A GEOSPATIAL ASSESSMENT OF THE VARIATION AND DISTRIBUTION PATTERNS OF BITUMEN DEPOSITS IN SOUTHERN ONDO STATE, NIGERIA

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Abstract
This study examines the spatial variation and distribution patterns of bitumen deposits in Southern Ondo State, Nigeria, using advanced geospatial techniques. The research aims to delineate the areal extent, spatial structure, and locational variability of bituminous formations across Odigbo, Irele, and Okitipupa Local Government Areas (LGAs). Spatial datasets, comprising geological maps, satellite imagery, and bitumen block coordinates, were analyzed using Geographic Information System (GIS) tools to quantify coverage, detect overlaps, and model distribution dynamics. Results reveal that bitumen deposits are unevenly distributed, with Irele LGA possessing the highest concentration (97.6% land coverage), followed by Okitipupa (73.8%) and Odigbo (33.4%). Blocks IV, V, and VI emerge as the most spatially extensive and economically promising zones. The observed distribution aligns with the sedimentary framework of the Dahomey Basin, indicating structural continuity and favorable depositional conditions for hydrocarbon accumulation. While the spatial abundance signifies substantial economic potential, it also presents ecological risks, including deforestation, soil degradation, and water contamination. The study emphasizes the necessity of sustainable exploration strategies that incorporate geospatial monitoring and environmental management frameworks. By integrating spatial analytics with resource evaluation, this research provides a data-driven foundation for policy formulation, concession planning, and the sustainable exploitation of Nigeria's bitumen belt. The findings reaffirm the strategic significance of Southern Ondo State as a vital frontier for bitumen development and contribute to advancing geospatial applications in mineral resource management.
Keywords: Bitumen deposits, Geospatial assessment, spatial variation, Dahomey Basin, GIS

Introduction

Mineral resources are naturally occurring inorganic materials that are extracted from the Earth and are the cornerstone of our modern world (Charles et. al, 2023). Their applications are practically limitless and permeate every aspect of our lives.

Mineral exploration is the scientific detective work that the mining industry does to find economically viable mineral resources beneath the surface of the Earth. This ongoing requirement is what drives the multi-stage process of resource search that propels our modern world (Geological Survey Ireland, 2024). The American Institute of Professional Geologists (2016) defines mineral exploration as a methodical process that involves geological evaluations, sampling, and other investigative procedures to discover and evaluate potential mineral resources. These definitions encompass the essence of mineral resources exploration, which is a systematic search and evaluation of mineral reserves for possible utilization, from many angles and situations.

Africa is known to have the most abundant deposits of metal-based minerals and gemstones globally. The African continent is well recognized for its copious natural riches. Africa has more than 30% of the global mineral reserves (Sharaky, 2014). Africa's substantial mineral wealth may be attributed mostly to the favorable geological conditions and frequent tectonic upheavals that occurred throughout the Precambrian period. The total value of mineral wealth mined in Africa during the last century by colonial and indigenous governments is estimated to be more than $10 trillion. While Africa has an abundance of mineral resources, they are not evenly distributed (Olade, 2022).

In terms of solid mineral resources, Nigeria is sometimes said to have "abundant" or "vast" supplies of a variety of rocks and industrial minerals that are not metallic, in addition to energy minerals, base metals, ferrous metals, and precious metals. According to the Nigeria Geological Survey Agency, more than forty distinct kinds of valuable minerals have been discovered in about 500 locations throughout the country. Nonetheless, the bulk of these minerals are plainly non-metallic, as shown by mineral production figures, and more over 75% of the reported occurrences are accurately categorized as "mineral showings" having little or no economic potential (Olade, 2019).

Nigeria has solid mineral deposits throughout its geological environment. Unlike oil, which primarily occurs in the Niger Delta region, all 36 states in the country have some mineral resources. Geological investigations have identified approximately 450 locations where mineral resources are distributed across geological belts. The geological setting in Nigeria strongly supports the widespread existence and wide range of mineral resources that are capable of being extracted for industrialization, foreign exchange, and the creation of related industries. One of the major mineral resources found in large deposit in Nigeria is the oil sand or otherwise referred to as bitumen which is estimated at 42 billion barrels (MSMD 2010). Bitumen is a dense and very viscous blend of hydrocarbons that occurs naturally. It is the most dense and viscous form of petroleum (Adejato *et al*, 2018). The composition of bitumen is similar to that of light crude oil; it is made of hydrogen, carbon, with a trace amount of sulfur together with oxygen. Bitumen is believed to have formed as a result of the breakdown of organic matter and the removal of impurities by water from light crude oil. According to Akinmosin *et al*. (2009), it is believed that Nigerian bitumen was similarly created. Bitumen can be obtained from a variety of sources. According to Yoon *et al.* (2009), its composition is exceedingly intricate, consisting of a wide range of compounds that have high boiling temperatures and molecules that have a low ratio of hydrogen to carbon.

The presence of significant bitumen deposits in southwestern Nigeria, particularly within Ondo State, has been well-documented, with both outcrop and subsurface occurrences stretching across an east-west belt (Jekayinfa et al., 2023; Mosobalaje et al., 2018). This bitumen belt extends approximately 120 km from Ijebu-Ode in the west to the tributaries of the Siluko River near Ofosu Village in the east, spanning across Lagos, Ogun, Ondo, and Edo states (Jekayinfa et al., 2023). These deposits are primarily found within the Dahomey sedimentary basin, where bitumen seeps are observed along river banks, cliff faces, and road cuts (Jekayinfa et al., 2023). While previous investigations have largely concentrated on the deeper, large-scale structures for potential hydrocarbon exploration, a critical gap exists in understanding the surficial and shallow subsurface distribution of these bitumen seeps, particularly within the top 5 meters (Jekayinfa et al., 2023). This knowledge gap is crucial for assessing environmental impacts, as in situ bitumen seeps can act as geogenic sources of soil and groundwater contamination (Jekayinfa et al., 2023).

Traditional mineral mapping methods can be costly and time-consuming, and in some cases, they are impractical due to inaccessibility (Karimi and Valadan, 2004). One promising avenue for mineral exploration is the use of modern technology which can used to reverse the lost glory in mineral exploration. Geospatial technology, which is the integration of geographic information systems (GIS), remote sensing, global positioning systems (GPS), and data analysis methods, plays a vital role in gold mineral exploration. Remote sensing has emerged as a powerful tool for the detection, identification, and mapping of mineral deposits (Katz, 1982). Remote sensing technology, which encompasses advancements in spatial, temporal, and spectral resolution, has become a game-changer in the field. It is particularly useful for mapping minerals in inaccessible regions, challenging terrains, and wider areas (Zhhe Zhu et. al, 2022). GIS has the ability to integrate data from multiple sources, allowing for a systematic approach to modeling, analyzing, and presenting spatially and temporally distributed data. Spatial modeling, powered by GIS, can generate robust distribution patterns of ore-related geological features, shedding light on the relationships between these features and mineral deposits coupled with the aid of AHP to evaluate the priority of the different criteria. AHP has been widely used to solve problems of multiple criteria in different research. Velmurugan et al., (2011) used AHP to demonstrate a concept that can assist designers in effective evaluation. GIS plays a very essential role in the study of mineral resources (Rajesh, 2004). The need for a systematic approach for modeling, analyzing and or presenting huge amounts of data (spatially and temporally distributed) could be answered by GIS (Khatami and Bahram, 2014). GIS can be differentiated from other information systems through its capability of handling and performing operations on geospatial data. The spatial data may be the location while the attribute data is the characteristics possessed by that location (Chang, 2012, Abdulwahab, 2018).Sayed and Mahmoud (2018) utilized airborne magnetic and radiometric data to identify potential gold mineralization zones in Egypt's central-eastern desert. They found that areas with coinciding alteration zones and high complexity lineaments, as well as porphyry, showed a strong likelihood for gold mineralization. Tao et al. (2019) investigated machine learning methods for GIS-based mineral prospectivity mapping in the Tongling ore district, eastern China. The study emphasized that spatial modeling helps delineate complex distribution patterns of ore-related geological features and uncover correlations between these features and mineral deposits. Yao et al. (2020) applied knowledge-driven methods prospectivity for mineral mapping (MPM) to identify polymetallic sulfide deposits in the Southwest Indian Ridge (46° to 52°E). The study emphasized the potential of seafloor polymetallic sulfides as important targets in marine mineral exploration. By using fuzzy logic and fuzzy analytic hierarchy process (AHP), the researchers integrated topographic, geophysical, and geological data to develop exploration criteria for mapping prospective areas. Despite the absence of certain critical exploration evidence (such as hydrothermal alteration and geochemical anomalies), the knowledge-driven methods effectively predicted favorable metallogenic zones, offering a basis for future exploration of seafloor sulfide resources. Rakotondramano et al. (2021) used remote sensing techniques to estimate gold mineralization in the Betsiriry region, western Madagascar. Khalid et al. (2020) applied remote sensing and GIS techniques for gold prospecting and regional geological mapping in North Kordofan State, central Sudan.

This study therefore aims to address this deficit by employing an integrated geospatial approach to comprehensively map and analyze the spatial variation and distribution patterns of bitumen deposits in Southern Ondo State, Nigeria, focusing on their environmental implications rather than solely their economic potential (Jekayinfa et al., 2023a, 2023b). This approach is crucial for delineating the spatial extent of these seeps and informing targeted environmental management strategies in affected regions, particularly concerning the safety of drinking water (Jekayinfa et al., 2023).

Study Area

The Nigerian bitumen belt is situated in the onshore areas that constitute the eastern Dahomey (Benin) Basin, namely between latitudes 6°00'N and 7°00'N of the equator, and longitudes 3°45'E and 5°45'E of Greenwich meridian. The belt spans about 120 km, stretching from Lagos State to Akotogbo in Ondo State and Siluko in Edo State (Adegoke *et al*., 1981, See Fig 1.1). The Benin Basin, an expanse of sedimentary deposits along the coast, extends from the western part of Nigeria towards Togo and the Republic of Benin. This region is home to the largest portion of Nigeria's bitumen reserves. The entire region is built upon the crystalline basement rocks (Sheikh, 2003; FMSMD, 2006). The bitumen belt of Ondo State, which encompasses the local government districts of Odigbo, Irele, and Okitipupa, is the focus of this investigation (see figure 2 for more information). Odigbo, Irele, and Okitipupa are the three local government areas that make up the research area. These regions each include a component of the bitumen belt. The study area is located in the southern part of the lowlands of Ondo State. It is located between the latitudes of 06°00' North and 07°00' north of the equator and the longitudes of 03°45' East and 05°45' east of the Greenwich Meridian (See Fig. 1). It is situated at a height of about 125 meters above sea level. The Yoruba ethnic group, who speak Ikale, Ondo, and Yoruba dialects, make up the majority of the population in the area.

According to the National Population Commission (1991), the inhabitants in the southern area of Ondo were expected to be 1,230,531 at the census that took place in 2006. By 2023, that number had increased to almost 1,872,400. These people had concentrated in cities and villages, forming agglomerations or clusters. Additionally, the majority of these settlements' (towns and villages') development happened without any systematic planning; according to Jeje (1988), buildings just appeared without reference to physical planning, especially as traditional urbanization evolved in many Yoruba settlements in the late 18th century.

Due to the fact that it is situated in a tropical rainforest, the region under study is subject to two separate seasons: the rainfall period, which lasts between April until October, alongside the dry season, which lasts from November to March. The meteorological data that is currently available indicates that the southern region of Ondo State receives an annual rainfall total of more than 1,500 millimeters. A mean annual relative humidity of around 77.1% is found there, and the average yearly temperature ranges from 23 degrees Celsius to 27 degrees Celsius.

The research area is located inside the Dahomey Basin. The basin is lengthy, with a total length of around 800 kilometers, and it is narrow, running parallel to the coast. From southeast Ghana, it travels all the way to the westernmost point of the Niger Delta River. According to Burke et al. (1971), Klemme (1975), Whiteman (1982), and Kingston *et al.* (1983), the Dahomey Basin is a peri-cratonic basin that was developed in the early Cretaceous when rifting started as a result of the opening of the Gulf of Guinea.

An extensive era of thermally driven basin subsidence occurred from the mid-Cretaceous to the Tertiary, when the South American and African plates started to migrate to create place for the Atlantic Ocean (Mpanda, 1997). This phase was accompanied by basin thinning and crustal separation.

There is a significant accumulation of sediments in the Dahomey basin, which increases in thickness as it extends offshore. Omatsola and Adegoke (1981) recognized six lithostratigraphic units. The formations, listed in chronological order from oldest to youngest, are arranged as follows: Benin Formation (Oligocene-Recent), Oshosun Formation (Eocene), Ilaro Formation (Eocene), Ewekoro Formation (Paleocene), and Abeokuta Group (Cretaceous).

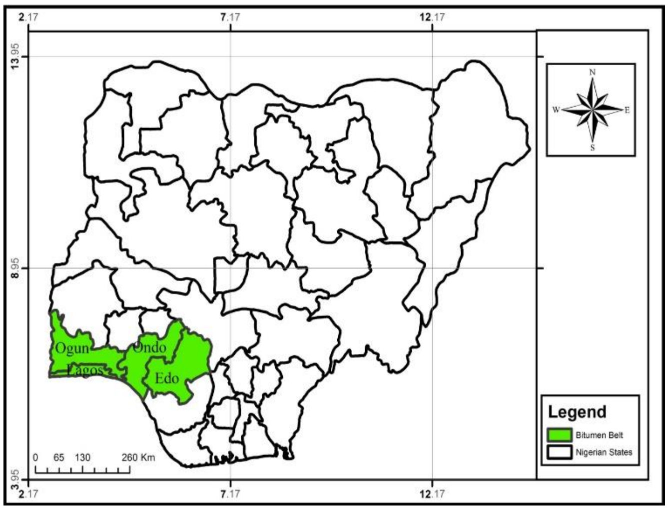

Fig 1: Bitumen Region in Nigeria.
Source: Department of Geography, Adeyemi Federal University of Education, Ondo

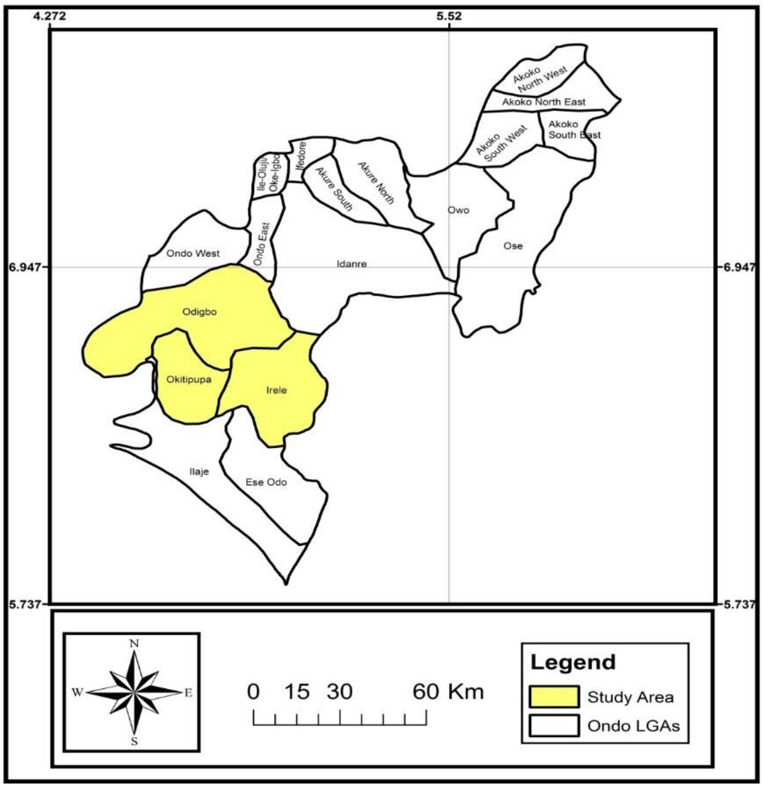

Fig 2: Local Government Area of the study area.
Source: Department of Geography, Adeyemi Federal University of Education, Ondo

Research Methodology

This study adopts a geospatial and quantitative research design to evaluate the spatial variation and distribution pattern of bitumen deposits in Southern Ondo State, Nigeria. The research integrates remote sensing (RS) and geographic information system (GIS) techniques with field validation to assess the geographical extent, spatial heterogeneity, and geological characteristics of the bituminous sands. The design emphasizes spatial modeling and data integration for comprehensive understanding of both surface and subsurface features. Such a geospatially driven approach enables the objective visualization, quantification, and interpretation of bitumen deposit patterns, ensuring spatial accuracy and analytical rigor consistent with international standards in geoscientific research (Jensen, 2015; Goodchild, 2020).

Secondary data sources were used for the study to ensure the accuracy, reliability, and completeness of the spatial assessment. Secondary data included geological and topographic maps (1:100,000 scale) sourced from the Nigerian Geological Survey Agency (NGSA), and well-log information obtained from the Nigerian Bitumen Development Project (NBDP). Georeferencing was performed to align all spatial datasets to the Universal Transverse Mercator (UTM) Zone 31N coordinate system based on the WGS 84 datum.
Hotspot analysis using Getis-Ord Gi* statistics identified statistically significant clusters of bitumen-rich zones, while spatial autocorrelation (Moran's I) quantified the degree of clustering versus randomness in bitumen distribution. Cartographic outputs were generated using ArcGIS Pro to ensure clear visualization of spatial relationships.

Results and Discussion

Areal Extent of Bitumen Deposit in Southern Ondo State.

Spatial extent pertains to the specific geographic area or region encompassed by an object. It establishes the limits and extent of a certain phenomenon or thing. Put simply, it involves ascertaining the spatial boundaries of an item. The geographical extent of the bitumen deposit refers to the geographic distribution of the deposit in the research region.

Figure 3 presented a detailed depiction of the spatial arrangement of bitumen blocks in a substantial area of Southern Ondo State, Nigeria. The diagram clearly illustrates the geographical range of bitumen deposits by marking the boundaries of bitumen blocks. The arrangement of these blocks exposes several fundamental patterns. The presence of bitumen blocks was seen to be concentrated in specific places, notably in the vicinity of Irele Local Government Area. This indicates a greater abundance of bitumen resources in these places, which makes them promising locations for exploration and development. Additionally, the bitumen blocks exhibit substantial variations in size, indicating disparities in the anticipated amount or caliber of bitumen reserves. Blocks of larger size indicate the presence of significant reserves, whilst smaller blocks indicate regions with lesser quantities of bitumen. Moreover, there are cases where bitumen blocks intersect, indicating possible regions with a significant concentration of bitumen or overlapping exploration permits. This situation might potentially create prospects for collaborative partnerships or mutually beneficial investigation. Bitumen is a dense and thick kind of petroleum. The comprehensive scope of its coverage is expected to lead to significant environmental deterioration, including ecosystems, bodies of water, and air purity. The process of extracting it frequently involves destroying extensive tracts of vegetation, which in turn disrupts natural ecosystems. Consequently, this might lead to a decline in biodiversity and the forced relocation of species. Bitumen manufacturing and storage have the potential of polluting both surface and groundwater with hazardous compounds, which can have adverse effects on nearby populations and ecosystems.

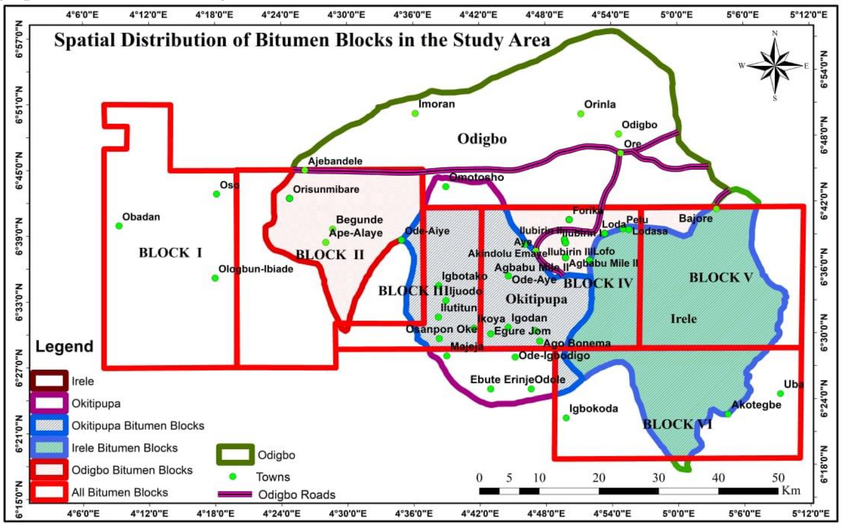

Figure 3: Spatial extent of bitumen deposit in southern Ondo State.
Source: Author's Analysis, 2025.

Bitumen Deposit extent in Odigbo Local Government Area

Among the six bitumen blocks located in Southern Ondo State, only four of them, namely Blocks II, III, IV, and V, were discovered to establish a relationship with Odigbo LGA. Table 1 displays the area coverage of Block II, which is 409.9km2 (67.3%). Blocks III, IV, and IV cover areas of 1.30km2 (0.21%), 159.7km2 (26.2%), and

38.3km2 (6.27%) correspondingly. The primary location where bitumen is predominantly found in Odigbo Local Government Area is in Block II, as determined by the Nigerian Geological Survey Agency. Following Block II, bitumen deposits are also present in Block IV and Block V. Block III, on the other hand, has the lowest amount of bitumen deposit.

Odigbo has a land area of 1,807.79km2, with 609.2km2 (33.37%) of the region containing bitumen deposits. This indicates that bitumen was deposited in little more than one fourth of the whole land area of Odigbo LGA. The geographical extent of the bitumen deposit is seen in Figure 4

Table 1: Spatial extent of Bitumen Deposit in Odigbo Local Government Area

AREA EXTENT OF BITUMEN BLOCKS IN ODIGBO LGA		
Block Name	**Area Extent (sq. Kilometer)**	**Extent Rate (%)**
BLOCK II	409.9	67.3
BLOCK III	1.30	0.21
BLOCK IV	159.7	26.2
BLOCK V	38.3	6.27
Total	**609.2**	**100**

Source: Author’s Analysis, 2025.

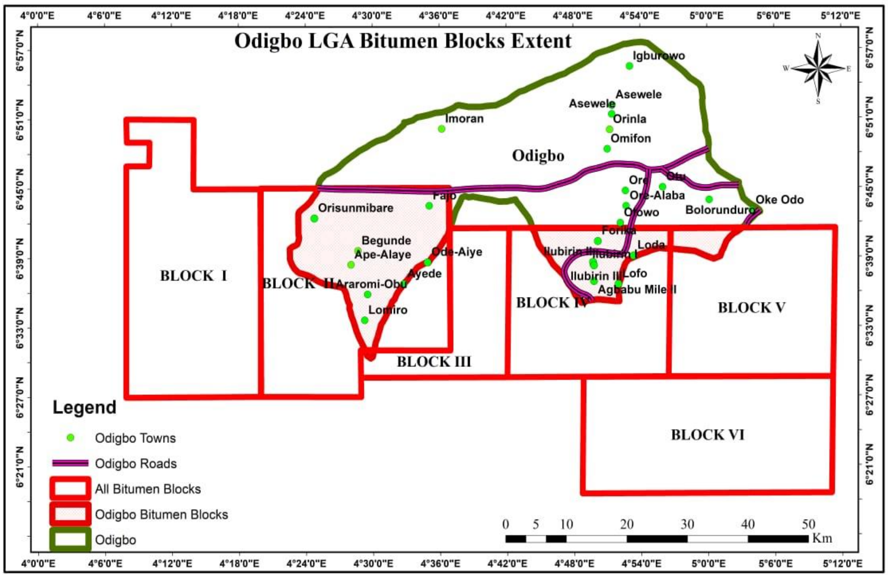

Figure 4: Spatial extent of bitumen deposit in Odigbo Local Government Area.

Source: Author’s Analysis, 2025

Areal extent of Bitumen Deposit in Irele LGA

Irele Local Government Area has a total area of 960.06 sq km and is situated inside three bituminous blocks out of the total six blocks. These blocks are specifically identified as Blocks IV, V, and VI. The survey found that about 97.6% of Irele Local Government Area is located within the bitumen blocks. Specifically, Block IV occupies 174.51km2 (18.56%), while Block V and Block VI span 462.96km2 (49.23%) and 302.99km2 (32.22%)

correspondingly (Table 2). It may be inferred that the majority of the land area in Irele Local Government Area is composed of bitumen. This was also supported by Figure 5.

Table 2: Spatial extent of Bitumen Deposit in Irele Local Government Area

AREA EXTENT OF BITUMEN BLOCKS IN IRELE LGA		
Block Name	**Area Extent (sqr. kilometer)**	**Extent Rate (%)**
BLOCK IV	174.51	18.56
BLOCK V	462.96	49.23
BLOCK VI	302.99	32.22
Total	**940.46**	**100**

Source: Author's Analysis, 2025.

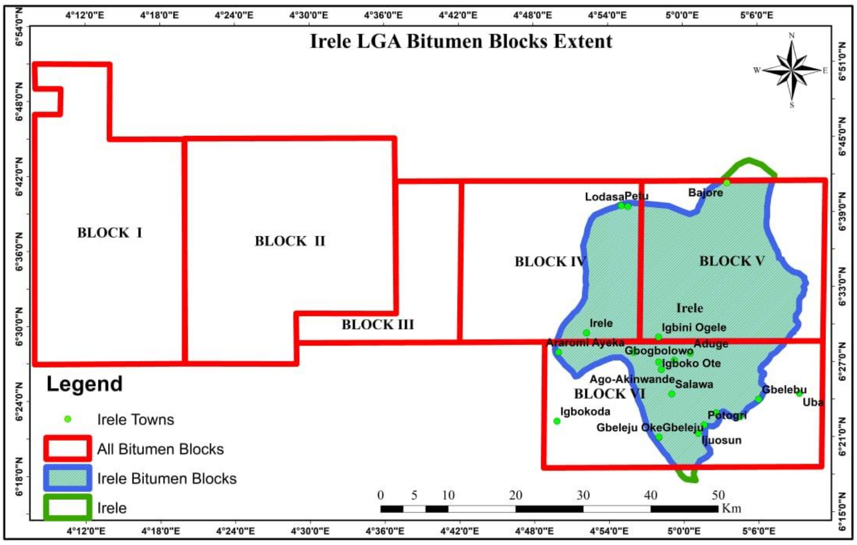

Figure 5: Spatial extent of bitumen deposit in Irele Local Government Area
Source: Author's Analysis, 2025.

Areal extent of Bitumen Deposit in Okitipupa LGA

Table 3 displayed the geographical extent of the bitumen deposit in Okitipupa Local Government Area. The table indicates the presence of four (4) bitumen blocks in Okitipupa LGA, namely blocks II, III, IV, and VI. Block II encompasses an area of 40.96 Sq. km, which represents 6.93% of the total area. Blocks III, IV, and VI have an area of 231.29 square kilometers (39.14%), 297.46 square kilometers (50.34%), and 21.17 Sq. kilometers (3.58%) accordingly. Okitipupa covers a total area of 800.31 square kilometers, with bitumen blocks occupying 590.41 square kilometers (73.8%) of the entire area. The figure 5 illustrates the geographical range of the bitumen deposit.

Table 3: Spatial extent of Bitumen in Okitipupa Local Government Area

AREA EXTENT OF BITUMEN BLOCKS IN OKITIPUPA LGA		
Block Name	**Area Extent (sq. kilometre)**	**Extent Rate (%)**
BLOCK II	40.96	6.93
BLOCK III	231.29	39.14

\BLOCK IV	297.46	50.34
BLOCK VI	21.7	3.58
Total	**590.41**	**100**

Source: Author's Analysis, 2025

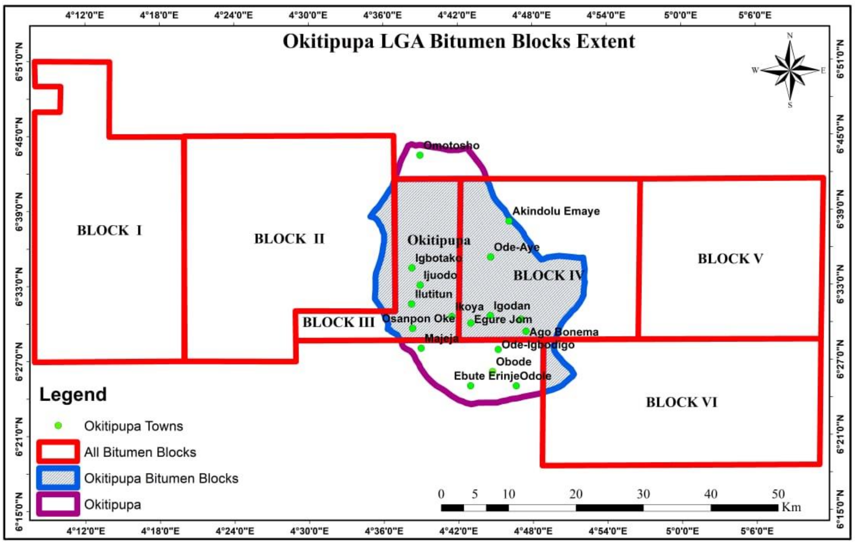

Figure 5: Spatial extent of Bitumen in Okitipupa Local Government Area
Source: Author's Analysis, 2025

Geospatial Pattern and Implications

The spatial arrangement of the bitumen blocks displays an identifiable north-south gradient, with higher deposit concentrations in the southern and southwestern portions of the study area. This pattern aligns with the broader geological trends of the Dahomey Basin, where bituminous sands are typically found in troughs and depressions along paleo-channels (Oladapo & Adeoye, 2019). The spatial continuity among blocks suggests that the bitumen deposits may originate from the same sedimentary processes and share similar lithological characteristics (Elueze, 2020).

The observed variations in block size and density also imply differing bitumen thicknesses and grades, which are crucial parameters for extraction feasibility. Larger contiguous blocks, such as Blocks IV and V, signify more economically viable reserves that can support industrial-scale mining operations. In contrast, smaller and fragmented blocks may require localized, small-scale extraction techniques to minimize environmental disruption (Salami et al., 2022).

Moreover, the spatial overlap between certain blocks particularly in Okitipupa and Irele may indicate zones of structural deformation or overlapping concession boundaries. This scenario underscores the need for coordinated resource governance to prevent conflicts among concession holders and to optimize extraction efficiency through shared infrastructure (Ikuemonisan et al., 2021).

While the spatial abundance of bitumen presents significant economic opportunities, it also poses environmental challenges that warrant critical attention. The large areal extent of bitumen-bearing formations, especially in Irele and Okitipupa, overlaps with areas of dense vegetation and diverse ecosystems. The extraction process, which often involves surface mining, is likely to cause deforestation, loss of biodiversity, and habitat fragmentation (Aigbedion & Iyayi, 2020).

Furthermore, the disturbance of soil and vegetation cover during bitumen exploitation may accelerate erosion and sedimentation in nearby rivers and wetlands. Contamination from bitumen residues and hydrocarbons could impair both surface and groundwater quality, affecting communities' dependent on these water sources (Obaje et al., 2021). Similar environmental outcomes have been observed in Canada's Athabasca Oil Sands and Venezuela's Orinoco Belt, where large-scale bitumen extraction has led to significant ecological degradation (Gosselin et al., 2010).

Hence, environmental management must be integral to any exploration strategy in Southern Ondo State. The adoption of geospatial tools for continuous environmental monitoring could help mitigate these risks by identifying critical zones of ecological sensitivity before mining begins (Ayeni & Olorunfemi, 2023).
The spatial distribution pattern of bitumen in Southern Ondo State has profound implications for regional development. The concentration of deposits in Irele and Okitipupa suggests that these areas could emerge as industrial hubs for bitumen-based production, creating opportunities for employment, infrastructure development, and increased internally generated revenue (Oluwatola et al., 2020). However, this potential is contingent on sustainable policy implementation and equitable benefit-sharing mechanisms.

Odigbo's moderate bitumen endowment also presents opportunities for localized economic diversification. The region could serve as a logistical and processing corridor linking inland production to coastal export routes, leveraging its proximity to transportation networks and industrial corridors (Adepoju & Abiodun, 2021).
Nevertheless, socio-economic benefits must be balanced against environmental and social costs. Previous experiences from oil-producing regions in the Niger Delta reveal that unregulated extraction often results in pollution, community displacement, and conflict (Nwilo et al., 2022). Therefore, geospatial data must be used not only for resource quantification but also for spatial planning that integrates environmental protection, community participation, and social equity (Salami et al., 2022).

The geospatial findings from this study align with earlier assessments by the NGSA, confirming Southern Ondo State as one of Nigeria's most bitumen-rich zones. However, unlike earlier reports that relied mainly on geological mapping, this research employs geospatial techniques that allow for a more precise delineation of spatial extents and inter-block relationships. This methodological advancement enhances the accuracy of resource estimation and facilitates evidence-based decision-making (Ayeni & Olorunfemi, 2023).

Policy-wise, the uneven spatial distribution of bitumen resources necessitates a region-specific approach to exploration licensing and environmental oversight. Irele, being the most resource-rich, requires strict regulatory frameworks to manage intensive extraction activities, while Odigbo and Okitipupa could adopt more integrated land-use models combining resource extraction with agricultural and urban development (Elueze, 2020).
Additionally, the identification of overlapping block boundaries highlights the importance of geospatial data in resolving concession disputes. Establishing a centralized geospatial repository managed by the Ministry of Mines and Steel Development could streamline exploration rights, improve transparency, and prevent duplication of permits (Ikuemonisan et al., 2021).

The findings also emphasize the importance of sustainable extraction practices in maintaining ecological balance and community welfare. Incorporating remote sensing and GIS-based environmental monitoring systems will enable early detection of degradation and pollution, supporting adaptive management. Furthermore, the promotion of cleaner extraction technologies, such as in-situ upgrading and controlled thermal recovery, could reduce carbon emissions and soil disruption (Gosselin et al., 2010).

Beyond environmental considerations, the development of the bitumen sector in Southern Ondo State should align with Nigeria's energy transition goals. As global economies shift toward decarbonization, bitumen exploitation must be guided by policies that balance fossil fuel dependence with renewable energy investment (Obaje et al., 2021). The geospatial mapping from this study provides the spatial intelligence necessary for such balanced planning.
The geospatial assessment of bitumen deposits in Southern Ondo State reveals a distinct spatial pattern characterized by concentration, variability, and overlap across Odigbo, Irele, and Okitipupa LGAs. Irele emerges as the most resource-rich, followed by Okitipupa and Odigbo. While the spatial abundance indicates vast economic potential, it simultaneously raises environmental and governance concerns. The findings advocate for a geospatially informed, environmentally conscious, and community-centered approach to bitumen exploration. Such an integrated strategy will not only optimize resource utilization but also ensure sustainability and equitable development in Southern Ondo State and beyond.

Conclusion
This study has provided a comprehensive geospatial assessment of the spatial variation and distribution patterns of bitumen deposits in Southern Ondo State, Nigeria. Using GIS-based spatial analysis, the research established that bitumen deposits are unevenly distributed across the study area, with Irele Local Government Area having the highest concentration, followed by Okitipupa and Odigbo. The identified bitumen blocks, particularly Blocks IV, V, and VI, exhibit significant areal extents and spatial overlaps, underscoring the region's rich hydrocarbon

potential within the Dahomey Basin. These variations reflect the underlying geological processes and depositional history that have shaped the mineral landscape of Southern Ondo State.

Beyond the geological and spatial insights, the study highlights the dual nature of bitumen resource development—that is, its vast economic potential and its significant environmental risks. The findings underscore the urgent need for sustainable exploration practices that integrate environmental safeguards, geospatial monitoring, and community-inclusive policies. The adoption of GIS and remote sensing technologies offers a reliable framework for continuous assessment and informed decision-making.

Ultimately, this research contributes to the growing body of knowledge on Nigeria's bitumen belt and provides an empirical foundation for future exploration planning, policy formulation, and environmental management. If strategically harnessed through sustainable and transparent governance, the bitumen resources of Southern Ondo State could serve as a catalyst for regional development, technological innovation, and national energy diversification.

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