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

Abstract
The vulnerability to contamination of the aquifer at 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). Data that correspond to the seven parameters of the DRASTIC model were collected and converted into seven thematic maps using GIS. These maps which define the depth to water level (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I) and hydraulic conductivity (C) were generated to develop the DRASTIC map. The results obtained from this study showed that 7% of the area was classified as 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 systems in 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. Future disposal sites should be located in areas identified to have low groundwater vulnerability. The study suggests that this model will be helpful to environmental regulators, policymakers, and the general public in making sound decisions on groundwater protection, land use, and resource management of the study area.

Keywords: Groundwater vulnerability, shallow aquifer, DRASTIC model, Osubi metropolis

1.0 INTRODUCTION

The quality of groundwater is a serious concern, especially in areas where groundwater is the chief source of water supply. Globally, the quality of groundwater is deteriorating as a result of increasing industrialization, urbanization, and other anthropogenic causes (Khan et al. 2011; Dimitriou and Moussoulis 2011). 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. Due to the absence of municipal pipe-borne water in the study area, 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 land areas may be more prone to contamination than others, this concept is referred to as Groundwater Vulnerability (Piscopo, 2001). Groundwater vulnerability is defined as the probability of contaminants seeping and migrating into the groundwater system by percolation and diffusion from the ground surface (Shirazi et al., 2013). 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 (National Research Council, 1993).

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 oil-producing parts of the Niger Delta region of Nigeria (Ofomola, 2015). 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 them more 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.

The DRASTIC model was developed by Aller et al., (1987), with the goal of assessing the likelihood that groundwater would be polluted (Saatsaz *et al.*, 2011). The overall aim of the model is to identify 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 the required input data are readily available. Also, the DRASTIC index can be modified to include anthropogenic influences on groundwater pollution to give a modified form called the DRASTIC Specific Vulnerability Index (DSVI) (Chiedza and Kwazikwakhe, 2013; Gogu and Dassargues, 2000). This method has been used extensively by several researchers Ibe et al., (2001), Nas et al., (2006), Rahman (2008); Shirazi et al., (2013); Edet. (2013), Azubuike et al., (2015), and Saheed (2020). DRASTIC is used in this study to assess the aquifer's risk by determining geology, hydrologic, and land use features. The models' database is obtained from the interpretation of several thematic maps and the assessment of groundwater mode of occurrence, aquifer features, unsaturated zone, and soil media properties.

The overall aim of this study is to assess vulnerability in the shallow aquifer at Osubi, Niger Delta Nigeria as a basis for developing an appropriate protection strategy for the resource. The objectives of the present work are to determine the DRASTIC model parameters in order to ascertain the vulnerability of groundwater in the study area to pollution and produce 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

Osubi metropolis is situated in Okpe Local Government Area of Delta State, in the Niger Delta region of Nigeria. It is located within latitude 5^0 35' 50'' N and longitude 5^0 49' 10''E with a population of approximately 10,000 people. The climate of Osubi is mainly tropical with an alternating wet and dry season. The average annual temperatures range from about 22^0C to 34^0C, while the average annual rainfall is reported to be between 1,501 mm and 2000 mm (Akpoborie, 2011; NIMET, 2003). It is important that the area under study be understood geologically, as it bears relevance to the vulnerability potential of its groundwater resource. The geologic map and memoir of the study area show that it is underlain by three major sub-surface lithostratigraphic units which are; the Benin Formation, Agbada Formation, and Akata Formation, which are overlain by superficial deposits of alluvium of a Quaternary to Recent age known as the Sombreiro-Warri Deltaic Plain sands.

The Paleocene to Recent Akata Formation consists of a thick shale sequence with silty and sandy layers deposited adjacent to the advancing delta (Michele et al., 1999). The Akata Formation has a thickness of about 7000 metres and covers the entire delta region. The Agbada Formation is located above the Akata Formation and contains alternating sequences of sandstone and shales (Short & Stauble, 1967). The Benin Formation is a continental Eocene to Recent deposit which comprises of loose sands with intercalations of lenses of shale and clay which increase towards the base, with a thickness of up to 2000 metres (Short & Stauble, 1967; Whiteman, 1982; Doust & Omatosola, 1990). The Benin formation is the major aquifer in the studied area, with appreciable groundwater storage and recharge of over 6.63 x 108m 3 per annum (Oteze, 1981).

The Quaternary to Recent Sombreiro-Warri Deltaic Plain sands consists of sandy silt, brownish lateritic soils (clayey/silt sand), and fine-medium/coarse grained unconsolidated sands. The Formation generally does not exceed 120 meters in thickness and it is predominantly unconfined while the lateritic unit ranges from 4-5 metres in thickness.

2.0 MATERIALS AND METHODS

2.1 The DRASTIC Method

The DRASTIC model is a widely used overlay and index model used to evaluate groundwater pollution potential on a regional scale. It is a point count system model parameter weighing and rating model, designed to produce vulnerability scores by combining several thematic maps for detailed 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 reflects the relationship among the parameters and their relative importance and sensitivity to vulnerability. Parameters with more weights are judged to be more important in groundwater vulnerability enhancement/attenuation. Each of the seven parameters is given a rating interval from 1 to 10, with a weight string (varying from 1 to 5). The most significant parameters have weights of 5; the least significant, a weight of 1. The weight and description of the parameters used in the DRASTIC model are shown in Table 1.

Table 1: The DRASTIC model parameters (Aller *et al.,* 1987)

Factor	**Symbol**	**Description**	**Relative weight**
Depth to groundwater	D	Represents the depth from the ground surface to the water table, deeper water table levels imply less chance for contamination to occur.	5
Net Recharge	R	Net recharge Represents the amount of water that penetrates the ground surface and reaches the water table, recharge water represents the vehicle for transporting pollutants.	4
Aquifer media	A	Refers to the saturated zone material properties, it controls the pollutant attenuation processes.	3
Soil media	S	Represents the uppermost weathered portion of the unsaturated zone and controls the amount of recharge that can infiltrate downward.	2
Topography	T	Refers to the slope of the land surface, it dictates whether the runoff will remain on the surface to allow contaminant percolation to the saturated zone.	1
Impact of vadose zone	I	Is defined as the unsaturated zone material, it controls the passage and attenuation of the contaminated material to the saturated zone.	5
Hydraulic conductivity	C	Hydraulic conductivity Indicates the ability of the aquifer to transmit water, and hence determines the rate of flow of contaminant material within the groundwater system.	3

The DRASTIC index is made up by a sum of products rating for weight of the seven parameters; the ratings for each interval are multiplied by the weight for the parameter and the products are summed to obtain the final numerical score or index. The higher the DRASTIC index, the greater the groundwater contamination potential.

Table 2: Criteria of the vulnerability assessment by using DRASTIC method (Engel *et al.,* 1996).

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.

$\mathbf{D_r}$ = ratings to the depth to water table
$\mathbf{D_w}$ = weights assigned to the depth to water table
$\mathbf{R_r}$ = ratings for ranges of net recharge
$\mathbf{R_w}$ = weights for net recharge
$\mathbf{A_r}$ = ratings assigned to aquifer media
$\mathbf{A_w}$ = weights assigned to aquifer media
$\mathbf{S_r}$ = ratings for the soil media
$\mathbf{S_w}$ = weights for the soil media
$\mathbf{T_r}$ = ratings for topography (slope)
$\mathbf{T_w}$ = weights assigned to topography
$\mathbf{I_r}$ = ratings assigned to vadose zone
$\mathbf{I_w}$ = weights assigned to vadose zone
$\mathbf{C_r}$ = ratings assigned to hydraulic conductivity
$\mathbf{C_w}$ = 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 can be further divided into four categories: low, moderate, high and very high. Each category reflects an aquifer's inherent capacity to become contaminated. The higher DRASTIC index number shows the greater pollution potential risk to one another. DRASTIC INDEX is relative and dimensionless that depends on the geological and hydro geological characteristics of an aquifer. Each of the DRSTIC parameters has been expressed as thematic layer using QGIS.

2.2 Creation of the seven DRASTIC parameters using QGIS

The Gostatistical Analyst Tool from the QGIS 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 Aller *et al.,* (1987). This method was done for depth to groundwater, aquifer media, soil media, hydraulic conductivity, and impact of vadose zone. However for topography, satellite imagery was used, and the slope was extracted by raster tools in QGIS i.e. Digital elevation model (satellite image).

3.0 RESULTS AND DISCUSSION

In order to undertake a detailed hydrogeological assessment of pollution potential using the DRASTIC method, seven thematic maps which depict the DRASTIC model parameters have to be prepared, and each of the parameter evaluated.

3.1 Depth to Water Table

Depth to water table is the distance it takes for pollutants to move through the soil media before getting to the groundwater table. The depth of the water table 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 (Ofomola, 2015). The rating values assigned for the study area are based on the DRASTIC quantitative parameters presented in Table 3. 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 Figure1.

Table 3: DRASTIC quantitative parameters (Aller *et al.,* 1987; Shirazi *et al.,* 2013)

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 × 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

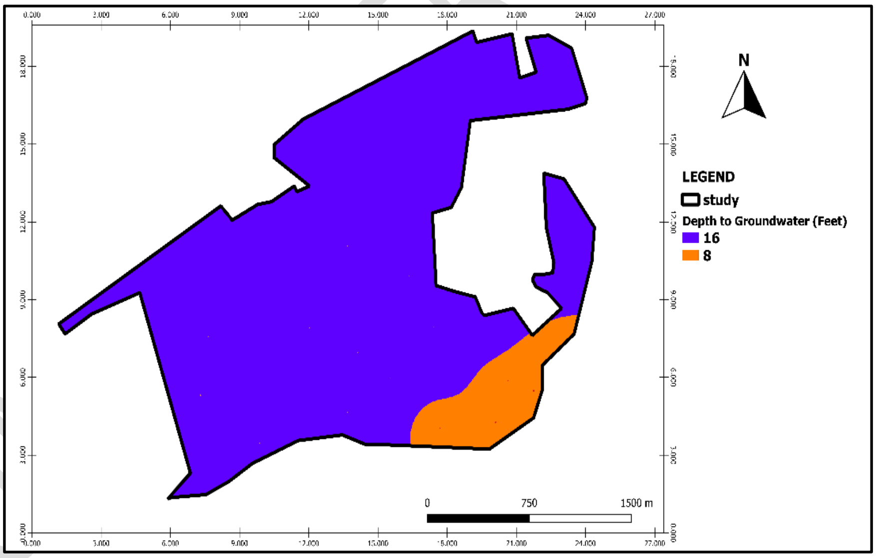

Figure 1: Depth to groundwater level map of the study area

3.2 The Net Recharge

The net recharge is the quantity of water per unit area from rainfall and other sources available that percolate downwards to recharge the aquifer. Net recharge is controlled by several factors such as amount and timing of rainfall, rate of infiltration, slope, nature of the overlying soil, porosity, and permeability of the soil. Recharge is the main means through which pollutants are transported to the water table, and down to the zone of saturation. This implies that the higher the rate of recharge, the more the potential for groundwater pollution. The study area receives about 3000 to 3300 mm/year of rainfall (Efe *et al.*, (2013), 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 shown in Figure 2.

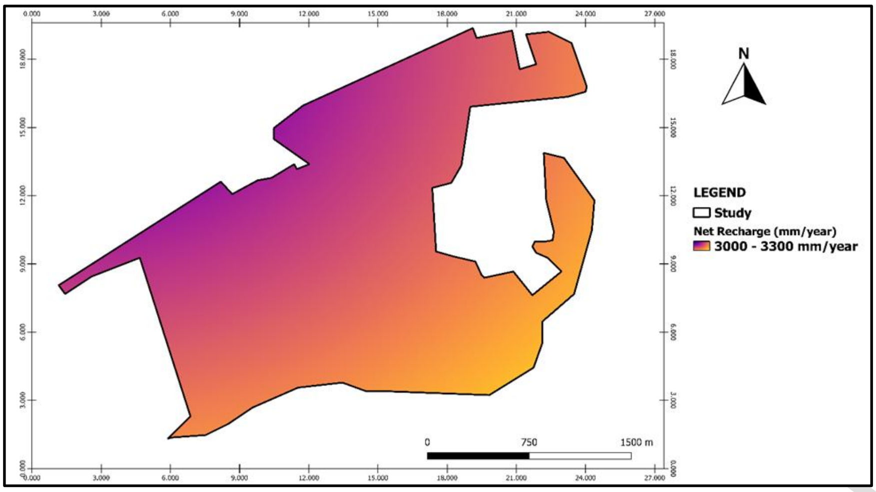

Figure 2: Net recharge map of the study area

3.3 The Aquifer Media

An aquifer is a permeable water-bearing rock strata or sediment that easily transmits sufficient quantities of groundwater. The aquifer media describes the nature 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 affects the flow within the aquifer. This flow path controls the rate at which pollutants contact within the aquifer (Aller et al. 1987). Data used for the aquifer media was obtained from previous research works in the study region. Based on the DRASTIC quantitative parameters, the rating assigned to the aquifer of the study area, which consists predominantly of sand is 8, and the resultant aquifer media map is presented in Figure 3.

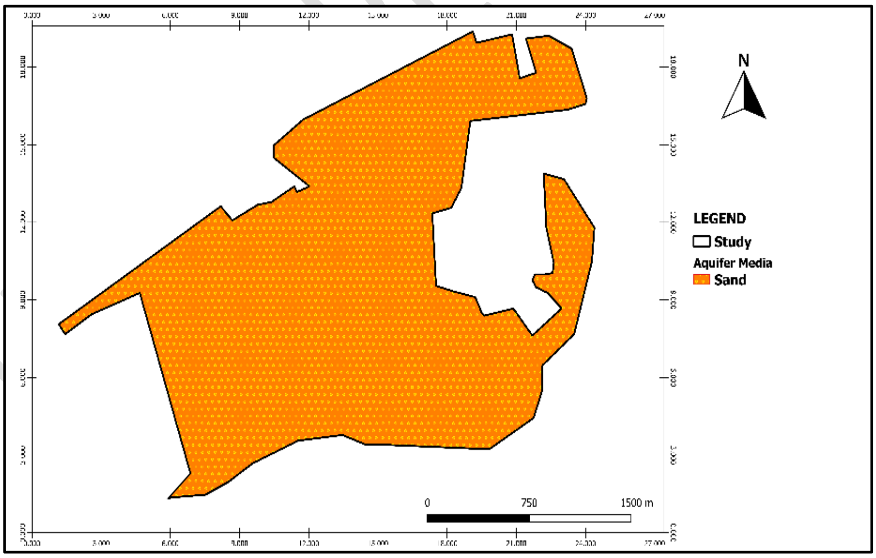

Figure 3: Aquifer media map of the study area

3.4 The Soil Media

This parameter refers to the uppermost portion of the vadose zone characterized by significant biological activity. For the purpose of the DRASTIC model, the soil is commonly considered the upper weathered zone of the earth. This parameter is important because it affects the rate at which recharge infiltrates into the ground and the rate at which contaminants may be attenuated. The texture of the soil greatly affects the ability of contaminants to move through the soil. The soil media map (Figure 4) of the study area was prepared from data collected from previous research works. The DRASTIC rating ranges for various soil textures is shown in Table 3.

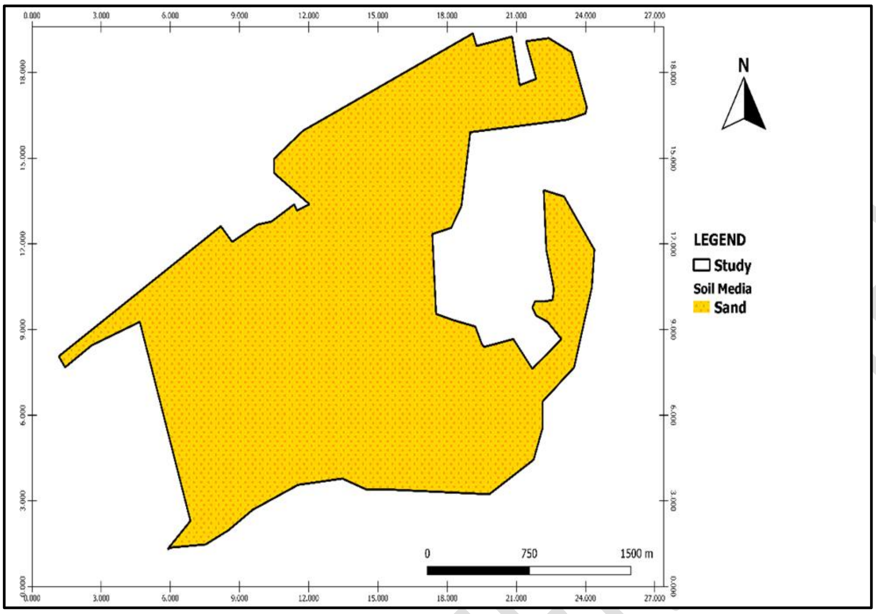

Figure 4: Soil media map of the study area

3.5 Topography

This parameter describes the variability of the slope of the land in the study area. The topography largely affects the possibility 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 influences the land area wherein polluted runoff will flow to, before infiltrating groundwater. Runoff from farmlands often laden with pesticides and other agrochemicals usually moves from areas of higher elevation to a lower elevation, this, therefore, makes lower slopes more vulnerable to pollution. In the study area, the slope ranges from 0 - 18% (Figure 5), and it was classified according to the ratings provided by Aller *et al.,* (Table 3).

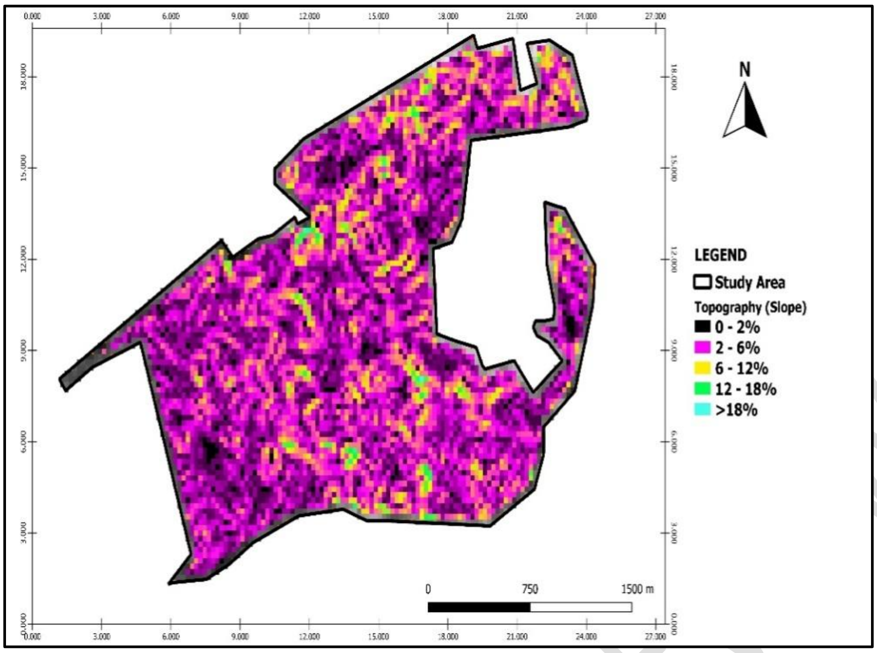

Figure 5: Topographic map of the study area

3.6 Impact of Vadose Zone

This parameter describes the effect of the unsaturated zone, which is the part of the subsurface, above the water table where the pores between the rocks are partially filled with water. The nature of the materials in the vadose zone media controls the migration or attenuation of pollutants into the aquifer.
A number of processes that occur in the vadose zone, may control its pollution potential, these include chemical reactions, mechanical filtration, biodegradation, neutralization, volatilization, and dispersion (Piscopo, 2001). 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 silty sand and was assigned a rating of 1(Table 3) based on the DRASTIC classification. The impact of vadose zone map is presented in Figure 6.

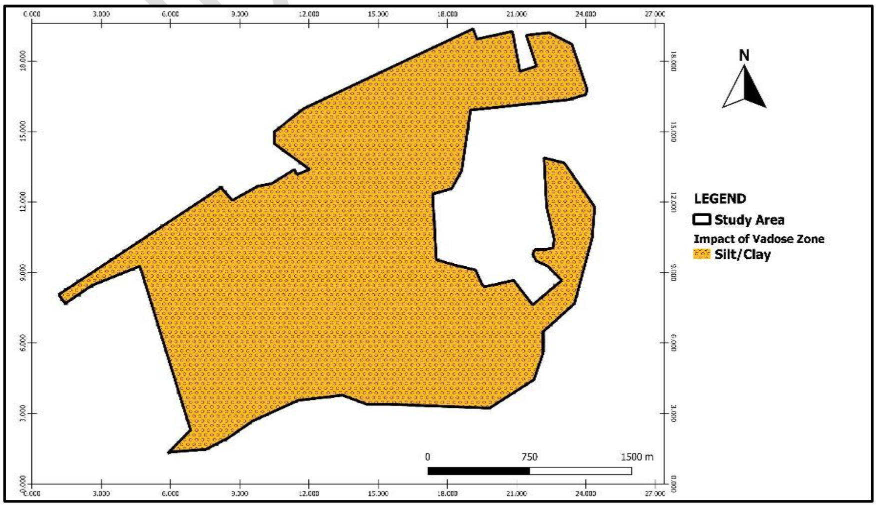

Figure 6: Impact of vadose zone map of the study area

3.7. Hydraulic Conductivity

This parameter shows the rate at which infiltrating water is transmitted into the groundwater. 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 within 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 (Glenn, 2019). The hydraulic conductivity of the aquifer media of the study area was less than 4 m/day (Figure) and was assigned the rating 1.

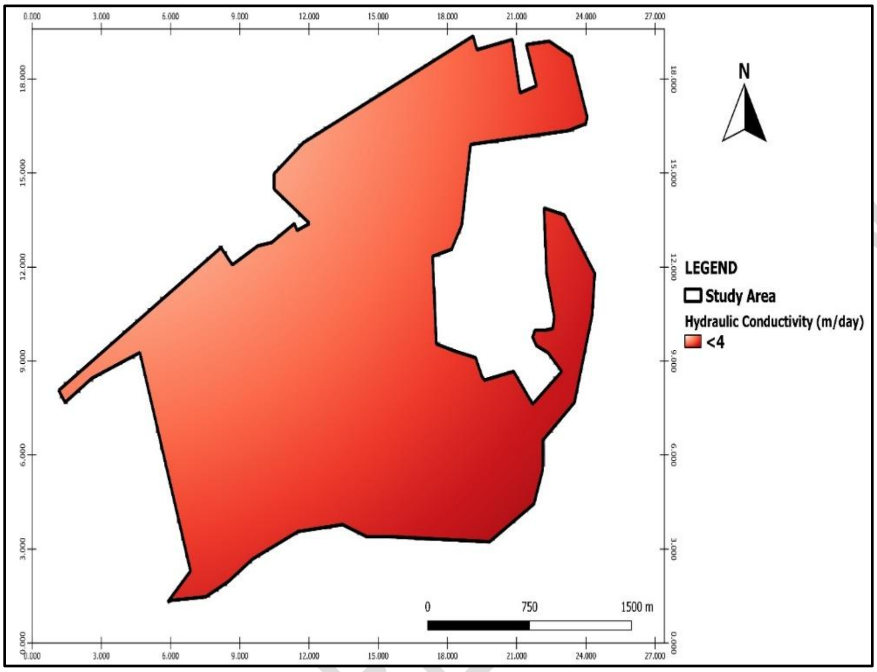

Figure 7: Hydraulic conductivity map of the study area

3.8 Land Use

Human activities and land use has a major impact on groundwater vulnerability. The use of land for industrial, commercial, and agricultural purposes greatly increases its susceptibility to groundwater pollution. Generally land areas with high anthropogenic activities have a high potential for groundwater contamination (Eke *et al*., 2015). 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 land use classification of the study area 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.

3.9 Development of DRASTIC map

The DRASTIC index map shows the four vulnerability ratings (Figure 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 all in raster format and values for each overlay are assigned according to the pixel value of each area that resulted from multiplying the ratings with its appropriate 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.

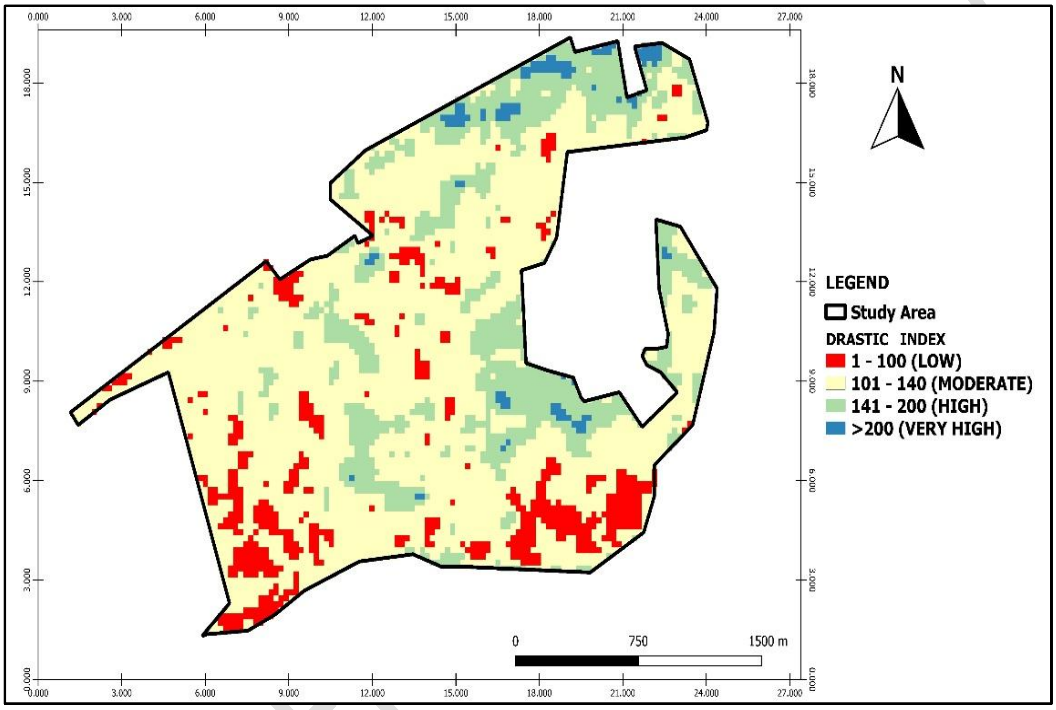

Figure 8: The DRASTIC aquifer vulnerability map of Osubi

4.0 Conclusion

The shallow aquifer of Osubi metropolis, Niger Delta, Nigeria was assessed by employing GIS and the empirical index DRASTIC model of the U.S. Environmental Protection Agency (EPA). Furthermore, the modified DRASTIC approach was used to evaluate the impact of land use activities on groundwater vulnerability. Seven DRASTIC parameters were used to represent the natural hydrogeological settings of the aquifer, depth to groundwater (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity(C). 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 systems should 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 determine the extent of pollution of the groundwater in those areas.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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