Corrosivity relationship for management of buried pipelines: A case study of Rivers state, Nigeria

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Research Article

Keywords: Soil corrosivity, Corrosion Map, Wenner Method, pH, Soil Resistivity, Rivers State

Posted Date: September 21st, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2073801/v1

Abstract

Control and management of corrosion have always been the concern of oil and gas asset management teams due to the challenging outcomes of failed facilities in service due to corrosion. Corrosion has an impact on human safety, environmental safety, and productivity; thus, it is important to know how corrosive an environment is in order to make the best investment decisions for facilities that are prone to corrosion. There are various ways of identifying environmental corrosivity, but there is no distinct map or relation with combined soil pH and resistivity impact unique to an environment that suggests the corrosion severity of such an environment, which could be due to the complexities of variables involved in defining the extent of corrosivity. This research aims to create a corrosion map using the MATLAB computing environment for Rivers State, a mega oil-producing state in the Niger Delta, based on soil resistivity and pH across different parts of the state with ongoing oil and gas activities for the purpose of a quick look decision-making guide. To determine corrosivity, such a map should only need to identify the soil resistivity and pH of a certain site. The pilot test conducted using 40-point soil pH and resistivity data suggested that it is feasible to develop a unique corrosivity map for a region since the result showed an R-square value of 70.03%. However, possible constraints of the mapping process were discussed, as well as suggestions for a wider survey and improvement.

1. Introduction

The Niger Delta region, of which Rivers State is a part, is considered the hub of the Nigerian economy because of its enormous oil and gas reserves. Petroleum and its derivatives dominate the Nigerian economy, accounting for nearly 98% of exports, above 80% of government revenue, and 70% of government spending (Akpotor 2019). For decades, oil exploration and extraction have taken place in the Niger Delta. It has had disastrous implications for the region's ecosystem as well as the people who live there (Kadafa 2012).

Corrosion is the degradation of a material by electrochemical reaction with its environment (Jerome et al. 2015). An anode, a cathode, an electrolyte, and a metallic path are the four components that make up the corrosion cell (Zaki Ahmad 2006).

One of the safest and most dependable methods of transporting hydrocarbons is via pipeline. Pipeline inspections at regular intervals and maintaining the pipeline system's integrity are top priorities (Bondada et al. 2018). The carbon steel pipelines used in the oil and gas industry are exposed to a variety of conditions, and the operating environment plays a significant role in pipeline failure. Corrosion in pipelines is one of the most serious problems that the oil and gas sectors face around the world (Unueroh et al. 2016). Corrosion in the oil and gas sector has greatly raised the overhead cost of pipeline operations due to the replacement of corroded equipment and damage to neighbouring equipment. Corrosion attacks and ultimately pipeline failure pose economic, health, safety, and environmental consequences in the oil and gas sector (Ameh et al. 2018). About 25% of failures in the oil and gas industry are caused by corrosion, with sweet and sour corrosion in pipelines accounting for more than half of these failures. Corrosion experts must understand corrosion mechanisms, risk assessment criteria, and mitigation measures in order to reduce pipeline failure and extend pipeline lifespan (Ossai 2012). Losses due to corrosion can be classified under Direct Losses and Indirect Losses. Direct Losses are those that can be quantitatively accounted for, such as replacement cost, protection cost, and corrosion inhibition. While Indirect Losses are those that cannot be quantitatively evaluated, such as loss of products to spill and fire, loss of revenue due to downtime, loss of efficiency of equipment, contamination of products, environmental pollution, over-design to make allowance for metal loss, and delays that may arise from lawsuits and ill-will. Although most studies have focused on the direct costs of corrosion, it is agreed that the indirect impact of corrosion is significantly greater (Fayomi et al. 2019). According to studies by NACE International in 2013, the global cost of corrosion is projected to be US$2.5 trillion, which is equivalent to 3.4% of the global Gross Domestic Product (GDP). It is projected that implementing available corrosion control measures might save between 15% and 35% of the cost of corrosion and this study's findings are expected to contribute to it.

Corrosion can be assessed indirectly by measuring the soil's corrosivity, which is influenced by a number of variables, the most prominent of which are the soil's moisture content, acidity, aeration, and electrical resistivity. Water is necessary for the corrosion process to occur, and soils that are particularly corrosive are thought to have a moisture content above 20%. Acidic conditions for soil acidity enhance the breakdown of metals. Therefore, the corrosion rate increases as pH decreases. On the other hand, if the soil contains soluble sulphates, soil aeration is thought to encourage corrosion. In these types of soils, sulphate-reducing bacteria can flourish. These bacteria convert sulphates into sulphides, and this conversion results in the oxidation of elemental hydrogen, which is the process that encompasses these bacteria in corrosion mechanisms. Soil resistivity, perhaps the most essential factor, gives an indication of the concentration of soil electrolyte, which is crucial to the corrosion process. Low resistivity soils will promote corrosion; in other words, the higher the corrosion rate, the lower the resistivity of the soil (Kingdom and Abam 2021). According to (Roberge 1999) there is a relationship between soil corrosivity, and soil resistivity, and their findings suggested that soil resistivities less than 10 Ωm, 10 to 30 Ωm, 30 to 50 Ωm, 50 to 100 Ωm, 100 to 200 Ωm and greater than 200 Ωm should be regarded as extremely corrosive, highly corrosive, corrosive, moderately corrosive, mildly corrosive and essentially noncorrosive respectively.

Resistivity has been considered the most important variable to investigate in the area of soil corrosivity because of the correlation between corrosion and conductivity. Highly resistive soils tend to retard the effects of ionic currents, which are linked to corrosion reactions. The Wenner four-pin method or electromagnetic measurements can be used to determine soil resistivity (Arriba-Rodriguez et al. 2018). Corrosion risk can be calculated using soil resistivity and pH values to estimate the degree of corrosivity of the soil. Soils with low resistivity, low pH, and high chloride and sulphate concentrations are typically the most corrosive. At low pH, clayey soils have low resistivity and high corrosivity, and those contaminated with crude oil and saline water are extremely corrosive at pH values less than 5.5 (Irunkwor and Ngerebara 2018). According to the findings of Sing *et al.*, measuring soil resistivity can be used as an early indicator of the potential for corrosion growth rate. Because soil resistivity is a function of soil moisture and ionic soluble salt concentrations, it is regarded as the most comprehensive indication of soil corrosivity. Without the need for extensive sampling programs, soil resistivity can be used to measure and map soil parameters (Sing et al. 2013). It has also been argued that the resistivity of the soil is one of the most crucial design factors when taking into account the installation of cathodic protection for underground pipelines (Alhabobi and Albayati 2016). When evaluating the environment's corrosivity toward underground structures, soil resistivity testing is a critical factor. In a soil box, soil resistivity can also be measured, and the results can be used as a reference. The data, on the other hand, does not adequately reflect in-situ resistivity conditions. As a result, this study exclusively takes into account data collected on-site utilizing the Wenner four-electrode method and average pH values from works of literature to develop a corrosivity map for Rivers State. By identifying geographic variations in corrosion process intensity within Rivers State, this map will describe the actual soil corrosivity.

2. Materials And Experimental Method

2.1 pH in Rivers State

Buried steel pipes are exposed to a range of environmental reactions and changes, the most significant of which is corrosion (Zhang et al. 2017). The kind or type of the surrounding formation, as well as the solution contained inside the pipeline have an impact on this. The condition of the formation water informs how acidic or alkaline the sediment will be (Wang et al. 2021); pH affects the rate at which the pipeline corrodes. According to (Arriba-Rodriguez et al. 2018) 0 to 5, 5 to 6.5, 6.5 to 12, and greater than 12 represent severe, moderate, neutral, and low corrosivity on the pH scale.

In a region like the River State, the pH value varies from one city to another based on industrial activities which affect the land and the atmosphere's acidity or alkalinity (Dirisu et al. 2016). To support this claim, studies conducted in Ogba-Egbema-Ndomi, River State, a region of many industrial activities, suggested the pH value to be in the range of 4.0–3.6 at a depth of 200m and 7.3 at a depth of 2000m for both rainwater and soil formation (Osang et al. 2017). These figures, on the other hand, cannot be used to explain other parts of the state with lower levels of environmental discharge that can affect soil pH. As a result, further surveys at Elechi Creek in River State discovered that the pH value ranged from 6.2 to 7.6 (Ngah et al. 2017). The acidic oxides created by flaring could be responsible for the low pH values in industrial locations like Ogba-Egbema-Ndomi (Uyigue and Enujekwu 2017) and, Rivers State, which is an oil-producing state and contains sulphur in its formation (Onwuka et al. 2021), which could be a result of drilling or oil spillage that modifies pH (Ewida 2014); the formation becomes acidic when carbon dioxide is dissolved, and the Sulphur (S_8) deposited in the layer is hydrolysed in the formation water.

Table 1
Studies on the soil pH of Rivers State.

Location	pH Range	Average pH	Degree of Corrosivity	Ref.
Ogba-Egbema	3.60–4.00	3.80	Severe	(Osang et al. 2017)
Ogba-Egbema	6.50–7.30	6.90	Neutral	(Osang et al. 2017)
Obio-Akpor	6.20–7.60	6.90	Neutral	(Ngah et al. 2017)
Ahoada West	5.02–6.94	5.98	Moderate	(Onwuka et al. 2021)
Ikwere	5.68–7.37	6.53	Neutral	(Onwuka et al. 2021)
Oyigbo	4.25–6.03	5.14	Severe	(Onwuka et al. 2021)
Eleme	5.98–7.61	6.79	Neutral	(Onwuka et al. 2021)
Etche	5.50–6.57	6.04	Moderate	(Onwuka et al. 2021)
Emohua	6.48–9.22	7.85	Low	(Onwuka et al. 2021)

Based on the reviews of literature examined in Table 1, the pH value of Rivers State can be assumed to be slightly acidic as the average range is between 3.80 and 7.85. The precipitation of Sulphur on the steel's surface will lower the activation energy barrier which in turn lowers the bonding force between the metals when the dissolution of the surface metal atoms has set in. Therefore, as the concentration varies with depth in submerged pipelines, the high concentration solution inside the pits and the difference in oxygen concentration inside and outside the pits would speed up the dissolution of metal in the pores, resulting in deeper pits (Meng et al. 2008; Tian et al. 2014).

In trying to maintain electrical neutrality, Corrosive Cl^- causes pits that result in severe damage to pipeline steel (Gong et al. 2020). Understanding the corrosion mechanism under S_8 deposition requires the use of effective measurement devices to prevent pipeline failure. Acid formation produced by sulphur hydrolysis is the key factor influencing corrosion (MacDonald et al. 1978). It also suggested that as the pH value rises, the rate of corrosion reduces. It is worth noting that the rate of corrosion reduces to a negligible level (less than 0.024mm/y) when the pH value reaches 12 and 13 (Tang et al. 2015). However, under favourable pH conditions for sulphate-reducing bacteria, the corrosion rate reduces as the pH increases from 5.5 to 7.0 but gradually gains momentum after the neutral pH value = 7.0 and reaches the maximum rate at 9.5 (Ismail et al. 2014). This shows that the metal loss rate is low in the region of pH approaching the neutral level of pH 7. As a result, in extremely acidic or strongly alkaline formations, SRB can have a significant impact on corrosion rate (Gong et al. 2021).

Furthermore, the research on the rate of corrosion on carbon type of steel pipes at different pH levels (Tang et al. 2015) supports the findings which revealed that the corrosion rate at both high and low impressed current cathodic protection is almost similar to pH value in the range (7–10) while the corrosion rate at pH = 4 is higher about double due to the acidity of the solution (Matloub et al. 2018) and these results are agreed with the literature stating that the rate of corrosion increases with increasing the acidity (Revie and Uhlig 2008). The rate of corrosion without impressed current cathodic protection indicates an increase in the corrosion rate with the decrease of pH (Matloub et al. 2018). The principal corrosion depolarizers in acidic soil from the simulation solution appear to be H^+ and O_2 (Revie and Uhlig 2008). H^+ and O_2 are the dominant corrosion depolarizers in acidic soil (Wang et al. 2019). The nature of the corrosion on the steel pipes is determined by the varying ratios of oxygen-absorption and hydrogen evolution corrosion at different pH and DO content, as previously stated. As the pH value decreases, the dissolved oxygen reduces, and the proportion of hydrogen evolution increases, which in return results in a fast rate of corrosion reaction on the surface of the steel (Tian et al. 2014).

The coupling impact of the formation pH and the DO content determines the corrosion pattern of the pipeline in the acidic soil simulation solution (Yan et al. 2014). In general, increasing DO in the same pH system speeds up the cathode corrosion process while simultaneously encouraging corrosion product development (Wang et al. 2019). The fraction of the HE reaction increased in the solution with the same DO level, and the corrosion worsened as the pH dropped. The dissolved oxygen within the formation, on the other hand, falls with depth, validating the hypothesis that the rate of corrosion of buried pipes lowers as the pit becomes deeper due to lower dissolved oxygen at certain depths (Wang et al. 2019).

2.2 Soil Resistivity in Rivers State

In Eligbolo-eliozu, Obio/akpor local government area of Rivers State, (Ogbonna, V. A., Nwankwoala, H. O., & Lawal 2017) investigated the effect of landfills on groundwater quality using Wenner Array 2-D resistivity imaging. The 2-D resistivity image results showed that the soil and groundwater surrounding the landfill had been contaminated with leachate and waste gases and had resistivities ranging from 180Ωm to 428Ωm and 125Ωm to 2844Ωm, respectively. These resistivities were most occurrent at depths of 11.9m. Their findings showed the impact of landfills on groundwater quality and brought urgent attention to the need for proper waste management regulations with continuous monitoring.

Critical studies have been done on the soil effect on electrical earth resistance in Woji, Port Harcourt (Idoniboyeobu et al. 2018). The authors had hoped to analyze the characteristics of soil samples from the sites under both enhanced and unenhanced conditions such as texture, temperature, depth, and type of soil for better performance.

In Ahoada Community, another region in Port Harcourt, Rivers State, (Abdulkhanan et al. 2022) investigated hydrocarbon pollution using a GIS for mapping oil spill hotspots in the region. The authors collected three categories of soil samples such as IMS, RS and CS in several hotspot vandalization areas and used the resistivity method to evaluate the extent of hydrocarbon pollution up to a depth of 19.7m. In their findings, they recorded resistivity values ranging from 56–100000Ωm at depths 0.1–0.5m from the surface. At depths of 5m below the ground surface, the resistivity ratings had plummeted to between 15000–100000Ωm, with a lateral distance range from 36m to around 54m. Other resistivity recordings are shown in the image below:

Ukperede line 1, one of the vandalization hotspots in Rivers State's Ahaoda West Local Government, exhibits a declining resistivity rating below the earth's surface up to a depth of 19.7 m. This could be a result of different reasons such as lithology changes, groundwater quality, and other soil properties. Furthermore, the investigation of soil resistivity and subsurface lithology to assess the corrosivity of Obama-Kolo creek pipeline in Rumuekpe community, inside Emohua local government area of Rivers State suggested that the region's resistivity values range from 8 Ωm to 78 Ωm at depths 2-12m (Bright U and Horsfall 2020). The average thickness of the area was about 7m, and the mean resistivity calculated was 43 Ωm. There are different ways in which soil resistivity values have been gotten as shown in Table 2 and regardless of the ways used, they are unique to the location in which it was conducted and the qualities that characterized it.

Table 2
Reviews on soil resistivity in Rivers State.

Niger Delta	LGAs in Rivers	Soil resistivity	Remark	Ref.
Rivers State	Eligbolo-eliozu;	180Ωm; 428Ωm; 125Ωm; 2844Ωm,	The study used the Wenner Array 2-D resistivity imaging to measure the resistivity and water contamination up to depths of 11.9m	(Ogbonna, V. A., Nwankwoala, H. O., & Lawal 2017)
	Obio/akpor	Electrical Resistivity: 1.33–9.77 Ωm for sandy clay. 2.09–23.06 Ωm for sandy clay loamy. 3.26–128.0 Ωm for loamy sand. Apparent Resistivity: 125 Ωm for sandy clay. 1.448 x 103 Ωm for loamy sand	Resistivity measurements were taken with regards to soil types.	(Nwankwo 2013)
	Woji	141.26 Ωm; 370.64 Ωm; 2452.8 Ωm; 289.09 Ωm; etc.	Resistivity was measured for different soil samples. Thus, yielded different resistivity values.	(Idoniboyeobu et al. 2018)
	Ahaoda East	56–100000Ωm at depths 0.1–0.5m	Resistivity measurements were taken from the surface up to depths of 19.7m	(Abdulkhanan et al. 2022)
	Ahaoda West	15000–100000Ωm at depths 5m to 19.7m		
	Emohua	8 Ωm to 78 Ωm at depths 2-12m with mean of 43 Ωm	Resistivity measurements were taken from depths of 2-12m	(Bright U and Horsfall 2020)

In a study on the effect of dry and wet soil (caused by rainfall) on soil resistivity, (Salehi et al. 2014) assessed the soil resistivity and ground resistance at two different locations using the Wenner's four-pole equal method. One of the locations contained wet soil, while the other was dry soil. The authors measured the acceptability of the resistivity recordings by evaluating the root mean square errors and discovered it to be only 0 % and 4.92 % for wt and dry oils respectively. This experimental measurement showed that irrespective of the resistivity tool used (Wenner's 4-pole, and VES method), the resistivity values may differ depending on the soil type, and weather conditions. This assessment was equally conducted by (Warner 1969), who investigated how wet clay-loam soil containing dissolved salts showed lower resistivity, unlike dry soils with higher resistivity and no soluble salts. Table 3 shows clearer comparisons between soil resistivity testing designs.

Table 3
Comparison of experimental designs of Soil resistivity tests

Ref.	Resistivity Imaging	Study purpose	Study Observations	Fluid assessed
(Ogbonna, V. A., Nwankwoala, H. O., & Lawal 2017)	Wenner Array 2-D resistivity imaging	To assess the impact of landfill on groundwater quality	The result from the 2-D resistivity image showed the presence of contamination by leachate and waste gases in the groundwater and soil in the vicinity of the landfill	Waste gas, Leachate plume
(Ekeocha et al. 2012)	Vertical Electrical Sounding (VES) and 2-D resistivity imaging	To evaluate the effect of waste dump on soil and groundwater resources	The results were presented in terms of resistivity, thickness, and depth. Layers whose thickness and depth (> 65m) could not be assessed were said to have very low resistivities.	Leachate plume
(Alagbe 2018)	vertical electrical soundings (VES) using modified Wenner array method	Aimed at evaluation of subsurface soil corrosivity using electrical resistivity methods	Using the different techniques outlined in the study, the results obtained were able to detect the suitability of the different layers for burying storage metallic tanks.	-
(Okiongbo et al. 2019)	Vertical Electrical Sounding (VES)	Aimed at measuring the corrosion risk of superficial soils of four Niger Delta regions	Due to the variations in elevation, it was noticed that the spatial distribution of the resistivity was influenced by factors such as water level and quality, soil type and property as well as elevation.	-

2.3 Wenner's Method

To acquire resistivity data using the Wenner 4-point test method, four spikes arranged on a straight line and spaced equidistant are driven into the ground. A current of known voltage is then passed between the electrodes placed at the two ends known as the current probes. Having done this, the resistance of the two middle spikes is measured, and its potential difference (potential probes) is calculated (Salehi et al. 2014). It is important that the resistivity test be conducted as close to the site as possible for better results.

Wenner resistivity survey was developed by (Warner 1969) to identify subsurface features and the location of water. The objective of this method was to record the resistivity changes with depth and correlate this data with the available geological information. To determine the resistivity of the strata, Wenner passed a current between two electrodes on the surface, as the distance between the electrodes increased, it is observed that the penetration depth increases likewise. By doing so, the penetration of current below the surface is often about one-third of the distance between the two current electrodes at the surface (Mukund et al. 2017). One distinctive approach in Wenner's method is that the array spacing is often increased gradually in steps, keeping the midpoint fixed. The four electrodes with predefined array spacing are moved in steps, and their measurements are recorded after the next subsequent movement. Table 6 below shows the strengths and weaknesses of Wenner's 4-probe test.

Asides Wenner's 4-point method, another widely used method for conducting electrical resistivity assessment is the Vertical electrical sounding (VES) or Schlumberger sounding. The VES method is best used to assess the thickness of overburden as well as that of weathered/fractured zones with great accuracy(Joseph Olakunle Coker 2012)(Abdullahi 2015). This method differs from Wenner's approach in the way the two current electrodes are placed at much larger intervals than those between the two (inner) potential electrodes.

In a comparative assessment of both Wenner and Schlumberger electrical resistivity methods, (Mukund et al. 2017) noted a great difficulty in operating the Wenner configuration, because the depth to spread ratio was 1:3. This meant that it was very difficult and sometimes impossible to record data at depths beyond 100m. In addition, it was also very easy to record and interpret data from the Wenner method without using the curve matching technique, thus reducing error. This was because of the inverse slope type used in the Wenner method. The Schlumberger method (VES) on the other hand is known to have a software option that takes care of errors when matching with the curves. While this approach may seem innovative, there tend to be discrepancies in the original values of the layers and the discrepancies, depending on the personnel handling the operation. The VES method is also known to be very easy to operate and takes lesser time to complete as a result of the wider spacing of the electrodes. It may not be very easy to interpret the data generated by the curve matching technique in the VES method, and if more layers are required, it may be difficult and time-consuming to identify all the different curves. Both the Wenner's and VES methods give accurate readings, however, they may not be applicable in urban areas due to the spacing required between the electrodes and may be difficult for very hard rocks or terrain.

2.4 3D Mapping using MATLAB

MATLAB is a mathematical computational simulation platform that aids in the analysis of variables observed to have a certain behaviour that can be measured, some researchers also describe it as a flexible interactive system for numerical analysis and in some cases, assumptions are made in MATLAB to reduce complexities and fit the behaviour to a particular model that has a close representation to the reality (Ostertagová 2012; Moler and Little 2020). There are different types of models used in MATLAB to achieve a particular behaviour during analysis, and we have linear regression, nonlinear regression, logistics regression, and polynomial regression, amongst others (Zhang et al. 2012; Shardt 2015). These models mostly depend on the degrees of the variables involved and for the purpose of this study we used the polynomial regression model. The polynomial model of curves (equations 1 & 2) and how its degrees are expressed in MATLAB (Table 4) is expressed as shown below (MathWorks 2022).

$$y = \sum_{i=1}^{n+1} p_i x^{n+1-i}$$

1

And simply expressed in MATLAB for a relation of x degree 1 and y degree 3 as shown below.

$$f(x,y) = p00 + p10 * x + p01 * y + p11 * x * y + p02 * y^2 + p12 * x * y^2 + p03 * y^3$$

2

Table 4
Expression of polynomial regression degrees in MATLAB.

Degree	Zero	1st	2nd
1st	X	xy	xy^2
2nd	x^2	x^2y	N/A

In this study, f(x,y) is considered the corrosivity, y is the soil pH and x is the soil resistivity. The polynomial regression used in this study has a major advantage of data flexibility that is not complicated, and its linearity makes the fitting process easy. However, the higher the degrees, the fits become unstable and good fits are produced within the data range but may diverge outside the data range.

The data from the reviews above can be used to generate a 3D signature for corrosivity on MATLAB similar to Fig. 3, however, for a readable corrosivity mapping, the same expression can be superimposed to form a ripple map of reading off the corrosivity of a region which will be further explained in the next section. The confidence boundary conditions and the goodness of fits during 3D simulations are also important conditions this study highlighted and ensured the normalization of data.

3. Results And Discussion

Pilot test

A pilot test was conducted and 40-points soil pH and soil resistivity data across Rivers State were gathered to conduct a pilot test for suggesting the corrosivity of the region. After superimposing the data as explained in the previous section, the contour corrosivity plot was generated as shown below showing the correlation between the soil pH, soil resistivity and severity of corrosion at different levels. Unlike other works of literatures, this study digitized corrosivity from 1 to 5, with 5 being severe and 1 low corrosion. Soil resistivities of > 10000 Ωm, 10000 to 1000 Ωm, 1000 to 100 Ωm, 100 to 10 Ωm and < 10 with their respective pH values represented 1, 2, 3, 4 and 5 respectively.

Map Description

The maps show different layers whose size, shape, and direction show the extent of corrosion in relation to the pH and soil resistivity of that location.

The coefficients developed within 95% confidence bounds are:

p00 = 16.22 (-7.676, 40.12), p10 = -0.002236 (-0.01061, 0.006136), p01 = -6.642 (-19.83, 6.541), p11 = 0.0002348 (-0.002276, 0.002745), p02 = 1.183 (-1.155, 3.52), p12 = 1.653e-06 (-0.0001849, 0.0001882), p03 = -0.0699 (-0.2044, 0.06458)

The goodness of fit estimates for the corrosivity map are:

SSE: 10.04, R-square: 0.7003, Adjusted R-square: 0.6459, RMSE: 0.5515

The corrosivity map creates a good representation of the environment for decision making, reading the traditional contour lines, it is noticed that there are different levels of corrosivity as we move from left to right. Some levels are large because the corrosivity of that region experiences the same damaging effect within the region before moving to the next contour line. It gets less corrosive as it moves from left to right and from bottom to top. The map shows that the most corrosive region is the yellow region while the least corrosive are regions indicated with blue. However, Rivers State in general could be said to be moderately corrosive because of the large gaps between contour lines in the middle. The correctness of the mapping with respect to the corrosivity of Rivers State is 70.03% as suggested by the R-square value, which further means that apart from the soil pH and the soil resistivity there are other variables that could influence the corrosivity of the region such as lithology, groundwater quality or other soil properties as suggested in the earlier part of this study, but they are less significant when compared to soil resistivity and soil pH. Also, the SSE, RMSE, and the Adjusted R-square values suggest minimum error.

Validating this with studies in Rivers State that have simultaneously conducted a soil pH and soil resistivity test at the same point; for example, (Afa 2011) conducted a survey in Portharcourt, it's upland and coastal areas and the resistivity was within 16 Ωm to 40 Ωm and pH 4.75 to 6.12. It was concluded that the environment was corrosive which aligns with the corrosivity map in Fig. 4 (which falls within the orange region), however, the colour coding of the map further clarifies the extent of corrosivity for such a corrosive environment. Also, (Anyanwu et al. 2014) identified a soil pH and soil resistivity of 5.64 and

69.8 Ωm in Rivers state and it was concluded from a corrosion plot that Rivers is corrosive at such point as it still falls in the orange region of Fig. 4, justifying this study's finding.

These all imply that developing a regional corrosivity map is achievable with minimum errors when the surveys are extensively conducted. The outcomes of the mapping justify works of literature that have been cited in this work or conducted over the years, hence, it is evident to opine that a corrosivity map for Rivers State is necessary to assist in the planning of oil and gas development in the region.

Outlook

In this section, a total overview of the reviews so far was made based on shortcomings and challenges of the subject of study (see Table 5), and the proposed study pathway inferred was highlighted with the sole aim of pointing researchers to a specific direction that can be explored for further innovation for curbing corrosion of buried oil and gas pipelines.

Table 5
Study Outlook

Challenges & Shortcomings	Proposed study pathway
The pilot test in Fig. 4 provided a fast glance at what the environment looks like to guide investment decisions based on corrosion, but it cannot be completely depended on because it was based on studies of literature.	A soil pH and soil resistivity survey should be conducted in all key locations of active oil and gas activities around the region, and the more data used, the more accurate the map's judgments will be.
The study suggested that about 30% of factors that can impact underground corrosion were not considered therefore, corrosivity factors are not limited to soil pH and soil resistivity.	The model used in this study is unique and can be reproduced across multiple locations with more variables to better understand a region's corrosivity. A typical example is the temperature gradient (Idoniboyeobu et al. 2018). Since buried pipelines experience an increased temperature different from atmospheric temperature and studies have shown that temperature could facilitate corrosion, therefore it is necessary to include a variable like a temperature gradient for examining the extent of corrosion of a region.
The pH and soil resistivity of a region might change with an increase in groundwater and concentration. However, this was not considered in the mapping of the region. Also, the reviews from works of literature used did not identify the period when the data was collected.	While gathering data for developing a standard corrosivity map of any region, the extreme conditions of the environment could be the best fit for data collection. A typical example is the periods of maximum rainfall or high industrial emissions, that could result in acidic rainfall.
There were several noticeable resistivity issues, especially when dealing with regions with variations in topography (Okiongbo et al. 2019). This caused spatial distribution in resistivity values. These resistivity variations were affected by elevation, water level and quality, soil type and properties. This challenge may occur in several other locations in Rivers State and may be difficult to accurately measure the resistivity values.	In regions with variation in topography, a range of resistivity values should be provided with regard to soil type and properties, elevation, water level, and quality.
In (Alagbe 2018), the findings showed using a combination of VES and Wenner’s method may give low to no resistivity results, especially when the depths and thickness of the layer could not be reached. This might be a challenge when developing a resistivity/corrosion map of Rivers State.	The author may indicate a low or no resistivity result in these regions.
The Wenner’s and VES methods have significant benefits. However, depending on the topography or the urbanization of the region being measured, it might be difficult to use any of the two methods because they require a wide distance.	In immensely urbanized regions, an alternative electrode array can be adopted such as Bipole-Bipole Array, which requires a considerably smaller distance between the receiver and transmitter dipoles

4. Conclusions

In conclusion, this study identified soil pH and soil resistivity as key factors that can influence the corrosion of buried oil and gas facilities, and the reviews cited in this paper summarized the observations and findings of several researchers on the extensive use of pH or soil resistivity in understanding corrosion severity. The limitations and challenges that come with it were also explored. However, the important takeaway from the findings thus far is that a corrosivity map can be developed for regional corrosion control and management, and the sample developed using MATLAB as shown in figure 4 suggests that such a map can be readable, helpful, and with less error. Given the intensive oil and gas activity in the region, a detailed pH and soil resistivity survey in Rivers State is required. The survey's findings could be utilised to improve the corrosivity map and serve as a benchmark for corrosion decision-making in the region.

Abbreviations

AC – Applied current

CS – Control soil

DO – Dissolved Oxygen

GDP – Gross Domestic Product

GIS – Geographic information system

HE – Hydrogen Evolution

IMS – Impacted Soil

LGA – Local Government Area

NACE – National Association of Corrosion Engineers

SCC – Stress Corrosion Cracking

SRB – Sulphur Reducing Bacteria

SSE – Sum of squares due to error

RMSE – Root Mean Squared Error

RS – Remediated soil

Declarations

Credit Author Contribution Statement

Azubuike Hope Amadi: Conceptualization, Methodology, Validation, writing original draft, Writing/review/editing, Data curation. **Joseph A. Ajienka**: Conceptualization, Methodology, Review/editing, Supervision. **Onyewuchi Akaranta**: Supervision and review. **Kehinde Ajayi**: Writing – review & editing. **Paul Obinna Okafor**: Writing & editing. **Chiedozie Valentine Oluigbo**: Writing & editing.

Funding

This research was funded by World Bank through the World Bank Africa Center of Excellence in Oilfield Chemicals Research, University of Port Harcourt, Nigeria.

Declaration of Conflicting Interest

No conflict of interest

Acknowledgements

The authors thank the World Bank Africa Center of Excellence in Oilfield Chemicals Research, University of Port Harcourt for providing funding and an institutional platform for actualizing this research.

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Figures

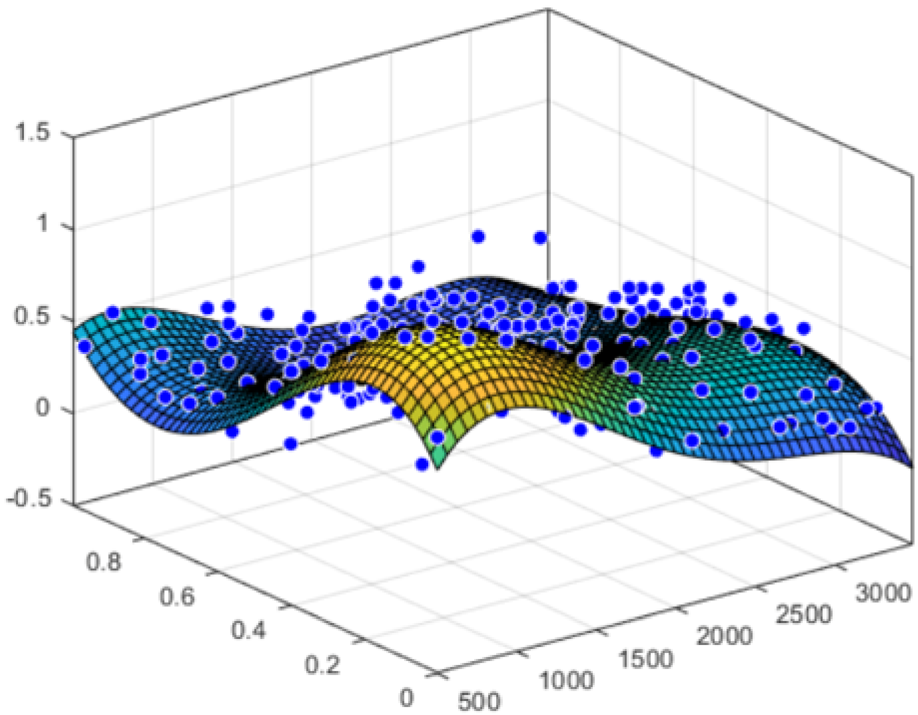

Figure 1

3: 3D sample of variable projections using MATLAB polynomial regression (MathWorks 2022).

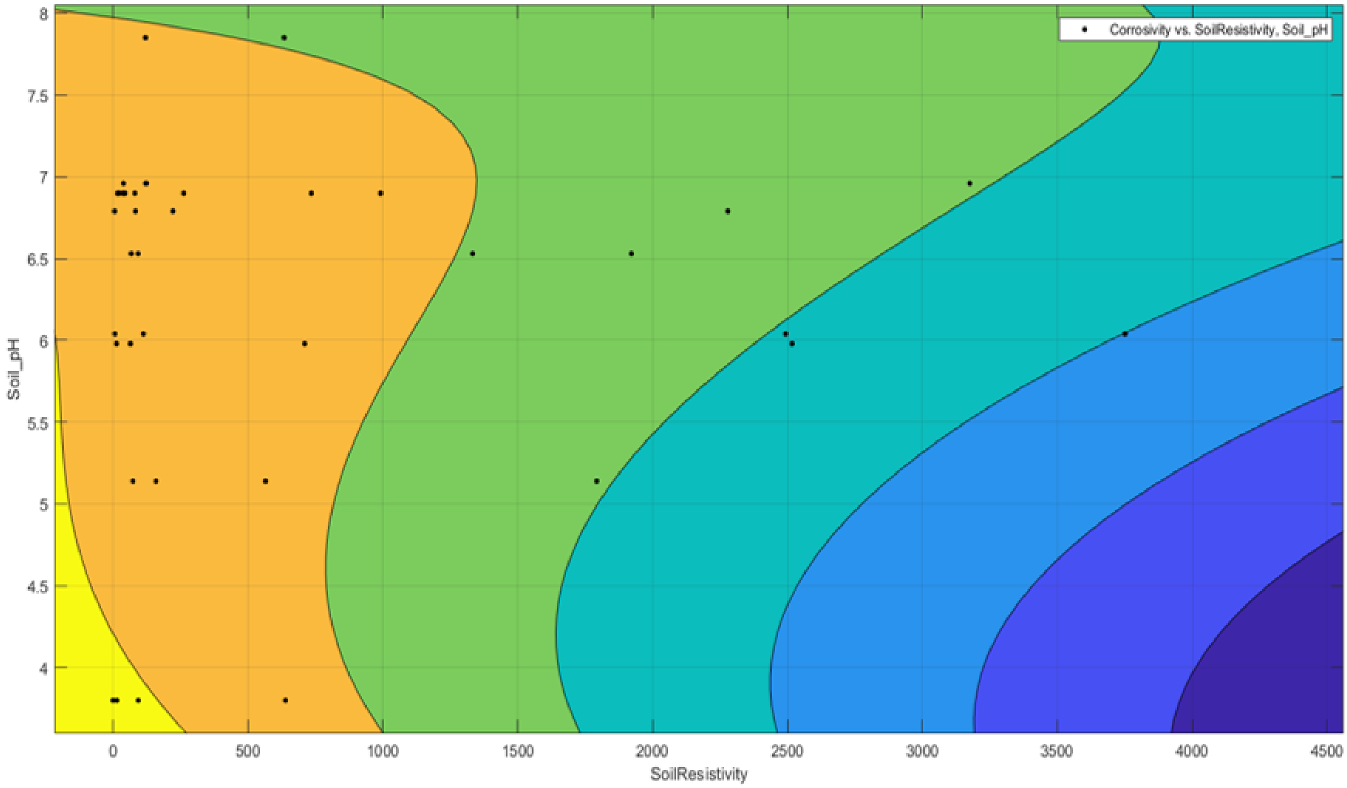

Figure 2

4: Corrosivity Map of Rivers State, Nigeria.