Sahel Journal of Life Sciences FUDMA (SAJOLS)
June 2025 Vol. 3(2): 239-250
ISSN: 3027-0456 (Print)
ISSN: 1595-5915 (Online)
DOI: *https://doi.org/10.33003/sajols-2025-0302-29*

Research Article

Spatial and Geostatistical Analysis of Variability of Soil Exchangeable Basic Cations Along River Wudil Floodplain, Kano State, Nigeria

***Yasir Ibrahim Khallah[1], Muhammad Adamu Aliyu [2], Anas Sulaiman Musa[3] and Bala Muhamad[4]**

[1]Association of Nigerian Authors (ANA), Kano State Branch, Kano Sate, Nigeria
[2]Department of Soil Science and Land Resources Management, Federal University Wukari, Taraba State, Nigeria
[3]Department of Soil Science, Kaduna State University, Kaduna State, Nigeria
[4]Audu Bako College of Agriculture, Thomas Dambatta, Kano State, Nigeria
****Corresponding Author's email***: yaseerkallah@yahoo.com; **Phone: +2348034629585**

ABSTRACT
This study investigated the spatial variability of soil exchangeable basic cations along the River Wudil floodplain in Wudil Local Government Area, Kano State, Nigeria. A total of 150 soil samples were collected at a depth of 0–30 cm using a systematic 100 × 200 m grid sampling technique. Calcium (Ca), Magnesium (Mg), Potassium (K), and Sodium (Na) were analyzed in the laboratory. Both classical and geostatistical methods, including semivariogram analysis and ordinary kriging, were employed to describe the properties and spatial correlation of the cations. The results revealed that Ca and Na exhibited strong spatial dependence, while Mg and K showed moderate spatial dependence. The variability was highest for calcium (39.4%) and lowest for sodium (16.7%), indicating considerable heterogeneity across the floodplain soils. This spatial variability suggests that uniform soil management practices may be inefficient for the area. Therefore, integrated soil fertility management through the combined use of organic and inorganic fertilizers is recommended to address nutrient imbalances. Additionally, site-specific nutrient management strategies should be developed to enhance resource use efficiency and crop productivity. Overall, the study demonstrates that geostatistical techniques are effective tools for assessing soil fertility status and guiding precision agriculture. Understanding the spatial distribution of soil cations is vital for sustainable land use planning and improved agricultural productivity in floodplain ecosystems.

Keywords: Floodplain; Geostatistical Analysis; Kiriging; Soil Exchangeable Basic Cations; Spatial Variability

Citation: Khallah, Y.I., Aliyu, M.A., Musa, A.S. & Muhamad, B. (2025). Spatial and Geostatistical Analysis of Variability of Soil Exchangeable Basic Cations Along River Wudil Floodplain, Kano State, Nigeria. *Sahel Journal of Life Sciences FUDMA*, 3(2): 239-250. DOI: https://doi.org/10.33003/sajols-2025-030222-29

INTRODUCTION

A floodplain is a low-lying area of land adjacent to a stream or river, extending from the banks of the channel to the base of the surrounding valley walls, which is subject to periodic inundation during episodes of high discharge (Goudie, 2004). Floodplains typically consist of levees, flood basins, point bars, and oxbow lakes. These areas are considered highly productive ecosystems (Mitsch & Gosselink, 2000), as frequent flooding events transport nutrient-rich sediments from upstream catchments, replenishing soil fertility. The fine and coarse sediments carried by floodwaters are deposited across the floodplain landscape, contributing to its dynamic nature. Soils formed within floodplains often exhibit considerable variation in their morphological, physical, and chemical properties, which can be attributed to differences in sedimentation history, micro-relief, drainage conditions, and mineralogical composition (Hossain *et al.,* 2011).

Floodplain soils are vital for agricultural productivity, especially in regions such as Kano State, Nigeria, where fertile alluvial deposits sustain intensive crop cultivation (Brady & Weil, 2017). These soils exhibit considerable spatial variability in physicochemical properties, which directly influence nutrient availability, soil fertility, and ultimately crop yields (Webster & Oliver, 2007; Odunze *et al.,* 2020).

Exchangeable basic cations i.e. calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and sodium (Na^{+}) play key roles in maintaining soil chemical balance and supporting plant growth (Brady & Weil, 2017; Sparks, 2003). Thus, detailed knowledge of their spatial distribution is essential for efficient nutrient management and sustainable agricultural practices (Khan *et al*., 2021).

The distribution of exchangeable basic cations within soils is often highly variable due to differences in parent material, topography, hydrological conditions, and land use practices (McBratney *et al*., 2003; Webster & Oliver, 2007). Such spatial heterogeneity can result in localized nutrient deficiencies or excesses, directly influencing soil fertility and crop productivity (Adugna & Molla, 2017).

Geostatistical techniques, including semivariogram analysis and kriging, have been widely used to quantify and map spatial variability in soil properties (Isaaks & Srivastava, 1989; Goovaerts, 1998). These approaches facilitate better understanding of the scale and pattern of variability, helping to design targeted soil management interventions (Oliver, 2010). Studies in diverse floodplain environments, including those in Nigeria and other tropical regions, have revealed that spatial dependence of exchangeable cations is influenced by factors such as parent material, flooding regime, and land use (Ibeawuchi *et al*., 2016; Adugna & Molla, 2017; Fenta *et al*., 2018). However, limited geostatistical data exist specifically for the River Wudil floodplain, highlighting the need for focused investigation to guide localized soil fertility improvement.

This study applies geostatistical methods to assess the spatial variability of soil exchangeable basic cations along the River Wudil floodplain in Kano State, Nigeria. The outcomes will support optimized fertilizer recommendations and sustainable land use planning to enhance agricultural productivity in this important floodplain system. Therefore, investigating the spatial patterns of exchangeable basic cations is fundamental for advancing precision agriculture and promoting sustainable land management practices (Fenta *et al*., 2018).

The main objective of this study is to determine the spatial variability of soil Exchangeable Basic Cations along of Wudil River floodplain. The specific objectives of the study were to determine the status and degree of spatial variability of soil exchangeable basic cations in the study area; to map out the spatial distribution of soil exchangeable basic cations in the study area and; to assess relationships between the soil properties in the study area.

MATERIALS AND METHODS

Study Area

The study was conducted along Wudil River, which lies between latitude 11.798180^0 & 11.76196^0 north and longitude 8.8272030^0 & 8.762978^0 east. It covers a distance of 27.326 km, in Wudil Local Government, Kano State (Fig. 1).

Field Study

Reconnaissance visits were conducted to determine the extent of the floodplain area. The total extent of the floodplain area was found to be 27.326 km by 0.3 km. A 10 km by 0.3 km area was determined along the floodplain area using Google Maps, and other specific types of data like geographic coordinates and topographic information, were collected during the reconnaissance.

Arc GIS (version 10.3.1) was used to create a 300-meter buffer along the river beds (Fig. 2). The buffer created allows for uniform soil sampling. Grids of 100 by 200 meters were superimposed on the geotag-buffered areas. A total of 150 grid points identified within the buffer were uploaded into the Geographic Positioning System (GPS) for accurate ground truthing and sampling (Fig. 3). The soil samples were collected at a depth of 0-30cm of each centre of the grid points. Soil auger was used for sample collection. The soils were properly labelled, packaged and taken to the laboratory for analysis.

Laboratory Analysis

The collected soil samples were air-dried, ground and passed through a 2mm sieve. The soil samples were analyzed in the laboratory based on the Mehlich-3 extraction procedure (Mehlich, 1984).

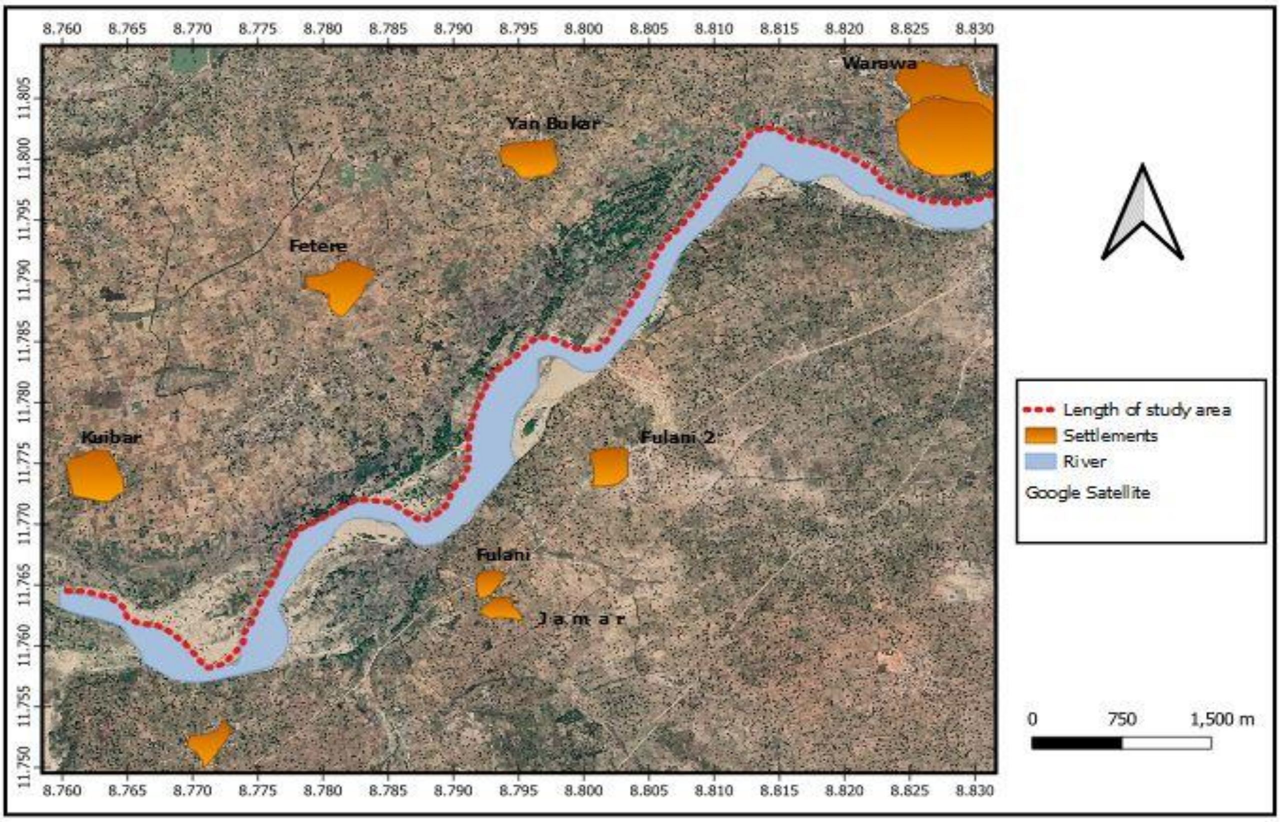

Figure 1: Location of the study area
Source: Generated using ArcMap 10.3.1

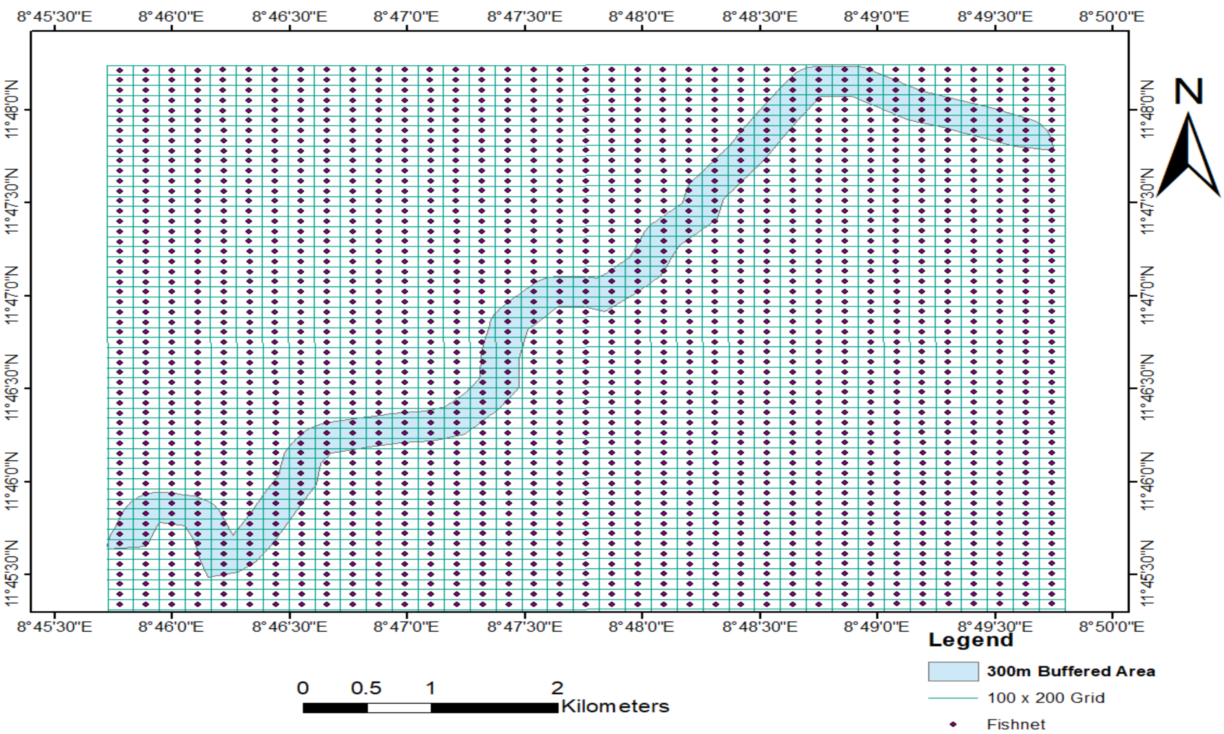

Figure 2: Map Showing the 300 Meters Buffer, a Fishnet and a Grid of 100 by 200 Meters
Source: Generated using ArcMap 10.3.1

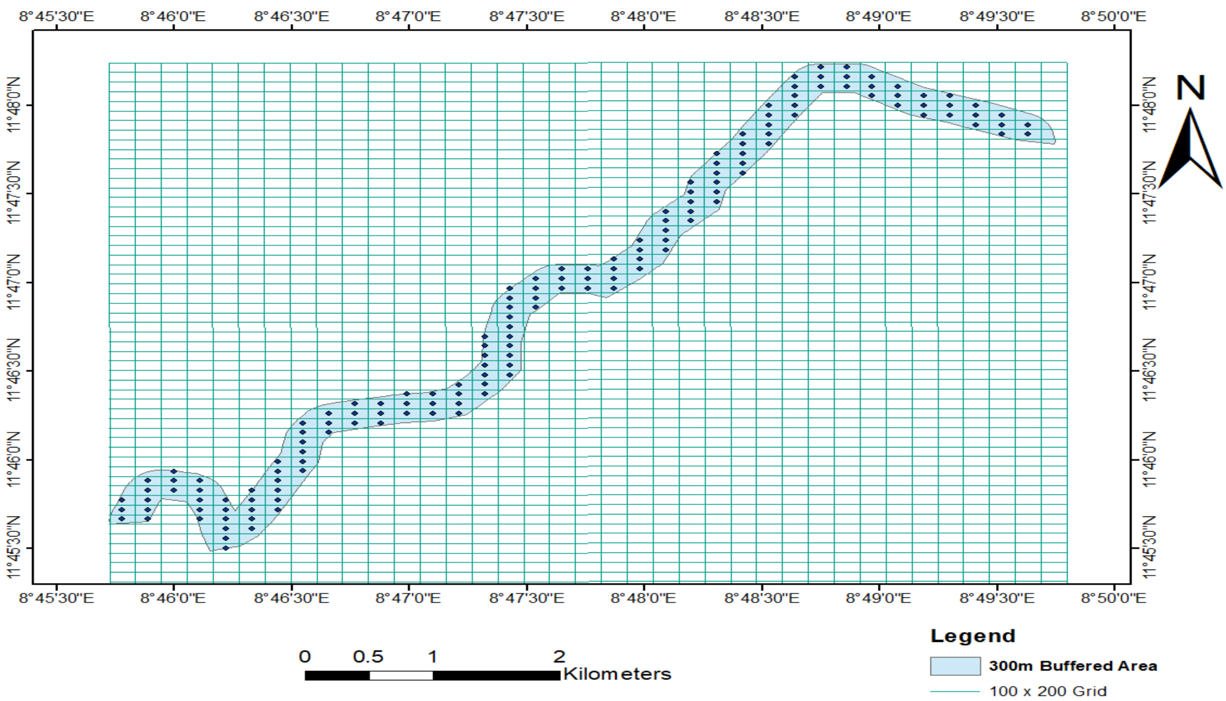

Figure 3: Map Showing the Sampling Points in the Study Area
Source: Generated using ArcMap 10.3.1

Data Analysis

Descriptive Statistics

To understand the characteristics of the collected data, descriptive statistics (mean, median, minimum, maximum, standard deviation (SD), coefficient of variation (CV), skewness and kurtosis) were employed using JMP Pro 15.0 statistical software. Moreover, a correlation matrix was used to evaluate the relationship between the soil properties.

Geostatistical Analysis

Geostatistical software (ArcMap10.3.1) was used to analyze the spatial dependence and to map out the spatial distribution of the soil properties. The degree of spatial dependence for each variable was determined with geostatistical methods using semivariogram analysis and kriging. Ordinary Kriging was selected as a geostatistical method because it is considered one of the most accurate interpolation techniques, which assumes that variables close in space tend to be more similar than those further away (Goovaerts, 1999).

The hypothesis and parities used to calculate semivariograms were described by Burgess and Webster (1980). Experimental semivariograms were obtained from omnidirectional semivariances, γ(h), of a set of spatial observations, z (x_i), which were calculated as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z_{(i+h)} - Z_i]^2$$

Where (h) is the number of experimental pairs [Z*(i+h)*, Z *i*] of data separated by a vector h.

Experimental semivariograms were fitted by theoretical models with parameters: nugget (Co), sill (Co+C_1), and range of spatial dependence (a). Model selection for semivariograms was performed based on nugget and mean error (ME).

Using the Geostatistical Analyst tool (ArcGIS) and selecting the ordinary kriging methods, a semivariogram was created for each measured property. In the Kriging method, different semivariogram models (spherical, exponential, circular and stable) were evaluated, and the best-fitted model of each parameter was selected using a cross-validation technique, which permits the evaluation of the prediction accuracy. Mathematical models with minimum mean error (ME) and nugget values that are closer to zero were selected.

In the cross-validation techniques, statistical tools involving mean error (ME) and nugget values were used to identify the best-fitted semivariogram model. Models with the smallest mean error (ME) and smallest nugget value are the most fitted semi-variogram models, thus indicating the best accurate spatial predictions.

To determine the spatial dependence, the nugget-to-sill ratio (nugget ratio expressed in percentage), is used to define spatial dependence of soil properties: if the ratio is < 25%, there is strong spatial dependence; if it is 25 to 75%, there is moderate spatial dependence; and if the ratio is >

75%, spatial dependence is weak (Cambardella *et al.,* 1994). The nugget ratio was determined by dividing the nugget value of each parameter by its sill value and subsequently multiplying the result by 100.

RESULTS AND DISCUSSION

Status and Degree of Spatial Variability of the Soil Parameters

For most of the soil properties, the mean and median values were nearly similar, with most median values either equal to or less than the mean. This descriptive statistic attested to the fact, that the measure of central tendency was not dominated by outliers. Many previous works have reported such similarities in mean and median for several soil quality indicators (Shukla, Lal, and Ebinger, 2004; Duffera, White, and Weisz, 2007; Hou-Long *et al.*, 2010; Brady & Weil, 2017).

Classical descriptive statistics of the Exchangeable Basic Cations, as shown in Table 1, show calcium contents ranging from 0.96 to 5.51 cmolmol/kg with a mean value of 2.51. It has a CV value of 39.4 % indicating a high level of variability across the sampling points (Ogunkule, 1993). Calcium deviated to the right from the normal distribution curve by having a skewness value of 0.93 and a heavy-tailed distribution with a kurtosis value of 0.687. Across the study area, Magnesium ranged from 0.47 to 1.32 cmolmol/kg and had a hadean value of 0.79 cmolmol kg. The coefficient of variability (CV) for magnesium is 26.3% which is considered to be moderately variable across the study area. It has a positive skewness of 0.07 and a negative kurtosis of -0.76. Potassium contents ranged from 0.13 to 0.55 mol (+)/kg with a mean value of 0.26 mol (+)/kg. It has a CV value of 26.25 % indicating a moderate level of variability across the sampling points. Potassium components showed both positive skewness (1.10) and kurtosis (2.02). Sodium contents ranged from 0.07 to 0.17 cmol(+)/kg with mean a value of 0.11 cmol(+)/kg. It has a CV value of 16.7 % which also indicates a moderate level of variability across the sampling points. Sodium content deviated to the right from the normal distribution curve by having a skewness value of 0.83 and a heavy-tailed distribution, having a kurtosis value of 2.04.

The strong to moderate level variability in the exchangeable basic cations might depend on the nature and conditions of the soil and management practices. The distribution of exchangeable basic cations in most agricultural soil is generally Ca > Mg > K > Na with a pH of 5.5 or more (Bohn *et al.,* 2001; Fasil & Charles, 2009; Teshome *et al.,* 2013; Lal, 2015). Heluf and Wakene (2006) revealed that variations in the distribution of exchangeable bases depend on the mineral present, particle size distribution, degree of weathering, soil management practices, climatic conditions, degree of soil development, the intensity of cultivation, external inputs (ashes and manure) and the parent material from which the soil is formed.

Table 1: Descriptive statistic for the soil properties

Properties	Min	Max	Mean	Median	SD	Variance	CV (%)	Skewness	Kurtosis
Ca (cmol(+)/kg)	0.96	5.51	2.5101	2.42	0.989	0.9791	39.4	0.934	0.687
Mg (cmol(+)/kg)	0.47	1.32	0.7918	0.805	0.208	0.0434	26.3	0.0743	-0.7617
K (cmol(+)/kg)	0.13	0.55	0.2628	0.26	0.0690	0.0048	26.3	1.0970	2.0229
Na (cmol(+)/kg)	0.07	0.17	0.1103	0.11	0.0184	0.0003	16.7	0.8325	2.0422

Generated using JMP Pro 15.0

Spatial Distribution and Pattern of the Soil Properties

As shown in Table 2, the nugget ratio values indicated the presence of strong and moderate level spatial dependence for the soil parameters (values between 0.0 and 68.4%). There was strong spatial dependence in calcium (0%) and sodium (0.0035%), and a moderate spatial dependence in magnesium (42.54%) and potassium (68.43%).

The strong spatial dependence observed in calcium and sodium might be affected mainly by intrinsic factors (i.e., soil formation factors, such as soil parent material and texture) and frequency of inundation and duration of flooding that brings in nutrient-rich sediments from surrounding watersheds to the flood plain area (Santra, Chopra and Chakraboty, 2008; Wei *et al*. 2009; Junk *et al.,* 2011; Lal, 2015; Brady & Weil, 2017).

The moderate level of spatial dependence observed in potassium and magnesium might be caused largely by soil moisture conditions in the study area and extrinsic variations such as fertilizer application, tillage, and other management practices (Cambardella *et al*., 1994).

Table 2: Semivariogram Models and Parameters for the Soil Properties

Variable	Model	Nugget, (C_0)	Sill, (C_0+C)	Range (m)	ME	RMSSE	Nugget ratio (%)
Ca (cmol(+)/kg)	Exponential	0.0000	0.0929	0.18	0.0147	0.9845	0.0000
Mg (cmol(+)/kg)	Circular	0.0182	0.0429	0.18	0.0009	0.9925	42.5443
K (cmol(+)/kg)	Exponential	0.0036	0.0053	1.60	-7.4222	1.0019	68.4316
Na (cmol(+)/kg)	Exponential	0.0003	7.6588	4.64	-0.0002	1.0391	0.0035

Generated using ArcMap 10.3.1

Spatial Distribution and Pattern of the Exchangeable Basic Cations

Calcium contents were best fitted by the exponential model (Table 3). The contents ranged from 0.96 to 5.51 (cmol(+)/kg) across the study area (Table 1). The nugget component was zero (0.00) for soil calcium. A smaller range value of 0.18 m was observed for the calcium content (Table 2). The lower interpolated range for calcium contents occupied a total area of 0.58 (km)^2, which is equivalent to 19 % of the total study area (Table 3). The middle-interpolated range occupied the extreme northeast end, middle and towards the southwest end of the study area (Figure 4). It occupied the highest area among the three interpolated calcium values, which was 1.53 (km)^2, equivalent to 52 % of the total area (Table 5). The upper interpolated range of calcium contents of the study area occupied a total area of 0.95 (km)^2, which is equivalent to 31 % of the total study area (Table 3). It has a RMSSE value of 0.9845 as indicated by Table 2.

The zero-nugget content of soil calcium indicates a spatial continuity between the neighbouring points and is well supported by Sun *et al.* (2003), who reported approximately a zero-nugget effect of calcium for cultivated soils. Smaller range values of (0.18 m) showed that observed values of the soil property were not influenced by other values of this property over greater distances (Isaaks and Srivastava, 1989; Oliver & Webster, 2015). Its RMSSE value of (0.9845), as indicated by Table 3, shows that there was a slight underestimation of calcium content.

Magnesium was observed to be best fitted to the circular semivariogram mathematical model and has a small range of 0.18m (Table 2). Having a small range, as according to PazGonzales (2003) and Brady & Weil (2017), indicated that there is a spatial continuity between the neighboring points, and observed values of the magnesium contents were not influenced by other values of this property over greater distances (Isaaks and Srivastava, 1989; Oliver & Webster, 2015).

The upper interpolated range of the magnesium contents was observed close to the middle of the study area; a small of its patches were distributed across the study area (Figure 5). The upper range occupied a total area of 1.32 (km)^2, which is equivalent to 43 % of the study area. A lower interpolated range of magnesium contents was observed at the extreme southwest end of the study area, and some of its patches were observed at the middle point of the study area (Figure 5). They occupied an area of 0.34 (km)^2, which is equivalent to 11 % of the total study area (Table 3). The Middle-interpolated range of magnesium contents of the study area, as depicted by the interpolated map of magnesium, occupied a total area of 1.40 (km)^2, which is equivalent to 46 % of the total study area (Table 3).

Table 3: Area and the Percentages of Interpolated Ranges of Exchangeable Cations

Range	Area (km)^2	Area (%)
K (cmol(+)/kg)		
Lower	1.33	44
Middle	1.45	47
Upper	0.28	9
Ca (cmol(+)/kg)		
Lower	0.58	19
Middle	1.53	50
Upper	0.95	31
Mg (cmol(+)/kg)		
Lower	0.34	11
Middle	1.40	46
Upper	1.32	43
Na (cmol(+)/kg)		
Lower	0.31	10
Middle	1.97	64
Upper	0.78	26

Generated using ArcMap 10.3.1

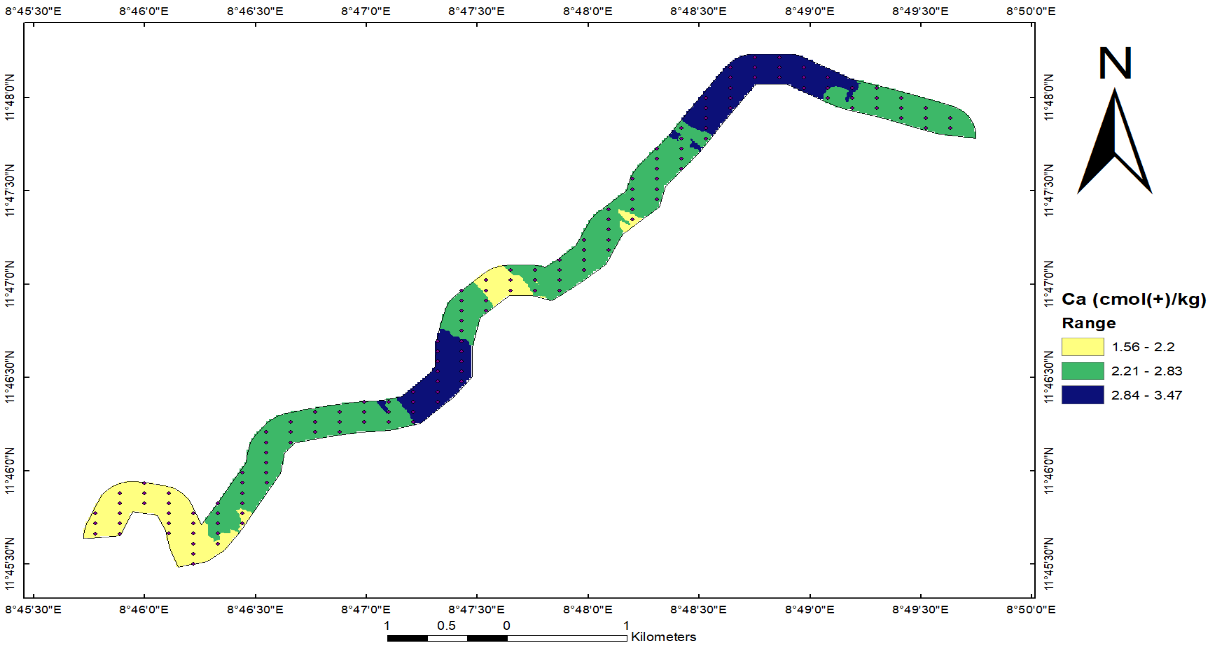

Figure 4: Interpolated Map of Calcium distribution in the study area
Source: Generated using ArcMap 10.3.1

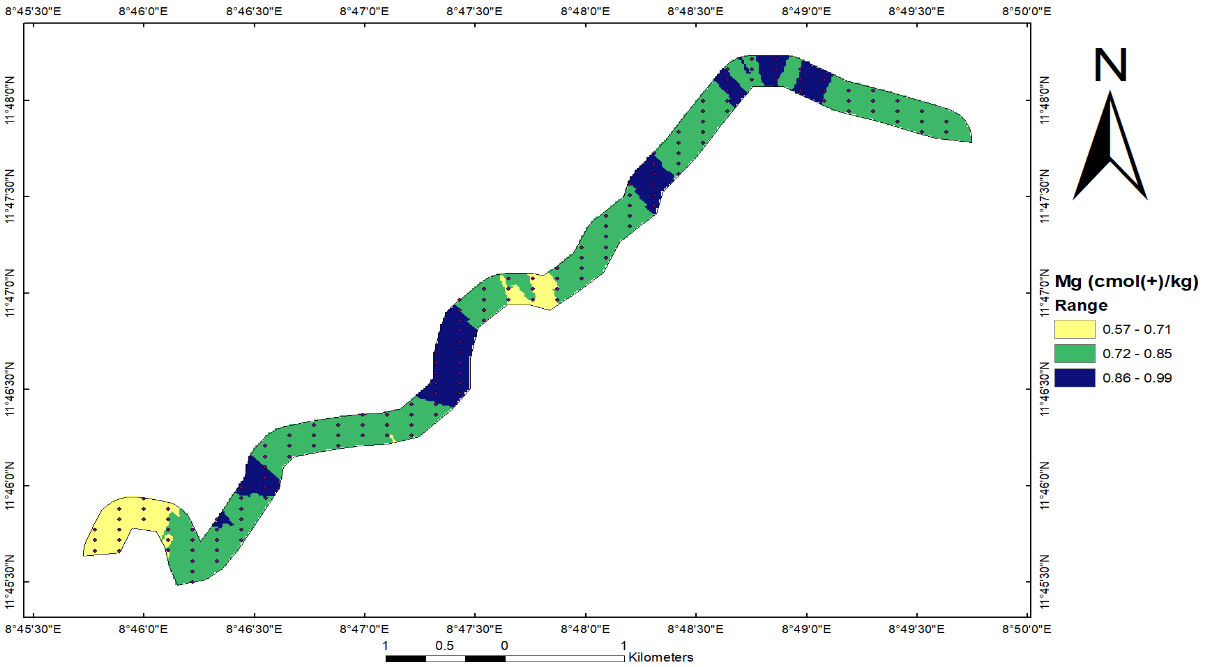

Figure 5: Interpolated Map of Magnesium distribution in the study area
Source: Generated using ArcMap 10.3.1

Potassium contents ranged from 0.13 to 0.55 (cmol(+)/kg) across the study area. It fits the exponential method as had been shown in the research of Yi-chang *et al.* (2009) and Mohammadi and RaeisiGahrooei (2003), and has a small nugget value of 0.00. Potassium was observed to have a smaller range value of 1.60 m (Table 2) which indicated small errors in measurements and low random variance in the study area (Vieira, 2000; Oliver & Webster, 2015). The lower interpolated range of potassium contents of the study area, as depicted by the interpolated map of potassium (Figure 6), occupied a total area of 1.33 $(km)^2$, which is equivalent to 44 % of the total study area (Table 3). The lower interpolated range was observed at the extreme northeast end, centre and extreme southwest end of the study area (Figure 6). The middle-interpolated range of potassium contents occupied an area of 1.45 $(km)^2$, equivalent to 47 %, and was distributed across the study area (Figure 6).

The upper interpolated range of potassium contents was observed around the centre when moving from the southwest towards the northeast side of the study area. It occupied an area of 0.29 (km)^2, which is equivalent to 9 % of the total area (Table 3). A smaller range value (1.60 m) was observed in potassium, and indicating that observed values of the soil property are not influenced by other values of this property over greater distances (Isaaks and Srivastava, 1989; Oliver & Webster, 2015).

Sodium contents fitted the exponential method as had been shown in the research of Yi-chang *et al.* (2009), and a small value of the nugget effect (0.0004) was observed which indicates small errors in measurements and low random variance in the study area (Vieira, 2000; Oliver & Webster, 2015). The contents have a medium-range value of 46.4 m (Table 2) and ranged from 0.07 to 0.17 (col (+)/kg) across the study area. A lower interpolated range of sodium contents was observed at the extreme southwest end of the study area, and a little patch was observed around the northeast end of the study area (Figure 7). The lower range has a total area of 0.31 (km)^2, which is equivalent to 10 % of the total study area (Table 3). The Middle-interpolated range of sodium contents was distributed at the centre of the study area, which occupied an area of 1.97 (km)^2, equivalent to 64 % of the study area (Table 3). An upper interpolated range of sodium contents was observed at the centre and an area towards the northeast side of the study area (Figure 7). It occupied an area of 0.78 (km)^2, which is equivalent to 26 % (Table 3). Sodium contents were observed to have a RMSSE value of 1.04 indicating a slight overestimation of sodium contents (Table 1). The medium-range value of (46.4 m) observed in sodium indicated that observed values of the soil property are not influenced by other values of this property over greater distances (Isaaks and Srivastava, 1989; Oliver & Webster, 2015).

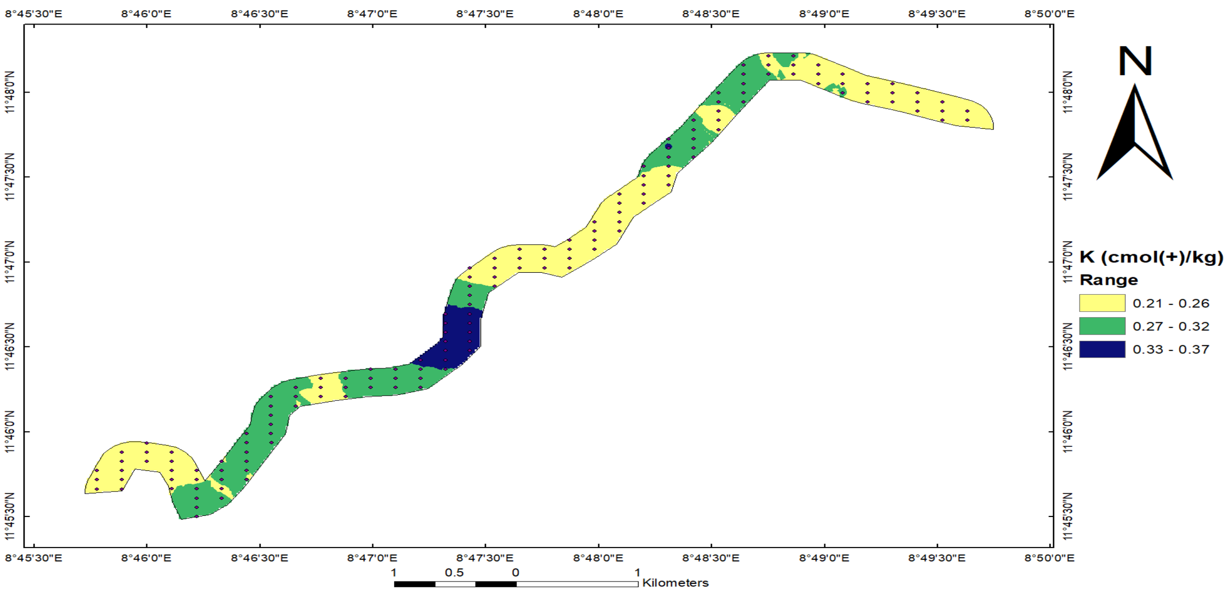

Figure 6: Interpolated Map of Potassium Distribution across the Study Area
Source: Generated using ArcMap 10.3.1

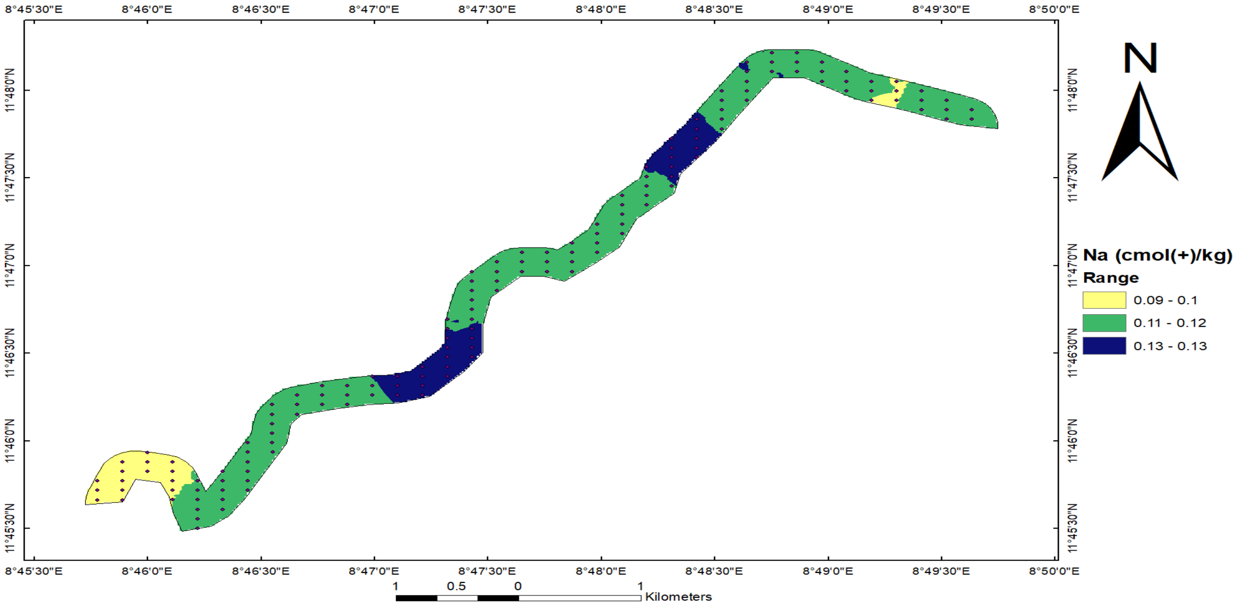

Figure 7: Interpolated Map of Sodium Distribution in the Study Area
Source: Generated using ArcMap 10.3.1

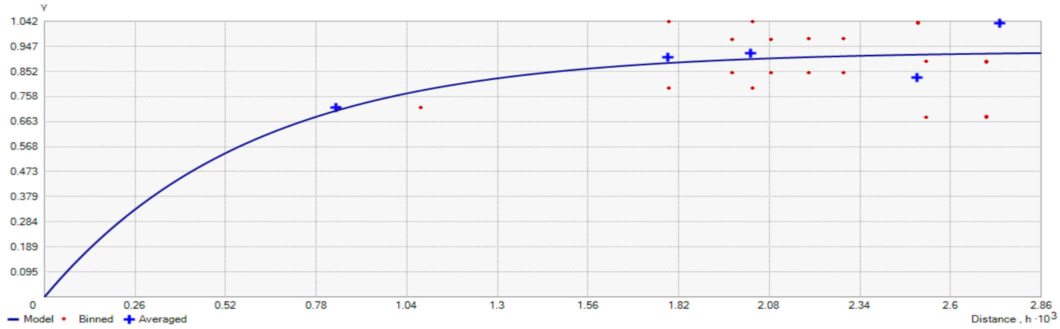

Figure 8: Semivariogram of Calcium
Source: Generated using ArcMap 10.3.1

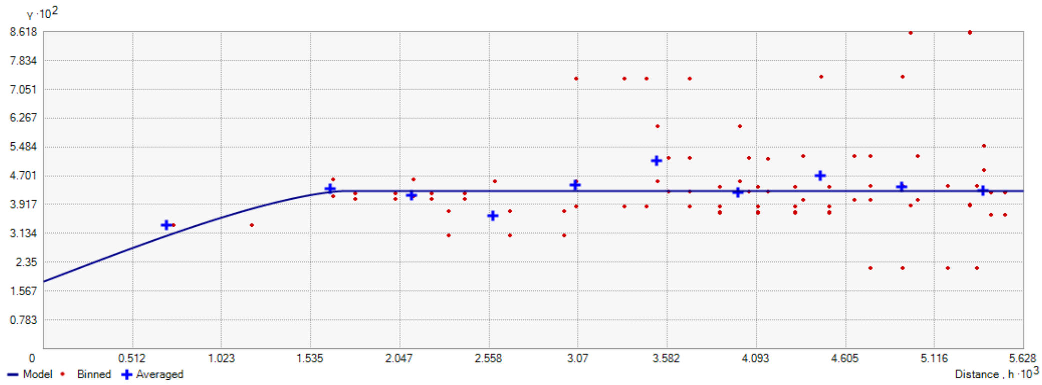

Figure 9: Semivariogram of Magnesium
Source: Generated using ArcMap 10.3.1

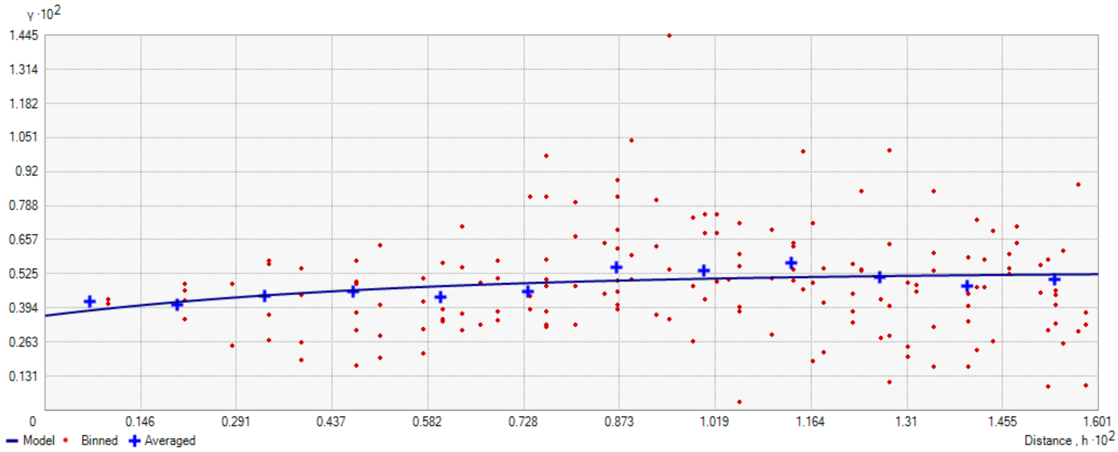

Figure 10: Semivariogram of Potassium
Source: Generated using ArcMap 10.3.1

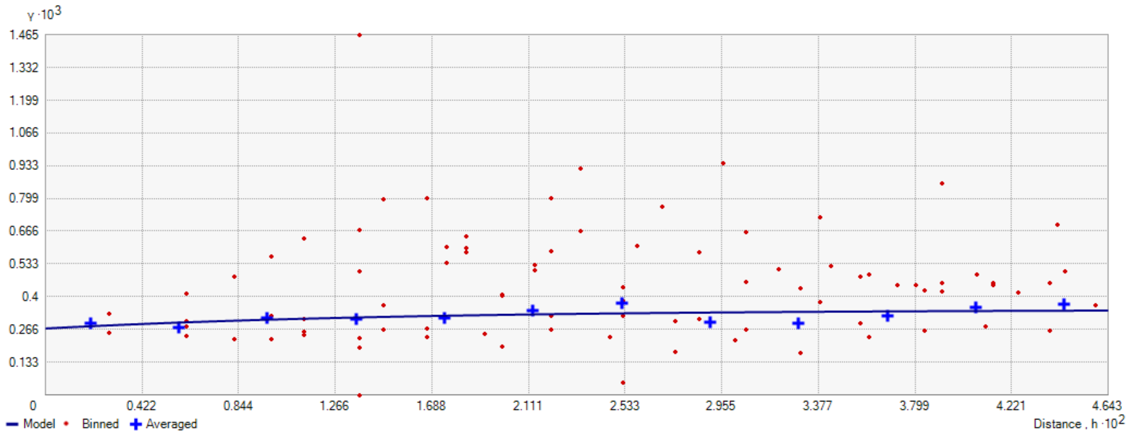

Figure 11: Semivariogram of Sodium
Source: Generated using ArcMap 10.3.1

Relation between the Soil Properties

The result shown in Table 4 indicated that there was a highly significant positive relation between calcium and magnesium (0.7), and between calcium and sodium (0.4). Significant positive correlations were also identified between sodium and magnesium.

The relationship existing among soil physicochemical properties, which, positively or negatively interfered with nutrient availability (Onwudike, 2015; Lai, 2018). The significant positive relationships observed between Calcium and Magnesium, Calcium and Sodium, and Sodium and Magnesium means that the depletion of any one of them would lead to a corresponding depletion of the other and vice versa (Tale and Ingole, 2015; Lai, 2018).

Table 4: Relationship among the Soil Properties

Variable	Ca	Mg	K	Na
Ca (cmol(+)/kg)	1.0			
Mg (cmol(+)/kg)	0.7**	1.0		
K (cmol(+)/kg)	0.1	0.1	1.0	
Na (cmol(+)/kg)	0.4**	0.3*	0.1	1.0

**Correlation is significant at 0.01 level, *correlation is significant at 0.05 level

CONCLUSION

This study identified medium to high spatial variability in soil properties along the River Wudil floodplain, Kano State, Nigeria. Variability was influenced by soil formation processes, flooding-induced sediment deposition, erosion, and local management practices such as tillage and fertilizer application. The findings provide valuable insights for site-specific nutrient management, precision farming, and sustainable environmental stewardship. Geostatistical prediction maps developed in this study serve as effective tools for planning, monitoring, and optimizing crop production by accurately locating key soil properties within the floodplain.

Based on the study's findings, it is recommended that integrated soil fertility management incorporating both organic and inorganic fertilizers be adopted in the study area, given the strong spatial dependence of calcium and sodium. Additionally, a site-specific nutrient management strategy should be developed, considering the dominant structural and random factors, particularly due to the high spatial variability observed in calcium and manganese across the floodplain.

REFERENCES

Adugna, T., & Molla, E. (2017). Spatial variability of selected soil properties in the upper catchment of the Awash River Basin, Ethiopia. Applied and Environmental Soil Science, 2017, Article ID 4569713. https://doi.org/10.1155/2017/4569713

Bohn, H. L., McNeal, B. L., and O'Connor, G. A. (2001). Soil Chemistry. 3 rd Edn. John Wiley and Sons, Inc., USA.

Brady, N. C., & Weil, R. R. (2017). The nature and properties of soils (15th ed.). Pearson.

Burgess, T. M. and R. Webster, 1980. Optimal interpolation and isarithmic mapping of soil properties. I. The semi-variogram and punctual kriging. Journal of Soil Science, 31: 315-331.

Cambardella, C. A., Moorman, T. B., Novak, J. M., Parkin, T. B., Karlen, D. L., Turco, R. F., and Konopka, A. E.: Field-scale variability of soil properties in Central Iowa soils, Soil Sci. Soc. Am. J., 58, 1501–1511, 1994.

Duffera, M., J. G. White, and R. Weisz. 2007. Spatial variability of southeastern U.S. coastal plain soil physical properties: Implications for site-specific management. *Geoderma* 137:327–339.

Fassil K, Charles Y (2009) Soil Fertility Status and Numass Fertilizer Recommendation of Typic Hapluusterts in the Northern Highlands of Ethiopia. World Appl Sci J 6(11): 1473-1480.

Fenta, A. A., Abegaz, A., & Getachew, A. (2018). Spatial variability and mapping of soil physicochemical properties in the upper Awash basin, Ethiopia. Environmental Systems Research, 7(4), 1-12. https://doi.org/10.1186/s40068-018-0106-2

Goovaerts, P. (1999). Geostatistics in soil science: State-of-the-art and future prospects. Geoderma, 89(1-2), 1-45.

Goudie, A. S. (2004). *Encyclopedia of Geomorphology,* vol. 1. Routledge, New York. ISBN 0-415-32737-7

Heluf Gebrekidan and Wakene Negassa. 2006. Impact of land use and management practices on chemical properties of some soils of Bako area, western Ethiopia. Ethiopian Journal of Natural Resources. 8(2): 177-197

Hossain, M.M., Z.H. Khan, M.S. Hussain and A.R. Mazumder, 2011. Characterization and classification of some intensively cultivated soils from the Ganges River floodplain of Bangladesh. Dhaka Univ. J. Biol. Sci., 20: 71-80.

Hou-Long, J., L. Guo-Shun, W. Xin-Zhong, S. Wen-Feng, Z. Rui-Na, Z. Chun-Hua, H. Hong-Chao, and L. Yan-Tao. 2010. Spatial variability of soil properties in a long-term tobacco plantation in central China. *Soil Science* 175:137–144.

Ibeawuchi, I. I., Ojimelukwe, P. C., & Nwosu, D. C. (2016). Soil fertility status of floodplain soils in southeastern Nigeria. International Journal of Agricultural Management and Development, 6(4), 369–378. https://doi.org/10.22004/ag.econ.235317

Isaaks E.H., Srivastava R.M. (1989): An introduction to applied geostatistics. Oxford Univ. Press, New York. ISSS-ISRIC-FAO (1998): World reference base for soil resources. World Soil Res. Rep. FAO, Rome, 84: 92.

Junk, W. J., Soares, M.G.M., Engle, V.L., Rodrigues, R.G., Melack,. J.M. (2011). Floodplains as ecosystems. Journal of Hydrology, 396(1-2), 1-12.

Khan, S., Khan, M. J., Akhtar, M., & Hafeez, M. (2021). Spatial variability of soil nutrients and its impact on crop productivity. Journal of Soil Science and Plant Nutrition, 21(2), 295-306. https://doi.org/10.1007/s42729-021-00485-2

Lal (2017). Soil Science and Sustainability. CRC Press.

Lal, R. (2015). Soil Degradation and Sustainability. CRC Press.

Lal, R. (2018). Soil Degradation and Sustainable Agriculture. CRC Press. DOI: 10.1201/9781351111097; ISBN: 978-1-351-11109-7

McBratney, A., Mendonça Santos, M. L., & Minasny, B. (2003). On digital soil mapping. Geoderma, 117(1-2), 3–52. https://doi.org/10.1016/S0016-7061(03)00223-4

Mehlich, A. (1984). Mehlich-3 soil test extractant: A modification of Mehlich-2 extractant. Communications in Soil Science and Plant Analysis, 15(12), 1409-1416.

Mitsch W.J, and Gosselink J.G (2000). Wetlands. New York: John Wiley and Sons; 2000.

Mohammadi, J., and RaeisiGahrooee, F., 2004, Fractal Description of the Impact of Long-term Grazing Exclusion on Spatial Variability of Some Soil Chemical Properties JWSS - Isfahan University of Technology, 7 (4), 25-37

Odunze, A. C., Okafor, J. C., & Ogban, P. D. (2020). Spatial variability and mapping of soil properties for sustainable land management in a tropical

floodplain. Geoderma Regional, 22, e00319. https://doi.org/10.1016/j.geodrs.2020.e00319
Ogunkunle, A.O., 1993. Variation of some soil properties along two toposequence on quartzite schist and banded gneiss in South-western Nigeria. *GeoJournal* 30(4): 399-402.
Oliver, M. A. (2010). Geostatistical applications for precision agriculture. Springer.
Oliver, M. A., & Webster, R. (2015). Basic Steps in Geostatistics: The Variogram and Spatial Autocorrelation. Springer.
Onwudike, S. U. (2020). Soil Physicochemical Properties and Nutrient Availability. Journal of Sustainable Agriculture, 14(3).
Paz Gonzales, A., Vieira, S.R. and Castro, T., 2000, The effect of cultivation on the spatial variability of selected properties of an umbric horizon, Geoderma, 97,273-292
Santra, P., Chopra, U.K., & Chakraborty, D. (2008). Spatial variability of soil properties and its application in predicting surface map of hydraulic parameters in an agricultural farm. *In Current science* (pp. 937-945). Bengaluru, India: Current Science Association.
Shukla, M. K., R. Lal, and M. Ebinger. 2004. Soil quality indicators for the North Appalachian experimental watersheds in Coshocton, Ohio. *Soil Science* 169:195–205.
Sparks, D. L. (2003). Environmental soil chemistry (2nd ed.). Academic Press.
Sun B, Zhou SL, Zhao QG (2003). Evaluation of spatial and temporal changes of soil quality based on geostatistical analysis in the hill region of subtropical China. Geoderma. 115: 85-99.
Tale, K.S. and S. Ingole, 2015. A review on the role of physicochemical properties in soil quality. Chem. Sci. Rev. Lett., 4: 57-66.
Teshome, A., D. Rolker and J. de Graaff, 2013. Financial viability of soil and water conservation technologies in Northwestern Ethiopian highlands. Applied Geogr., 37: 139-149.
Vieira, S.R. Geoestatística em estudos de variabilidade espacial do solo. In: NOVAIS, R.F.; Alvarez V., V.H. & Schaefer, C.E.G.R., eds. Tópicos em ciência do solo. Viçosa, MG, Sociedade Brasileira de Ciência de Solo, 2000. p.1-54.
Webster, R., & Oliver, M. A. (2007). Geostatistics for environmental scientists (2nd ed.). Wiley.
Wei J.B., Xiao D.N., Zeng H., Y.K. Fu, Spatialvariability of soil properties in relation to land use and topography in a typical small watershed of the black soil region, northeastern China, Environ. Geol. 53 (2008) 1663–1672.
Yi-chang, W., You-lu, B., Ji-yun, J., Fang, Z., Li-ping, Z., and Xiao-qiang, L., 2009, Spatial Variability of Soil Chemical Properties in the Reclaiming Marine Foreland to Yellow Sea of China, Agricultural Sciences in China, 8(9), 1103-1111.