Modelling Land Suitability for Optimal Rice Cultivation in Ebonyi State, Nigeria: A Comparative Study of Empirical Bayesian Kriging and Inverse Distance Weighted Geostatistical Models

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Abstract—**This study addresses the diminishing yields and food insecurity caused by declining rice production, a critical staple in Nigeria. Focused on Ebonyi State, the research employs GIS-based land suitability analysis to pinpoint the most suitable locations for rice cultivation. Environmental variables such as geology, soil types (Nitisols, Acrisols), elevation (0-28 m), slope (0-48%), and hydrology are examined. Geostatistical methods, including Empirical Bayesian Kriging (EBK), Inverse Distance Weighted (IDW), and Radial Basis Function (RBF), are used to model spatial variations. Multiple linear regression establishes quantifiable relationships between these factors and rice suitability. Analysis of Variance (ANOVA) underscores the significant impact of local government (p=0.0217), community, and water source (p=0.0431) on suitability. Central Ebonyi exhibits the highest flow accumulation (160.53 ratio). EBK emerges as the most accurate model with a Root Mean Square Error (RMSE) of 12.61. Regression models emphasise the influence of administrative factors on suitability. The study's results not only shed light on environmental constraints and opportunities but also offer crucial insights for enhancing rice productivity. This information is pivotal for shaping agricultural practices, and policies, and ultimately improving food security. Policymakers, agricultural agencies, and farmers stand to benefit significantly from the study's key findings, guiding them in selecting optimal cultivation sites, implementing effective practices, and making informed decisions to foster efficient and sustainable rice farming in Ebonyi.**

Keywords—Rice cultivation, agricultural sustainability, food security, GIS, land suitability analysis, geostatistics, environmental factors, multiple regression, ANOVA

I. Introduction

Rice is of considerable economic importance in many developing countries and has become an important crop in many developed countries where consumption has increased significantly. With the rapid growth of the world's population, it has become necessary to meet the growing demand for rice [1]. Rice farming plays a crucial role in Nigeria because it serves as a staple food and has a significant impact on the country's economy. Nigeria holds the distinction of being a major producer and consumer of rice within Africa [2]. However, despite its domestic production capacity, Nigeria also relies on substantial imports of rice [3].

The decreasing crop yields, particularly in the case of rice, in Nigeria can be attributed to various factors [4]. These include fluctuating climatic conditions, increasing pressure on land due to population growth and the subsequent reduction in farm sizes, instability and migrations resulting from ethnic conflicts and conflicts between farmers and herders, and the inability of peasant farmers to access fertilizers. Additionally, conservative attitudes toward modern agricultural techniques and market forces act as disincentives, along with challenges related to soil quality, terrain, and relief. According to Food and Agriculture Organization [2]. Nigeria's Ebonyi state is a significant rice-producing region. Onyeneke et al., 2021 noted that Ebonyi state's prevailing climatic conditions and excellent soils are ideal for growing rice. To increase rice productivity while ensuring land and environmental sustainability, countries must adopt an integrated approach that improves their ability to effectively plan and monitor the optimal utilisation and management of their land resources [5]. Geographic Information System (GIS) based analytic hierarchy process (AHP) multi-criteria analysis is one such integrated approach employed by [6, 7] a assess land suitability for rice cultivation in the great Mwea region, Kenya. To align rice farming with environmental sustainability while maximising economic outputs. This study aimed at utilising GIS-based multi-criteria decision model (MCDM) land suitability analysis in conjunction with the Food and Agricultural Organization (FAO) framework to identify suitable and unsuitable land for rice cultivation in the designated area. Researchers in [5, 8, 9, 10, 11] have employed diverse methods and models to assess the variability of essential spatial properties and their impact on rice cultivation. These spatial properties frequently include elements such as soil composition, which includes important characteristics such as nutrient content, pH levels, and water retention capacity. Furthermore, researchers examine elevation data to better understand how an area's physical landscape, such as slopes or contours, affects water drainage and irrigation practices. Climate variables, land cover types, and proximity to bodies of water may also be considered. Those methods unveiled relationships between environmental factors and rice crop performance by analysing these spatial properties. This improves site selections, agricultural practices, crop yield, and overall farming efficiency.

[12, 13, 14, 15] Highlighted that land suitability analysis is a necessary step in making the best use of available land resources. Low agricultural yields have been exacerbated by a lack of understanding of the optimal combination of factors suitable for rice production. The studies used advanced tools and methodologies such as geospatial analysis, remote sensing, and geographic information systems (GIS) multi-criteria assessment using the analytical hierarchy approach to provide powerful tools for integrating multiple data layers and extracting meaningful insights and to address the challenges associated with managing and analysing large amounts of spatial data for rice land suitability assessment. Hence, the primary aim of this current research is to utilise an ensemble approach and conduct a comparison of geostatistical models and niche modelling techniques. The study seeks to account for spatial variability and autocorrelation to generate a comprehensive land suitability map specifically for rice cultivation in Ebonyi state, Nigeria.

II. MATERIALS AND METHOD

A. *Study Area Description*

Ebonyi State is one of Nigeria's 36 states, located in the country's southeastern region. The state is bounded to the north by Benue State, to the west by Ebonyi State, to the east by Cross River State, and to the south by Abia State. According to the most recent estimates, Ebonyi State has a population of approximately 3 million people [16], with Igbo being the predominant language spoken in the state [17]. The state has a land area of approximately 5,670 square kilometres (2,190 square miles), making it one of Nigeria's smaller states in terms of size [18].

Climate-wise, Ebonyi State has a tropical climate with distinct wet and dry seasons. The wet season, which lasts from April to October, is distinguished by higher rainfall and humidity [19]. The dry season, on the other hand, lasts from November to March and is marked by lower precipitation and higher temperatures. The state's average annual temperature ranges between 26 and 28 degrees Celsius (79- and 82 degrees Fahrenheit) [5]. Ebonyi State's landscape is characterised by undulating plains and hills [15], as well as the presence of several rivers and streams. These natural bodies of water, such as the well-known Cross River, contribute to the state's agricultural productivity while also providing opportunities for fishing and other water-related activities [15].

B. *Data and Sources*

The optical and infrared bands of Sentinel-2 satellite imagery with 20 m resolution were stacked and reprojected from WGS 1984 to UTM zone 32N for the study area. This enabled land cover detection. Different indices like normalized difference vegetation index (NDVI) were calculated to identify water resources, vegetation, and agricultural areas. The watershed was delineated and slope, elevation, and flow direction data for the study area were extracted from the SPOT 5 digital elevation model (DEM).

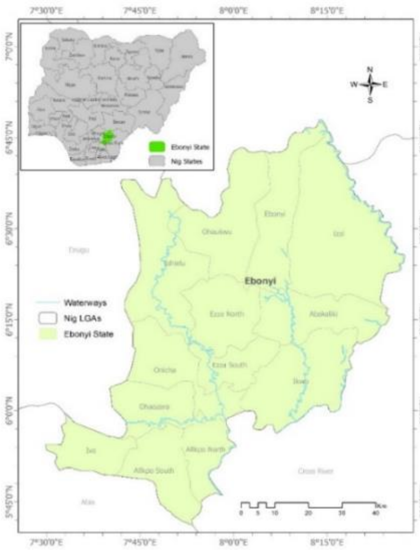


Fig. 1. Map showing the study area Ebonyi state, Nigeria

TABLE 1: DATA SETS

	Data	Variables	Year	Source	Format
1	Basemap	Relief Map	Last updated to 2023/06/12	Esri ArcGIS base map https://esri.com	Raster
2	Satellite Images	Landuse/cover Classification	2018, 2019, 2020, 2021 & 2022	Esri Living Atlas https://livingatlas.arcgis.com/landcoverexplorer/	Raster
4	Administrative boundaries	Nigerian States and Local Government Area	recent	GRID3 https://grid3.gov.ng	Shapefiles
5	Open Street Map (OSM)	Landuse type	Last updated 2023/06/12	OpenStreetMap https://download.geofabrik.de/africa/nigeria.html	Shapefiles
6	SPOT 5	Elevation, slope & hydrology	2010	United States Geological Survey https://earthex	Raster

				plorer.usgs.us .gv	
7	Soil and Geology	Lithology and soil	recent	Nigerian Geological Survey Agency https://ngsa.gov.ng/	Shapefiles

C. *Preprocessing and Data Analysis*

The collected data were Cleaned and preprocessed to remove any errors, outliers, or inconsistencies. Exploratory data analysis was conducted to understand the distribution and characteristics of the data and then Calculations of descriptive statistics for each environmental factor. Utilize the ArcGIS Pro 3.1 software to implement the geostatistical techniques. collected data were imported into a spatial database. Parameters were set up for each geostatistical technique (EBK and IDW) based on the data characteristics and research objectives see Fig.3. Geostatistical techniques were applied to generate maps and visualisations showing the spatial variability of the suitability factor for rice production in Ebonyi State.

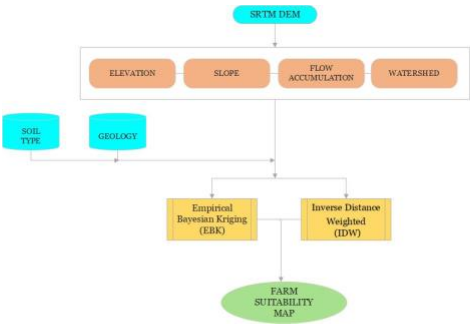


Fig. 2. Analysis flowchart

D. *Empirical Bayesian Kriging (EBK)*

The process of creating a reliable kriging model is made easier by the geostatistical interpolation method known as empirical Bayesian kriging (EBK). This technique combines estimation and prediction by treating parameters as random variables or factors contributing to the suitability of rice farming in the study area that call for conditional prediction based on observed data [24]. Predictive distribution results in EBK predictions.
Kriging formula:

$$P_{z(x_o)}(Z(x_o)|Z=z)$$
$$= \int_{D_\beta \times D_{\sigma^2} \times D_\phi} \mathrm{P}z(x_o),\beta,\sigma^2,\phi(Z(x_o),\beta,\sigma^2,\phi|\boldsymbol{Z}$$
$$=\boldsymbol{z})d\beta d\sigma^2 d\phi$$

$$= \int_{D_\beta \times D_{\sigma^2} \times D_\phi} \mathrm{P}z(x_o),\beta,\sigma^2,\phi(Z(x_o),\beta,\sigma^2,\phi|\boldsymbol{Z}=\boldsymbol{z})$$
$$\boldsymbol{P}\beta,\sigma^2,\phi(\beta,\sigma^2,\phi|\boldsymbol{Z}=\boldsymbol{z})d\beta d\sigma^2 d\phi \quad (1)$$

The density $\boldsymbol{P}\beta,\sigma^2,\phi(\beta,\sigma^2,\phi|\boldsymbol{Z}=\boldsymbol{z})d\beta d\sigma^2 d\phi$ is recognized as a Student's t-density when assuming that the prior belongs to the same family as the one described at the end of this section [22]. However, the integral is often challenging to compute.

E. *Inverse Distance Weighted (IDW)*

Inverse Distance Weighted (IDW) interpolation, a deterministic spatial interpolation method, was employed to estimate suitable locations for rice farming in the study area using known rice farm locations and their corresponding weighted values. The IDW interpolation formula (equation 3) estimates the unknown value $\mathcal{X}^*$ as potential locations for rice farms in the study area. The weight $\mathcal{W}$ in the formula represents the inverse distance of a point to each known point value $\mathcal{X}$ used in the calculation.

$$\mathcal{X}^* = \frac{\mathcal{W}_1\mathcal{X}_1+\mathcal{W}_2\mathcal{X}_2+\mathcal{W}_3\mathcal{X}_3+\ldots+\mathcal{W}_n\mathcal{X}_{1n}}{\mathcal{W}_1+\mathcal{W}_2+\mathcal{W}_3+\ldots+\mathcal{W}_n} \quad (2)$$

$$\mathcal{X} = \frac{\sum_i^n \frac{w_i}{d_{i\beta}}}{\sum_i^n \frac{1}{d_{i\beta}}} \quad (3)$$

III. RESULTS

A. *Soil and Geology*

The soil of the study area in Ebonyi reveals the presence of several soil types, namely Acrisols, Aisols, Cambisols, Gleysols, and Nitisols. Among these, the most dominant soil type is Nitisols, which extends from the northeastern part to the southeastern part of the area. The lithology of Ebonyi showcases a variety of soil types, each possessing unique characteristics that influence their suitability for irrigated rice farming. These soil types include shallow brown sandy shale soil (labelled as "L" on the map), red-brown sandstone soil, red clayey basalt soil, pale brown loamy alluvial soil, and yellowish-red gravelly acid crystalline rocks.

B. *Elevation and Slope*

Digital Elevation Model (DEM) from SRTM was used to generate the elevation and slope map of the study area. The elevation of the study area ranges from 5m to 28 m, areas with higher elevation in the study area are the Northern part and the southern part of the study area, LGA such as Afikpo North and South in the southern part of the study area have a relatively higher elevation same thing is applies to Ohauku, Ishielu LGA which is in the Northern part of the study area, relatively low elevation are in the west and Eastern central of the study areas see fig. 4d. The slope map is calculated in percentage, the slope of the study area ranges from 0% to 48.3%, locations with higher elevation are the areas with high slope percentage, Afikpo North and South constitute the areas with the highest range of slope value while the other location has a relatively low slope percentage value see fig.4f.

C. *Flow Accumulation*

The total flow accumulation data of Ebonyi have a value ranging from 0 to 1,212,583, the area has a very low accumulation with little location across the Ebonyi. The flow accumulation in Ebonyi State is very low, with most areas having a value of less than 1,000. The highest flow accumulation is found in the southeastern part of the state, near the confluence of the Ebonyi River and the Niger River.

The low flow accumulation also contributes to the high rate of soil erosion in the state.

The catchment area of Ebonyi State is divided into 67 catchment areas fig. 4b. Each catchment area is responsible for the collection and treatment of wastewater from a specific area of the state. The southeastern part of the state has the most catchment areas. The central, northeastern, and southwestern parts of the state have smaller catchment areas.

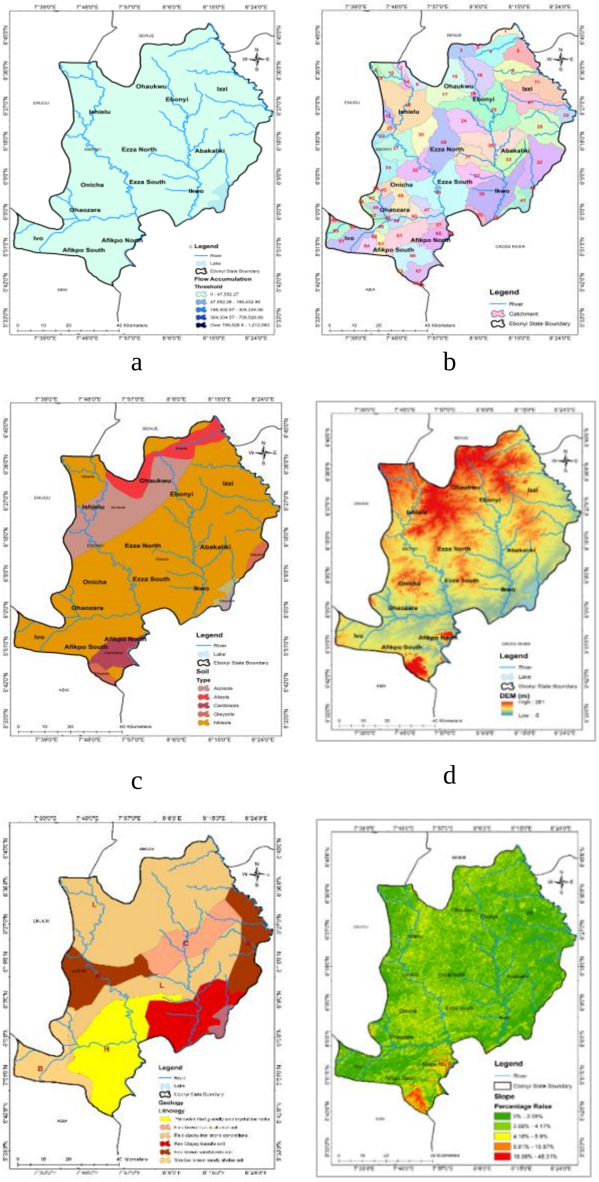
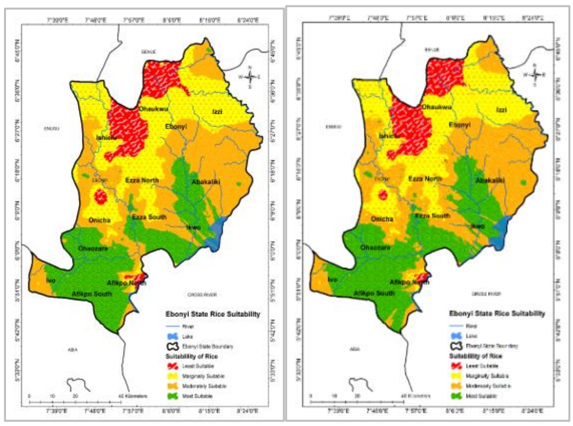


Fig. 3. Equation 4: mapping showing a) Flow accumulation, b) River catchment, c) Soil texture, d) Elevation, e) geology and f) slope of the study area

D. Suitability Analysis Model Evaluation

In the process of developing an irrigation model suitability analysis, three regression models were evaluated: Empirical Bayesian Kriging (EBK) and Inverse distance weighted (IDW). These models aimed to predict the relationship between the independent variable, represented and the dependent variable. The evaluation of these models involved assessing their prediction errors using various statistical metrics. For the EBK model, the regression function was determined to be $0.82x + 17.31$. The evaluation was conducted on a dataset comprising 1447 samples. The mean prediction error was found to be 0.03, indicating that, on average, the predicted values were close to the actual values. The root-mean-square error, a measure of the overall model accuracy, was 12.61. The mean standardized error and root-mean-square standardized error were calculated as 0.002 and 0.98, respectively. Additionally, the average standard error was determined to be 12.81. The RBF model yielded a regression function of $0.82x + 17.4$. Similar to the EBK model, the evaluation was performed on the same dataset of 1447 samples. The mean prediction error for this model was 0.08, indicating a slightly larger deviation from the actual values compared to the EBK model. The root-mean-square error was calculated as 14.34, suggesting a moderate level of accuracy. The IDW model was evaluated, with a regression function of $0.82x + 18$. The prediction errors for this 26 model showed a larger mean error of 0.41 and a root-mean-square error of 14.05. These results suggest that the IDW model had the highest deviation from the actual values among the three evaluated models. The evaluation of these models provides insights into their performance for the irrigation model suitability analysis. The EBK model demonstrated relatively smaller prediction errors, indicating a better fit to the data compared to the IDW model see Fig. 4



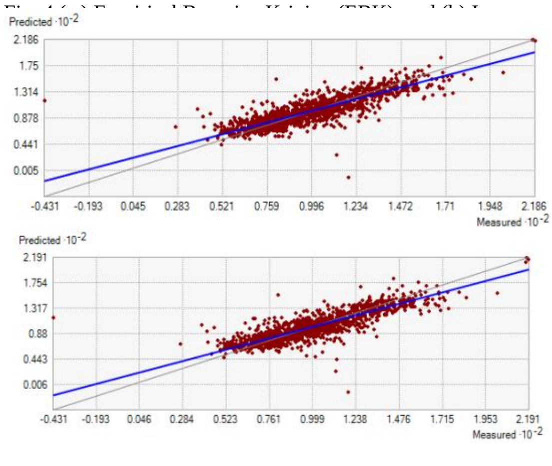


Fig. 5. Predicated values for a) EBK model and b) IDW model

E. Multiple Linear Regression

The multiple linear regression was used to develop models for each environmental factor. Suitability for rice production is the dependent variable and the environmental factors as independent variables. coefficients of the regression models were Determined to quantify the relationship between each environmental factor and rice suitability. The regression equation can be represented as:

$$Rice\ suitability\ =\ \beta_o + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n$$

Where:

$Suitability\ =\ Suitability\ for\ rice\ production\ in\ the\ Ebonyi\ state$

$\beta_o, \beta_1, \beta_2 \ldots \beta_n =$ Regression coefficient

$X_1, X_2 \ldots X_n =$ Environmental factors and criteria

i) Factor Hypothesis Testing

From the ANOVA table, the $p - value = 0.0217 < 0.05$ for the *local government assembly (LGA)* factor. The null hypothesis is rejected, thus, concluding that it is statistically significant in the study. This further confirms that the local government assembly (LGA) considered for the study influences flow accumulation on average.

Also, the $p - value = 0.00 < 0.05$ for the *Community* factor, which is statistically significant in the study. The null hypothesis is rejected, so, we can conclude that the selected Community has a great influence on the flow accumulation of rice production.

TABLE 2: ANOVA MODEL SUMMARY

Source of Variation	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
LGA	9	868170	96463	7.432	0.0217
Community	2922	6146859	89544	45.401	0.0000
Water. Source	6	1328499	221417	15.992	0.0431
Residuals	3046	7868000	223250		

Finally, the $p - value = 0.0431 < 0.05$ for the *Water source* factor. Thus, The null hypothesis is rejected, so, we can conclude that the selected source of water considered for the rice production has a great influence on the flow accumulation due to the possibilities of run-offs see Table 2.

In addition, no interaction of the three variables above was found to be significant for the study. As a result, the main effects of local government assembly (LGA), Community, and water sources were studied for further analysis.

IV. DISCUSSION AND CONCLUSION

The data analysis reveals that Flow Accumulation, with an average maximum of 160.53 in the Bilonwe Iyokpa ntezi community and Ishielu Local Government Area, signifies robust drainage systems, enhancing the potential for increased rice production. This substantial water supply ensures proper soil nutrient levels, contributing to enhanced rice quality and yield, thereby boosting production and revenue. Conversely, communities such as Amuda, Ledeba, Igwebuike, Ekka, OkpotoI, Azuramura, and Ekwetekwe/Ogbuinyagu, registering an average Flow Accumulation close to zero, depict insufficient water supply or poorly maintained drainage systems, adversely impacting production [17]. Future research could consider studying water sources, local government assembly (LGA), and community as random effects, capturing variations of interest for further analysis. Regarding geology, Ebonyi's diverse lithological types significantly influence the area's suitability for irrigated rice farming. The dominant shallow brown sandy shale soil, while well-draining, requires meticulous water and nutrient management [5]. Other types like red-brown sandstone soil and pale brown loamy alluvial soil offer moderate drainage and excellent water retention, making them conducive for rice cultivation. Conversely, red clayey basalt soil and yellowish-red gravelly acid crystalline rocks necessitate specific management practices to address challenges related to water retention and nutrient availability.

The soil classification in the study area includes Acrisols, Aisols, Cambisols, Gleysols, and Nitisols, with Nitisols being the predominant soil type, Acrisols, despite challenges related to nutrient deficiency and acidity, can be improved through suitable soil amendments [14]. Aisols, characterized by sandy texture and low water-holding capacity, may require additional irrigation and nutrient management for successful rice farming [14]. Cambisols, with better water-holding capacity compared to Aisols, are suitable for irrigated rice cultivation with proper irrigation and fertility management. Gleysols, characterized by poor drainage, may require measures for drainage improvement, creating a conducive environment for rice plants. Nitisols, known for their excellent water-holding capacity, fertility, and organic matter content, emerge as highly suitable for irrigated rice farming, providing an optimal environment for successful rice cultivation. These findings offer valuable insights into the factors influencing rice cultivation suitability in Ebonyi, guiding future agricultural practices and policies [1, 5, 6, 11, 15].

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