assigned to them in both [R] and [R_m] maps respectively. In the [R] map, the barren land and built-up were the least vulnerable parts with ratings of 3 and 1,

Table 3. Summary of results of the water balance equation and net recharge distribution.

Average annual rain (P_a) [mm]		2143		
Evapotranspiration (ET) [mm]		Lower limit (ET_l) ¹ 800 - 1000		Upper limit (ET_o) ² 1449.8
Effective rain (P-ET) [mm]		1243		693.2
Land use	Area ratio	Recharge coeff. ($1-R_r$) [mm]	Net recharge [mm]	Rating
Arable land	0.17	0.9	97.5 - 118.5	6
Vegetation	0.39	0.85	210.7 - 407.1	9
Built-up	0.36	0.2	46.3 - 89.5	3
Barren land	0.09	0.4	22.2 - 42.9	1

¹ ET_l is the evapotranspiration values from literature based on the regional basin according to Hayward and Oguntuyinbo, (1987) and Ophori (2007). The average of the range (900 mm) was used in the calculation. ² ET_o was estimated from the FAO's ET calculator. It represents the reference evapotranspiration.

**Figure 7.** Rating maps of (a) net recharge [R] and (b) modified net recharge [R_m].

whereas a rating of 6 was assigned to the built-up class in the [R_m] map. This higher rating in the built-up class of R_m is because of the harmful impact of some practices already observed and reported in the groundwater quality.

Aquifer media [A]

The aquifer media describes rock types that store groundwater in the saturated zone. The lithology of the boreholes in the area suggests that the aquifer media lie between medium-grained to very fine gravelly materials. Rocks that are porous and unconsolidated have higher

capacities to store and transmit groundwater compared to consolidated rock materials, making them more vulnerable to contamination. These sand types make the groundwater moderately prone to contamination because of the medium to high aquifer porosity. Therefore, a uniform rating of 8 was assigned to the aquifer media based on the ranges described in Aller et al. (1987).

Soil media [S]

The soil media is the topmost part of the vadose. The porosity of the soil media determines the extent of its

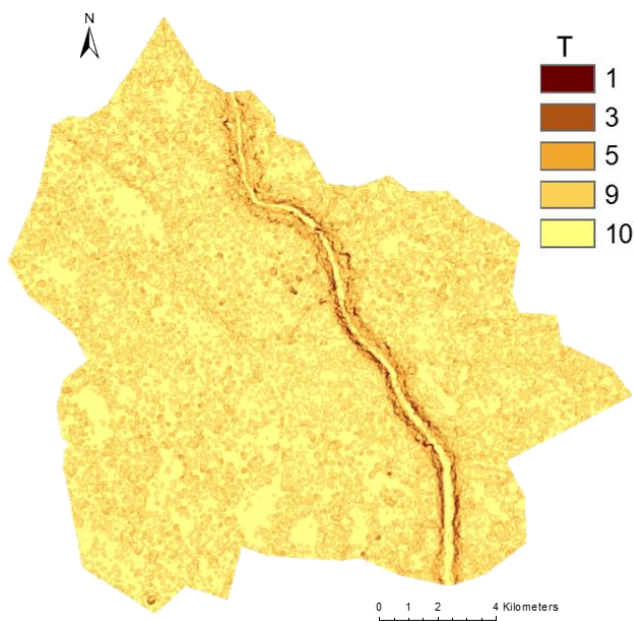


Figure 8. Topography rating map [T].
Source: Modified from Ijioma (2021b).

water holding capacity and the ease, with which contaminants can be transmitted from the surface to the saturated zone. The DRASTIC concept assumes that a more porous soil medium is more susceptible to aquifer contamination than the less porous ones. This implies that soil media with clayey or silty materials have a higher water holding capacity. It takes a long time for a surface contaminant to be transmitted through it than with soils that have sandy textures. Since the soil medium is uniform through the area, a single rating of 6 was assigned to represent the soil medium. This implies that the rate of vertical transmission of rainwater is moderated because of the significant clay-silt proportion in the loam soil found in the area.

Topography/Slope [T]

The topography of the area is described by the slope rating map (Figure 8). The DRASTIC concept assumes that flat landforms do not encourage storm runoffs. This means that surface contamination will have more time to percolate through the unsaturated to the saturated zone. When compared with a steep or sloppy landform, rapid run-off reduces the risk of groundwater contamination but heightens the chance of surface water contamination risk. The analysis of the results showed that most parts of the study area are predominantly flat (Ijioma 2021b). These parts have been rated between 9 and 10. The steep sloppy parts occurred along the shoulder of the Aba River with ratings lying between 1 and 3. The predominant flat areas make the groundwater to be more vulnerable.

Impact of the vadose zone [I]

The vadose characteristics were assumed to be the same throughout the area and a rating of 6 was assigned to the rating map. The DRASTIC approach suggests that an aquifer overlaid by a silty and clayey vadose zone require more time for a surface contaminant to travel through the unsaturated zone to the aquifer. In this case, there is sufficient time for attenuation in the vadose media. The top sandy clay layer in the upper parts of the vadose in the area slows down the transfer of rainwater and facilitates an extended attenuation time for any contaminants in the unsaturated zone. This gives the aquifer moderate protection from certain surface contaminants.

Hydraulic conductivity [C]

The concept of DRASTIC assumes when the conductivity is high, there is a higher chance of contaminants transmission in the saturated zone. The hydraulic conductivity K_f values ranged from 1×10^{-3} to 9.6×10^{-2} m/s, with an average of 1.52×10^{-3} m/s have been reported in the area. Based on these values a uniform rating of 10 was assigned throughout for the rating map. The implication of the assigned K_f value means a high contamination risk for the aquifer.

The hydraulic conductivity describes the ease with which water moves laterally through the aquifer. The transmission of contaminants depends on the porosity of the aquifer materials, and it is a function of time.

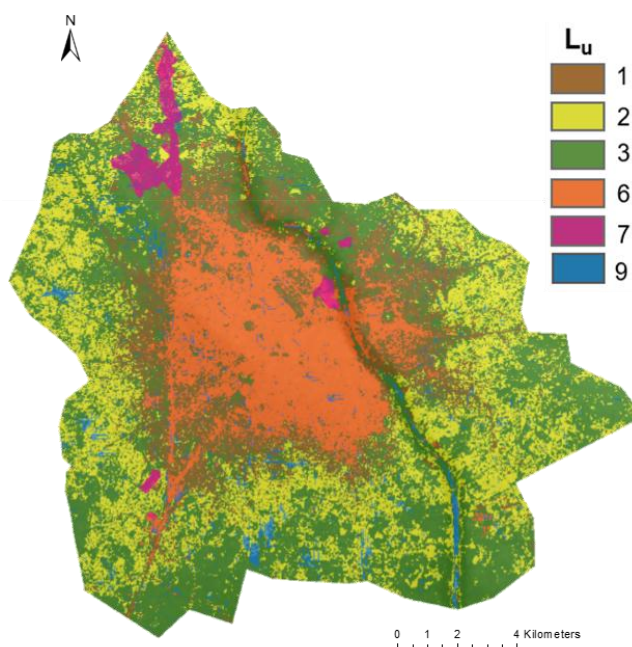


Figure 9. Land-use rating map.

Table 4. Summary of pump subclasses categorization, average withdrawal, designated and impact rating.

Important urban subclasses	Daily withdrawal (m ³)	Rating	Impact designation
Large scale breweries and manufacturing industries	> 400	10	Extreme
Medium-scale manufacturing	100 - 400	8	High
Hotels with swimming pool	100 - 300	8	High
Water bottling	50 - 100	6	Medium
Hotels and restaurants	15 - 50	5	Medium
Pumps on residential blocks	1 - 9	2	Low

Source: Ijioma (2021b).

Anthropogenic thematic/rating maps

Land-use [L_u]

The ratings for the identified land-use classes follow the order: water class (9) > industrial (7) > built-up (6) > vegetated (3) > arable (2) > barren land (1) based on the 2017 map (Figure 9). The surface water and pond areas are the most vulnerable parts due to the lack of physical protection with a rating of 9. The industrial zones were assigned a high rating of 7 because this land use practice is a point source. It has been observed that most industries commonly use cesspits to drain their effluents without prior treatment in the area. The use of septic drains and other similarly identified activities form parts of the contamination hotspots that harm groundwater in the area (Ijioma, 2021b). These practices culminate in the high ratings within the impervious built-up areas. This is

because such urban activities harm the quality both chemically and bacteriologically as reported in Ijioma (2021a, b).

Impact of active pumps [Pa]

The impact of active pumps depends on the daily withdrawal rates and the land-use activity for which the pump serves. Table 4 summarized some important urban sub-classes, of the pumps, average daily withdrawals and their corresponding impact ratings. The spatial distribution of the 234 pumps and categorization are depicted in Figure 10a. Most of the pumps are used for domestic and small-scale commercial purposes are rated low between 2 and 5. The industrial pumps found in large scale manufacturing facilities such as the breweries companies have the highest impact ratings (between 8

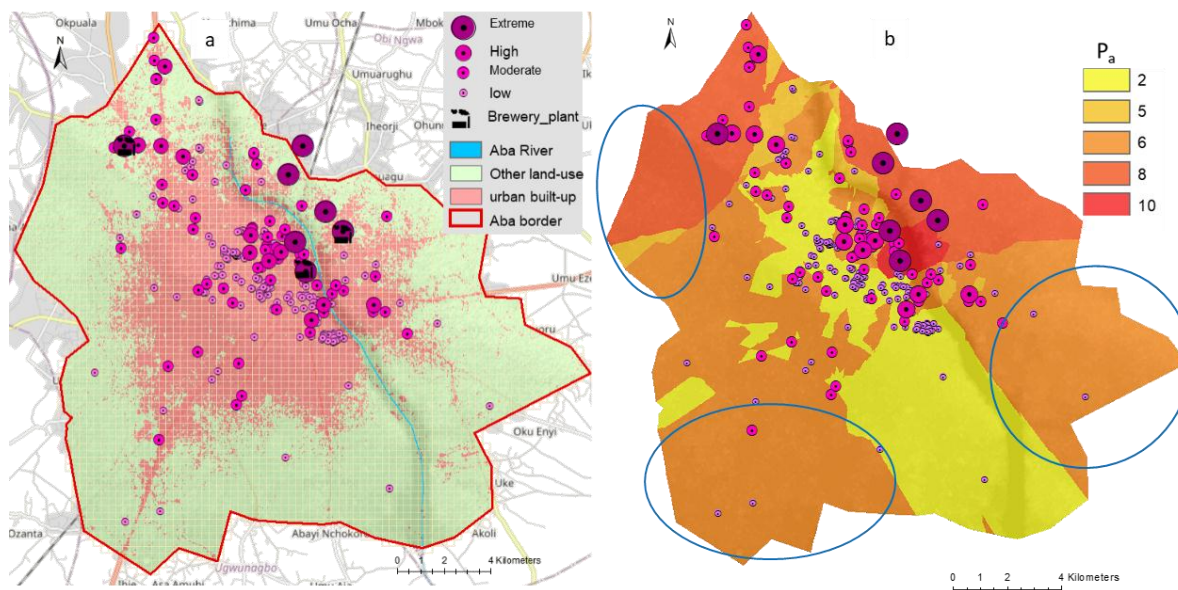


Figure 10. Maps of impact of active pumps distribution (a) showing subclasses of pumps and (b) rating map [P_a]. Source: Modified from Ijioma (2021b).

and 10). Some skewed rating values were observed on the kriging map of the active pumps (Figure 10b). Some anomalies were identified within the blue elliptical shapes, where there are scanty or no pumps because the kriging interpolation assigned rating values according to the pumps closest to these parts. These values were overall high and underscores the predictions of the rating map. This is because there are insignificant land-use activities taking place in these parts.

Comparison of results between DRASTIC and DRASTIC-L_uP_a methods

The results of the DRASTIC and DRASTIC-L_uP_a vulnerability assessments maps are illustrated in Figures 11a and b, respectively and summarized in Table 5. The indices classification of the DRASTIC model revealed only three vulnerability classes (low, medium and high) and four classes (low, medium, high and very high) for the DRASTIC-L_uP_a. Figure 11a revealed that the area designated with “low” vulnerability make up 15%, 79.1% for “medium”, and 5.9% for “high” vulnerability classes in the DRASTIC model. Relating Figure 11a results with the land use map, the model suggests that the groundwater in most parts of the densely built-up areas is classified as “low” vulnerability. The vegetated and arable lands in the peri-urban parts were classified as “medium” vulnerability. The Aba River and some parts in the southwestern corridor were designated “high” vulnerability. The lack of physical protection over the river makes it highly vulnerable.

In general, the “medium” class represents, the intrinsic

baseline vulnerability class in the area. This baseline vulnerability class corroborates with the results of the DRASTIC studies carried out within the regional basin (Ibe et al., 2003; Ijeh, 2013; Edet, 2014; Amadi et al., 2014; Mgbolu et al., 2019). The analysis of the DRASTIC-L_uP_a model (Figure 11b) showed the following designation, 3.2% - “low”, 54.3% - “medium”, 41.8% - “high” and 0.7% - “very high” classes of the total area. In both models, the “medium” vulnerability class remained the predominant category. It was found that appreciable changes in the vulnerability classes happened when the results of the two models (DRASTIC and DRASTIC-L_uP_a) were compared. The impact of the anthropogenic (that is, modified net recharge rate, land-use and impact of active pumps) layers were the cause of the spatial transitions in the vulnerability classes. The analysis of the comparison revealed that the low vulnerability class of the DRASTIC, especially in the densely built-up parts was reduced by 11.8% in the DRASTIC-L_uP_a. The classified “medium” vulnerability parts in the DRASTIC method was reduced by 24.8%, however, the “high” and “very high” vulnerability classes in the DRASTIC-L_uP_a increased by 35.9 and 0.7%, respectively. These transitions represent the specific vulnerability in the groundwater in these parts. However, part of the transitional effect was drawn from the impact of the active pumps rating map as identified within the ellipses (Figure 11b). There are little or no explainable land-use or physiological differentiation in the identified parts that might be responsible for the shift in the vulnerability. Therefore, it was found that the anomalies in the [P_a] rating map worsen the informative values of the DRASTIC-L_uP_a model for these parts.

Despite the observed differences in both models, the

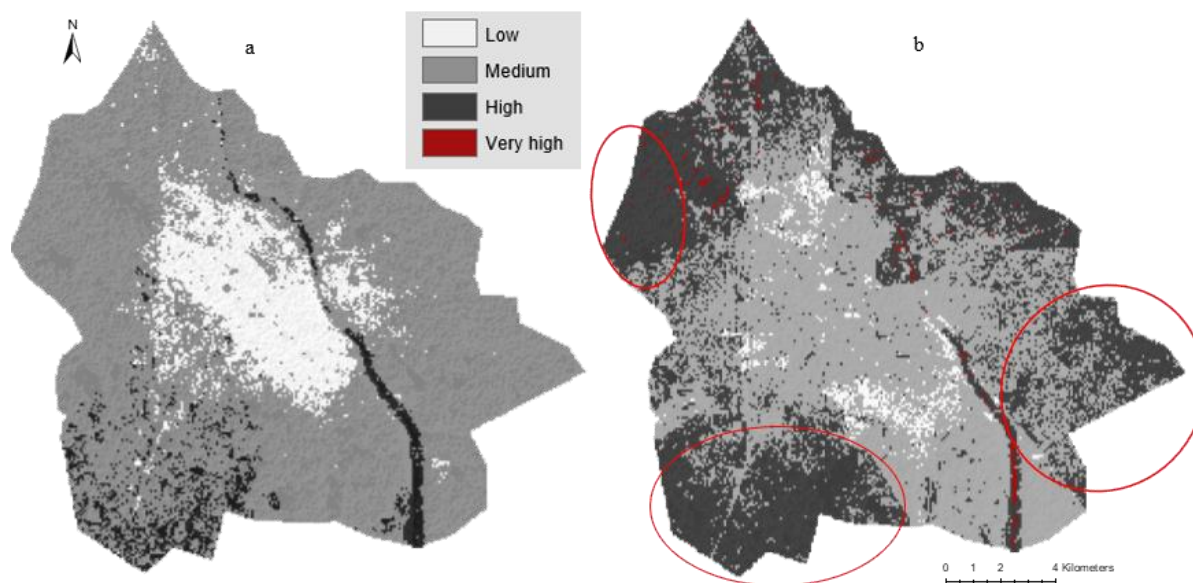


Figure 11. The vulnerability assessment maps showing the results of (a) DRASTIC and (b) DRASTIC- L_uP_a models for the area.

accuracy was not validated. This is because the average chemical quality of the groundwater remained within the recommended limits in most parts of the area. However, some spatial changes were observed in the quality of the groundwater especially within the densest urbanized parts (Ijioma, 2021a). Yet, most anthropogenic-linked indicators in groundwater are within the recommended limits for drinking water in the area. Again, the high volume of rainwater received in the area has a considerable diluting effect on the groundwater, keeping the quality indicators in check. As the population continue to grow, the harmful impact of land use on the groundwater quality will become conspicuous and dangerous for human consumption.

Sensitivity of the intrinsic parameters in the vulnerability map

The result of the DRASTIC method revealed that the depth to water table (D) and net recharge rating (R) were the most sensitive parameters that influenced the differentiation in the outcome of the classical vulnerability assessment map. The net recharge rating caused the most significant changes due to the anthropogenic impact of the urban land use causing low infiltration in parts of the dense built-up parts. The urban land use introduced surface sealing in the densely built-up parts and barren land surrounding the built-up parts. The areas designated with “low” groundwater vulnerability class were surrounded by the predominant “medium” vulnerability class (Figure 11a). Ibe et al. (2003) in their assessment

of part of the regional basin in Owerri reported that the groundwater vulnerability was mostly influenced by intrinsic factors such as porosity, the depth to the water table, and topography. In addition, the parts designated “high” vulnerability observed in the southwestern area were caused by changes in the depth to the water table and this agrees with the findings of Ibe et al. (2003). Again, the low reference elevation in some parts of the southwestern area makes the groundwater table elevation higher and more vulnerable than the other parts of the study area. However, the mix in the composition and lithographical arrangement of the geological materials throughout the study area explained the moderate protection in the aquifer and the “medium” baseline vulnerability designation on the groundwater.

Validating the impact of active pumps on groundwater quality

The validation of the accuracy for the impact of pumping was based on the premise that a large volume of groundwater abstracted exacerbates the quality of the groundwater if there is a nearby contamination source. The presence of total petroleum hydrocarbon (TPH) in the tube wells were determined to demonstrate the influence of daily withdrawals on the quality of groundwater. Table 6 summarized the results of the pumping, the radius of influence estimations and the impact on the groundwater quality. The findings revealed that pumps with high withdrawal generate a wider radius of influence. The radii of influences of the pumps were

Table 5. Analysis of the spatial distribution of the vulnerability classes in the DRASTIC and DRASTIC-L_uP_a assessment methods.

Vulnerability class	DRASTIC		DRASTIC-L _u P _a		Differences in vulnerability (%)
	Area (km ²)	Area (%)	Area (km ²)	Area (%)	
Very low	0.0	0	0.0	0	0.0
Low	35.5	15.0	7.7	3.2	-11.8
Medium	187.4	79.1	128.7	54.3	-24.8
High	14.1	5.9	99.0	41.8	35.9
Very High	0.0	0	1.5	0.7	0.7

Table 6. Estimation of the pumps' radii of influence and their impact on the groundwater quality.

Hydraulic property	Tube-wells			Remark(s)
	BH _{T3}	BH _{T5}	BH _{AB}	
Storage capacity V (m ³)	190	380	60	Field measurement
Time t (s)	42222	84444	13333	Pumping time measured
Height h (m)	29.1	29.3	29.4	Field measurement
Radius of influence, R (m)	253	358	143	-
TPH in water sample (mg/l)	0.5	0.7	ND	-
Pump rate (m ³ /s)		4.5×10^{-3}		Field measurement
Hydraulic conductivity K_f (m/s)		1.5×10^{-3}		Agharanya and Dim (2018)
Effective porosity $[n]$		0.26		Agharanya and Dim (2018)

ND = Not detected.

Source: Modified from Ijioma (2021b).

arrayed in descending order of magnitude: BH_{T5} ($R_{T5} = 358$ m), > BH_{T3} ($R_{T3} = 253$ m) > BH_{AB} ($R_{TAB} = 143$ m). The estimated radii are directly proportional to the volume of the overhead storage volume for each pump and the time required to fill the tanks. The closer a pump's zone of influence to the contamination plume, the easier it is for the groundwater to be contaminated. The results revealed that BH_{T5} with the largest storage volume and radius of influence has interacted with the petroleum product plume. A concentration of TPH = 0.74 mg/l was found in the sample of BH_{T5}. This concentration of TPH impacts taste and odour on the groundwater because the value is above the WHO limits for drinking water quality. This was followed by BH_{T3}, with TPH concentration = 0.54 mg/l in the groundwater sample. Although R_{T3} did not directly interact with the hydrocarbon plume, however, there was an intersection between R_{T3} and R_{T5} . This interaction might be responsible for the contamination found in the BH_{T3} sample. However, no TPH concentration was detected in the BH_{AB}, because the storage tank capacity was not large enough to cause a change in the natural flow of the groundwater. This demonstration can validate the impact of active pumps on the DRASTIC-L_uP_a model in this part of the study area, where contamination has already been observed. The transitioning of groundwater vulnerability from "medium" to "high" and "high" to "very high" classes were also seen

in these parts. However, these vulnerability classes were not captured in the DRASTIC model.

Conclusion

The vulnerability characterization carried out for the main drinking water source in Aba Nigeria, suggests that the intrinsic properties of the aquifer provide moderate protection to the groundwater. Based on the DRASTIC model, the densely residential and commercial parts predicted as having "low" vulnerability were assumed because of the artificial surface sealing in these parts. This sealing offered extra protection to the aquifer and slow down the leaching of potential surface contaminants. However, the "low" vulnerability prediction within the densest residential parts cannot explain the observed gradual deterioration in the groundwater quality. Therefore, the assessment of groundwater vulnerability within developing urban areas where urban land-use and other poor environmental practices, which can harm the groundwater should be re-evaluated. The DRASTIC-L_uP_a model was proposed to adapt the impact of anthropogenic parameters such as some urban land activities and active pumps around contaminated areas into the DRASTIC approach. The identified anthropogenic layers account for the observed transitions in the

vulnerability classes, between both models. This modification in the DRASTIC approach enhanced the predictability of the model especially within the densely residential and commercial parts making the DRASTIC- L_uP_a model easily transferrable to many developing urban areas with similar urbanization patterns as found in Aba City. One of the practical implications of the DRASTIC- L_uP_a model is that it identified areas that can be protected and used for safe drinking water abstraction in the study area. Based on this fact, parts of the area classified as “low” to “medium” vulnerability that is not affected by the densely urban built-up parts can be delineated and protected for source water extraction. As part of the study limitations coarse resolutions in some, rating maps created some anomalies in form of discontinuity or missing pixels observed in models’ outcomes. For instance, the DEM and Landsat imagery (approximately 30 m) influenced the output of the depth to the water table, land-use and net-recharge rating maps. A finer resolution of these data can be used when implementing the model for a small area coverage as Aba. Again, the impact of low data density in parts of the impact of active pumps rating map worsen the informative values and reliability of the results in parts of the modified model.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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ABBREVIATIONS

AVI, Aquifer vulnerability index; **COP**, concentration of flow, overlaying layer and precipitation; **DEM**, digital elevation model; **DRASTIC**, depth to the water, net recharge rate, aquifer material, soil type, topography, impact of vadose and hydraulic conductivity; **DRASTIC- L_uP_a** , depth to the water, net recharge rate, aquifer material, soil type, topography, impact of vadose, hydraulic conductivity, land-use and impact of active pumps; **EPIK**, Epikarst, protective cover, infiltration conditions, Karst network development; **GLEAMS**, groundwater loading effects of agricultural management

systems; **GOD**, groundwater hydraulic confinement, aquifer overlaying strata resistivity and depth to the water table; **HSPF**, hydrological simulation program Fortran; **MODFLOW**, MODular groundwater FLOW model; **SEEPAGE**, system for early evaluation of pollution potential from agricultural groundwater environments; **SINTACS**, Soggienza-depth to groundwater (S); Infiltrazione - effective Infiltration (I); Non saturo - unsaturated zone attenuation capacity (N), Tipologia della copertura - Soil overburden attenuation capacity (T); Acquifero - Saturated zone features (A), Conducibilità - Hydraulic Conductivity (C), and Superficie topografica - Topographic surface slope (S); **SRTM**, shuttle radar topographic mission; **SWAT**, soil and water analysis tool; **TPH**, total petroleum hydrocarbon; **WQI**, water quality index.

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APPENDIX

Table A-1. Assigned numerical range, rating and weight for each hydrogeologic setting in the DRASTIC model.

Parameter range	Rating
Depth to water table (m)	
0.0-1.5	10
1.5-4.6	9
4.6-9.1	7
9.1-15.2	5
15.2-22.9	3
22.9-30.5	2
>30.5	1
Net recharge rate (mm)	
>254	9
177.8-254	8
101.6-177.8	6
50.8-101.6	3
0.0-50.8	1
Aquifer media	
Karst limestone	10
Basalt	9
Sand and gravel	8
Massive limestone	6
Massive sandstone	6
Bedded sandstone, limestone & shale	6
Glacial till	5
Weathered metamorphic/igneous	4
Metamorphic/Igneous	3
Massive shale	2
Topography (% rise of the slope)	
0-2	10
2-6	9
6-12	5
12-18	3
>18	1
Hydraulic conductivity (m/day)	
>86	10
45-85	8
30-45	6
13-30	4
4.5-13	2
0-4.5	1
Impact of vadose zone	
Karst limestone	10
Basalt	9
Sand and gravel	8
Metamorphic/Igneous	4
Sand and Gravel with significant silt and clay	6

Table A-1. Contd.

Bedded limestone, sandstone, shale	6
Sandstone	6
Limestone	6
Shale	3
Silt/Clay	3
Confining layer	1
Soil media	
Thin or absent	10
Gravel	10
Sand	9
Peat	8
Shrinking and/or aggregated clay	7
Sandy loam	6
Loam	5
Silty loam	6
Clay loam	3
Muck	2
Nonshrinking and non-aggregated clay	1
Impact of active pump (m³)	
>400	10
100-400	8
50-100	6
15-50	5
0-15	2
Assigned weight	
Depth to water-table [D]	5
Net recharge rate [R]	4
Aquifer media [A]	3
Soil Media [S]	2
Topography [T]	1
Impact of vadose [I]	5
Hydraulic Conductivity [C]	3
Impact of pumps [P _a]	5
Land use [LU]	5

The units of some of the hydrogeologic settings, such as D, R, C and P_a are expressed in SI units.

Source: Aller et al. (1987).

Table A-2. Summary of ratings for the DRASTIC and DRASTIC-L_uP_a parameters.

Intrinsic properties	Rating
<i>Depth to water-table (m)</i>	
6.0-9.1	7
9.2-15.2	5
15.2-22.9	3
23.0-30.5	2
> 30.5	1
<i>Topography (%)</i>	
0-2	10
3-6	9
7-12	5
13-18	3
>18	1
<i>Net recharge [R] (mm)</i>	
21-43.3	1
46.9-83.8	3
112.2-214	6
138.9-268	9
<i>Impact of vadose</i>	
Sand & gravel with silt	6
<i>Aquifer media</i>	
Sand & gravel	8
<i>Hydraulic conductivity (m/s)</i>	
> 10 ⁻³	10
<i>Soil media</i>	
Sandy loam	6
<i>Impact of pump (m³)</i>	
1-10	2
11-50	5
51-100	6
101- 400	8
>400	10
Anthropogenic properties	
<i>Land-use map</i>	
Barren land	1
Arable land	3
Vegetated	3
Built-up	6
Water bodies	9
<i>Net recharge [R_m] (mm)</i>	
21-43.3	6
46.9-83.8	3
112.2-214	6
138.9-268	9

Source: Ijioma (2021b).