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Impact of distance from the water body on the point of zero charge of Dutsin-Ma Dam floodplain soils, Katsina State, Nigeria

ALIYU ABDULKADIR ♥, ISMAILA ZUBAIRU MANNE, SUFIYANU SANI
Department of Soil Science, Faculty of Agriculture, Federal University Dutsin-Ma. P.M.B. 5001 Dutsin-Ma, Katsina State, Nigeria.
Tel.: +234-8000000011, ♥email: aabdulkadir@fudutsinma.edu.ng

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Abstract. *Abdulkadir A, Manne IZ, Sani S. 2025. Impact of distance from the water body on the point of zero charge of Dutsin-Ma Dam floodplain soils, Katsina State, Nigeria. Intl J Bonorowo Wetlands 15: 1-6.* This study investigates the point of zero charge (ZPC) and its influence on soil chemical properties in the floodplain around the Dutsin-Ma Dam. The report rigorously examines how proximity to the dam influences critical soil parameters such as pH changes (ΔpH), ZPC, and surface potential (Ψ0) across three zones: Onshore, Mid-shore, and Offshore. Soil samples from these three zones were meticulously analyzed to assess variations in these parameters, which are vital for understanding soil fertility and nutrient availability. The results show that ΔpH decreases with increasing distance from the dam, indicating reduced pH fluctuation in offshore soils. ZPC values increase from onshore to offshore, suggesting that soils farther from the dam reach zero net charge at higher pH levels. Additionally, the surface potential (Ψ0) becomes increasingly negative with distance from the dam, indicating a lower offshore cation exchange capacity (CEC). These findings underscore the significant influence of dam proximity on soil chemical properties, which has practical implications for soil management and agricultural practices. Understanding ZPC and related parameters is essential for optimizing soil fertility and promoting sustainability in floodplain environments. This research provides actionable insights that can empower practitioners to improve agricultural practices and long-term soil health in regions impacted by dam-induced flooding.

Keywords: Dutsin-Ma Dam floodplains, electrical conductivity, point of zero charge, soil fertility, soil management, soil pH

INTRODUCTION

Soil, a complex and dynamic mixture of minerals, organic matter, water, air, and living organisms, has an important role in sustaining life on Earth (Huntley et al. 2023). The composition and characteristics of soil influence various natural processes and human activities, for example, agriculture, forestry, construction, and environmental management. One of the critical parameters in soil chemistry and physics is the determination of the point of zero charge (PZC), a key factor in soil management, nutrient availability, and contaminant retention (Penn and Cambarto 2019; Mohawesh 2020).

Soils in tropical regions, which cover almost 38% of the Earth's surface, are characterized by high mineral and amorphous colloid content, contributing to their amphoteric surface properties (Borrelli et al. 2020). These characteristics have profound implications for agricultural soil management, particularly in relation to the retention and mobility of ionic contaminants (Kome et al. 2019). The soil surface charge, a crucial aspect of soil management, is regulated not only by the activity of potential-determining ions (H^+ and OH^-) but also by the electrolyte concentrations (ionic strength) in the environment (Wen et al. 2020). The role of electrolyte concentration is significant, as it influences the soil's surface charge, which can be positive, negative, or neutral depending on the pH. The pH value where the net particle charge becomes zero is known as the point of zero charge (PZC), a concept of utmost importance for describing variable-charge surfaces (Parks and de Bruyn 1961; Morais et al. 1976; Appel et al. 2003).

Understanding soils' PZC is critical for determining their anion exchange capacity (AEC) and cation exchange capacity (CEC), which directly affect nutrient retention and contaminant behavior. When a soil's pH exceeds its PZC, the surface carries a net negative charge, leading to increased CEC, where positively charged ions (cations) are exchanged (Mohawesh 2020). Conversely, when the soil's pH falls below its PZC, the surface tends to retain negatively charged ions (anions), exhibiting AEC behavior.

Various methods have been developed to determine the point of zero charge in soils and materials with variable surface charges. Among these, potentiometric titration is commonly used to assess changes in surface potential in response to the activities of H^+ and OH^-, thereby determining the point of zero salt effect (PZSE) or the point of zero net proton charge (PZNPC) (van Raij and Peech 1972; Parker et al. 1979; Marcano-Martinez and McBride 1989). Another approach, non-specific ion adsorption, measures the electrostatic adsorption of cations and anions to identify the point of zero net charge (PZNC). Some researchers have also utilized methods based on charged particles' mobility in an electric field (O'Brien and Rowlands 1993; Findlay et al. 1996). While these techniques have been effective for studying pure minerals, such as kaolinite and gibbsite, the complexity of soil systems—due to their heterogeneous nature and particle size variation—makes charge mobility more difficult to detect (Barrow 1987; Sposito 1989; Lewis-Russ 1991; Sposito 2016).

This research aims to determine the point of zero charge (PZC) of the Dutsin-Ma Dam floodplain soils and to assess how the PZC varies with distance from the water body. This research has significant practical implications, as it will provide insights into soil chemical properties that are directly relevant to understanding nutrient dynamics, soil fertility, and agricultural practices in the floodplain environment.

MATERIALS AND METHODS

Location of sampling sites

The study was carried out in Dutsin-ma, Katsina state, Nigeria. Soil samples were collected from floodplain areas where irrigation farming is carried out throughout the rainy and dry seasons throughout the year. The study site was located between latitude 12° 20.823N and longitude 7°30.455E and 500 m above sea level) in the Sudan Savannah ecological zone of Nigeria. The relative humidity of the study area is moderately high all year-round, and the temperature range is between 21 and 35°C.

Sampling design

Soil samples were collected from three different sites of the floodplain (onshore, midshore and offshore) based on their proximity to the dam. From each selected site, 10 soil samples were taken using an auger from a depth of 0-30 cm (topsoil) making a total of 30 soil samples.

General analytical methods

This study used soil-pertinent properties obtained using standard methods as described by Estefan et al. (2013). The pH readings were taken in water at a 1:10 soil/water ratio to model the CEC and AEC values (same soil/ water ratio) measured in the ion adsorption portion of the experiment. Effective CEC was extrapolated from ion adsorption curves at 0.001 M ionic strength (I) at field pH (1:10 soil/ water ratio), as this I was most representative of the soil.

Determination of point of zero charge

A series of NaCl solutions at concentrations of 0.1, 0.01, and 0.001 M were prepared. 1g of soil was added to beakers containing 10 mL of the electrolyte solutions. pH of each suspension was adjusted to range from 2 to 10 using 0.1 M HCl or NaOH. It was covered and shaken the suspensions, allowing them to equilibrate for 24 hours to 7 days; the final pH after equilibration was measured. The final pH was plotted against the initial pH. The intersection of curves at different electrolyte concentrations indicates the PZC or finds the pH where the net proton charge equals zero.

Estimating change in pH

The ΔpH of the soil samples was calculated using the following formula:

$\Delta pH = pH(KCl) - pH\ (H_2O)$ (Kome et al. 2018).

The surface electrical potential

The surface electrical potential (Ψ0) in mV was estimated using the Nernst equation, which Chaves et al. (2016) reduced as follows:

$\Psi_0 = 59.1(PZC - pH\ (H_2O))$

Data analysis

With SPSS software version 23 for Windows, soil properties of different sites of cultivated soil were analyzed using Analysis of Variance (ANOVA). The ANOVA test was also used for significant differences of C and N associated with each of the particle-size fractions. Mean values of soil properties and C and N concentrations in the particle size fraction were compared using Fisher's Protected Least Significant of Difference (LSD) at a 5% level of significance.

RESULTS AND DISCUSSIONS

Chemical characteristics of the experimental soil

Table 1 presents the descriptive statistics of the chemical properties of the experimental soil in the floodplain of the Dutsin-ma dam, which includes key parameters such as pH (in both H_2O and KCl), electrical conductivity (EC), point of zero charge (ZPC), and exchangeable cations (Ca, Mg, K, Na), among others. The statistics include the minimum, maximum, mean, standard deviation, variance, skewness, and kurtosis for each parameter, offering insights into their distribution and variability, which is similar to the findings of Aki and Isong (2018).

The mean pH in H_2O is 5.69, ranging from 4.8 to 6.7, with a moderate variability (standard deviation of 0.63). The pH in KCl is slightly lower, with a mean of 5.28. The positive skewness and kurtosis indicate that the distribution of pH values is left-skewed with relatively few high values, suggesting that most soil samples are more acidic (Abdulkadir et al. 2022). The variance is slightly higher in pH (KCl), implying greater variability in this measurement compared to pH (H_2O). The EC values have a wide range from 0.19 to 2.90, with a mean of 0.70, and exhibit high variability (standard deviation of 0.85), which is in agreement with the findings of Sani et al. (2019; 2022). The positive skewness (2.18) indicates a long tail with higher EC values, while the high kurtosis (4.08) suggests a sharp peak, implying a few extremely high values in the dataset.

The ΔpH (difference between pH in H_2O and KCl) ranges from -0.80 to -0.10, with a mean of -0.41. The relatively low standard deviation (0.24) shows moderate variability in the differences. Negative skewness (-0.48) and kurtosis (-1.24) suggest a fairly uniform distribution with fewer extreme values. The ZPC values vary from 3.50 to 6.30, with a mean of 4.88. This variability is reflected in the standard deviation of 1.01, suggesting that ZPC differs considerably across soil samples. The slight negative skewness (-0.13) and kurtosis (-1.52) imply a left-skewed distribution with relatively fewer extreme values. The surface potential ranges from -94.56 to -11.82 mV, with a mean of -48.27 mV. The high standard deviation (27.82) and variance (773.71) indicate significant variability in surface potential across different samples. This wide range reflects the influence of various factors on soil cation exchange capacity (Habib et al. 2024).

Calcium (Ca) shows a range from 1.72 to 4.66 cmol/kg, with a mean of 3.40 cmol/kg, indicating moderate variability. Similar trends are observed for magnesium (Mg) and potassium (K), with means of 1.73 cmol/kg and 3.71 cmol/kg, respectively, which is in accordance with the findings of Abdulkadir et al. (2020). Sodium (Na) exhibits the least variability, with a narrow range (0.68 to 0.97 cmol/kg) and a mean of 0.83 cmol/kg. The exchangeable cations generally show low skewness and kurtosis, suggesting relatively normal distributions with moderate variability. The TEB ranges from 5.72 to 12.92 cmol/kg, with a mean of 9.66 cmol/kg, showing a moderate standard deviation of 2.36. The distribution of TEB is slightly left-skewed (-0.15), with fewer extreme values. Available phosphorus shows a mean of 22.65 mg/kg, ranging from 15.41 to 32.44 mg/kg. The positive skewness (0.41) and slightly negative kurtosis (-1.22) suggest that most samples have phosphorus levels around the mean, with a few high values. The ECEC ranges from 5.89 to 13.59 cmol/kg, with a mean of 10.02 cmol/kg, indicating moderate variability. The slight negative skewness (-0.12) and kurtosis (-1.07) reflect a relatively even distribution of ECEC values across samples.

The variability of experimental soil chemical properties, a novel aspect of our research, highlights the influence of the floodplain environment on soil characteristics. The wide range in pH values, both in H_2O and KCl, a unique finding, indicates differences in acidity across sample locations, which can significantly influence nutrient availability and microbial activity (Habib et al. 2024). The variation in ZPC values, another novel discovery of soil's capacity to adsorb cations and anions, varies considerably across the samples. This suggests that soils closer to or farther from the water body may differ in their ability to retain nutrients or contaminants. Electrical conductivity, a measure of the soil's salinity, shows a highly skewed distribution with a few outliers, indicating localized areas with significantly higher salt concentrations. This could be due to variations in soil moisture content or the influence of floodwaters from the dam (Loneragan 1975)

The exchangeable cations, particularly calcium, magnesium, and potassium, exhibit moderate variability, reflecting differences in soil fertility across the floodplain. Sodium, with its low variability, indicates that it is less affected by the proximity to the water body. The results provide valuable insights into the floodplain soil's chemical properties, which are crucial for understanding soil fertility, nutrient retention, and potential agricultural productivity in the region. Understanding these variations can inform better soil management practices tailored to the specific needs of different zones within the floodplain.

Influence of distance from the water on some selected chemical properties of the experimental soil

Table 2 provides data on some selected chemical properties of soil at different distances from a dam: onshore, mid-shore, and offshore. The properties measured are pH in water (pH (H_2O)), pH in potassium chloride (pH(KCl)), electrical conductivity (EC), total exchangeable bases (TEB), exchangeable acidity (EA), and effective cation exchange capacity (ECEC).

Table 1. Descriptive statistics of the chemical properties of the experimental soil

	Minimum	Maximum	Mean	Standard Deviation	Variance	Skewness	Kurtosis
pH(H_2O)	4.8	6.7	5.69	0.63	0.403	0.41	-1.234
pH(KCl)	4.2	6.5	5.28	0.81	0.652	0.09	-1.466
EC	0.19	2.90	0.70	0.85	0.718	2.18	4.078
ΔPH	-0.80	-0.10	-0.41	0.24	0.055	-0.48	-1.242
ZPC	3.50	6.30	4.88	1.01	1.01	-0.13	-1.522
Ψ_0	-94.56	-11.82	-48.27	27.82	773.71	-0.48	-1.242
Ca	1.72	4.66	3.40	0.93	0.86	-0.33	-0.760
Mg	1.08	2.36	1.73	0.44	0.20	0.07	-1.282
K	1.64	5.12	3.71	1.04	1.09	-0.48	-0.272
Na	0.68	0.97	0.83	0.10	0.01	-0.18	-1.506
EA	0.17	0.67	0.36	0.17	0.03	0.87	0.040
TEB	5.72	12.92	9.66	2.36	5.58	-0.15	-1.067
Av. P	15.41	32.44	22.65	5.83	34.04	0.41	-1.225
ECEC	5.89	13.59	10.02	2.51	6.31	-0.12	-1.073

Note: EA: Exchangeable Acidity, EC: Electrical Conductivity, TEB: Total Exchangeable Bases, Av. P: Available Phosphorus, ECEC: Effective Cation Exchange Capacity, ZPC: Zero Point of Charge, Ψ_0: Surface electrical potential

Table 2. Selected chemical properties of soil at different distances from a dam

Position	pH(H_2O)	pH(KCl)	EC	TEB	EA	ECEC	OC
Onshore	5.075c	4.500c	0.9025	12.357a	0.5425a	12.90a	1.0950a
Midshore	5.525b	5.250b	0.8150	9.592a	0.3300b	9.92b	0.7650b
Offshore	6.475a	6.225a	0.3675	7.040c	0.2100b	7.25c	0.4000c
SED	0.1379	0.1728	0.634	0.518	0.0740	0.551	0.0742

Table 3. The influence of distance from the dam on some selected soil chemical properties

Position	ΔpH	ZPC	Ψ_0
Onshore	-0.5750b	3.925c	-82.74b
Midshore	-0.2750a	4.975b	-32.51a
Offshore	-0.2500a	5.975a	-29.55a
SED	0.1258	0.269	8.70

Soil pH increases significantly from onshore to offshore, with offshore soils being more alkaline; similar to pH (H_2O), pH (KCl) increases significantly with distance from the dam, indicating a decrease in soil acidity offshore. EC decreases with distance from the dam, suggesting lower salinity levels offshore; TEB is highest onshore and decreases with increasing distance from the dam. Higher TEB onshore indicates more nutrient availability close to the dam; ECEC follows a similar trend to TEB, being highest onshore and decreasing offshore, indicating a higher nutrient-holding capacity near the dam.

Influence of distance from the dam on some selected soil chemical properties

ΔpH decreases with distance from the dam, suggesting that soil pH stabilizes further away from the water source, ZPC increases with distance from the dam, indicating a higher pH at which the soil surface has zero net charge offshore, Ψ0 decreases (becomes less negative) with distance from the dam, suggesting that the soil's ability to retain cations decreases further away from the dam.

In this study, we investigated the correlations between pH in water and various soil properties. Table 3 presents our findings. We found that pH (H_2O) and pH(KCl) have a very strong positive correlation of 0.968, indicating that pH measured in water and salt solution are highly related and tend to increase or decrease together. pH (H_2O) and EC have a Weak negative correlation of -0.252, suggesting a slight inverse relationship between soil pH in water and electrical conductivity, though not significant. pH (H_2O) and ΔpH have a Moderate positive correlation: 0.497, indicating a relationship where higher pH in water tends to be associated with higher differences in pH, though not significant. pH (H_2O) and ZPC have a Strong positive correlation of 0.911, suggesting that as pH in water increases, the zero point of charge also increases significantly. pH (H_2O) and Ψ_0 have a Moderate positive correlation, the same as with ΔPH, indicating a relationship, though not significant. pH (H_2O) and EA have a Strong negative correlation: - 0.715, indicating that as pH in water increases, exchangeable acidity decreases significantly. pH (H_2O) and ECEC have a Very strong negative correlation of -0.871, indicating that as pH in water increases, effective cation exchange capacity decreases significantly (Dawaki et al. 2020).

In Table 2, the increase in soil pH (both pH (H_2O) and pH(KCl)) from onshore to offshore indicates a significant reduction in soil acidity as the distance from the dam increases. This trend could be due to the leaching of acidic components away from the shoreline or differences in soil management practices and vegetation cover. Higher pH levels offshore suggest better soil conditions for many crops, which prefer neutral to slightly alkaline soils. The decreasing trend in EC with distance from the dam suggests that soils closer to the dam have higher salinity levels. This could be attributed to the accumulation of salts through irrigation or floodwater from the dam. Lower salinity levels offshore are beneficial for plant growth, as high salinity can hinder water uptake by plants and affect soil structure. The higher TEB and EA values onshore indicate greater availability of exchangeable cations and higher soil acidity near the dam. These trends reflect the influence of water movement and deposition of minerals from the dam's waters. Managing these properties is crucial, as high exchangeable acidity can lead to aluminum toxicity, which adversely affects plant growth. Recent studies corroborate these findings, highlighting the impact of water bodies on surrounding soil properties. For instance, research has shown that proximity to water sources like dams can significantly influence soil pH, salinity, and nutrient availability (Lal 2011). Changes in soil properties with distance from water bodies are crucial for understanding soil management needs and optimizing agricultural practices (Doran and Zeiss 2000). In Table 3, The higher change in pH (ΔpH) onshore indicates greater variability in soil pH closer to the dam, likely due to the influence of water flux and mineral deposition. The reduced ΔpH offshore suggests more stable soil conditions, which is beneficial for plant growth as extreme pH fluctuations can adversely affect nutrient availability. The increase in ZPC from onshore to offshore indicates that the soil surface's net charge at a higher pH level increases with distance from the dam. This trend suggests that soils further from the dam are more capable of maintaining a stable charge environment, which can influence nutrient retention and soil structure. The significant negative surface potential (Ψ_0) onshore suggests a higher cation exchange capacity (CEC) closer to the dam, which could be beneficial for nutrient retention. However, this can also lead to higher soil acidity and potential toxicity issues. The less negative Ψ0 offshore indicates a decrease in CEC, potentially reducing nutrient retention but also reducing the risk of soil acidity and toxicity. Recent studies have highlighted the significant impact of proximity to water bodies on soil chemical properties. The variability in soil pH, ZPC, and surface potential is influenced by factors such as water movement, mineral deposition, and organic matter content (Lal 2011). Research also indicates that managing these properties is crucial for optimizing soil health and fertility, particularly in agricultural settings (Doran and Zeiss 2000). It is therefore important to understand the spatial variation of these properties can help in developing targeted soil management practices to improve crop productivity and sustainability (Bot and Benites 2005).

Table 4. Correlation analysis of the electrochemical properties of Dutsin-Ma Dam flood plain soil

	pH(H_2O)	**pH(KCl)**	**EC**	**ΔpH**	**ZPC**	**Ψ_0**	**EA**	**ECEC**
pH(H_2O)	1							
pH(KCl)	0.968**	1						
EC	-0.252	-0.096	1					
ΔpH	0.497	0.699*	0.386	1				
ZPC	0.911**	0.985**	0.013	.810**	1			
Ψ_0	0.497	0.699*	0.386	1.000**	0.810**	1		
EA	-0.715**	-0.850**	-0.147	-0.902**	-0.910**	-0.902**	1	
ECEC	-0.871**	-0.912**	0.190	-0.669*	-0.906**	-0.669*	0.872**	1

Note: **: Correlation is significant at the 0.01 level, *: Correlation is significant at the 0.05 level

Table 4 shows the very strong correlation between pH(H_2O)and pH(Salt), which implies that these measurements are highly consistent and reliable indicators of soil acidity. This relationship is crucial for soil management practices, as it helps in determining the soil's buffering capacity and potential response to amendments. The weak and non-significant correlations of EC with other parameters suggest that soil salinity, as measured by EC, does not strongly influence or influence the other soil properties measured in this study. This may indicate that the salinity levels are relatively stable or independent of pH and other chemical properties. The strong positive correlation between ZPC and both pH measurements (pH(H2O) and pH (salt)) suggests that higher soil pH is associated with higher ZPC. This relationship is critical for understanding soil's surface charge properties, which influence nutrient availability and retention. The perfect correlation between ΔpH and Ψ_0 (0.699*) indicates that these measurements are essentially identical, reflecting the same soil property. The relationship between Ψ_0 and other properties follows similar patterns to ΔpH. The strong negative correlations of EA and ECEC with pH measurements indicate that as soil pH increases, both EA and ECEC decrease. This suggests that more acidic soils have higher exchangeable acidity and cation exchange capacity, which could impact nutrient availability and soil structure. Managing soil pH could thus be essential for optimizing these properties.

The study concludes that proximity to the dam significantly affects soil chemical properties, impacting soil acidity, salinity, nutrient availability, and cation exchange capacity. Soils closer to the dam are more acidic and saline, with higher nutrient availability, but also higher exchangeable acidity, which can pose challenges for plant growth. In contrast, soils further from the dam exhibit more stable pH levels, lower salinity, and reduced acidity, creating more favorable conditions for plant growth and soil health.

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