NIPES

Journal of Science and Technology Research

Journal homepage: www.nipesjournals.org.ng

Assessing Aquifer Vulnerability to Contamination in the Vicinity of Osubi Dumpsite through the Application of DRASTIC Method

Okonkwo, H. N., Ilaboya, I.R., Kayode-Ojo, N.

Department of Civil Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State Nigeria

Article Info

Keywords: *Aquifer, Contamination, Vulnerability, DRASTIC, GIS, Osubi.*

Received 13 February 2024
Revised 24 March 2024
Accepted 23 April 2024
Available online 20 May 2024

https://doi.org/10.5281/zenodo.11224709

Abstract

In the Niger Delta region of Nigeria, rapid population growth in areas like Osubi, due to the construction of the Warri airport, has raised concerns about aquifer contamination. Factors such as wastewater, borrow pits, dumping sites, and agricultural activities contribute to this risk. This study assesses the vulnerability of the aquifer near the Osubi dumpsite to contamination using the DRASTIC method, integrating Geographic Information System (GIS) technology. Seven environmental parameters—Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity—are considered. Geophysical techniques, including vertical electrical sounding (VES), were used to gather data on depth to water table (D), hydraulic conductivity (C), and aquifer media (A) at ten points. Other data, including soil media (S), vadose zone impact (I), and topography (T), were obtained from previous studies and NASA's Shuttle Radar Topographic Mission (SRTM). Rainfall data were sourced from the PERSIANN system developed by the University of California. Using ArcGIS Pro 10.3, raster maps for each DRASTIC parameter were overlaid to generate a regional-scale aquifer vulnerability map. The resulting map highlights heightened vulnerability in the northwest and southwest regions, potentially linked to historical land usage shifts from the proposed Osubi airport site to the Osubi dumpsite. Additionally, an average depth to the water table ranging from 14m to 22m suggests a shorter contamination travel time, exacerbated by predominantly sandy soil media facilitating infiltration and increasing contamination risk to the aquifer.

1.0. Introduction

Water, an essential resource for life, faces increasing pollution challenges, intensifying the need to ensure its quality for human consumption [1, 2]. Groundwater, sourced from aquifers beneath the earth's surface, represents a vital reservoir of fresh and clean water [3, 4, 5]. In Nigeria, reliance on groundwater as potential sources for drinking water is significant, with estimates suggesting that 60% of the population, including 73% in rural areas and 45% in urban areas, depend on it [6].

Osubi, situated near Warri in the Niger Delta region, experiences rapid growth due to its proximity to the Warri Airport and the Nigeria Petroleum Training Institute (PTI), along with its connection to the oil-producing Niger Delta area. This growth has led to a surge in population and unchecked disposal of industrial and domestic wastes, posing a direct threat to the environment, particularly groundwater resources. Aquifer vulnerability assessments play a crucial role in understanding the potential risks of groundwater contamination, especially in regions where anthropogenic activities, such as waste disposal, pose significant environmental challenges [3, 4]. Previous studies have highlighted the importance of employing robust methodologies to assess aquifer vulnerability, with a particular emphasis on integrating various hydrogeological parameters to accurately delineate areas susceptible to contamination [5]. In similar regions to the study area, such as those with intensive urbanization, industrial activities, and agricultural practices, aquifer vulnerability assessments have been instrumental in guiding groundwater management and environmental protection efforts [6]. For instance, studies in comparable settings have utilized methods such as the DRASTIC (Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and Conductivity) model to assess groundwater vulnerability, demonstrating its applicability and effectiveness in identifying areas at risk of contamination. Furthermore, advancements in remote sensing and geospatial analysis techniques have facilitated the integration of satellite imagery and GIS-based modeling approaches into aquifer vulnerability assessments, providing valuable insights into spatial patterns and trends in groundwater vulnerability [7, 8].
Assessing aquifer vulnerability involves evaluating the potential for groundwater contamination from natural and anthropogenic sources. Various techniques exist for this assessment, including process-based, statistical, and overlay methods [8]. Overlay methods, such as GOD [9], aquifer vulnerability index (AVI) [10], SEEPAGE [11], new index of aquifer susceptibility [12], and DRASTIC [13], have been widely utilized. Despite these advancements, there remains a need for further research to address the limitations and uncertainties associated with existing vulnerability assessment methods and to develop innovative approaches tailored to specific hydrogeological settings. Therefore, this study aims to contribute to the existing body of literature by conducting a comprehensive aquifer vulnerability assessment near the Osubi dumpsite, employing the DRASTIC method and incorporating field data to enhance the accuracy and reliability of the results. By doing so, this research seeks to inform groundwater management strategies and environmental protection measures in similar regions facing similar challenges, thereby addressing a critical gap in the current literature and advancing knowledge in the field of hydrogeology and environmental science.

2.0 Methodology

2.1 Description of Study Area

Osubi, a town situated in Delta State within the Okpe Local Government Area of southern Nigeria, resonates predominantly with the Urhobo dialect and boasts a population of approximately 8,000 residents. It stands as one of the twenty-five local government areas (LGAs) nestled within Delta State, a constituent of Nigeria's South-South geopolitical zone. Geographically, Osubi's coordinates are marked at 5°26′N 5°57′E, as depicted in Figure 1, showcasing the town's location alongside its adjoining dumpsite.

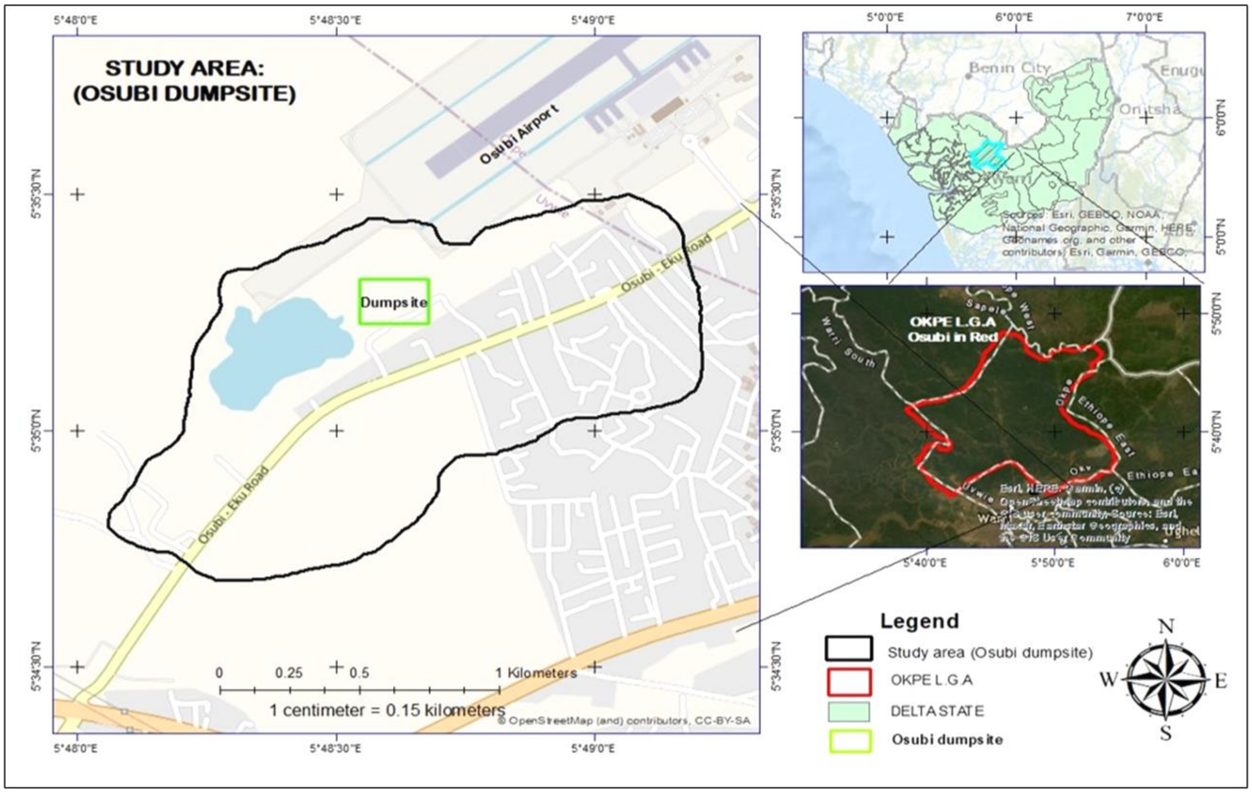

Figure 1: Map of Study area

The administrative hub of the Okpe Local Government Area is Ororeokpe, flanked by neighboring districts such as Ughelli, Uvwie, and Udu. Noteworthy landmarks within the vicinity encompass the sprawling campus of the Petroleum Training Institute and the Osubi Airstrip. The terrain of Okpe LGA is crisscrossed by several rivers and streams, with an average temperature hovering around 25°C. The region experiences a distinct seasonal cycle characterized by a rainy season and a dry season, with an annual precipitation estimate of 3170 mm.

2.2 Lithology of study area

Examining the lithology of the research area reveals parallels with the Niger Delta Basin, typified by three principal depobelts evident in the sedimentary fills. These depobelts trace the evolution of sediments from deep marine mud-sized grains to denser sand-sized grains, indicative of a basin regression over time. The lithological transformations in the region stem from various factors, a subject illustrated in Figure 2, depicting the lithology of the Niger Delta.

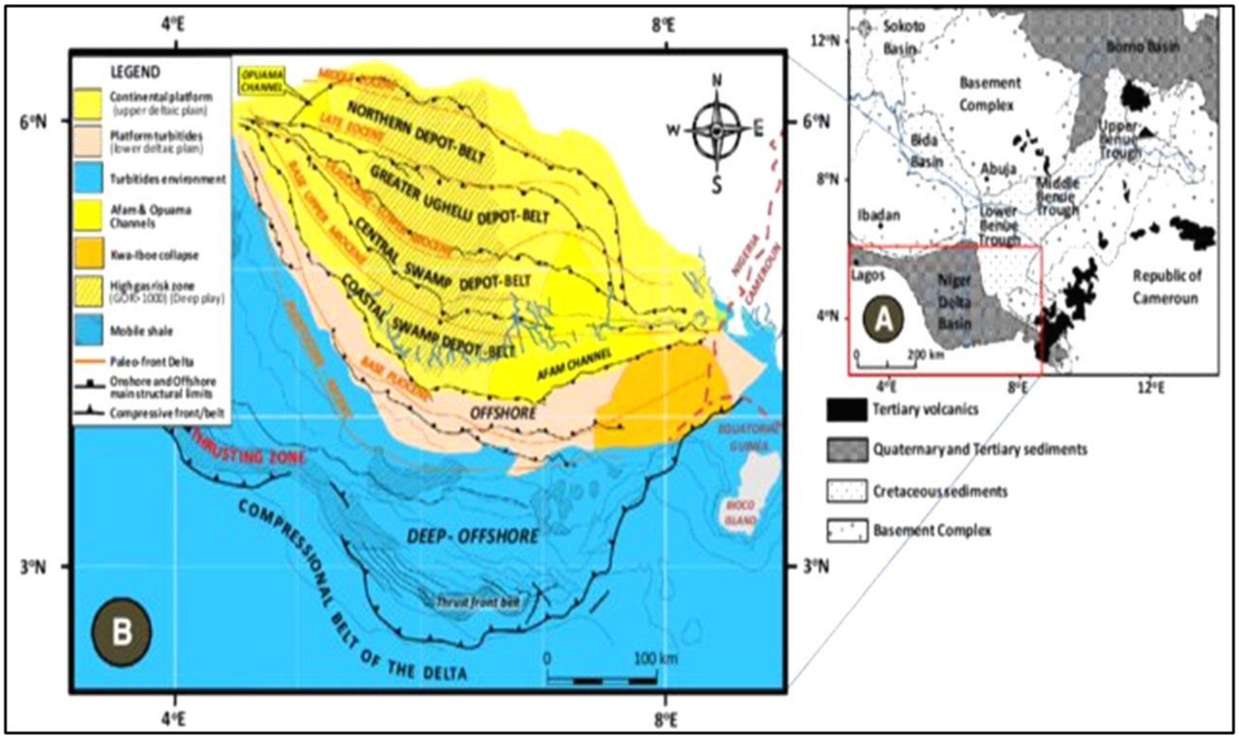

Figure 2: Lithology of the Niger Delta

Topographically, the terrain surrounding Osubi boasts a predominantly level landscape, subtly sloping towards the sea. Positioned beneath this terrain lies the Sombriero deltaic plain, characterized by low-lying Quaternary sands. These sands exhibit a composition ranging from fine to medium and coarse-grained, occasionally interspersed with gravel and feldspar [14, 15, 16, 17]. The plain maintains a gentle gradient, ascending gradually at approximately 1:960 toward the north and northeast, with elevations peaking no higher than 20 meters above sea level.

2.3 Data Collection and Analysis

The DRASTIC methodology was applied comprehensively to assess groundwater vulnerability to contamination. Depth to water (D) was obtained through analysis of well logs and groundwater monitoring network data, while recharge (R) rates were estimated using hydrological models and empirical methods based on meteorological records and land use characteristics. Aquifer media (A) characteristics were derived from geological maps and hydrogeological studies, and soil media (S) properties were determined through soil surveys and laboratory analysis of soil samples. Topographic data (T) including elevation, slope, and drainage patterns were extracted from digital elevation models and topographic maps, while the impact of the vadose zone (I) was assessed based on soil moisture content and land use practices. Conductivity of the aquifer (C) was determined through laboratory tests and aquifer testing methods. Each parameter was assigned a rating based on its influence on groundwater vulnerability, and these ratings were combined using a weighted overlay method to generate a vulnerability map identifying areas of high, moderate, and low vulnerability to contamination as presented in Figure 3.

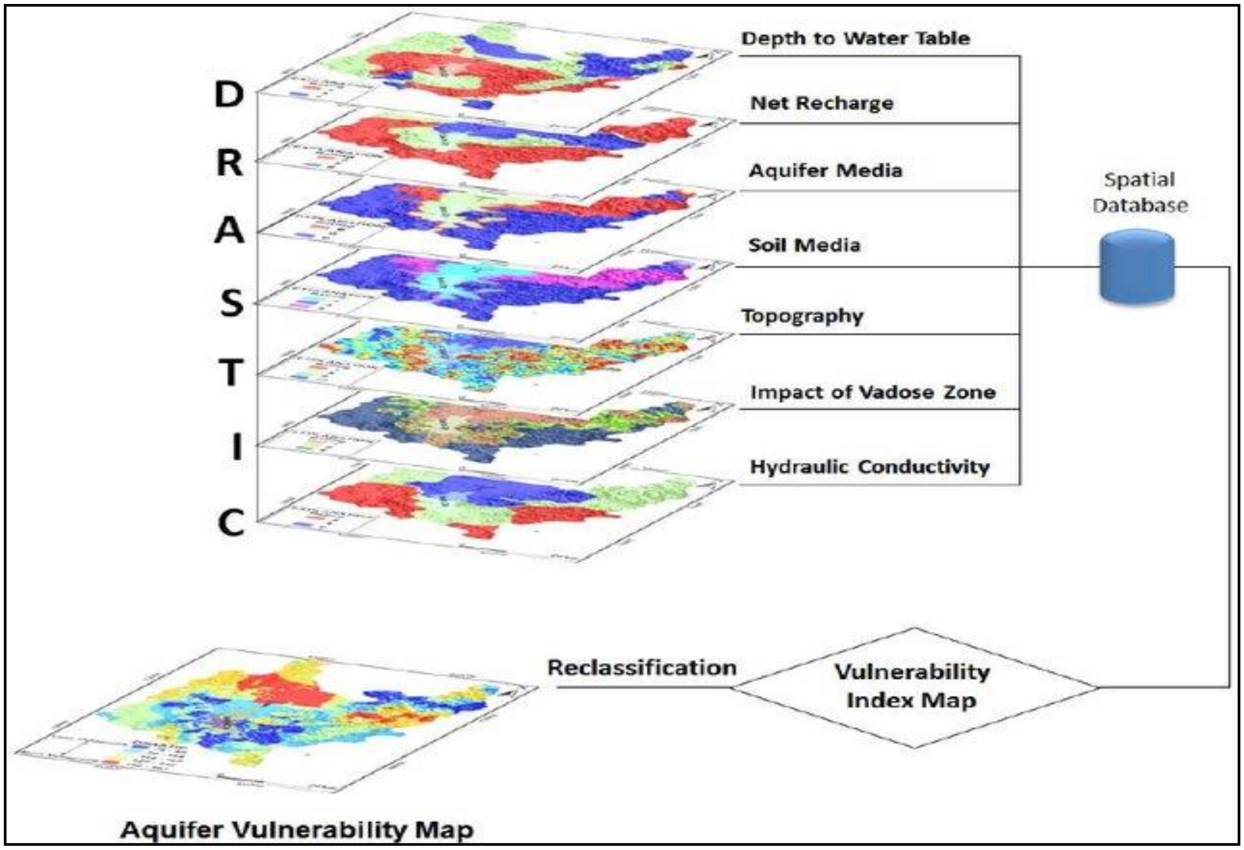

Figure 5: Methodology flowchart for DRASTIC method [18]

To acquire data for the determination of Depth to water table, Vertical Electrical Sounding (VES) was carried out on ten (10) points around the study area. The sounding locations were plotted in the GIS environment using the Latitude and Longitude of each point. For the net recharge, the mathematical expression developed by Umaru et al. (2019) for computing Net recharge from storm rainfall was employed as follows

$$\text{Net Recharge (R)} = 0.621\left(P - 1.019\right)^{0.814} \quad (1)$$

Where P is the total precipitation for a given time period

2.4 Validation of the Vulnerability Map

The methodology for calculating the kappa statistic involved comparing the predicted vulnerability classes generated by the DRASTIC method with observed groundwater quality data. Firstly, the study area was divided into grid cells, with each cell assigned a vulnerability class based on the DRASTIC index values. Subsequently, validation data, such as groundwater quality measurements, were used to classify each grid cell into actual vulnerability categories. Then, a cross-tabulation matrix was constructed to compare the predicted and observed vulnerability classifications. From this matrix, the kappa statistic was computed using the formula, taking into account the agreement between the predicted and observed classifications.

$$K_C = \frac{\left(N \times \sum C_{ii} - \sum r_i \times C_i\right)}{N^2 - \sum r_i \times C_i} \tag{2}$$

Where; c_{ii} represents the number of correctly classified samples in class ii, r_i is the total number of reference samples in class ii, and c_i is the total number of classified samples in class ii. number of reference samples in class ii, and c_i is the total number of classified samples in class ii. The overall accuracy (OA) was then computed as the proportion of correctly classified pixels or objects relative to the total number of samples, using the equation:

$$\text{OA} = \frac{\sum C_{ii}}{N} \times 100\% \tag{3}$$

3.0 Results and Discussion

3.1 Generation of DRASTIC Component Maps

In the assessment of the aquifer's vulnerability, thorough scrutiny was applied to the seven DRASTIC elements. Data for each element were meticulously collected and evaluated, following the guidelines outlined by [13]. Subsequently, individual DRASTIC rating maps were generated and presented in Figures 4 to 10.

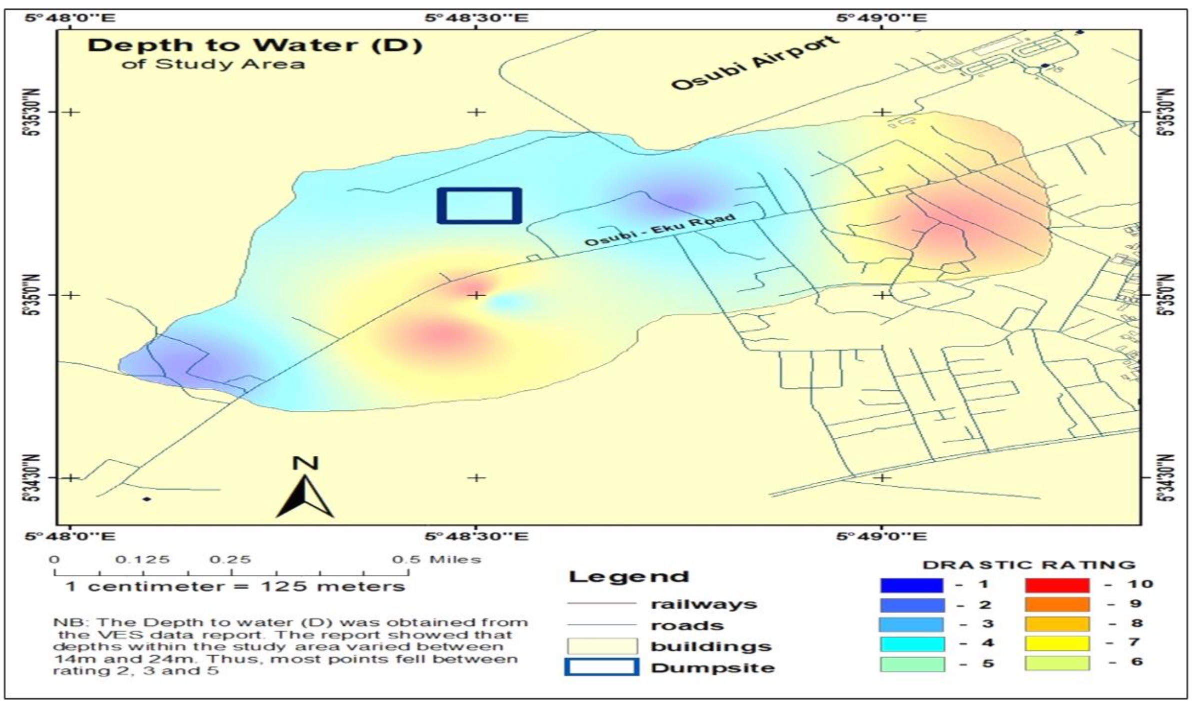

Figure 4: Map of the depth to water table

The depth to the water table significantly influences the vulnerability of an aquifer to leachate contamination. When the water table is shallow, contaminants from surface activities can more readily infiltrate the aquifer, as there's less soil to act as a natural filter and buffer. In such conditions, pollutants like leachate from landfills, agricultural runoff, or industrial waste can easily percolate through the soil layers and reach the groundwater, potentially causing contamination. Conversely, a deeper water table provides a thicker layer of soil to filter out contaminants, reducing the likelihood of contamination reaching the aquifer. Therefore, understanding and managing the depth to the water table is crucial for safeguarding groundwater quality and mitigating the risk of leachate contamination in aquifers. The estimated depth to water table around Osubi dumpsite is presented in Table 1.

Table 1: DRASTIC Parameter Values

S/N	Easting	Northing	Elevation	(D) (m)	(R)	(A)	(S)	(I)	(C) (d/m)
VES 1	05°48.443'	05°35.308'	15m	19	136.688	Sandy	Sandy Loam	Sand	0.5528
VES 2	05°48.417'	05°35.295'	15m	19	139.041	Sandy	Sandy Loam	Sand	0.4344
VES 3	05°48.336',	05°35.282'	14m	16	132.992	Sandy	Sandy Loam	Sand	0.7687
VES 4	05°48.526'	05°34.977'	2.5m	18	136.983	Sandy	Sandy Loam	Sand	0.2342
VES 5	05° 48.504	05° 35.022'	3m	15	142.846	Sandy	Sandy Loam	Sand	0.4577
VES 6	05°48.463'	5° 34.893'	5m	14	146.193	Sandy	Sandy Loam	Sand	0.4725
VES 7	05° 48.751'	05° 35.248'	8m	24	145.176	Sandy	Sandy Loam	Sand	0.6699
VES 8	05°48.783'	05° 35.189'	4m	18	143.575	Sandy	Sandy Loam	Sand	0.3167
VES 9	05°48.150'	05° 34.803'	9m	22	136.688	Sandy	Sandy Loam	Sand	0.3346
VES 10	05°49.076'	05°35.197'	3m	14	139.628	sand	Sandy Loam	sand	0.7245

Depth to water table ranging from 14m to 24m was recorded around Osubi dumpsite which can be said to be low. The net recharge map is presented in Figure 5.

The net recharge rate profoundly influences the vulnerability of an aquifer to leachate contamination. Net recharge represents the balance between water entering and leaving the aquifer, including precipitation, runoff, and infiltration. Higher net recharge rates increase the movement of water through the soil layers, potentially carrying contaminants deeper into the aquifer. In areas with high net recharge, such as regions with frequent rainfall or low evapotranspiration rates, there's a greater risk of leachate from landfills, agricultural chemicals, or industrial pollutants infiltrating the groundwater system. Conversely, lower net recharge rates result in slower groundwater movement, providing more time for natural attenuation processes to remove contaminants and reducing the risk of leachate contamination in aquifers. Figure 6 present the aquifer media map of the study area

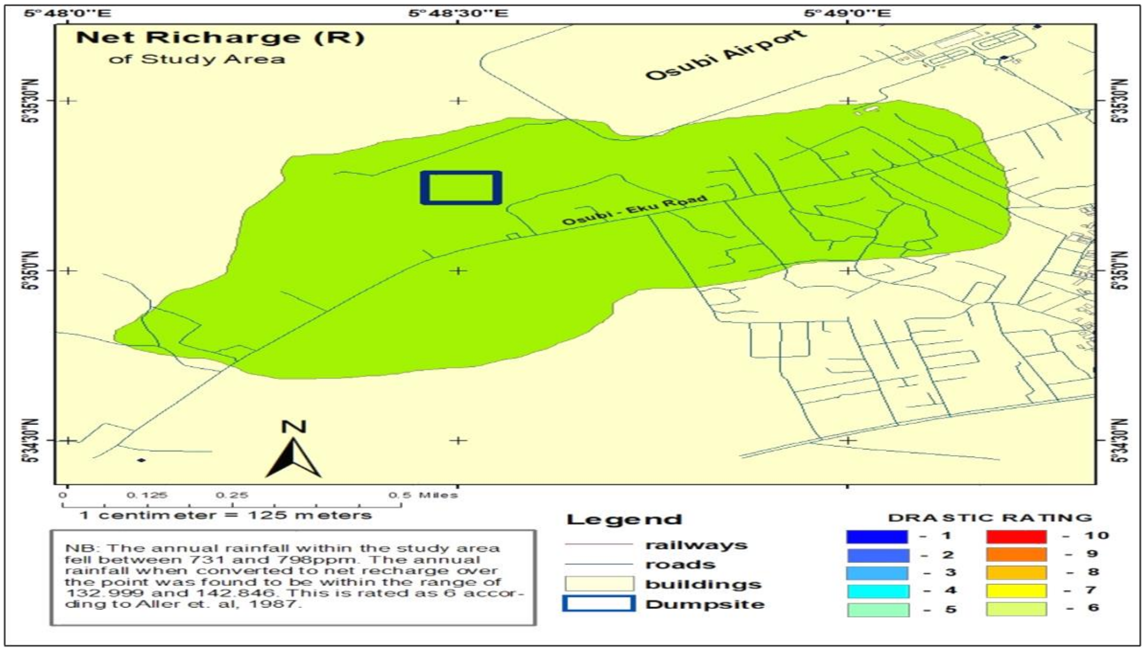

Figure 5: Net Recharge of the area surrounding Osubi dumpsite

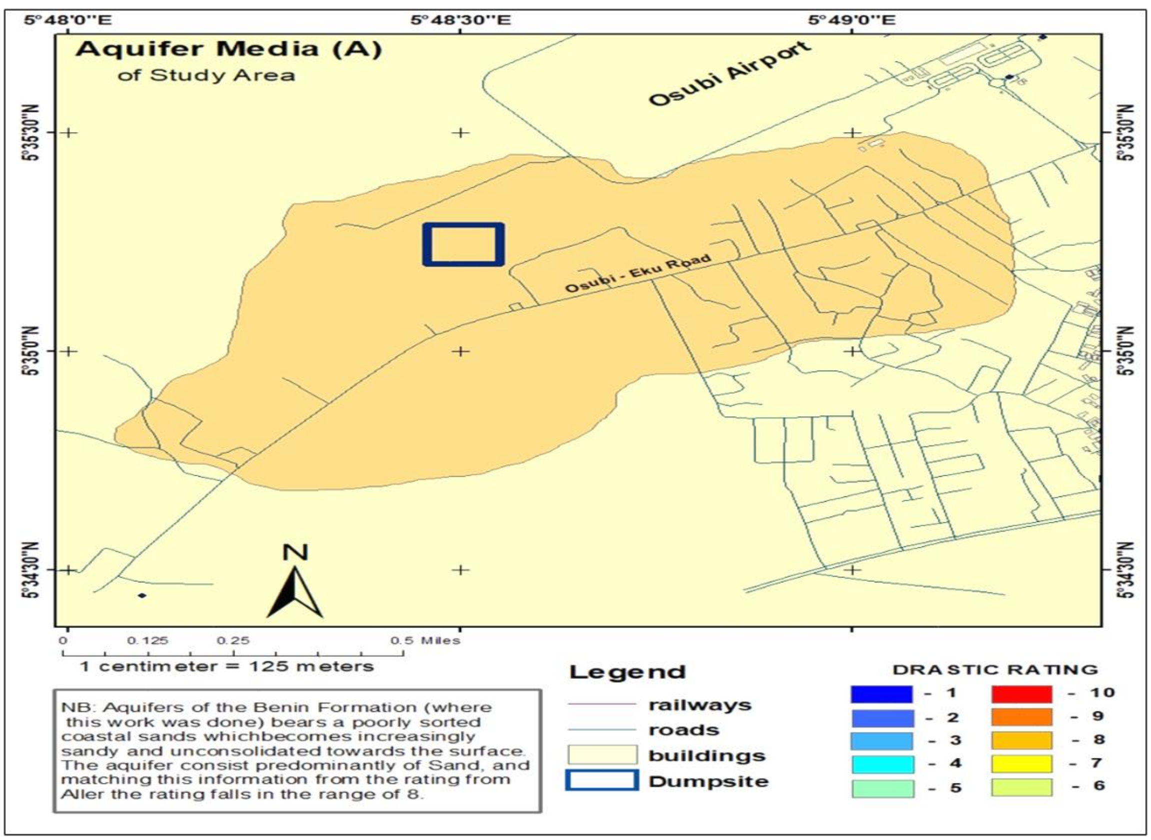

Figure 6: Aquifer media of the area surrounding Osubi dumpsite

Aquifer media composition significantly influences vulnerability to leachate contamination, with geological characteristics determining the rate and extent of contaminant transport. Porosity and permeability of aquifer materials play crucial roles: highly permeable materials like sand and gravel facilitate rapid contaminant migration, while low-permeability materials like clay may impede contaminant movement but increase surface runoff risk. Additionally, the presence of fractures or conduits in geological formations can enhance contaminant transport pathways, intensifying vulnerability. Understanding aquifer media properties is essential for assessing contamination risk and implementing effective protection measures to safeguard groundwater quality. Figure 7 presents the soil media map of the study area.

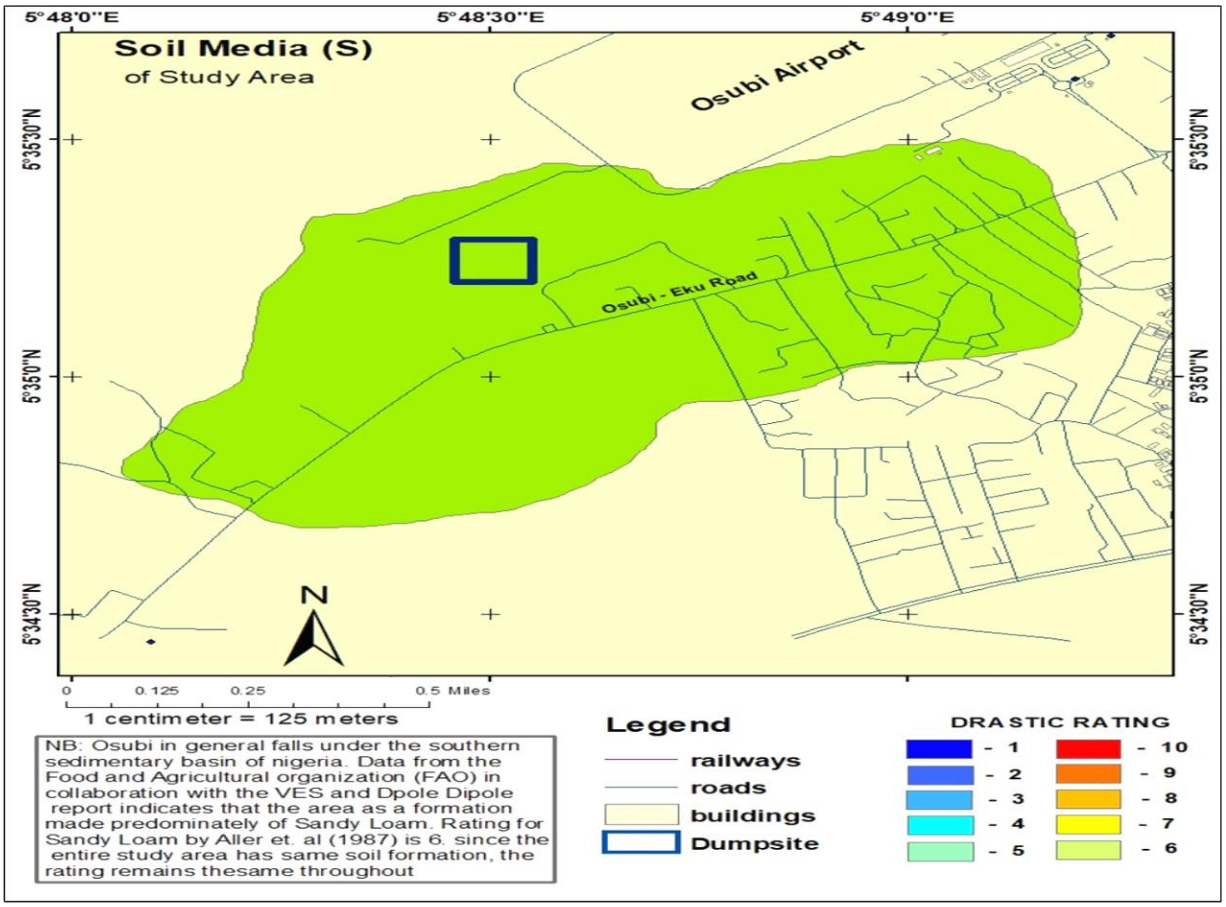

Figure 7: Soil media of the area surrounding Osubi dumpsite

Soil characteristics profoundly influence the vulnerability of aquifers to leachate contamination, acting as both a natural filter and barrier. Factors such as soil texture, composition, and permeability play pivotal roles: fine-textured soils like clay, with lower permeability, impede contaminant movement into aquifers but heighten surface runoff risk, while coarse-textured soils like sand, with higher permeability, facilitate rapid contaminant transport into groundwater. Additionally, soil composition influences contaminant retention, with organic-rich soils capable of adsorbing and retaining contaminants, and highly weathered soils potentially exhibiting reduced filtration capacity. The topographical map of the study area is presented in Figure 8

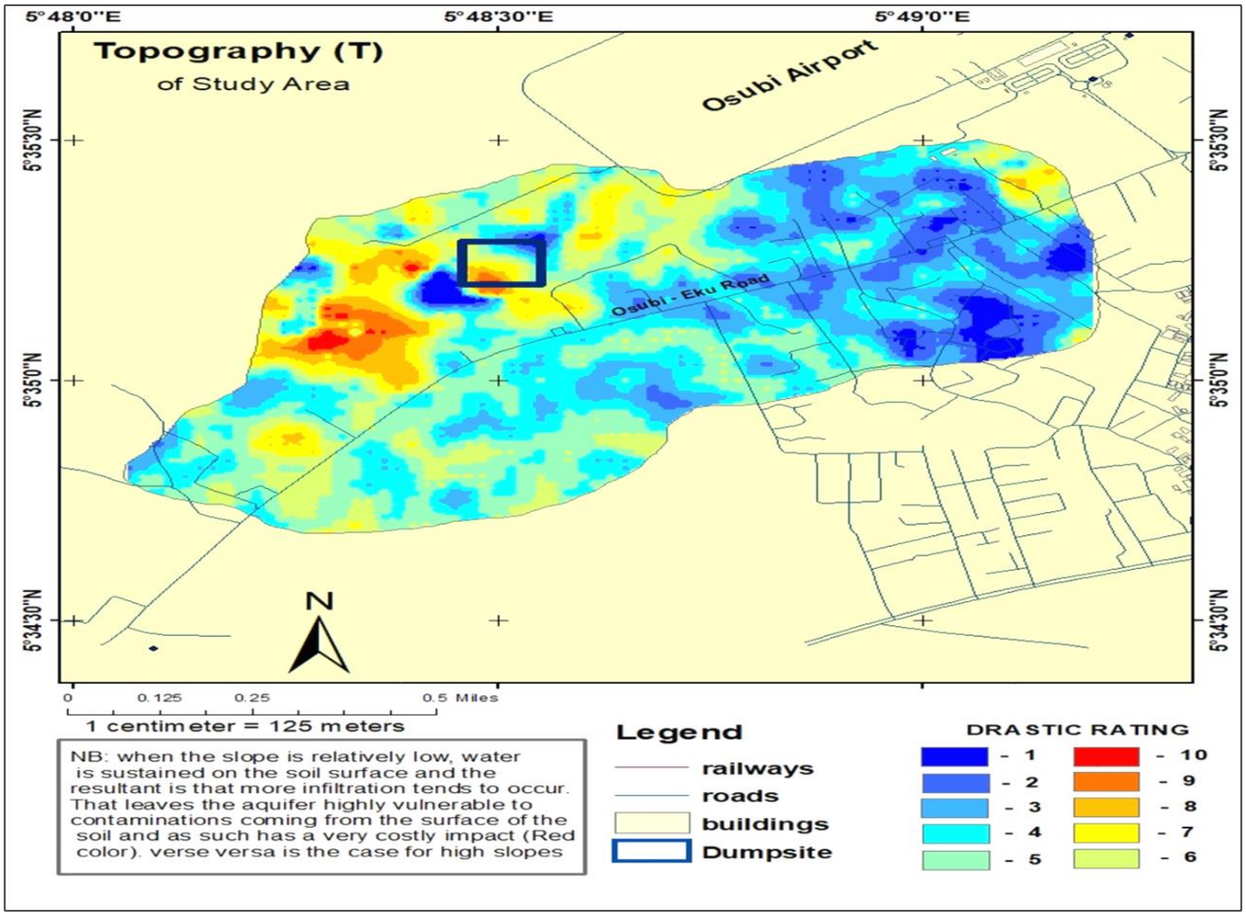

Figure 8: Topography of the area surrounding Osubi dumpsite

Topography plays a pivotal role in determining the vulnerability of aquifers to leachate contamination, with steep slopes increasing the risk due to faster surface runoff, potentially carrying pollutants into groundwater sources, while flat or gently sloping terrain may allow for slower infiltration and natural filtration processes, reducing the risk. Additionally, the presence of surface depressions or valleys in the landscape can create localized areas of concentration for contaminants, exacerbating the potential for contamination of aquifers. The vadose zone, the unsaturated layer of soil above the water table, plays a critical role in determining aquifer vulnerability to leachate contamination. Its characteristics, such as soil texture, depth, and moisture content, influence the fate and transport of contaminants. Infiltrating contaminants may undergo physical, chemical, and biological processes within the vadose zone, potentially attenuating or enhancing their migration to the water table. Factors such as high permeability and low organic matter content can increase the risk of rapid contaminant transport through the vadose zone, while denser soils and higher organic matter content may provide greater retention and attenuation of contaminants.

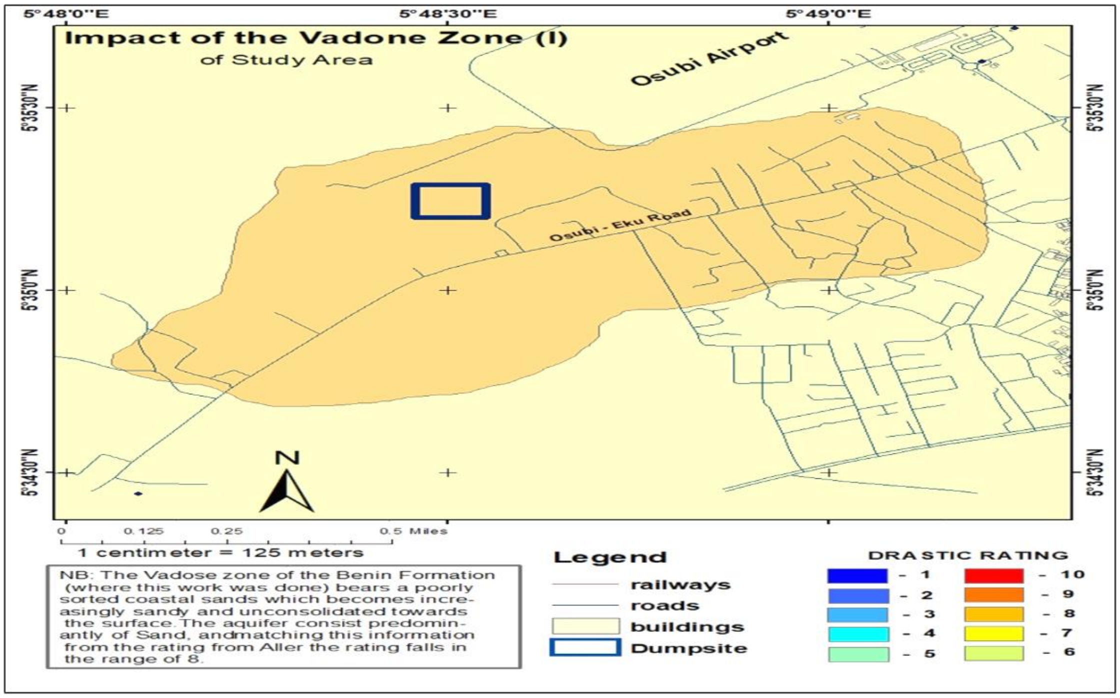

Figure 9: Impact of Vadose zone of the area surrounding Osubi dumpsite

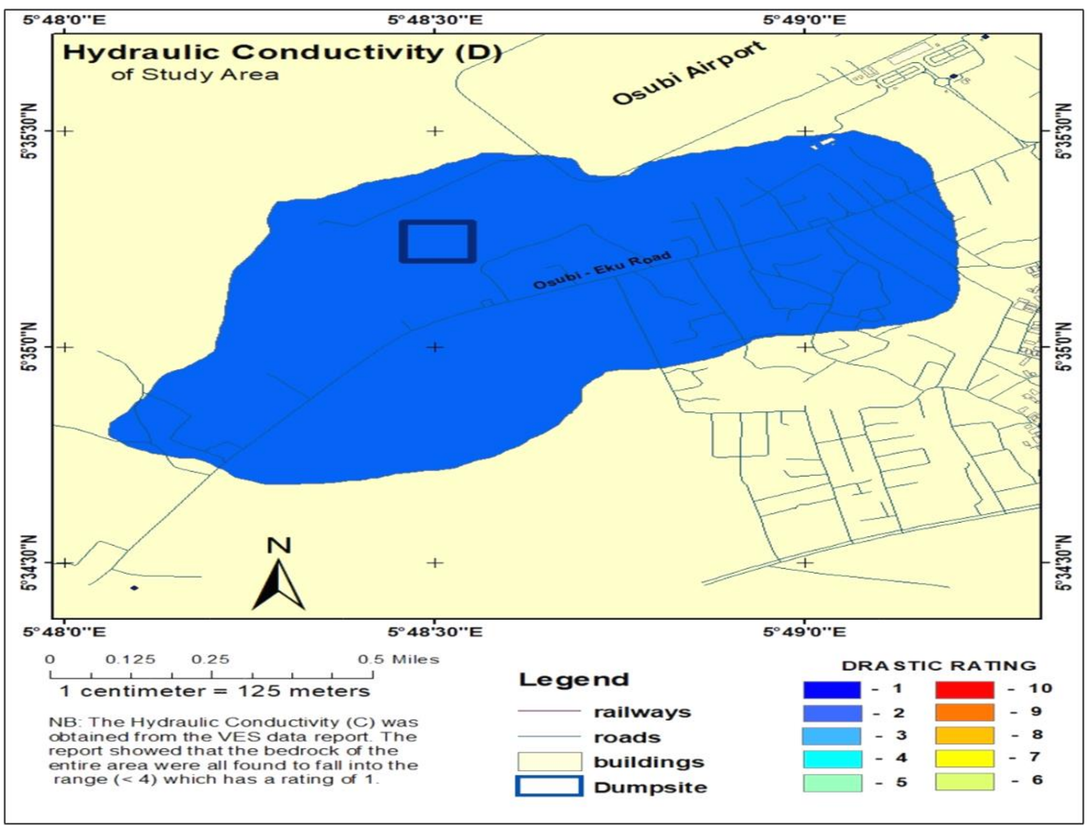

Figure 10: Hydraulic conductivity of the area surrounding Osubi dumpsite

Aquifer hydraulic conductivity, representing the ability of an aquifer to transmit water, profoundly influences its vulnerability to leachate contamination. High hydraulic conductivity means water can flow more freely through the aquifer, potentially facilitating rapid movement of contaminants into groundwater. Conversely, low hydraulic conductivity may impede contaminant migration but might also increase the likelihood of surface runoff and pooling, leading to localized contamination. Understanding the hydraulic conductivity of aquifers is crucial for assessing the potential pathways and rates of contaminant transport, guiding the development of effective protection and remediation measures to safeguard groundwater quality.

An overlay analysis ensued by amalgamating these maps, with weights assigned based on their significance and relevance was conducted. The resulting output from this overlay analysis produced the vulnerability map of the aquifer within the study area, with a particular focus on Osubi, illustrated in Figure 11.

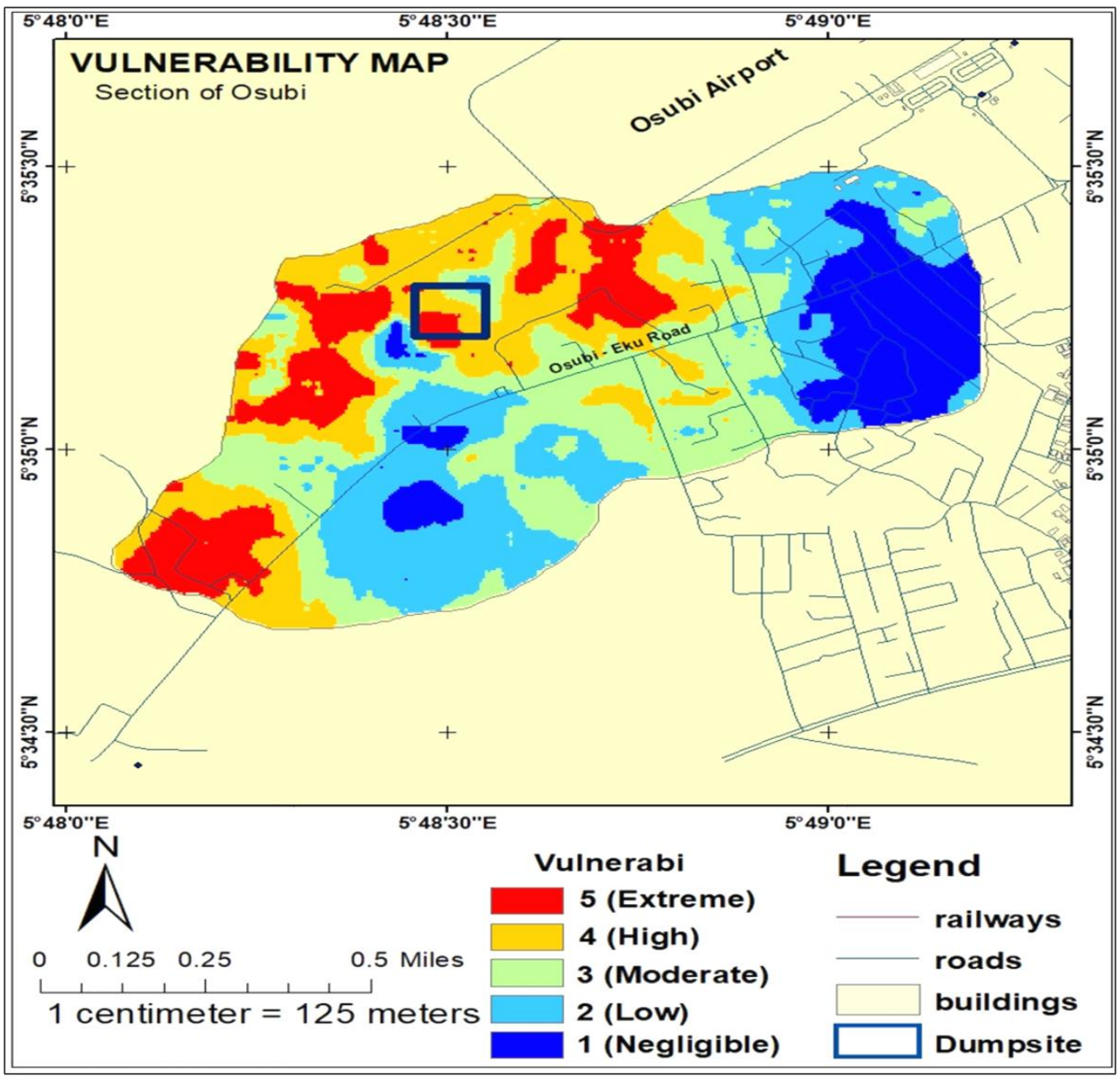

Figure 27: Aquifer Vulnerability Map of Osubi

The vulnerability of the aquifer in the Osubi study area was assessed using the seven DRASTIC elements, with data collected and rated accordingly. Individual DRASTIC rating maps were generated and overlaid through an overlay analysis, incorporating weighted factors based on their significance. The resulting vulnerability map, illustrated in Figure 2, delineates areas of extreme vulnerability (marked in red) and lesser vulnerability (blue). These areas were classified into five categories: Extreme, High, Moderate, Low, and Negligible, with the latter presenting minimal risk of contamination and thus suitable for borehole or drinking well placement. Notably, heightened vulnerability is evident in the northwest and southwest regions, potentially attributed to historical land usage shifts resulting from the transformation of these areas from the proposed Osubi airport site to the Osubi dumpsite. Furthermore, the average depth to the water table ranging from 14m to 22m suggests a shorter contamination travel time, exacerbated by the predominantly sandy soil media facilitating infiltration and increasing contamination risk to the aquifer.

3.2.Validation of the Vulnerability Map

Results of the validation analysis which include computation of the overall accuracy (OA) and the kappa coefficient (K_C) is presented in Table 2.

Table 2: Accuracy assessment of vulnerability map

	Depth to Watar Map	**Net Recharge**	**Aquifer media map**	**Soil media map**	**Topographic map**	**Impact of Vadose zone map**	**Hydraulic conductivity map**
Overall Accuracy	78.2	84.6	85.7	86.8	88.3	78.9	83.1
Kappa Statistics	78.6	82.8	85.3	89.1	79.3	88.3	87.1

In considering the limitations and potential uncertainties associated with the DRASTIC method and the data used in this study, several factors merit discussion to provide a comprehensive understanding of the results' scope and applicability. Firstly, while the DRASTIC method offers a systematic framework for assessing aquifer vulnerability, it inherently relies on various assumptions and simplifications that may introduce uncertainties. These include the static nature of some parameters, such as lithology and soil type, which may change over time due to natural processes or anthropogenic activities. Additionally, the DRASTIC method does not account for dynamic factors like seasonal variations in groundwater levels or the influence of climate change on hydrological patterns, which could impact vulnerability assessments. Furthermore, the accuracy of the vulnerability map generated through the DRASTIC method is contingent upon the quality and availability of input data, such as hydrogeological parameters and land use information. Uncertainties associated with data collection methods, measurement errors, and spatial resolution can affect the reliability of the vulnerability assessment results.

4.0 Conclusion

The aquifer vulnerability map produced through the DRASTIC overlay method serves as a valuable tool for multiple purposes. It not only aids in selecting optimal borehole drilling locations within Osubi but also provides valuable insights into the hydrogeological conditions of the area.

Based on the vulnerability assessment near the Osubi dumpsite using the DRASTIC method, key recommendations for groundwater management and environmental protection include implementing protective measures such as buffer zones and waste management regulations, conducting regular groundwater monitoring, enhancing public awareness and education, exploring alternative waste disposal methods, fostering collaborative management approaches, integrating geophysical techniques for enhanced assessment accuracy, and prioritizing long-term research and monitoring efforts to track changes in groundwater quality and vulnerability over time. These strategies aim to mitigate contamination risks, ensure sustainable groundwater use, and protect the environment in Osubi and similar regions facing similar challenges.

References

[1] Olatunji, J., Odediran, A., Obaro, R., Olasehinde, P. (2015). "Assessment of Groundwater Quality of Ilorin Metropolis using Water Quality Index Approach", Nigerian Journal of Technological Development, 12: 18-21.

[2] Balamurugan, P., Kumar, P. S., Shankar, K., Nagavinothini, R., & Vijayasurya, K. (2020). Non-carcinogenic risk assessment of groundwater in Southern Part of Salem District in Tamilnadu, India. Journal of the Chilean Chemical Society, 65, 4697–4707.

[3] Bawoke, G. T., & Anteneh, Z. L. (2020). Spatial assessment and appraisal of groundwater suitability for drinking consumption in Andasa watershed using water quality index (WQI) and GIS techniques: Blue Nile Basin, Northwestern Ethiopia. Cogent Engineering, 7(1), 1748950.

[4] Hei, L., Bouchaou, L., Tadoumant, S., & Reichert, B. (2020). Index-based groundwater vulnerability and water quality assessment in the arid region of Tata city (Morocco), Groundwater for Sustainable Development, 100344

[5] Majolagbe, A. O., Kasali, A. A., & Ghaniyu, L. O. (2011). Quality Assessment of Groundwater in the Vicinity of Dumpsites in Ifo and Lagos, South Western Nigeria. Advances in Applied Sciences Research, 2, 289-298.

[6] Oseji, J. O., Egbai, J. C., Okolie, E. C., & Ese, E. C. (2018). Investigation of the aquifer protective capacity and groundwater quality around some open dumpsites in Sapele Delta state, Nigeria. Applied and Environmental Soil Science, 1

[7] Ofomola, M. O. (2015). "Integrated Geophysical and Hydrogeochemical Studies of Shallow Aquifer Contamination in Osubi, Near Warri, Southern Nigeria," Journal of Earth Sciences and Geotechnical Engineering, 5(4): 79-102

[8] Fritch, T. G., McKnight, C. L., Yelderman, J. C. and Arnold, A. L. (2000). "An aquifer vulnerability assessment of the Paluxy aquifer, central Texas, USA, using GIS and a modified DRASTIC approach", *Environ. Management*, *25*: 337-345.

[9] Foster, S. S. D. 1987. Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: van Duijvenboden, W., van Waegeningh, H. G. (ed). Vulnerability of Soil and Groundwater to Pollutants. TNO Comm. on Hydro. Research, The Hague, The Netherlands. Proceeding and Information 38: pp. 69–86.

[10] Van Stemproot, D., Ewert, L. and Wassenaar, L. (1993). "Aquifer vulnerability index: a GIS compatible method for groundwater vulnerability mapping", *Can. Water Resour. J. 18* (1), 25–37

[11] Navulur, K.C. (1996). Groundwater Vulnerability Evaluation to Nitrate Pollution on a Regional Scale Using GIS (Unpublished Doctoral dissertation). Purdue University, Indiana.

[12] Ribeiro, L. (2000). A new index of aquifer susceptibility to agricultural pollution. Internal report, ER-SHA/CVRM, Instituto Superior Tecnico, Lisbon, Portugal, 12 pp.

[13] Aller, L., Bennett, T., Lehr, J. H., Petty, R. J., Hackett, G., (1987). "DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Settings", EPA-600/2-87-035

[14] Akpokodje, E. G. and Etu-Efeotor. J. O. (1987). "The Occurrence and Economic Potential of clean sand deposits of the Niger Delta", *Journal of African Earth Sciences, 6*(1): 61-65

[15] Olobaniyi, S. B. and Owoyemi, F. B. (2006). "Characterization by Factor Analysis of the Chemical Facies of Ground Water in the Deltaic Plain Sands Aquifer of Warri Western Niger Delta, Nigeria", *African Journal of Science and Technology, 7*: 73-81.

[16] Odemerho, F. O. and Ejemeyovwi, D. O. (2007). "The Physiographic Provinces and Drainage Systems of Delta State, Nigeria", In: F.O. Odemerho et al.(eds) Delta State in Maps, Delta State University, Abraka: 9-17.

[17] Wigwe, G. A. (1975). "The Niger Delta: Physical", In G.E.K. Ofomata (ed). Nigeria in maps: Eastern States. *Ethiope Publ. House, Benin City*: 380–400.

[18] Yahia, A., and El-Mansouri, B. (2011); Assessment of Aquifer Vulnerability Based on GIS and ARCGIS Methods: A Case Study of the Sana'a Basin (Yemen), Journal of Water Resource and Protection, 3, 845-855