Groundwater Vulnerability Assessment in Osubi Metropolis, Niger Delta, Nigeria using DRASTIC and GIS techniques

ABSTRACT

The vulnerability to contamination of the aquiferat Osubi, Niger Delta, was assessed in order to develop a foundation strategy for safeguarding its groundwater resources using the DRASTIC model and geographic information system (GIS). Using GIS, data corresponding to the seven DRASTIC model parameters were collected and translated into seven thematic maps. The DRASTIC map was created using these maps, which describe the depth to water level (D), net recharge (R), aquifer media (A), soil media (S), topography (T), influence of the vadose zone (I), and hydraulic conductivity (C).The results obtained from this study showed that 7% of the area was classifiedas very-high vulnerability to pollution, 18% was classified as high vulnerability, 60% was classified as moderate vulnerability and 15% as low vulnerability. The most vulnerable areas occur around waste dumpsites, and some septic systemsin residential areas. Policies should be put in place to make it easier to close possible pollution sources in high-vulnerability areas, such as open dump sites, leaking underground storage tanks at fuel stations, effluent discharge from industries, and pit latrines/sewage disposal units.

Keywords: DRASTIC model; groundwater vulnerability; Osubi metropolis;shallow aquifer.

1. INTRODUCTION

Groundwater quality is a major concern, especially in locations where groundwater is the primary source of water.Globally, the quality of groundwater is deteriorating as a result of increasing industrialization, urbanization, and other anthropogenic causes [1,2].The groundwater in the shallow aquifers of Osubi metropolis is important, because they constitute the principal source of potable water for the populace in the locality. Because the research location lacks municipal piped water, virtually every household resorts to providing their own water supply via boreholes without any sort of prior investigations to ascertain its quality and the suitability of the land for such a purpose. Because of the nature of the constituent materials that make up the soil of a particular location amongst other factors, some portions of the land may be more susceptible to contamination than others, this concept is referred to as Groundwater Vulnerability[3]. Groundwater vulnerability is defined as the probability of contaminants seeping and migrating into the groundwater system by percolation and diffusion from the ground surface [4]. It is also defined as the tendency or likelihood for contaminants to reach a specified position in the groundwater system after being released at some location above the uppermost aquifer [5].

Osubi metropolis is a developing municipal settlement, which has undergone rapid urbanization, industrialization, and rapid infrastructural development due to the presence of the Warri Airport (also known as Osubi Airstrip), a prominent educational institution within its locality, and its proximity to the major regions of Nigeria's Niger Delta region that produce oil [6]. These have therefore resulted to several anthropogenic activities such as indiscriminate dumping of both industrial and domestic wastes materials and untreated effluent on land, from diverse sources, which poses a direct threat to the shallow aquifers of the study area and human life at large. It is well known that pollutants from anthropogenic impacts (non-point sources or aerially scattered point sources) can eventually percolate into groundwater, thereby polluting it. The lithology of the shallow aquifers of the Osubi is both porous and permeable, this makes themmore susceptible to contamination from land use and other anthropogenic impacts. Hence, it is essential that a vulnerability assessment is undertaken in order to develop appropriate measures to prevent groundwater pollution and develop measures for aquifer protection.

[7] developed the DRASTIC modelwith the goal of assessing the likelihood that groundwater would be polluted [8].The model's overall goal is to determine zones in the shallow aquifer that are vulnerable which need to be protected. Several methods have been developed for assessing groundwater vulnerability, however, amongst these, several studies have revealed

that the DRASTIC method is the most appropriate. This is mainly because it can be used on a regional scale and necessary input data is easily accessible. The DRASTIC index can also be adjusted to account for human impact on groundwater pollution, resulting the DRASTIC Specific Vulnerability Index (DSVI) [9,10].[11,12,13, 4,14, 15, 16] have all employed this method extensively.DRASTIC is used in this study to assess the aquifer's risk by determining geology, hydrologic, and land use features. The database for the models is created by interpreting different thematic maps and assessing groundwater occurrence mode, aquifer features, unsaturated zone, and soil media properties.

The aim of this research is to assess vulnerability in the shallow aquifer at Osubi, Nigeria's Niger Delta, in order to establish an effective resource protection strategy. The objectives of this research are to identify the DRASTIC model parameters in order to determine the groundwater vulnerability in the study region to pollution and to create a groundwater vulnerability map for the study area using DRASTIC and Geographical Information System (GIS). Knowledge obtained from the present work will help environmental regulators, policymakers, and the general public in making sound decisions on groundwater protection land use, and resource management.

1.1 Location, Physiography and Geology of the Study Area

The city of Osubi is situated in the Okpe Local Government Area of Delta State, Nigeria's Niger Delta area. It is located within latitude 50 35'50" N and longitude 50 49' 10"E, it has a population of about 10,000 people.Osubi's climate is mostly tropical, with a wet and dry season that alternates. The meanyearly temperatures varies between 220C to 340C, while the average annual rainfall is reported to be between 1,501 mm and 2000 mm [17,18].It is really crucial to know the geology of the study area because it influences the groundwater resource's vulnerability potential. The Benin Formation, Agbada Formation, and Akata Formation are the three major sub-surface lithostratigraphic units, which are overlain by superficial alluvium deposits of Quaternary to Recent age known as the Sombreiro-Warri Deltaic Plain sands, according to the geologic map and memoir of the study area.

A broad shale sequence with silt and sandy strata formed near to the expanding delta makes up the Paleocene to Recent Akata Formation [19].The Akata Formation has a thickness of about 7000 metres and covers the entire delta region. The Agbada Formation, which lies above the Akata Formation, is made up of alternating sandstone and shales sequences [20]. The Benin Formation is a continental Eocene to Recent deposit that consists of loose sands with intercalations of lenses of shale and clay that increase in thickness towards the base, up to 2000 meters thick [20].The Benin formation is the primary aquifer in the study region, with an annual recharge rate of over 6.63 x 108m 3 [23].

The Sombreiro-Warri Deltaic plain sands, which is of Quaternary to Recent age consists of sandy silt, brownish lateritic soils (clayey/silt sand), and fine-medium/coarse grained unconsolidated sands. The Formation is mostly unconfined and has a maximum thickness of 120 meters, while the lateritic unit has a maximum thickness of 4-5 meters.

2.MATERIALS AND METHODS

2.1 The Drastic Method

The DRASTIC model is a widely used overlay and index approach for assessing regional groundwater pollution risk.It is a parameter weighing and rating model for a point count method, developed to provide vulnerability scores by integrating numerous thematic maps for a complete hydrogeological evaluation of pollution potential. The acronym DRASTIC stands for the parameters that are used in this method, which are hydrogeological features that affects the rate at which groundwater may become contaminated. These parameters are; depth to water table(D), net **r**echarge (R), **a**quifer media (A), **s**oil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity (C). The weight represents the link between the characteristics, as well as their respective relevance and vulnerability sensitivity. Groundwater vulnerability enhancement/attenuation is deemed to be more important for parameters with greater weights. Each of the seven parameters is given a score between 1 and 10, as well as a weight string (varying from 1 to 5).The most important factors have a weight of 5, while the least important have a weight of 1. [7], provide a full discussion of the parameters employed in the DRASTIC model used in this study.

The DRASTIC index is made up of a total of products that have been rated for the weight of the seven parameters; the ratings for each interval are multiplied by the parameter's weight, and the results are added together to get the final numerical score or index.Groundwater contamination is more likely as the DRASTIC index increases.

Table 1. Criteria of the vulnerability assessment by using DRASTIC method

Class vulnerability	**Low**	**Average**	**High**	**Very high**
Index	<101	101-140	141-200	>200

The DRASTIC vulnerability index was calculated by addition of the different products (score ^{x} weight of the corresponding parameter)

DRASTIC Index= $D_w D_r + R_w R_r + A_w A_r + S_w S_r + T_w T_r + I_w I_r + C_w C_r$

Where D, R, A, S, T, I and C are the seven parameters and the subscripts r and w are the corresponding ratings and weights, respectively.

D_r = ratings to the depth to water table
D_w = weights assigned to the depth to water table
R_r = ratings for ranges of net recharge
R_w = weights for net recharge
A_r = ratings assigned to aquifer media
A_w = weights assigned to aquifer media
S_r = ratings for the soil media
S_w = weights for the soil media
T_r= ratings for topography (slope)
T_w= weights assigned to topography
I_r = ratings assigned to vadose zone
I_w = weights assigned to vadose zone
C_r = ratings assigned to hydraulic conductivity
C_w = weights assigned to hydraulic conductivity

The partial index of each parameter is then calculated using the equation

Partial index= weight ^{x} rating

The DRASTIC index is divided into four levels: low, moderate, high, and extremely high. Each category represents an aquifer's potential for contamination. The higher the DRASTIC index number, the greater the pollution risk. The DRASTIC INDEX is a relative and dimensionless index that is based on an aquifer's geological and hydrogeological properties. Using QGIS version 3.16, each of the DRASTIC parameters has been expressed as a thematic layer.

2.2Creationof the seven DRASTICparameters using GIS

The Geostatistical Analyst Tool from the QGIS version 3.16 software was used to create layers for each of the seven DRASTIC parameters via interpolation. This was then converted to a raster surface layer through classification to create a raster map, where the ratings were assigned to the parameters. The classified raster layer was converted into a reclassified raster according to the rates by [7]. The depth to groundwater, aquifer media, soil media, hydraulic conductivity, and influence of the vadose zone were all measured using this method.However for topography, satellite imagery was used, and the slope was extracted using the raster tools in QGIS version 3.16i.e. Digital elevation model (satellite image).

3. RESULTS AND DISCUSSION

In order to undertake a detailed hydrogeologicalevaluation of pollutant risk using the DRASTIC method, seven thematic maps which depict the DRASTIC model parameters have to be prepared, and each of the parameter evaluated.

3.1Depth to Water Table

The distance pollutants travel through the soil media before reaching the groundwater table is referred to as the depth to water table. Water table depth varies seasonally and is highly influenced by the geology of the area, as different materials such as clay may attenuate the pollutants present in the groundwater, thereby affecting the pollutant travel time. This will thus significantly affect the assigning of rating values of the DRASTIC parameters. The depths to groundwater data used in this study were obtained from published articles based on works conducted by researchers on wells in the study region [6]. The rating values assigned for the study area arebased on the DRASTIC quantitative parameters presented in Table 2.The depth to water table varied between 8 to 16ft), with a rating of 9 based on DRASTIC classification, and the resultant map is shown in Fig.1.

Table 2. DRASTIC quantitative parameters [7,4]

Rating	Depth of water (m) $D \times (5)$	Net recharge (mm/year) $R \times (4)$	Aquifer media $A \times (3)$	Soil media $S \times (2)$	Topography (%) $T \times (1)$	Impact of the vadose zone $I \times (5)$	Hydraulic conductivity (m/s) $C \times (3)$
10	0–1.5		Karst limestone	Thin or absent, gravel	0–2	Karst limestone	$>9.5 \times 10^{-4}$
9	1.5–4.5	>250	Basalt	Sand stone and volcanic	2–3	Basalt	7×10^{-4}–9.5×10^{-4}
8		180–250	Sand and gravel	Peat	3–4	Sand and gravel	5×10^{-4}–7×10^{-4}
7	4.5–9.0		Massive sandstone and limestone	Shrinking and/or aggregate clay/ alluvium	4–5	Gravel, sand	20×10^{-4}–5×10^{-4}
6		100–180	Bedded sandstone, limestone	Sandy loam, schist, sand, karst, volcanic	5–6	Limestone, gravel, sand, clay	30×10^{-5}–20×10^{-4}
5	9–15		Glacial	Loam	6–10	Sandy silt	20×10^{-5}–30×10^{-5}
4			Weathered metamorphic/ igneous	Silty loam	10–12	Metamorphic gravel and sand	15×1^{-5}–20×10^{-5}
3	15–23	50–100	Metamorphic/ igneous	Clay loam	12–16	Shale, silt and clay	10×1^{-5}–15×10^{-5}
2	23–31		Massive shale	Muck, acid, granitoid	16-18	Silty clay	5×10^{-5}–10×10^{-5}
1	>31	0–50		Non shrink and non-aggregated clay	>18	Confining layer, granite	1.5×10^{-7}–5×10^{-5}

Land use classification	Rating
Animal husbandry, horticulture, urban and agricultural area	8
Palm tree and other permanent crops land	5
Water body	3
Swamps and marsh land, grass and wetland and others	2
Forest land	1

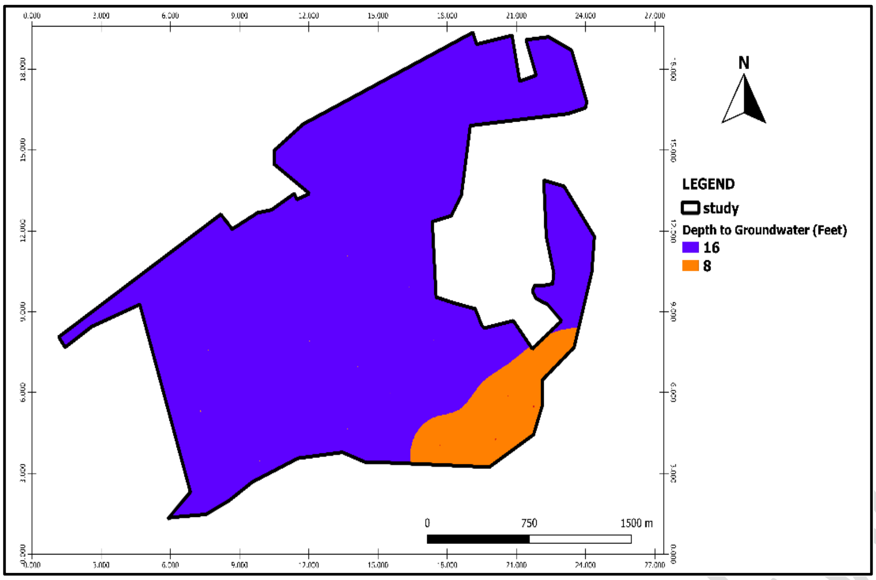

Fig. 1. Depth to groundwater level map of the study area

3.2 Net Recharge

The net recharge is the amount of water per unit area that percolates downward to recharge the aquifer from rainfall and other sources. Net recharge is controlled by several factors such as amount and timing of rainfall, rate of infiltration, slope, and nature of the overlying soil, porosity, and permeability of the soil.Recharge is the main means through which pollutants are moved to the water table, and down to the zone of saturationThis means that the higher the recharge rate, the greater the risk of groundwater pollution. The study area receives about 3000 to 3300 mm/year of rainfall [24], and is expected to have a high recharge rate because its aquifer is both porous and permeable. A recharge rating of 9 was given based on the DRASTIC classification (Table 3). The resultant net recharge map is represented in Fig. 2.

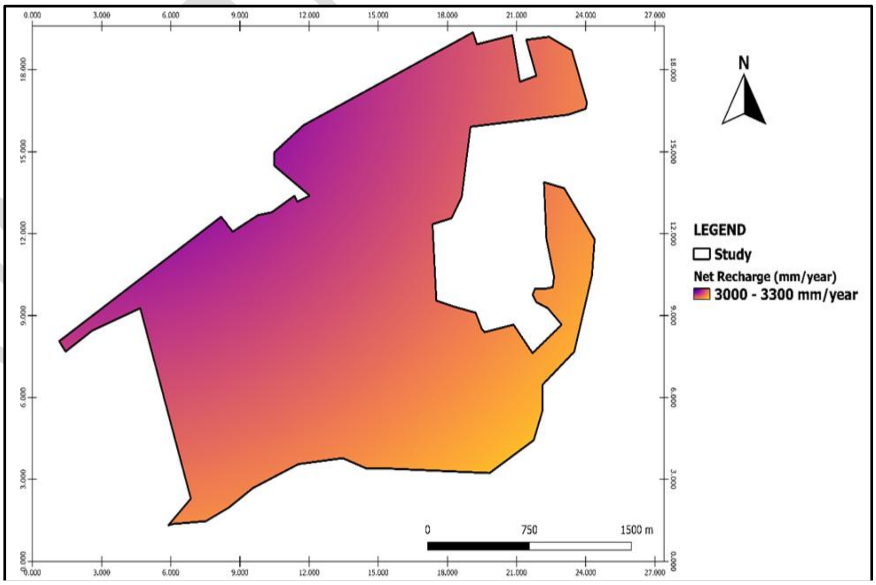

Fig.2. Net recharge map of the study area

3.3The Aquifer Media

An aquifer is a permeable water-bearing rock strata or sedimentthat easily transmits sufficient quantities of groundwater. The aquifer mediadescribes thenature of openings such as pore spaces, joints, faults, and fractures within the geologic unit(rock or sediment) that serves as a reservoir for groundwater. Generally, the more the openings in the aquifer, the higher the permeability and consequently vulnerability as well.The aquifer media influences the flow rate within the aquifer. This flow has an impact on the rate at which pollutants reach the aquifer [7]. Data used for the aquifer media was obtained from previous research works in the study region[6,20].Based on the DRASTIC quantitative parameters, the rating assigned to the aquifer of the study area, which consistspredominantlyof sand [6,20]is 8, and the resultant aquifer media map is presented in Fig. 3.

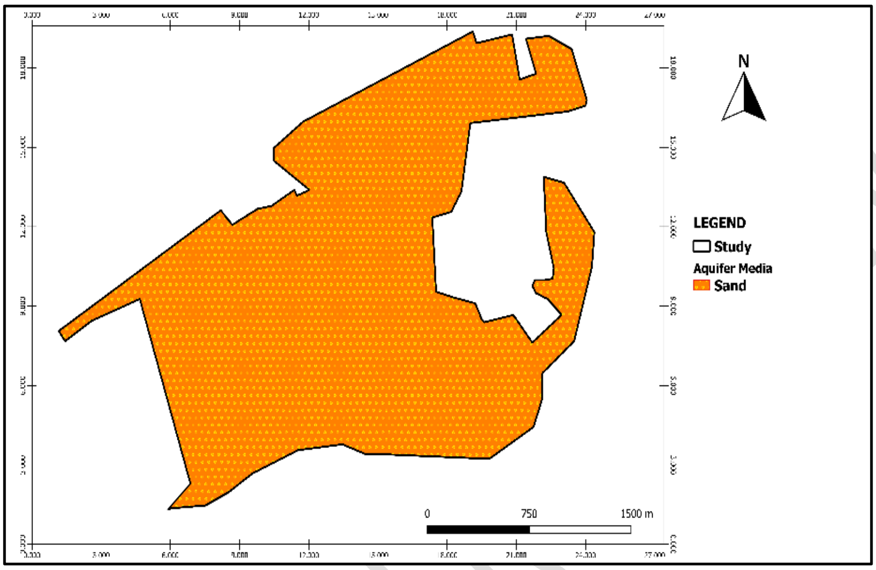

Fig.3. Aquifer media map of the study area

3.4 The Soil Media

This parameter refers to the vadose zone's topmost part, which is associated with high biological activity. For the purpose of the DRASTIC model, the soil is generally referred to as the upper weathered zone of the earth. This parameter is important because it affects the rate at which recharge infiltrates into the groundand the rate at which contaminants may be attenuated.The texture of the soil greatly affects the ability of contaminants to movethrough the soil. The study area's soil media map (Fig. 4) was created using data from previous research studies[6, 20]. The DRASTIC rating ranges for various soil textures is shown in Table 3.

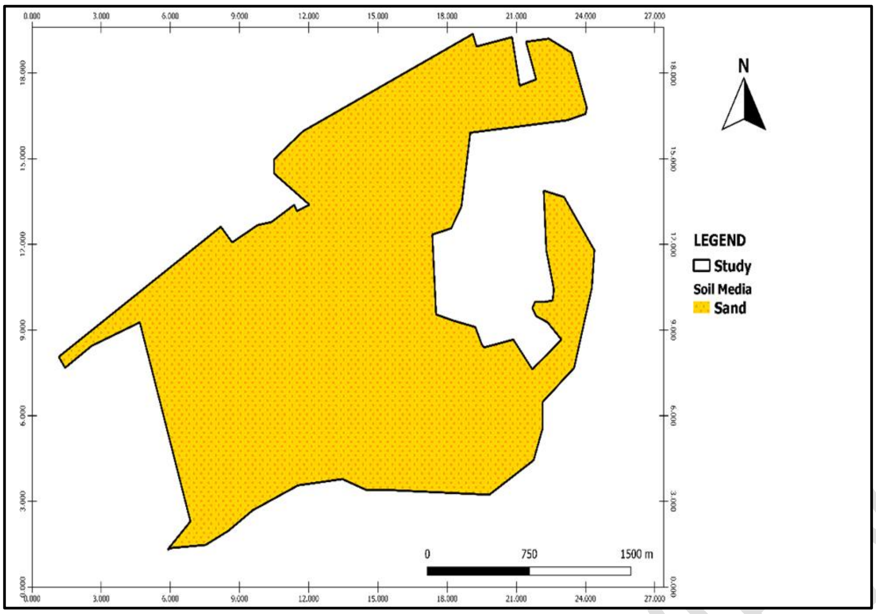

Fig.4. Soil media map of the study area

3.5 Topography

This parameter describesthe heterogeneity of the slope of the land in the study area. The topography largely affects thepossibility that a pollutant will runoff on the surface, or infiltrate into the groundwater aquifer. Land areas with gradual slopes have a greater tendency for groundwater to be infiltrated by polluted water, whereas areas with high or steep slopes have a lower chance because the pollutants would likely move quickly downwards, without having time to infiltrate groundwater. The topography also influencesthe land area wherein polluted runoff will flow to, before infiltrating groundwater. Runoff from farmlands often laden with pesticides and other agrochemicals usually movesfrom areas of higher to a lower altitude, this, therefore, makeslower slopes more susceptible to pollutants.In the study area, the slope ranges from 0 - 18% (Fig. 5), and it was classified according to the ratings provided by [7], (Table 3).

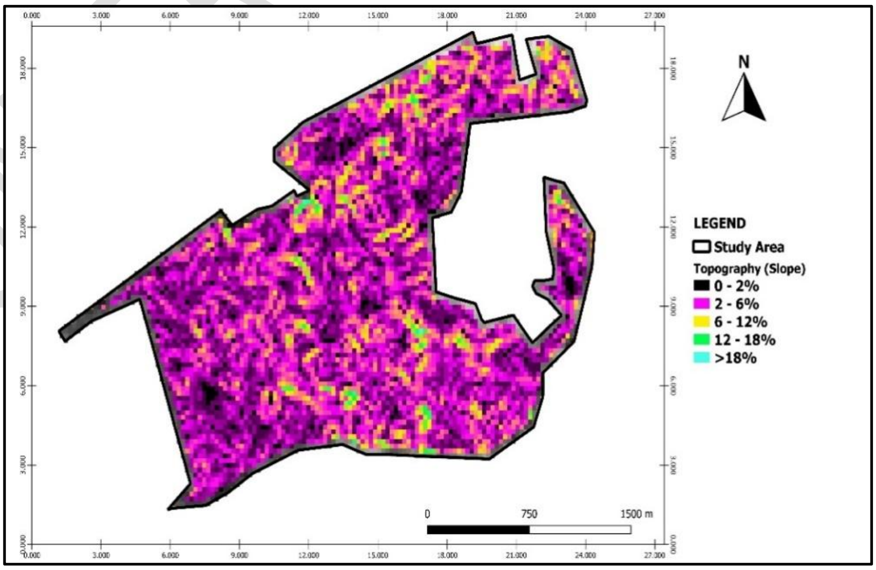

Fig. 5. Topographic map of the study area

3.6 Impact of Vadose Zone

The effect of the unsaturated zone, which is the section of the subsurface above the water table where the pores between the rocks are partially filled with water, is described by this parameter. Pollutant movement and attenuation into the aquifer are controlled by the constituents in the vadose zone medium. A number of processesthat occur in the vadose zone, may control its pollution potential, these include chemical reactions, mechanical filtration, biodegradation, neutralization, volatilization, and dispersion[3].For DRASTIC, the selection of the vadose zone media depends on the most significant media which influences pollution potential.
The vadose zone materials of the aquifer in the study area ranged from silt to clay or siltsand [6, 20] and was given a rating of 1(Table 3) based on the DRASTIC classification.Fig. 6 shows the impact of the vadose zone map.

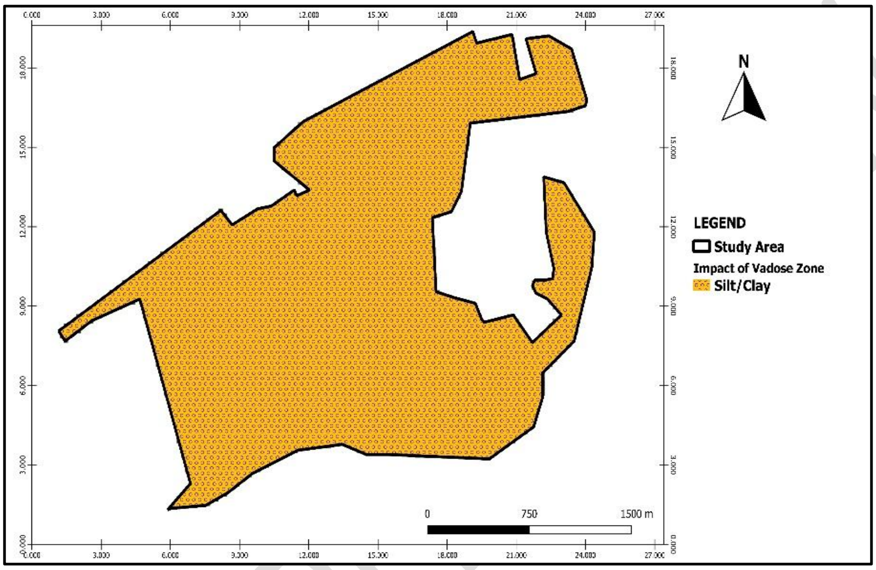

Fig. 6. Impact of vadose zone map of the study area

3.7. Hydraulic Conductivity

The rate at which infiltrating water is transmitted into the groundwater is described by this parameter.It controls the rate of groundwater movement, which in turn controls the degree and fate of the contaminants under a given hydraulic gradient. Hydraulic conductivity is controlled by the amount and interconnection of openings inside the aquifer. For the DRASTIC model, hydraulic conductivity is divided into ranges, with higher values indicating higher pollution potential. The hydraulic conductivity of the aquifer media was obtained from geologic literature [25]. The hydraulic conductivity of the aquifer media of the study area was less than 4 m/day (Fig. 7)and was given the rating 1.

Fig.7. Hydraulic conductivity map of the study area

3.8 Land Use

Groundwater vulnerability is influenced heavily by human activities and land use.The use of land for industrial, commercial, and agricultural purposes greatly increases its susceptibility to groundwater pollution. Groundwater contamination is more likely in places with a lot of anthropogenic activities[26]. The land use classifications of Osubi shows that a major part of the area is designated for urban settlements. The second major area is used for commercial activities, and the third is used for agricultural activities. The remaining parts of the area are classified as forestland, swamps and marshland. The research area's land use classification shows that the quality of groundwater may be greatly affected by anthropogenic influences. Human activities identified around the study area that could significantly contribute to groundwater pollution include: septic systems in built-up areas, pesticides from agricultural areas, waste dump sites, drilled water wells, untreated effluent from industries, abattoirs, and the leaking of petroleum hydrocarbon from underground storage tanks at filling stations.

3.9Development of DRASTIC map

The DRASTIC index mapshows the four vulnerability ratings (Fig. 8), which are low, moderate, high and very high. These were generated by the DRASTIC parameters merged into one according to the equation below in a GIS environment. The GIS coverage is fully raster, and overlay values are assigned based on the pixel value of each area, which is calculated by multiplying the ratings by the DRASTIC weight.

$DI = Dr \times 5 + Rr \times 4 + Ar \times 3 + Sr \times 2 + Tr \times 1 + Ir \times 5 + Cr \times 3$

Where:

DI = DRASTIC index
Dr= depth to groundwater (rated)
Rr= Recharge rate (rated)
Ar= Aquifer media (rated)
Sr= soil media (rated)
Tr= Topography (rated)
Ir=impact of vadose zone (rated)
Cr= hydraulic conductivity (rated)

The DRASTIC ratings indicate how vulnerable groundwater is to pollution. The map is not a representation of quantifiable data; rather, it's a projection of where future contaminants might appear based on land usage in those locations.

The DRASTIC indices are divided into four categories: very high vulnerability (more than 200), high vulnerability (141-200), moderate vulnerability (101-140), and low vulnerability (less than 100). (1-100). According to the DRASTIC map, 7% of the area is classified as extremely high vulnerability, 18% as high vulnerability, 60% as moderate vulnerability, and 15% as low vulnerability areas.

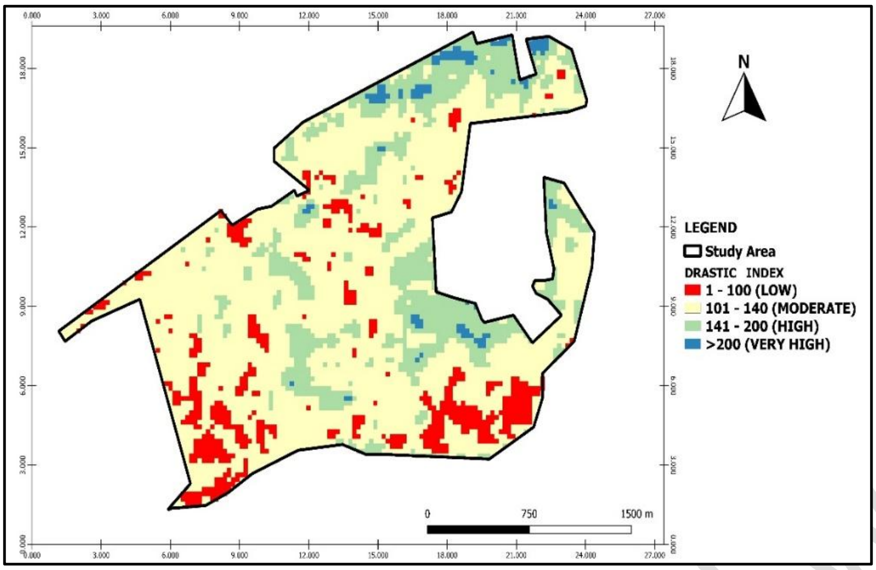

Fig.8.The DRASTIC aquifer vulnerability map of Osubi

4. SUMMARY ANDCONCLUSION

The shallow aquifer of Osubi metropolis, Niger Delta, Nigeria was assessed by employing GIS and the empirical index DRASTIC model. Furthermore, the modified DRASTIC approach was utilized to assess the effect of land use activities on groundwater vulnerability.The outcome of the DRASTIC map analysis is as follows: 7% of the area was classified as extremely high vulnerability, 18% as high vulnerability, 60% as moderate vulnerability, and 15% as low vulnerability. Waste disposal sites should not be located in areas with moderate to high vulnerability. Furthermore, indiscriminate disposal of waste at open dumpsites should be discontinued, and appropriate waste disposal methods which have minimal impact on the environment should be adopted. Sewage disposal/ soak away systemsshould not be located in areas classified with high and very high vulnerability. Policies should be put in place to stop pollution sources in high-vulnerability areas, such as open dumping sites,underground storage tanks stations, effluent discharge from industries, and pit latrines, and to situate future disposal sites in low-vulnerability areas. A site-specific assessment should be carried out in areas where the groundwater has been identified to be highly susceptible to pollutants with evident anthropogenic activities likely to affect groundwater quality, in order to assess the degree of groundwater pollution in those areas.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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