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Environmental and Geotechnical Assessment of Suitable Eco-Friendly Disposal Site for Tailings from Bitumen Mining

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ABSTRACT

The major occupation of people living within the bitumen region in Ondo State Nigeria are farming and fishing, and their sources of water intake includes streams and borehole, which can be polluted due to tailings spillage. This research aims at proffering solutions to tailings pollution challenges expected to face bitumen exploitation sites by finding the most suitable locations for the tailing ponds within the study area. Environmental, Geological and Geotechnical conditions of the study area were assessed with each having seven (7) different assessment criteria. Geography Information System (GIS) concept was then adopted to nest the result of these assessments into maps for analytical purposes and for selecting favourable zones for bitumen tailings deposit site. The result showed all zones of the study area favourable in four (4) of the seven (7) environmental conditions, with the southern section, being more favourable preffered, due to low erosion and high forest density. However, geological and geotechnical assessment results were more specific and diverse with different territories for each criteria, but predominantly at the southern and northern regions of the study area. Good collaboration between geologists, engineers, and local planners to ensure that the most suitable natural sites are selected for waste disposal facilities would minimize effectively the environmental degradation of bitumen mining activities on residents of the mining locations.

Keywords: Bitumen, Geography Information Systems (GIS), Site Selection, Geotechnical Assessment, Tailings, Pollution

1.0 INTRODUCTION

As a major source of energy and minerals for the huge manufacture of goods that are sold all over the world, mining is an important economic activity. The environmental impact of mining operations is most noticeable when it comes to materials, primarily low-grade ores and other unmarketable rock minerals that are employed in mineral beneficiation. For the purpose of exploring and exploiting bitumen in Ondo State and its neighboring State, the Federal Government of Nigeria granted licenses to potential investors and Ondo State. The majority of the people who live in the bitumen region work in agriculture and fisheries, and streams are the main source of water for them. Bituminous mining activities produce large amounts of mine tailings and chemicals used in the beneficiation process, which are stored in mine dumps where there is a risk of heavy metals and chemicals leaching into the soil, surface water, and groundwater, which could have a serious negative impact on ecosystems and pose a health risk to humans.

The residual materials left behind after precious minerals are extracted and recovered during mining operations are known as tailings. A tailing pond is a waste reservoir or storage facility where huge amounts of water required for processing are left behind after bitumen is recovered. The solids settle over time, allowing the water to be recovered. The slurry generated is then left behind. Pollution of both surface and groundwater are the main long term environmental hazards linked with such dumps of tailings. Contaminated surface waters in well-managed dumps can be treated, but groundwater contamination is more difficult to manage since, depending on the geology, contaminated leachate from the waste can easily sink downhill into the groundwater. In order to accomplish the goal of preventing contaminated leachate from entering the groundwater, it would be preferable to tackle the issue by combining cautious natural site selection with wise site management techniques. [1].

The development of liquid or solid waste management likely involves the most crucial steps being the selection of disposal sites and tailing ponds. The selection of disposal sites is typically done using conventional procedures, such as political interests or conventional decision-making techniques. Nonetheless, some of the best methods for comprehending disposal sites are now being recognized, including Remote Sensing (RS) and Geographic Information Systems (GIS) techniques. The ability to control many site aspects and terrain features has improved recently with advances in satellite technology and computing capacity. Geographic Information Systems (GIS), Geological and Geotechnical Engineering (geo-engineering) are important factors in site selection.

This study is required to investigate how to manage the tailings or waste from the proposed bitumen exploitation so as to avert the environmental pollution challenges facing bitumen exploitation sites. This will help in preventing the re-occurrence of community unrest faced because of oil pollution in the Niger Delta region.

Table 1, highlights contemporary study for water and waste deposit site selection which has been conducted at various places

Table 1: Review of Pond/Deposit Site Suitability Studies

References	**Study Area**	**Utilized Criteria**
Noori *et al* [2]	Greater Zab River, Northern Iraq (Water Supply)	Rainfall, geology, soil type, fault line, tectonic line, altitude, slope, road network, LU/LC, material used for dam construction
Mohammed *et al* [3]	Dam site suitability assessment at the Greater Zab River in northern Iraq (Dam Water Supply)	Geologic Formation, soil types, rainfall, faults, land use, road network, altitudes
Hossein *et al* [4]	Markaze province Iran, Himalayan region, India, (Landfill sites)	Floodway, surface water, groundwater depth, slope, road etc
Sayl *et al* [5]	Western dessert of Iraq	Western dessert of Iraq

2.0 METHODS

2.1 Regional Geology of Study Area

Bitumen deposits in Ondo State is restricted to the Okitipupa Ridge area and lies between Latitude 6˚ 30' and 6˚ 54' N and Longitudes 3˚ 30' and 5˚ 34' E. The sedimentary basin of Ondo State is bounded by Latitudes 5˚ 52' and 7˚ 00' N and Longitudes 4˚ 23' and 5˚ 54' E. The sedimentary basin of Ondo State falls within the eastern portion of the Dahomey Basin and underlain by the Coastal Alluvium at the extreme south and along major river flood plain [6].

These formations have variable hydrogeological characteristics. The shallow aquifers within the southern sedimentary portion of Ondo State have been investigated and found to be vulnerable to near-surface contaminants. The terrain is flat with gently undulating topography, and the geomorphologic units include sand ridges, lagoons, swamp flats, and creeks. Numerous rivers flow southward to the Atlantic Ocean, including the Owena, Oluwa, Oni, Ogbese, Ose, Ominla, Akeun, and Ufara. The major rivers flow through the sedimentary rocks in deeply incised valleys aligned in a north-south direction, into the coastal lagoons. Oteri and Atolagbe [7] observed that potable water supply to inhabitants in some of the communities in the sedimentary rock underlain southern (coastal belt) part of Ondo State had been a major problem due to salt water intrusion.. The major rivers flow through the sedimentary rocks in deeply incised valleys aligned in a north-south direction, into the coastal lagoons. The mean monthly temperature is 27˚C, with a mean monthly range of 2˚C. The mean annual total rainfall exceeds 2000 millimeters. Which cut across few Local Government areas like; Irele, Okitipupa, Ilaje, Odigbo and Ese-Odo as shown in Figure.1. Some localities are having surface deposit of bitumen among them are; Agbabu, Looda, Abusoro, Ode Aye, Idiobilayo, Oke Oyinbo, Oniparaga, Ogbere, Ilubirin, Mofere, Erekiti-Luwoye, Ode Erinje and others as shown in fig. 2, within Dahomey basin [6]

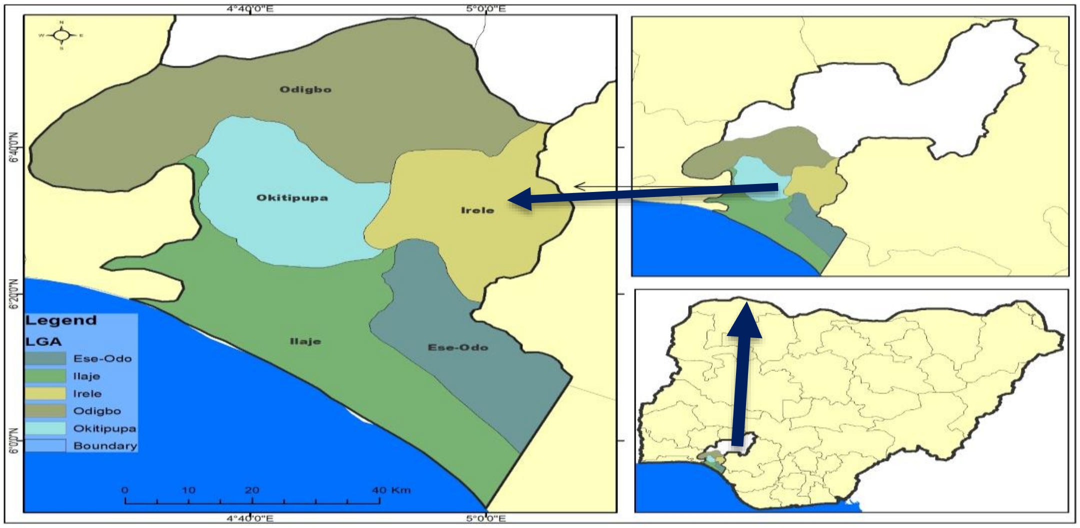


Fig. 1 Map of Local Government Areas with Bitumen Deposit in Ondo State from Nigeria Map (Source: Adapted from the ArcGIS Imagery)

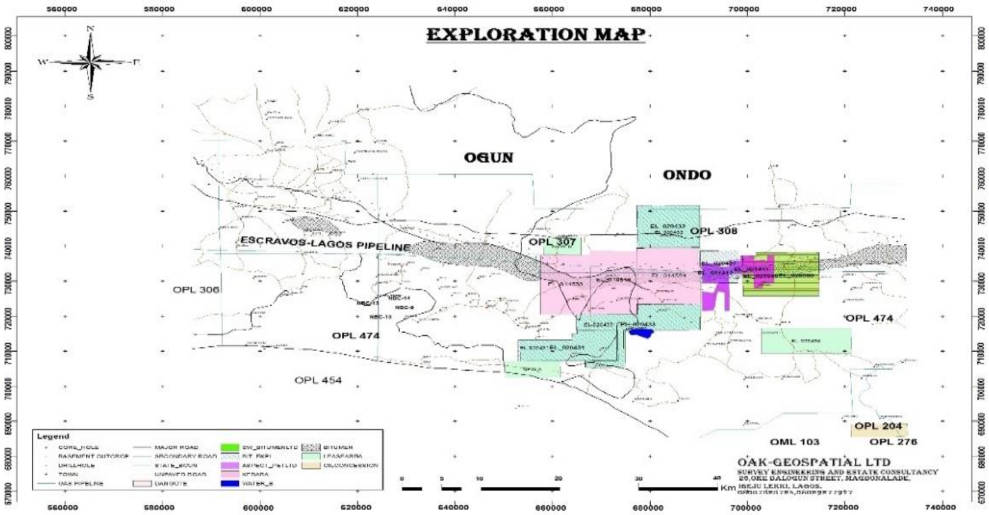


Fig. 2: Nigerian bitumen belt showing bitumen licensed blocks. (Source: Ministry of Special Duties, 2018)

2.2 Dataset for the Research

Dataset used in this study were obtained through digital image analyses of remote sensing-based indices. These data include;

- Normalized Difference Vegetation Index (NDVI) –Greenish of the area
- Soil- Adjusted Vegetation Index (SAVI)--------Index for soil types
- Analysis of the land surface temperature and emissivity
- GIS-based lithology mapping of the area
- Structural lithology formation mapping (Lineament density maps)
- LANDSAT images (Landsat 8)

- Sentinel-1 Radar images
- SRTM (DEM) images
- Topographical map of the area
- Soil and Geological maps of the area
- Climatic data
- Soil samples (Core samples) for particle size, Atterberg, hydraulic conductivity
- Geo-sections or borehole hydrostatic correlation
- Vertical Electrical Sounding data

2.3 Study Evaluation Criteria

Table 2 showed the criteria used in determining the tailing pond suitability sites. The main criteria are the geological, environmental and geotechnical, each with various sub-criteria for assessment.

Table 2: Criteria and Sub-criteria Indexes

CRITERIA	SUB-CRITERIA
Environmental –(LPFADDD)	• Land use • Precipitation/ Climate • Flood/ Erosion • Agricultural dense forest • Distance to the existing cities/ settlement • Distance to the road • Distance to the river
Geological –(SEDHBS)	• Soil types • Elevation/ Topography • Drainage pattern • Hydrogeological/ Groundwater potential • Bitumen deposit/ outcrops /occurrence • Slope • Geophysical
Geotechnical –(PACH)	• Particle size analysis • Atterberg limits • Hydraulic conductivity • Consolidation • Compaction • Specific gravity • Porosity and void ratio

2.4 Criteria Assessment and Investigation

The criteria selection involved site visits to identify and demarcate bitumen belt within Ondo State, with the bitumen bearing communities to collect data using the topographical map and concession Block map or Bitumen license map. The reconnaissance survey of the site was used to generate information using GIS for spatial mapping and modelling. Three important criteria (Environmental, Geological and Geotechnical) were identified and selected.

Electrical Resistivity method for geophysical investigation or testing were employed, where an electrical source and a receiver were used to measure electrical resistance of the soil types or different lithology. Geophysical investigations were conducted on thirty-five (35) points within the Bitumen belt. These were rastered and vectored with reference to coordinates of each location and layer on the study map for ranking, weighting, and reclassification. This enhanced the evaluation of the soil characteristics, depth of overburden, lithological correlation and hydrogeological characteristics.

The geotechnical investigations involved sample collections from 30 locations, in-situ tests, and laboratory analysis to investigate the parameters such as Atterberg Limits, soil classification, moisture-density relationship, drainage, bearing capacity, consolidation settlement, permeability and ground water level. The grain size analysis of samples collected were carried out by dry sieving method in accordance with the BS 1377: Part 2: 1990: Specific gravity ($\boldsymbol{G_s}$), Optimum Moisture Content (OMC), Maximum Dry Density (MDD), Aterberg limit, Liquid limit (WL), Plastic limit (PL), Plasticity Index (PI), Compaction test, Consolidation and Permeability/Hydraulic Conductivity. Also, water table elevation of existing thirty-three (33) boreholes within the study area were monitored for specific periods to evaluate the groundwater dynamics of the sites. Maps generated and analyzed were used to determine the suitable sites for construction of the tailing ponds.

All the criteria were investigated, interpretated, rastered and vectored for spatial optimization analysis on the study site. All the delineated area within and out of the bitumen blocks or deposit zone of the bitumen belt sites of Okitipupa, Odigbo, Irele, Ilaje and Ese-odo Local Government Area of Ondo State where GIS (ArcGIS™) were used to generate/ raster maps in respect to the criteria and sub-criteria. Figure 3 shows the flow chart of the study with Figure 4 showing the spatial sample locations.

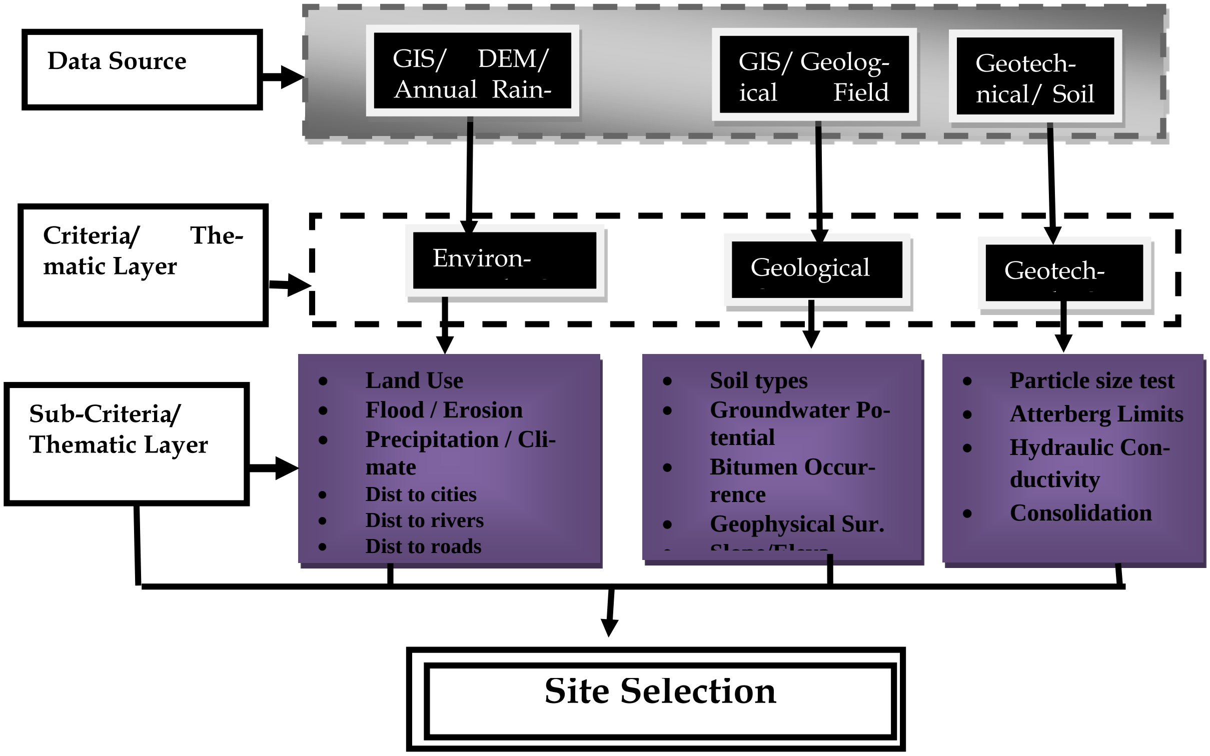


Fig. 3: Flow Chart of the Research Methodology

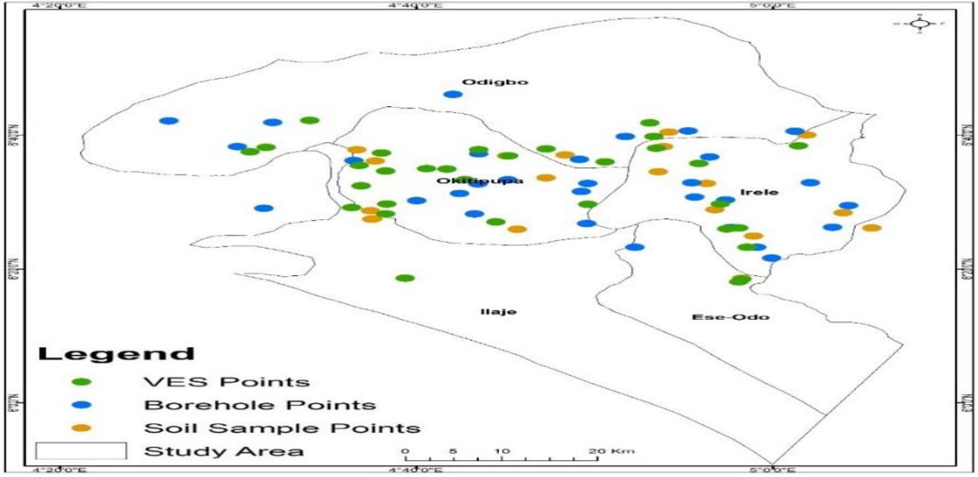


Fig. 4: Typical Spatial Map of the Sample Locations within the Study area

3.0RESULTS AND DISCUSSION

3.1 Environmental Criteria Identification and Analysis

Environmental criteria and sub criteria for spatial data analysis in form of GIS maps Figure (5-7) were generated. Each sub-criterion was scored between zero and nine according to its suitability or order of importance for constructing or establishing tailing stabilization ponds as presented below.

(i) Land use Criteria Analysis

Land use data were collected using ArcGIS^{TM} 2.0, to generate the spatial analysis map. Figure 5 (a & b). The GIS-spatial analysis map was used to analyze the distribution of land use types within the study area, understanding the spatial patterns and relationships between different land use categories which indicates wetlands and built-up areas at the Southwestern and Northern flank of the map. Undisturbed forests cover 46.7% of the study area, disturbed forests cover 20% of the area and water bodies cover the remaining part at the Southern zone of the map. The level of land use or built up in the context of siting a tailing dam can have significant implications for environmental and engineering considerations. High level of land use or built up can pose the following challenges: environmental impact, ecological disturbances, hydrological changes, infrastructural interference and migration cost.

(ii) Distance from Cities/ Settlement

Distance from cities or settlements can play a significant role in influencing the selection of tailings pond site locations. Closer locations might increase the risk of contamination from pollutants, affecting water sources and potentially exposing communities to hazards. Figure 5(g), shows the level of distance from cities/settlement as being ranged from 0-1.5km, 1.6-3.3km, 3.4-6.0km and 6.0-12.3km respectively within the study area. The study area is still in line with the position of Ruchin *et al.* [8] which suggested that tailing ponds should be located at least 500m away from the habituated area.

(iii) Distance from Road

Ruchin *et al.* [8] also reported that tailing ponds or Sewage treatment plant should be constructed within 200 m from road, so that it can have an easy access. Figure 5(f) shows that, the study area has at least 0-1,500m from roads, which indicate that different flanks of the mapped area are suitable for tailing ponds.

(iv) Distance to Existing Rivers

To reduce the cost of construction, six categories of distance to rivers 0–200, 201–400, 401-600, 601-800, 801-1000, 1001-1,600m were considered from the buffer zone within the study area in spatial map of Figure 9 (e). The study aligned with the position of Mahboobeh and Mohammed [9], which considered 500 m threshold value as a buffer zone for rivers and surface water body to protect riverbeds from leakage of wastewater, and to reduce the distance of effluent disposal and the pipe length.

(v) Precipitation

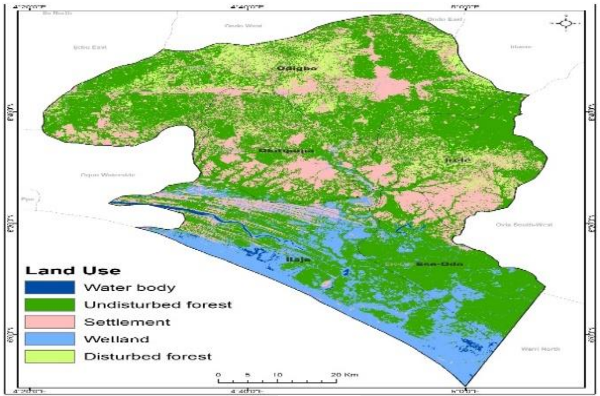
Figure 9(d) depicts the total annual rainfall data obtained from each station and a rainfall map of the study area was generated using Inverse Divergent Weight (IDW) interpolation techniques. The rainfall map was classified into four group for the period of year 2020–2022 to prepare the rainfall (precipitation) map. For the Bitumen belt, the recorded amount varied from 1,539mm minimum total annual rainfall to 1,828mm maximum total annual rainfall, with a difference of 299mm. Precipitation is high at the middle which is along West-Eastern part of the study area, compared to the low or minimum values (1,539-1,656mm) at the North-eastern, North-western and South-eastern regions. Al-Ruzouq *et al.* [10] opined that, high precipitation zones are considered good and appropriate for identifying suitable sites for water dam construction, but for this study low precipitation for tailing ponds suitable sites selection is being suggested to avoid flooding and overflow of waste.

(vi) Flood/Erosion (Rusle Model) Map

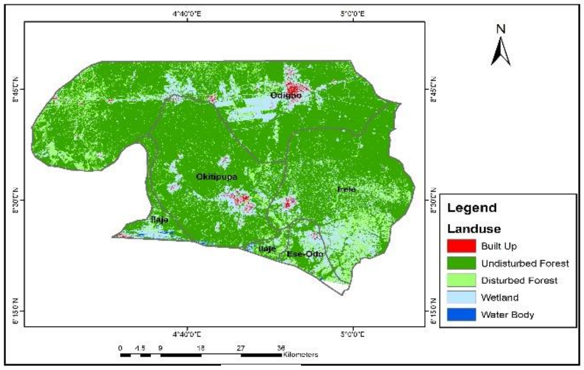
Flooding occurs when water overflows onto dry land, while erosion gradually wears away the Earth's surface by natural agents like water and wind. RUSLE model was selected and applied because, it can be easily integrated with GIS for better analysis. RUSLE was used for the assessment of annual soil loss according to Ganasri and Ramesh [11]. Figure 5(c) depicts low Rusle model value ranging from 0 - 2,000 ton/year at the Southern parts of the coastal area, 2,001 - 5,000ton/year at the Southwestern (SW) and Southeastern (SE) region It has 5,001-7,000ton/year around some parts of the SW and SE, with high value of 7,001 - 9,000ton/year at the Northwestern (NW) and Northeastern (NE) and North southern (NS) central of the study area. The only selected sites for the construction of the tailings pond are the Southeastern (SE) and Southwestern (SW) regions.

(vii) Agric Dense Forest Map

The Agricultural dense forest map in Figure 9(h) depicts areas that are not yet utilized. In the map, we have South-Southeastern (SSE), Northwestern (NW), Northern hemisphere and central that are underutilized, and can be selected as tailing pond sites, while the NE, SN and NE are well utilized in terms of settlement and other land or forest utility.



(a)



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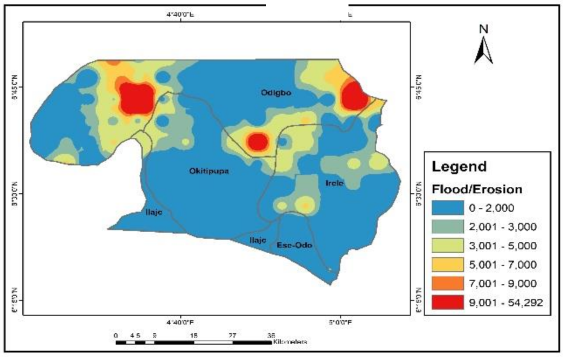

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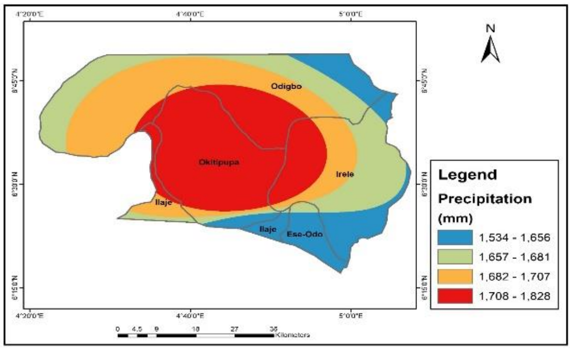

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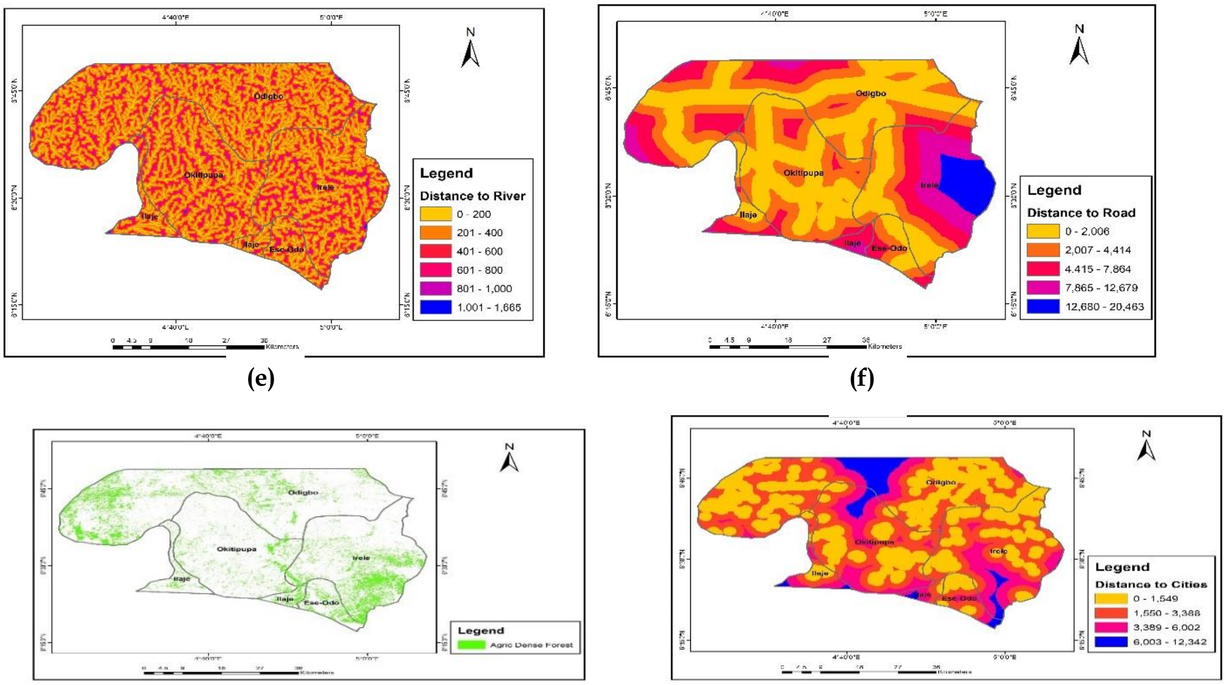


(e) (f)

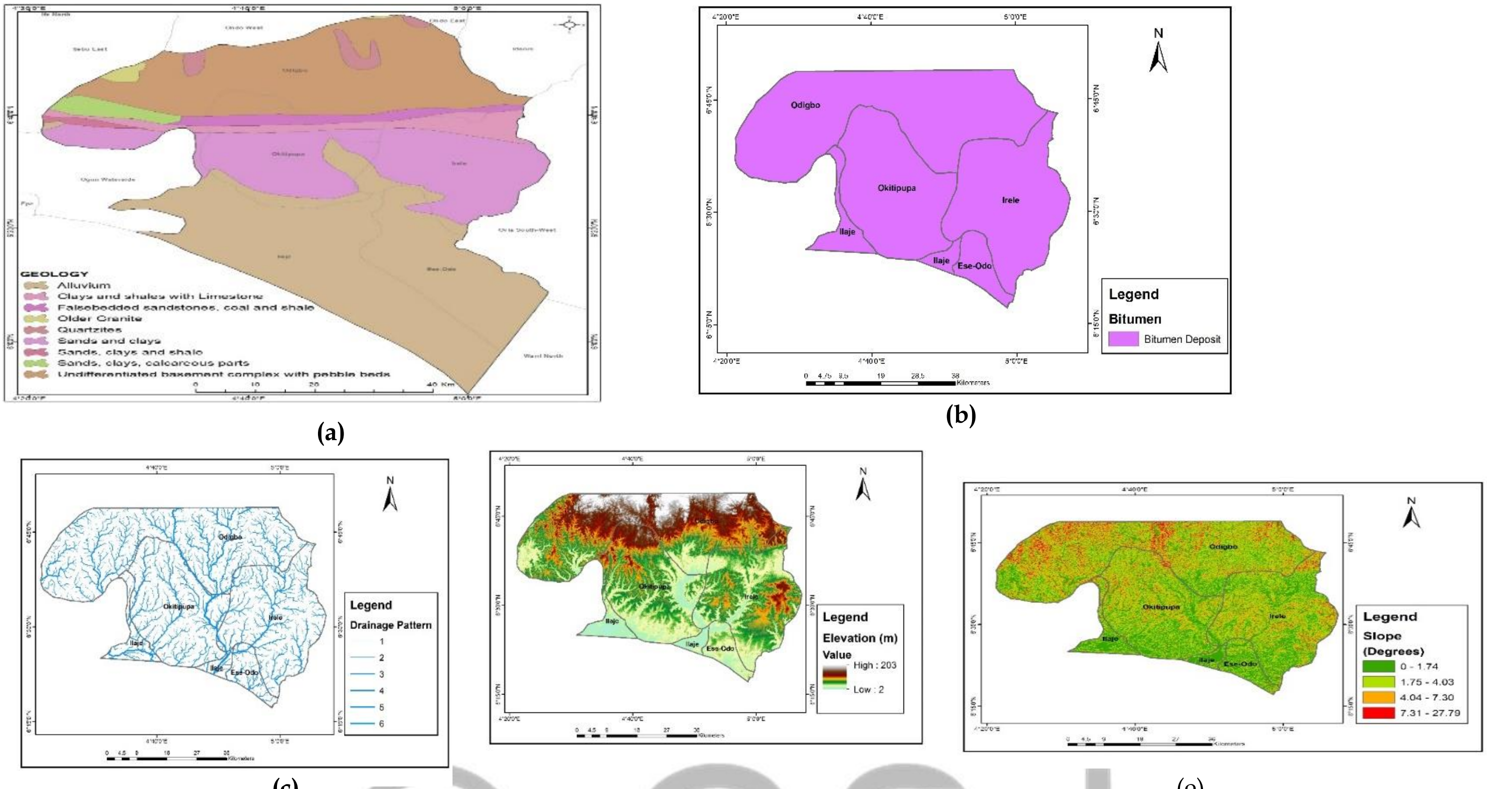
(g) (h)

Fig. 5: Generalized Spatial Maps of Criteria and Sub-Criteria of the Study Area (a) Land use/ Cover (b) Land use/ Cover of Sampled Area (c) Russle/ Flood/Erosion (d) Precipitation (e) Distance to River (f) Distance to Road (g) Distance to Cities (h) Agric Dense Forest

3.2 Geological Criteria Identification and Analysis

The geological sub-criteria identified are Geology/Soil types, Topography/ Elevation, Bitumen Deposit, Slope Drainage pattern/ Strahler. In a report of dam performance statistic, foundation problems are found out to be the most common causes of dam failure. Sedimentary rocks such as thick-bedded sandstones, flat-lying sandstones, and limestones are among the most satisfactory materials with the characteristics of different classes of rocks, which can stand for the preference for constructing dam or tailing ponds.

(i) Geological/ Soil Types Sub-Criteria Identification and Analysis



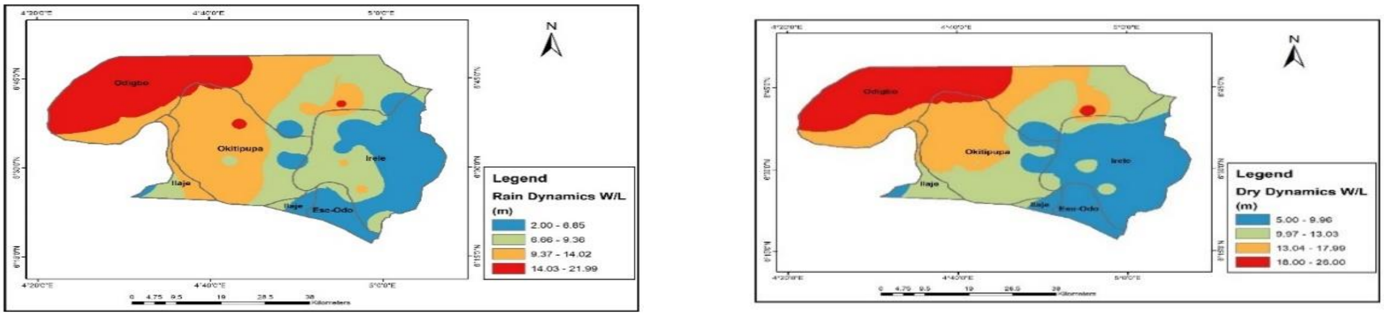
(a) **(b)**

(c) **(d)** (e)

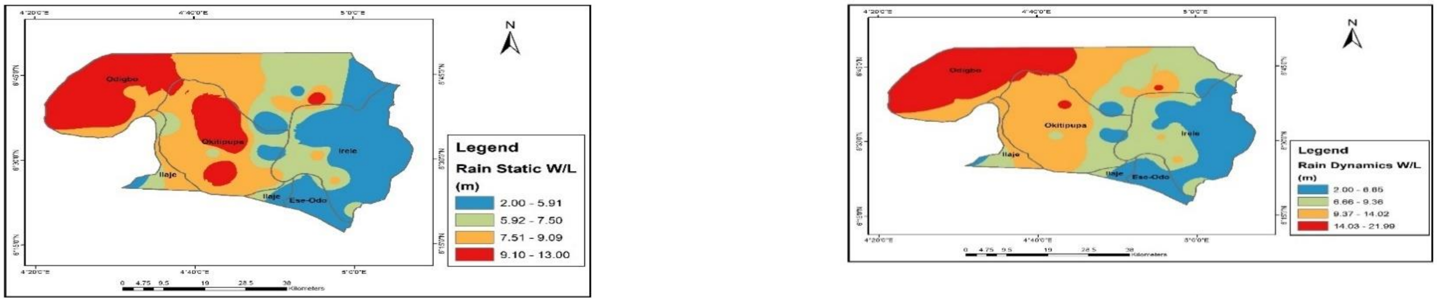
Fig. 6: Spatial Maps of Criteria and Sub-Criteria of Study Area within the Bitumen Belt (a) Geology/Soil Types (b) Bitumen Deposit (c) Elevation/Topography (d) Slope (e) Strahler/ Drainage Network

(ii) Hydrogeological Sub-Criteria Identification and Analysis

Hydrology plays a vital role in understanding the structure of available water resources: surface and sub-surface resources. Ground water conditions are usually related to the geology, and also affect siting conditions. The hydrogeological criteria maps from this study area were digitized using ArcGIS Pro 2.0 software. Displayed the hydro-dynamics conditions of its occurrence, distribution patterns, and formation of groundwater during dry and wet season. As these maps are based on the results of water static and dynamic levels during the period of dry and wet season from boreholes within the study area. The spatial maps are shown in Figure 7 (a-d).



(a) **(b)**



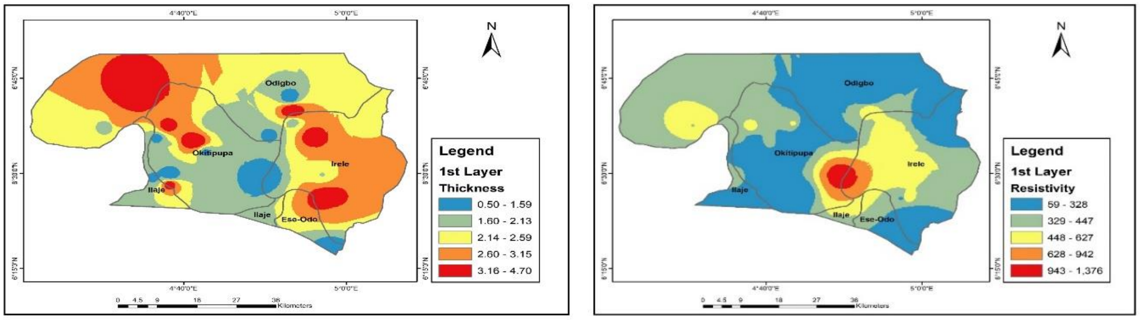
(c) (d)

Fig. 7(a-d): Spatial Maps of Hydro-Dynamics (Boreholes) Criteria of Study Area (a) Dry Season Static Water Level (b) Dry Season Dynamics Water Level (c) Rainy Season Static Water Level (d) Rainy Season Dynamics Water Level

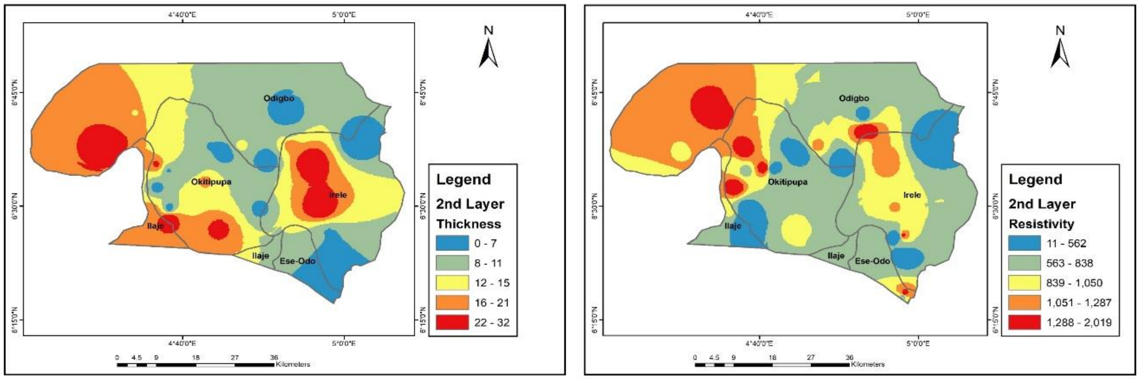
Figure 7(a-d) depicts the water level at different season of the year within the study area. Southeastern flank of the study area shows values that ranged from 2.00-9.96m which indicate, shallow static and dynamics water level at both dry and rainy season of the year. The Northwestern region indicates deeper static and dynamics water level at both seasons. At the Northeastern and Southwestern region, the value ranged from 5.92-17.99m during dry and rainy season at both static and dynamics water level. Considering the assertion of Fetter [12], which state that, the hydrogeological characteristics of an area can indicate the direction and speed of groundwater movement, helping to identify areas with minimal risk of contamination. This implies that, the high depth water level in these Northeastern and Southwestern regions make it considerable for tailing ponds sites locations, because water percolation or vertical movement of water would have been filtered before getting to the water table. The underground water dynamics or flow patterns in this study area is considered crucial when preventing tailings from contaminating local water sources.

(iii) Geophysical Sub-Criteria Identification and Analysis

This geophysical sub-criterion was adopted to delineate the geological defects at various depth of investigation and to interpret the lithological variations both in horizontal and vertical orientation, as well as groundwater condition in the study area. To measure vertical electrical sounding, the selected method was Schlumberger electrode array.



(a) (b)

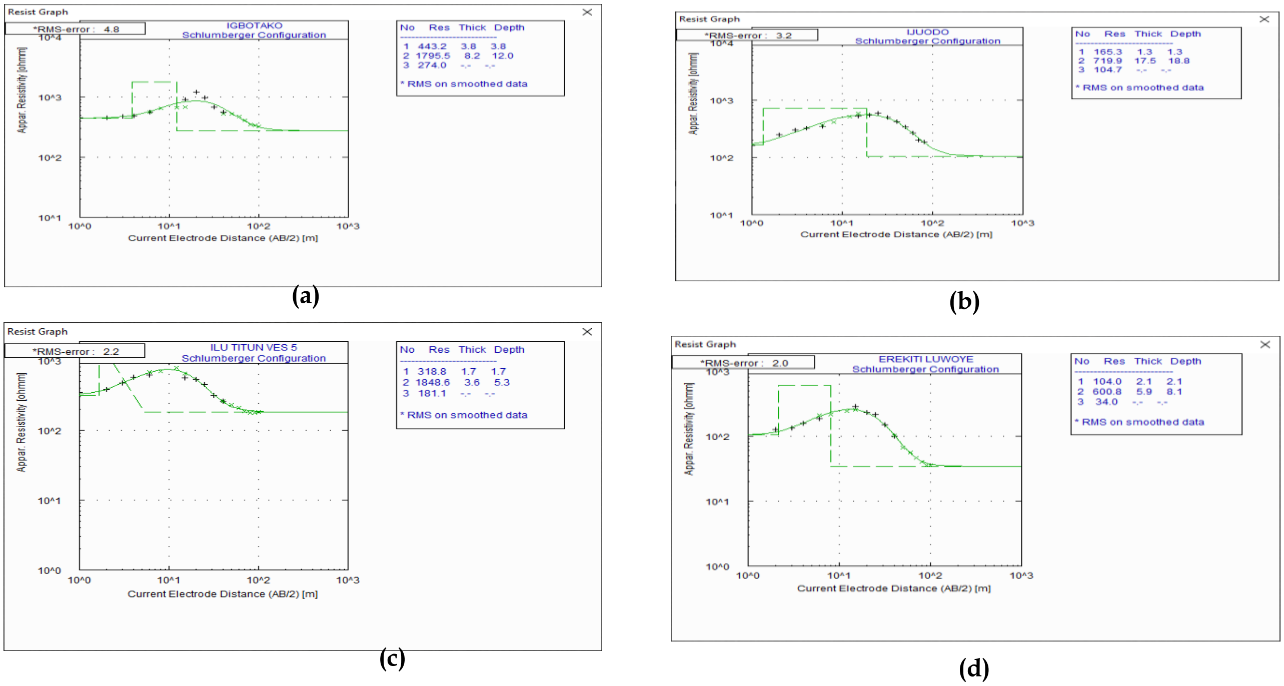


(c) (d)

Fig. 8(a-d): Spatial Maps of Geophysical Sub-Criteria Identified and Analyzed Vertical Electrica Sounding (VES) of the Study Area (a) First Layer Thickness (b) First Layer Resistivity (c) Second Layer Thickness (d) second Layer Resistivity

Figure 8(a-d) show the spatial map geophysical parameters and the results from the geophysical investigation which described the geophysical parameters like depth, lithological variation and the underground water conditions of the study area. The curve types identified are predominantly KQ, HK, KQH, AK and KH. Figure 9(a-d) curves. The interpretation of the resistivity curves obtained shows that 3-4 geo-electric layers were present in the subsurface. The spatial maps representing geo-electric sequences for the first model or layer thickness ranging from 2.60-4.70m at the Southeastern and Northwestern region as the topsoil. But, low at the Southern axis with values ranged from 0.5-2.13m within the study area.

At the Southwestern and Northeastern flanks, the values ranging from 2.14-2.59m. The resistivity values ranging from 59-1,376Ωm which is relatively high at the South-Northern axis which implies Alluvium sand deposit. At the Southeastern region, the resistivity values ranging from 448-627Ωm as the extension of the Alluvium Sand towards the Eastern axis. The resistivity value at the Northern, SW and NE axis is low compared to the Northern region that ranging from 329-447 Ωm. At the second layer, the thickness ranging from 0-32m, high at the NW, SW, SE and very low at the NW, Northern and SSE axis of the study area. The high resistivity depicts a lithology of sandy silty clay, sandstone, compacted sand and underlain by Bituminous layer, while the low resistivity depicts clayey sand. This finding aligned with the report of Adeyemi *et al.* [13], that, the first model/ layer generated is within the Bitumen belt which is characterized by a thin topsoil (less than 1m thick) comprising the overburden underlain by dry sand (1.0m - 4.6m thick) which overlies bituminous sand horizon (6m -19m thick). This horizon is underlain by sandy silty clay. The second model generated is defined by topsoil (0.5m -1.8m thick) underlain by bituminous sand horizon (2.5m -14.8m thick) which overlies saturated sand (1.9-11.3m thick). an impervious sandy silty clay layer underlies this aquifer. Outcrops of heavy oil sand deposit with thickness ranging from about 2.5m to 19.0m was observed between a depth of about 0.5m and 5.4m in the study area.



(a)

No	Res	Thick	Depth
1	443.2	3.8	3.8
2	1795.5	8.2	12.0
3	274.0	-.-	-.-

(b)

No	Res	Thick	Depth
1	165.3	1.3	1.3
2	719.9	17.5	18.8
3	104.7	-.-	-.-

(c)

No	Res	Thick	Depth
1	318.8	1.7	1.7
2	1848.6	3.6	5.3
3	181.1	-.-	-.-

(d)

No	Res	Thick	Depth
1	104.0	2.1	2.1
2	600.8	5.9	8.1
3	34.0	-.-	-.-

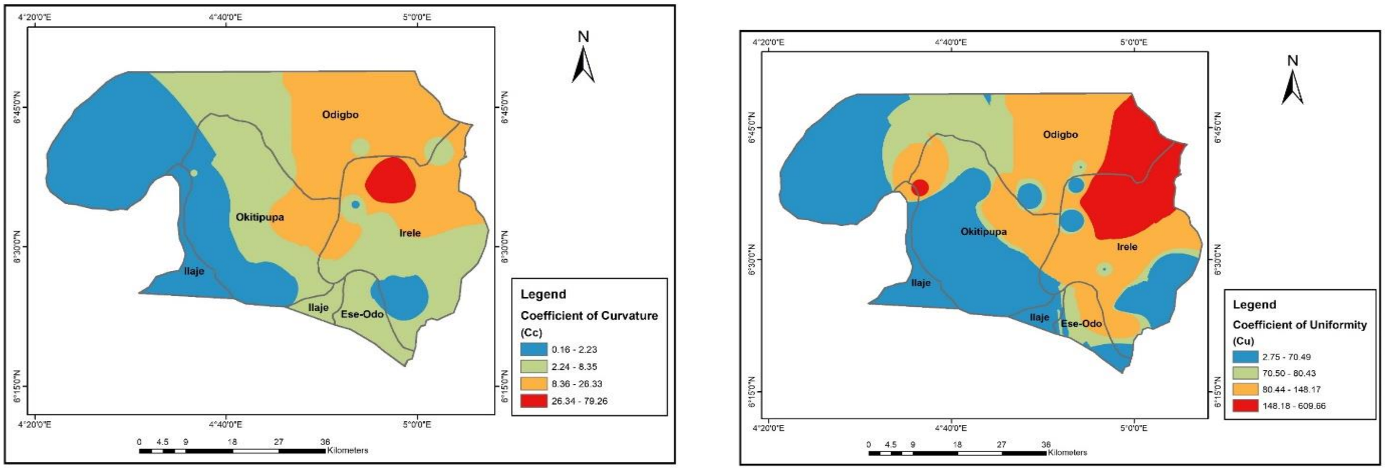
Fig. 9: Geophysical Sub-Criteria Iteration Curve Types (VES) of the Study Area

3.3 Geotechnical Criteria Identification and Analysis

The subsurface vulnerability to pollution and ponds failure is influenced by its geotechnical and soil properties. Areas with highly permeable materials, hydraulic conductivity, fractured bedrock and high rate of consolidation may have increased vulnerability to pollutants leaching into groundwater and super structure failure. In this research, to investigate the geotechnical condition of the study area, some important geotechnical sub-criteria index properties and classifications were analyzed below; the Specific gravity ($\boldsymbol{G_s}$), Moisture Content, Liquid limit (WL), Plastic limit (PL), Plasticity Index (PI), linear shrinkage, Compaction test, maximum dry density, optimum moisture content, Hydraulic Conductivity, porosity, void ratio, coefficient of permeability, compression and regression index of the soil sample.

(i) Particle Size Distribution of the Bitumen Belt

Table 3, shows the coefficient of curvatures (Cc) ranged from 0.16-79.26 and the coefficient of uniformity (Cu) ranging from 2.75-609.66. Also, from Figure 10(a and b) spatial maps of coefficient of curvature and uniformity denoted that, the soil is poorly graded to well graded alluvium and sand with the symbol SP-SW at the Northwestern to Southwestern region. Meanwhile, at the Northeastern and Northern flank, it is well-graded gravel to well graded sand. It is observed from the Southeastern (SE) and Northeastern (NE) flank, that the soil is well-graded sand to well-graded gravel as symbol SW-GW and classified in the Unified Soil Classification System. NE-SE and North-North southern (NNS) axis has well graded sand to well graded gravel and can be recommended for tailing ponds construction within the study area. This report supports the assertion of Al-Ruzouq *et al* [10] that, the occurrence of alluvium, silt and sand tends to recommend the axis as a suitable location for tailing ponds construction.



(a) **(b)**

Fig. 10(a-b): Spatial Maps of (a) Coefficient of Curvature (C_c) (b) Coefficient of Uniformity (C_u)

(ii) Specific Gravity of Soil in the Bitumen Belt in Ondo State

Table 3 shows the specific gravity of soil within the Bitumen belt of Ondo State ranged from1.99-2.73. Figure 11 shows that, the Northeastern flank has the lowest values that ranged from 1.99 -2.29. At the Northwestern and Southern region, the value ranged from 2.30 -2.43, when compared to the Southeastern and South-southeastern axes that have the highest values of 2.44 -2.73. Axes with higher specific gravity are selected for tailing ponds construction. For specific gravity (Gs), areas with high Gs are consider suitable because they are more compact for better stability and support for tailing ponds. Soils with higher specific gravity are typically denser and more compacted, providing better stability and support for the embankments of the tailing pond. This is essential to prevent erosion, slope failures, and breaches in the containment structures. They usually have lower porosity and permeability, reducing the potential for seepage from the tailing pond that can contaminate subsurface water This helps in preventing groundwater contamination and the escape of pollutants into the surrounding environment. High soil specific gravity helps prevent potential environmental hazards associated with tailing pond failures, such as water pollution, habitat destruction. contributes to the long-term performance and stability of the tailing pond, minimizing the need for costly maintenance and repairs.

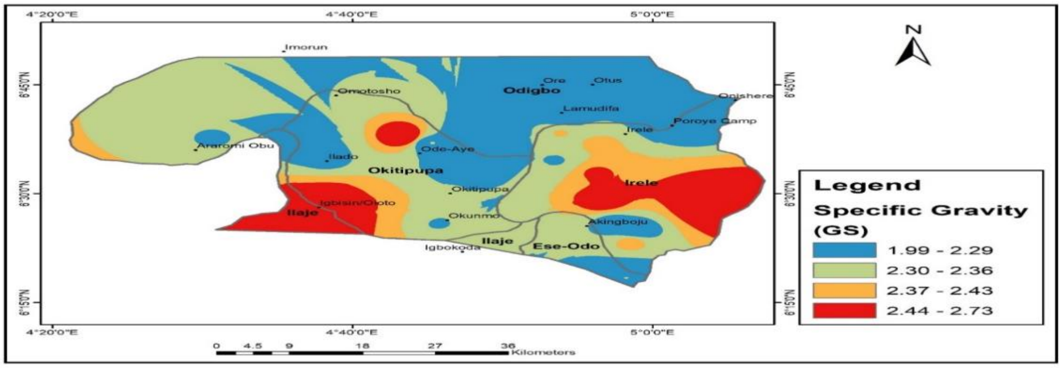
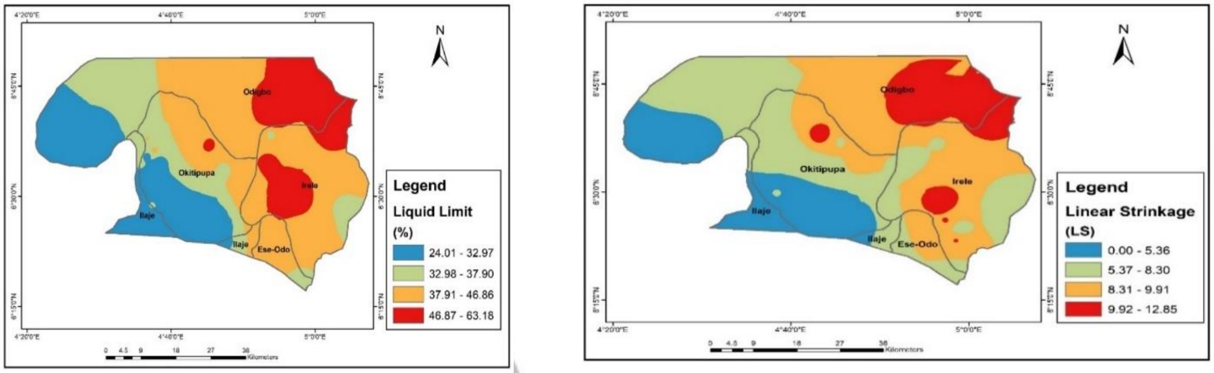


Fig. 11: Rastered Maps of Specific Gravity of soil Samples

(iii) Atterberg Limits of Soil in the Bitumen Belt in Ondo State

Table 3 shows that the liquid limit, plastic limit and linear shrinkage values ranged from 22.70-63.20%, 0.00-40.42% and 0.00-12.86%. which are high at the Northeastern and Southeastern axis but relatively low at the Northwestern to Southwestern region as shown in Figure 12 (a-b). Soils with high liquid limits and plastic limits are prone to become soft and unstable when saturated. High plastic and clay soils are not suitable, it may lead to failure when soaked and can be challenging to compact effectively, leading to potential settlement, where instability problems over time and embankment failures or erosion issues around tailing ponds. Soils with high linear shrinkage can develop cracks and voids, potentially compromising the integrity of containment structures around tailing ponds.



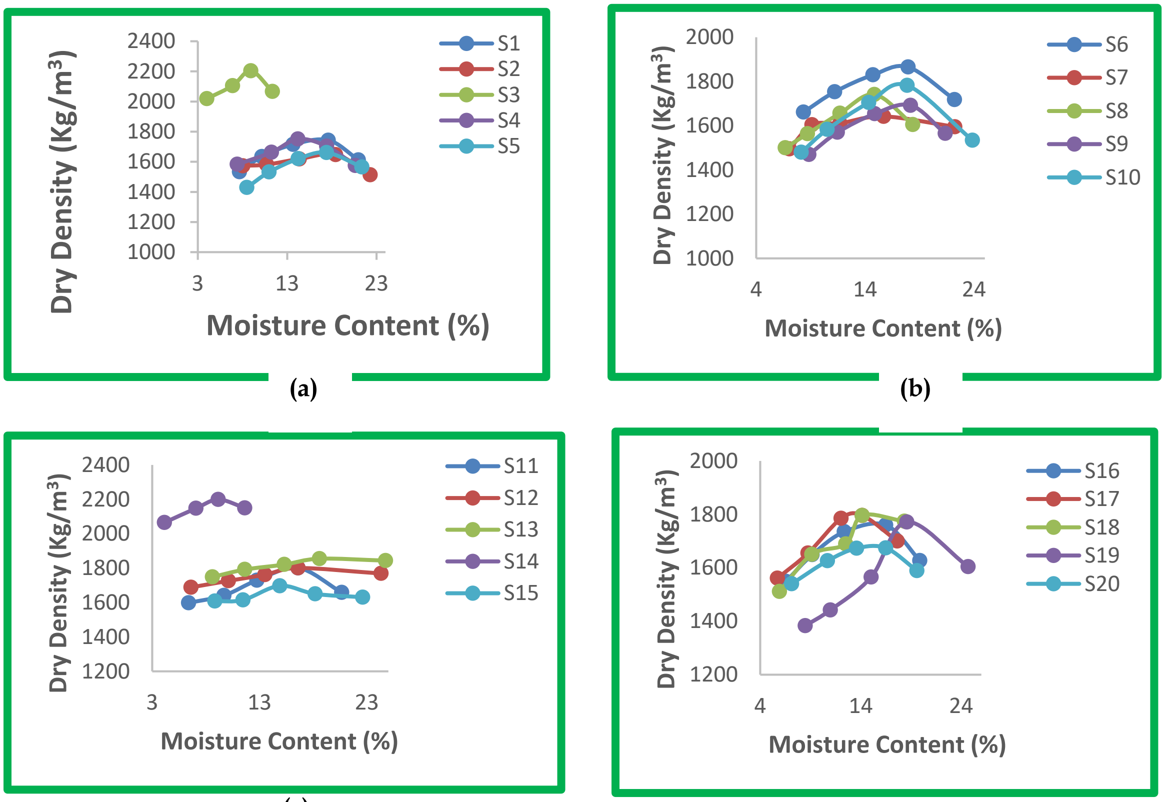
(a) **(b)**

Fig. 12(a-b): Spatial Maps of (a) Liquid limit (LL) (b) Linear Shrinkage (LS)

(iv) Compaction: Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) Sub-Criteria Properties

Figure 13 (a-d) show the compaction curve which gave the value of maximum dry densities (MDD) in kg/m^3 and the correspondent optimum moisture content (OMC) in percentage (%) for the sample locations. The value of the MDD ranged from 1640-2200 kg/m^3 and the correspondent OMC ranging from 8.92-18.76%.

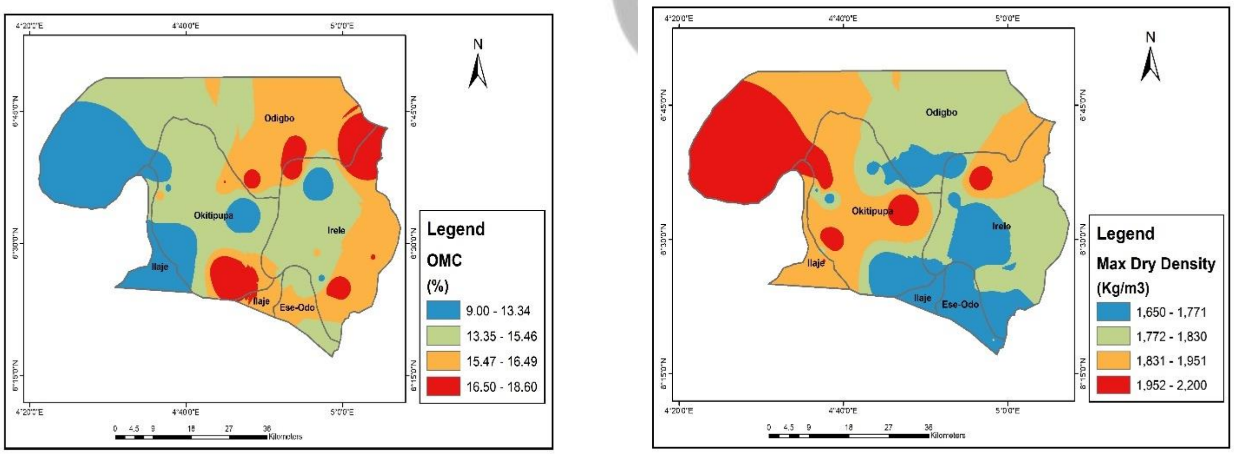
Figure 14(a & b) shows that, at the Northwestern and Southwestern flank of Figure 14(a), the optimum moisture content (OMC) is low with values that ranging from 9.00-13.34%, while in Figure 14(b) the maximum dry density (MDD) is high at that region, which means that, the region attained maximum dry density at lower optimum moisture content. At the Southern axis, OMC is high while MDD has low values. But at the center of the map, it implies low OMC corresponds to high MDD. Higher maximum dry densities generally indicate better compaction and stability of tailing ponds embankments. Proper compaction at the optimal moisture content creates a soil structure with lower permeability, reducing the potential for water to seep through the pond foundation and compromise its integrity. Therefore, high MDD zones are consider suitable for tailing ponds construction.



(a) (b)

(c) (d)

Fig. 13 (a-d): Maximum Dry Density and Optimum Moisture Content of Soil Samples (S) in the Bitumen Belt of Ondo State (a) S1-S5 (b) S6-S10 (c) S11-S15 (d) S16-S20



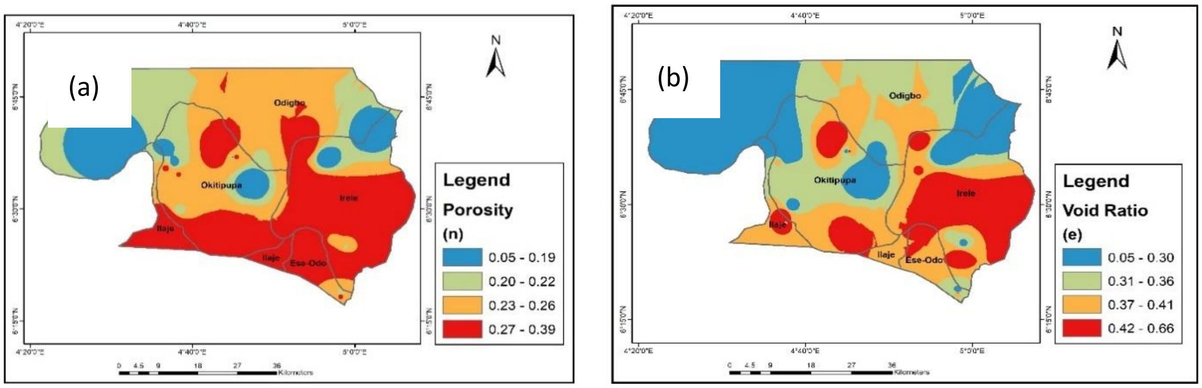
(a) (b)

Fig. 14(a and b) Spatial Maps of Soil Samples (a) Optimum Moisture Content (OMC) (b) Maximum Dry Density (MDD)

(v) Porosity and Void Ratio Sub-Criteria Properties

Figure 15 (a and b) are rastered map that illustrate the lowest values of porosity and void ratio that ranging from 0.05-0.19 and 0.05-0.30 at the Northwest and Northeastern region. While the highest values ranging from 0.27- 0.39 and 0.42- 0.66 at the Southwestern and Southeastern axes of the map. Meanwhile, compacted soils with appropriate porosity and void ratio contribute to the stability and load-bearing capacity of dam embankments and foundation. Porosity and void ratio influence the interconnectedness of void spaces within the soil. Lower porosity and void ratio generally lead to lower permeability, reducing the potential for water seepage and leachate through the dam structure and its foundation. Ares with high void ratio and porosity are consider unsuitable for tailing ponds construction. Compacted and well-graded soils with suitable porosity and void ratio enhance the load-bearing capacity of the foundation, which is crucial for preventing internal erosion and maintaining the pond's structural integrity. [14]

SAMPLE NOS	LOCATION	LAT PT Y	LOG PT X	SPECIFIC GRAVITY	L. LIMIT (LL%)	PLASTIC LIMIT (PL)	LINEAR SHRINK-	(MDD KG/M3)	(OMC %)
S1	ODE ERINJE	6.451^{0}N	4.741^{0}E	2.36	26.5	20.16	4.29	1750	17.50
S2	OBONDE	6.433^{0}N	4.761^{0}E	2.27	28	0	0	1650	18.50
S3	AGBAJE	6.561^{0}N	4.788^{0}E	2.21	36	20.75	8.57	2200	9.00
S4	LAFE	6.631^{0}N	4.725^{0}E	2.72	40	25.73	11.57	1760	14.50
S5	IDOGUN	6.618^{0}N	4.806^{0}E	1.99	39	26.64	9.73	1661	17.41
S6	OJA BAALE	6.616^{0}N	4.751^{0}E	2.02	47	24.9	10	1880	17.00
S7	GBELEJU LODA	6.616^{0}N	4.753^{0}E	2.43	50	22.98	6.43	1640	15.50
S8	IRELE ROAD	6.576^{0}N	4.893^{0}E	2.28	50	23.62	6.43	1760	15.00
S9	AYADI IRELE	6.639^{0}N	4.898^{0}E	2.37	36	25.64	8.73	1680	18.00
S10	IPETU IRELE	6.675^{0}N	4.903^{0}E	2.22	58	36.77	12.86	1800	17.00
S11	IYANSAN	6.436^{0}N	5.093^{0}E	2.48	33	14.12	7.14	1800	16.50
S12	IYANSAN CAMP	6.474^{0}N	5.066^{0}E	2.73	35.6	15.03	7.14	1800	16.50
S13	POROYE CAMP	6.668^{0}N	5.032^{0}E	2.06	52	26.7	11	1855	18.60
S14	LEGBOGBO	6.613^{0}N	4.941^{0}E	2.39	39	22.08	8.03	2100	9.00
S15	LEWORO	6.547^{0}N	4.938^{0}E	2.46	47.8	24.9	9	1700	15.00
S16	SALEWA	6.388^{0}N	4.976^{0}E	2.42	42	32.25	10	1760	16.00
S17	IJOSUN	6.434^{0}N	4.957^{0}E	2.21	41	30.2	10	1800	13.00
S18	AGADAGBA	6.311^{0}N	4.971^{0}E	2.03	36	26.21	7.14	1800	14.00
S19	AKINGBOJU CAMP	6.416^{0}N	4.982^{0}E	2.15	40	28.36	7.2	1780	18.50
S20	AGO RUWASE	6.482^{0}N	4.946^{0}E	2.56	63.2	40.42	11.86	1680	15.50
S21	OKUNMO	6.308^{0}N	4.971^{0}E	2.37	37.3	24.08	8.57	1680	15.20
S22	OLOTO/IGBISIN	6.496^{0}N	4.639^{0}E	2.5	24	20.95	6.21	2100	11.00
S23	GBEGUNRIN	6.459^{0}N	4.626^{0}E	2.69	22.7	0	0	2020	10.40
S24	GBOLOMI	6.458^{0}N	4.625^{0}E	2.52	33.2	0	0	1860	11.50
S25	IGBOBI	6.479^{0}N	4.624^{0}E	2.52	35.2	0	0	1780	12.00
S26	EREKITI	6.578^{0}N	4.638^{0}E	2.22	30	19.54	5.71	1720	15.40
S27	AGBETU	6.603^{0}N	4.628^{0}E	2.25	39	16.97	7.94	2080	13.00
S28	IWADA	6.592^{0}N	4.613^{0}E	2.25	32	20.98	6.71	1760	16.20
S29	ILADO	6.631^{0}N	4.611^{0}E	2.25	38	15.16	7.94	2020	12.20
S30	ARAROMI OBU	6.626^{0}N	4.511^{0}E	2.28	27.8	17.19	4.71	2200	11.50



(a) **(b)**

Fig. 15 (a & b) Maps of Soil Samples (a) Porosity "n" (b) Void Ratio "e"

(vi) Hydraulic Conductivity/ Permeability Sub-Criteria Properties

Figure 16 is a rastered map that illustrate the values of hydraulic conductivity or permeability ranging from 0.000-0.067 k(cm/sec). The lowest values that ranged from 0.001- 0.010 k(cm/sec) are within the Northeastern, Northwestern, and North-central region. While highest values of permeability ranging from 0.022- 0.067k(cm/sec) are in the SSE and SSW axes. Soils with high plasticity may have low permeability, which can be beneficial for preventing seepage from the tailing pond. However, excessively low permeability can also lead to poor drainage and potential buildup of pore pressure. Soil hydraulic conductivity plays a crucial role in selecting suitable sites for tailing ponds construction to ensure containment integrity and prevent environmental contamination. The hydraulic conductivity of subsurface materials affects how quickly water can move through them. Low hydraulic conductivity areas might limit the potential for contaminants to spread rapidly through the groundwater [14]

(vii) Consolidation Sub-Criteria Properties

The coefficient of consolidation or settlement (Cv/Mr) is shown in. Figure 17(a) while the re-compression index is shown in figure 17(b). It shows low value that ranged from 0.001-0.004 (mm/yr) at the SSE, N and NW flange, while high value that ranged from 0.008-0.011(mm/yr) were recorded at the SE axis. The zone with low values is suitable for tailing ponds construction because, it aligned with the submission and theories of Terzaghi [15] and as reported by ICMM [14] that, consolidation and recompression indexes provide critical information about the settlement behavior of soil, which is vital for selecting suitable sites for tailing pond construction. These properties help to ensure the stability of containment structures, prevent excessive settlement, and mitigate the risk of seepage and environmental impacts.

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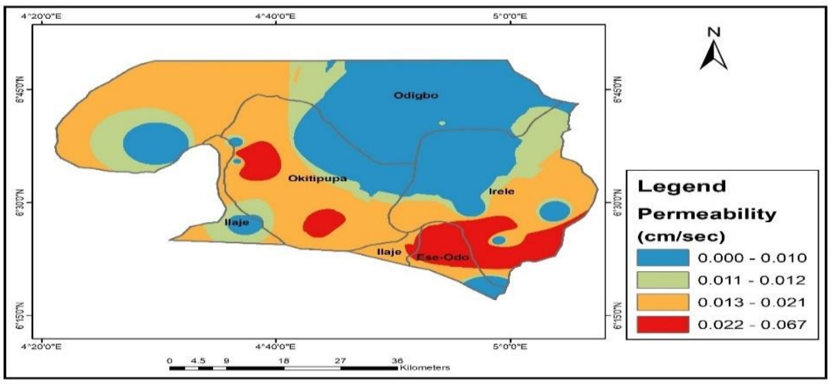
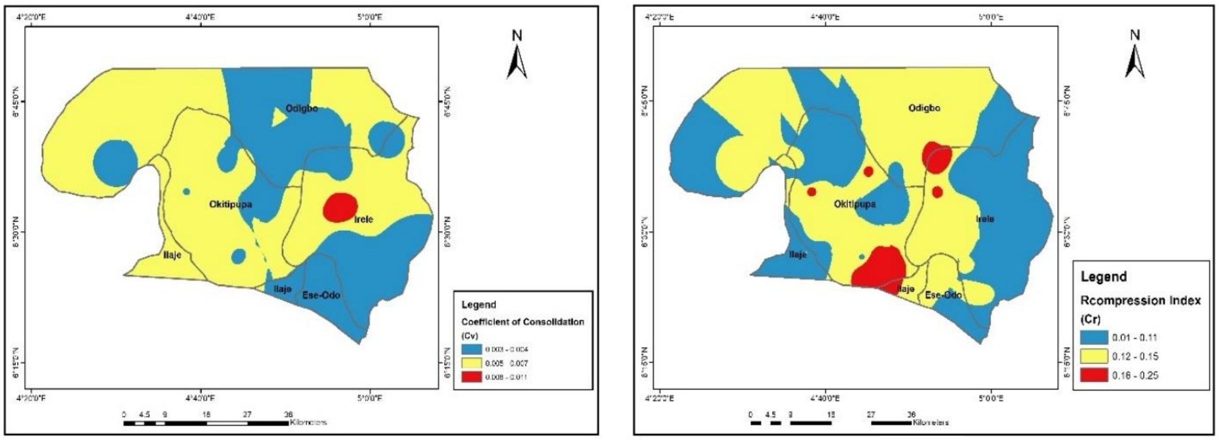


Fig. 16: Maps of Soil Samples: Permeability



(a) (b)

Fig. 17: Maps of Soil Samples: (a) Consolidation (Cv) and (b) Re-Compression (Cr)

4.0 Conclusion

Environmental, geological and geotechnical assessment for suitable bitumen tailings pond selection was carried out on the Okitipupa ridge area of Ondo state. For the environmental assessment, the result makes the study area suitable for tailings deposit for all the seven sub-criteria considered. However, the southern side of the study area was more favourable in terms of low soil erosion while the northern side is more favourable in terms of high dense forest rate (i.e. low level of utilization) and low precipitation rate.

The favourable sections of the study area for tailings deposit in terms of the seven (7) criteria under the geological assessment include: all sections(Soil type, bitumen deposit and geophysical), west sections (slope), north, south and central(elevation) , north and south(Drainage network), northeast and southwest(Hydrogeological), while that of the geotechnical assessment include southeast and northeast(Particle size distribution), south(specific gravity), northwest and southwest(Atterberg limits), northwest and southwest(Compaction), northwest and northeast (Porosity and void ratio) and north section (hydraulic conductivity and consolidation).

However, more studies need to be done in using decision making models to assign weights of importance/priority to these criteria and result nested into a map to generate a more specific sections of the study area that will be suitable for tailings deposit and meet the valuations of all criteria considered.

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