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MULTI-CRITERIA DECISION ANALYSIS FOR CORROSION RISK ASSESSMENT OF BURIED WATER PIPELINES: AN ANALYTIC HIERARCHY PROCESS APPROACH

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ABSTRACT

The management of buried water pipeline systems requires reliable methods for assessing corrosion risk due to the complex interaction of pipeline characteristics and soil environmental conditions. This study develops a structured decision-support framework for pipeline corrosion risk assessment based on Multi-Criteria Decision Analysis (MCDA) using the Analytic Hierarchy Process (AHP). Pipeline attributes (length, thickness, burial depth, age, diameter, and internal pressure) and soil parameters (pH, electrical conductivity, salinity, and resistivity) were evaluated within the buried water distribution network of Edo State Polytechnic, Usen, Nigeria, which spans approximately 4,008.6 meters. Attribute weights derived from pairwise comparisons identified pipe age (0.22), soil resistivity (0.19), and burial depth (0.16) as the most influential factors. Lesser contributions were observed for pipe length (0.06) and diameter (0.08). The computed Pipe Condition Index (PCI) values ranged from 0.31 (high-risk) to 0.82 (low-risk) across pipeline segments. The AHP consistency ratio (CR) was 0.07, confirming the judgments reliability. These findings highlight the utility of MCDA for quantifying corrosion susceptibility in buried pipelines. The PCI framework provides a transparent and replicable tool for prioritizing pipeline maintenance and offers a foundation for future integration with artificial intelligence and GIS-based predictive systems.

Keywords: Multi-Criteria Decision Analysis, Analytic Hierarchy Process, Pipe Condition Index, Corrosion Risk, Buried Pipelines

INTRODUCTION

Buried water pipelines are critical to water distribution and energy transportation, yet they remain highly susceptible to external corrosion, a leading cause of structural deterioration and failure. Corrosion-induced leaks and ruptures disrupt supply while imposing substantial economic and environmental costs (Abdelkader *et al.*, 2024). The challenge is particularly severe in developing regions where inspection data are scarce, maintenance is reactive, and underground assets are poorly documented (Taiwo *et al.*, 2023).

Pipeline corrosion arises from the interplay of structural and environmental conditions. Attributes such as wall thickness, burial depth, pipe age, and diameter interact with soil properties including resistivity, pH, salinity, and conductivity to drive deterioration (Zhang *et al.*, 2024). Traditional deterministic models often oversimplify these nonlinear interactions and are not easily adaptable to diverse site conditions, leading to under- or overestimation of corrosion risks (Tang *et al.*, 2021; Zeng *et al.*, 2025). This has motivated the adoption of decision-support frameworks that can integrate heterogeneous parameters into reliable risk assessments.

Multi-Criteria Decision Analysis (MCDA) provides such a framework by enabling structured evaluation of diverse attributes and incorporating expert judgment. Among MCDA methods, the Analytic Hierarchy Process (AHP) is particularly powerful due to its systematic pairwise comparison procedure, ability to derive relative weights, and built-in consistency checks (Saaty, 1980). Recent applications highlight its versatility: Ba *et al.* (2021) improved corrosion risk modeling of buried gas pipelines with a fuzzy AHP model; Chen *et al.* (2021) applied fuzzy AHP to assess casing corrosion in CO_2 injection wells; Farh *et al.* (2023) ranked causes of water pipeline corrosion; and Tian and Lv (2024) integrated fuzzy AHP with network-based structures to model gas pipeline leakage risks. These studies demonstrate AHP's reliability even under uncertainty.

Beyond methodological innovation, the literature shows the value of condition indices derived from weighted parameters. Abdelkader *et al.* (2024) prioritized water pipe deterioration factors with a fuzzy AHP–game theory model, Betgeri and Kumar (2023) developed a comprehensive MCDA-based rating system for wastewater pipelines, and Liu and Li (2023) reviewed hybrid MCDA approaches in infrastructure risk analysis. Together, these studies reinforce the adaptability of AHP and its extensions in contexts where inspection is costly or impractical. However, despite global advances, relatively few studies have systematically applied MCDA to buried water pipelines in sub-Saharan Africa, where recurrent corrosion-induced failures directly threaten service reliability. Local constraints such as poorly mapped utilities, limited inspection technologies, and scarce maintenance resources make context-specific decision-support tools essential (Taiwo *et al.*, 2023; Yahayya *et al.* 2011). Nigerian studies, such as Obaseki (2019), have demonstrated the potential of condition indices, but systematic MCDA-based corrosion risk assessments remain rare. For instance, Ezeonuogu *et al.* (2022) examined pipeline corrosivity in Rivers State using lithology and pore fluid; Adeyemo *et al.* (2024) assessed subsoil corrosivity in Akure through geoelectric methods; and Obiora *et al.* (2015) analyzed aquifer protective capacity and soil corrosivity in Makurdi. These local and regional studies provide important context but remain limited in systematic application of MCDA, underscoring the contribution of the present research. Against this background, the present study applies an AHP-based framework to the water distribution system of Edo State Polytechnic, Usen, Nigeria. In Nigeria and the wider West African region, a growing body of empirical work has begun to investigate soil corrosivity and groundwater chemistry relevant to buried pipelines. The objectives are to (i) derive relative weights for pipeline and soil parameters, (ii) compute a Pipe Condition Index (PCI) to prioritize pipeline segments, and (iii) identify the most influential drivers of deterioration. By integrating a locally adapted PCI within an AHP framework, the study contributes a transparent and replicable tool for pipeline asset management in data-scarce environments, while also laying the foundation for GIS-based mapping and predictive modeling using artificial intelligence.

MATERIALS AND METHODS

Study Area Description

The study was carried out within the campus of Edo State Polytechnic, Usen, situated in Ovia Southwest Local Government Area of Edo State, southern Nigeria. The institution is located approximately 45 km northwest of Benin City, lying within the humid tropical lowland rainforest belt. The area is characterized by annual rainfall exceeding 2000 mm, relative humidity above 70%, and mean daily temperatures ranging from 24°C to 32°C. These climatic conditions create soils with high moisture content, elevated salinity, and varying resistivity all of which significantly influence the aggressiveness of buried metallic pipelines. Topographically, the terrain is gently undulating, with surface elevations between 120 m and 150 m above sea level. The soils are predominantly lateritic, with sandy–clayey compositions prone to seasonal waterlogging during the rainy season. Such soils are associated with increased corrosivity due to their capacity to retain moisture and dissolved ions. The water distribution network at Edo State Polytechnic consists of approximately 4,008.6 meters of interconnected underground pipelines supplying residential, academic, and administrative facilities. The buried pipelines are typically located at shallow to moderate depths, ranging from 0.5 m to 3 m, and have experienced recurring failures attributed to external corrosion. Geographically, the study area is bounded within the following coordinates (UTM Zone 31N): Northwest: 06°44′18″N, 05°02′44″E, Northeast: 06°44′18″N, 05°03′12″E; Southwest: 06°43′50″N, 05°02′44″E, Southeast: 06°43′50″N, 05°03′12″E . Figure 1 represent the map of the study area. Figure 1 shows the study area map and Figure 2 is the flow diagram.

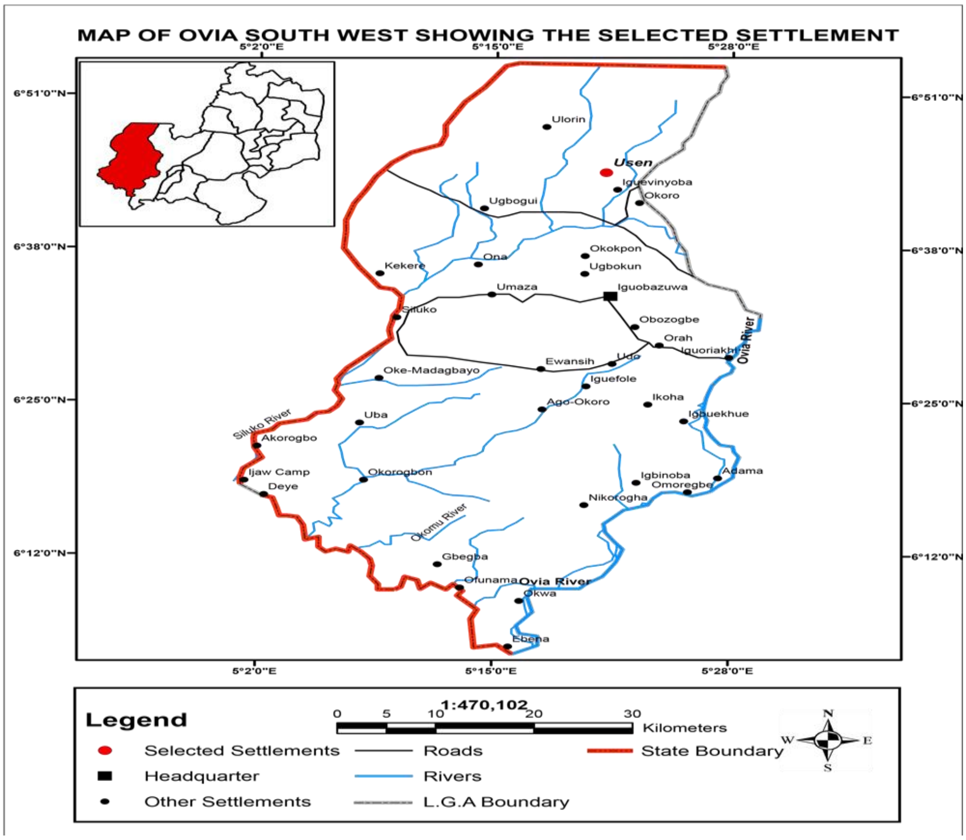

Figure 1: Map of the Study Area. Source: (Omoruyi *et al.* 2025)

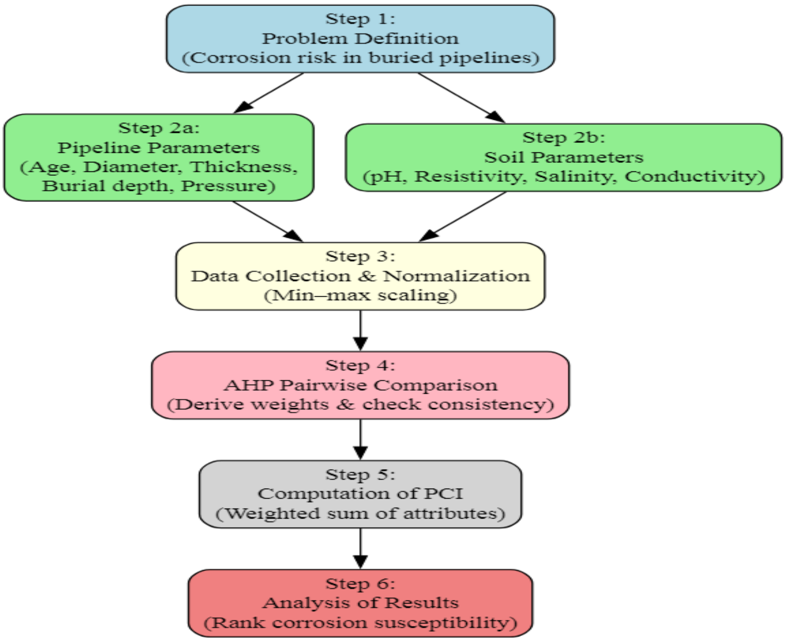

Figure 2: Flow Diagram of the Processes

Data Collection and Parameters

Two groups of variables were selected for the corrosion risk evaluation framework:

1. Pipeline-related parameters: length (km), wall thickness (mm), burial depth (m), age (years), diameter (mm), and internal operating pressure (bar).
2. Soil-related parameters**:** pH (pH units), electrical conductivity (µS/cm), salinity (ppt), and resistivity (Ω·m).

These attributes were prioritized because they are widely recognized in the literature as key external corrosion drivers for buried metallic pipelines (Zhang *et al*., 2024; Tang *et al*., 2021; Hussain *et al*., 2024). Other factors such as pipe coating condition, soil moisture, and chloride concentration were not included because corresponding field data were unavailable during this study. This limitation is acknowledged but future work can be made to incorporate more factors for a more comprehensive assessment as suggested by (Obaseki *et al*., 2019).

Sampling and Measurement Procedures

Field measurements were conducted across 45 junction points within the buried water distribution network at the study area. Soil resistivity was measured in situ using the Wenner four-probe method in accordance with ASTM G57-06, with triplicate readings averaged to improve reliability. Soil pH and electrical conductivity were determined using calibrated portable meters, while salinity was measured with a digital refractometer. Pipeline dimensions (diameter, wall thickness, and burial depth) were obtained from construction records and verified at exposed points, whereas pipeline age and pressure were obtained from utility records. All measurement devices were calibrated against manufacturer specifications prior to fieldwork.

Data Normalization

Since attributes were measured in different units, min–max normalization was applied to rescale values into the range [0,1], to ensure comparability across parameters. This approach has been widely used in AHP-based infrastructure studies (Farh *et al.*, 2023*;* Macêdo *et al.*, 2024). A sensitivity check was also performed using z-score normalization, and results showed negligible variation in PCI rankings (±0.03). This value further confirms the robustness of the chosen approach. Equation 1 was used to achieved the min–max normalization.

$$X_{norm} = \frac{X - X_{\min}}{X_{\max} = X_{\min}} \quad (1)$$

where X is the raw value, Xmin and Xmax are the minimum and maximum observed values, and Xnorm is the normalized variable.

Using the minimum and maximum values, the field measurement data were normalized to obtain the attribute scores and result is presented in Tables 1 and 2 respectively.

Table 1: Minimum and Maximum Value of Attribute Variables

Attributes	Minimum Value	Maximum Value	Difference
Soil pH	2.435	7.635	5.2
Soil Resistivity (Ω)	0.48	5.66	5.18
Soil EC (µS/cm)	65	486.5	421.5
Soil Salinity (g/l)	36.19	182.05	145.86
Pipe Depth (mm)	412	452	40
Pipe Thickness (inches)	1.011	1.41	0.399
Pipe Length (m)	0	2900	2900
Pipe Diameter (mm)	75	100	25
Pipe Age (yrs)	15	22	7
Pressure (m)	7.03	27.06	20.03

Table 2: Excerpt from the Normalized Weight of Attributes Using Min-max Scaling Method

Sample Point	Soil pH	Soil Resistivity Ω	Soil EC µS/cm	Soil Salinity mg/L	Pipe Depth (mm)	Pipe Thickness (inches)	Pipe Length (m)	Pipe Diameter (mm)	Pipe Age (yrs.)	Pressure (m)
JI	0.471	0.703	0.148	0.255	0.750	0.779	0.000	1.000	1.000	0.581
J2	0.438	0.892	0.241	0.303	0.825	0.749	0.034	1.000	1.000	0.321
J3	1.000	0.390	1.000	1.000	0.775	0.832	0.069	1.000	1.000	0.487
J4	0.898	0.597	0.428	0.698	0.800	0.807	0.103	1.000	1.000	0.720
J5	0.391	0.693	0.448	0.410	0.975	0.764	0.138	1.000	1.000	0.309
J6	0.537	0.766	0.304	0.256	0.850	0.875	0.172	1.000	1.000	0.128
J7	0.743	0.726	0.155	0.265	0.800	1.000	0.207	1.000	1.000	0.376
J8	0.668	1.000	0.276	0.458	0.650	0.754	0.241	1.000	1.000	0.237
J9	0.905	0.394	0.459	0.757	1.000	0.825	0.276	1.000	1.000	0.764
J10	0.428	0.541	0.129	0.226	0.700	0.932	0.310	1.000	1.000	0.825

Analytic Hierarchy Process (AHP)

Relative importance weights for the ten attributes were derived using the AHP technique. Pairwise comparisons were performed by a panel of five corrosion and civil engineers, each with over 10 years of professional experience in pipeline management. To minimize individual bias, median values of their judgments were adopted. Consistency of the pairwise comparison matrix was verified using the Consistency Ratio (CR), which yielded a value of 0.07 within the acceptable threshold of 0.10 (Saaty, 1980). Equation 2 was adopted for this purpose.

$$a_{ij} = \frac{1}{a_{ji}}, \; a_{ii} = 1 \qquad (2)$$

Weight Derivation

The normalized weights were computed from the principal eigenvector of the comparison matrix as depicted by equation 3:

$$A_w = \lambda_{max} w \qquad (3)$$

where w is the eigenvector and λmax is the maximum eigenvalue.

The Consistency Index (CI) and Consistency Ratio (CR) were calculated to ensure judgment reliability using equations 4 and 5.

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (4)$$

Where: λ_{max} refers to the maximum eigenvalue of matrix A, n is the number of criteria.

$$CR = \frac{CI}{RI} \qquad (5)$$

Where n is the number of attributes, and RI is the Random Index. A $CR < 0.1$ indicates acceptable consistency (Saaty, 1980).

Pipe Condition Index (PCI)

The PCI was developed as an integrated dimensionless indicator of pipeline condition. Following standard AHP practice, PCI was calculated as the weighted sum of normalized attribute scores. To enhance interpretability, PCI thresholds were aligned with benchmarks reported in prior studies: values <0.30 were classified as high risk, values between 0.30–0.60 as moderate risk, and values >0.60 as low risk (ElAbbasy *et al.*, 2014). This provides a meaningful context for decision-making and allows comparisons with existing water main condition studies. Equation 6 was used for PCI computation.

$$PCI = \sum_{i=1}^{n} w_i \times X_i \qquad (6)$$

Where PCI is the required pipe condition index, X_i is the normalized score of the i^{th} attribute and w_i is its weight.

RESULTS AND DISCUSSION

Derivation of Relative Weights for Pipeline and Soil Parameters Results

The AHP pairwise comparison matrix produced normalized weights for the ten attributes considered in the study (Table 3). The most influential factors were pipe age (0.22), soil resistivity (0.19), and burial depth (0.16), indicating that material degradation over time and soil aggressiveness strongly influence corrosion susceptibility. By contrast, attributes such as pipe length (0.06) and pipe diameter (0.08) were less influential, reflecting their indirect role in external corrosion. The Consistency Ratio (CR) was 0.07, below the recommended threshold of 0.1 (Saaty, 1980), confirming the reliability of the pairwise comparisons. Such verification is essential, as inconsistent judgments can distort parameter rankings and undermine robustness (Tian, & Lv, 2024).

The prominence of pipe age aligns with evidence that aging pipelines experience coating degradation, cathodic protection loss, and accumulated wear (Hussain *et al*., 2024; Zhu, 2023). Soil resistivity also emerged as a critical parameter, as low values accelerate ionic mobility and electrochemical reactions that promote corrosion (Farh *et al*. 2023; Macêdo, 2024). Burial depth ranked third, consistent with experimental findings showing that shallow pipes are vulnerable to fluctuating wet–dry cycles, while deeper pipes remain in persistently moist soils conducive to continuous corrosion (Moura & Santos, 2022).

By contrast, geometric parameters such as pipe diameter and length showed relatively low weights, consistent with other MCDA applications that emphasize their indirect impact compared to environmental and material factors (Macêdo, 2024). Overall, the derived weights reflect physical and electrochemical processes and align with global findings that consistently identify soil conditions and material aging as dominant corrosion drivers (Farh *et al*. 2023; Abdelkader *et al.* 2024).

Table 3: Normalized Weights of Pipeline and Soil Parameters

Attribute	Weight	Rank
Pipe age (years)	0.22	1
Soil resistivity (Ω·m)	0.19	2
Burial depth (m)	0.16	3
Wall thickness (mm)	0.12	4
Internal pressure (bar)	0.09	5
Diameter (mm)	0.08	6
Soil pH (pH units)	0.07	7
Electrical conductivity (µS/cm)	0.06	8
Salinity (ppt)	0.06	9
Length (km)	0.06	10

The high weight assigned to pipe age reflects the progressive deterioration of protective coatings and loss of cathodic protection, which increase vulnerability to external corrosion. Similarly, low soil resistivity enhances ionic mobility and accelerates electrochemical reactions, explaining its strong influence as a corrosion driver. Burial depth also plays a critical role as shallow pipelines are more exposed to fluctuating wet–dry cycles, while deeper pipelines remain in persistently moist soils that promote continuous corrosion activity. In contrast, pipe diameter and length exert only indirect effects, which explains their comparatively lower weights assignment.

Pipe Condition Index (PCI) Results

The Pipe Condition Index (PCI) values derived for the 45 junctions (J1–J45) are shown in Figure 4. To improve interpretability, PCI results were benchmarked against established thresholds. Values below 0.30 were classified as high risk, while 0.30–0.60 represented moderate risk, consistent with industry references such as AWWA guidelines and the framework reported by ElAbbasy *et al.* (2014). None of the segments in this study exceeded the 0.60 threshold, showing that the entire distribution network falls below internationally accepted performance standards. These classifications provide clear guidance for infrastructure management. Critical hotspots such as J32, J34, and J35 should be prioritized for immediate rehabilitation or replacement. Segments falling within the moderate range, such as J38 and J41, should be scheduled for preventive maintenance and closer monitoring to avoid progression into high-risk categories. This structured prioritization ensures that limited resources are allocated to the most vulnerable parts of the network.

Specifically, 11 junctions (including J6, J15–J17, and J31–J37) were classified as low risk, with PCI values ranging from 0.135 to 0.297. These particularly low values suggest areas of severe deterioration, likely driven by aggressive soil conditions and advanced pipe aging. Junction J32 recorded the lowest PCI (0.135), marking it as a critical hotspot for intervention.

The remaining junctions fell within the moderate-risk category, with PCI values between 0.306 and 0.463. Most pipeline sections clustered around the 0.30–0.40 range, confirming widespread but non-critical deterioration across the network. Notably, junctions J38 (0.423) and J41 (0.463) achieved the highest PCI scores, though still below the 0.60 safety benchmark.

These findings align with earlier work by Revie (2008) and Roberge (2012), who reported that aging pipelines in corrosive soils rarely achieve high condition indices. Similarly, ElAbbasy *et al.* (2014) used AHP-based prioritization for Canadian water mains and also found that most segments clustered within moderate risk ranges, with very few considered safe. More recent studies such as Moura & Santos (2022) and Macêdo *et al.* (2024) reaffirm that soil aggressiveness and pipe age are the dominant drivers of underground pipeline deterioration, which is consistent with the present results.

Influential Parameters and Corrosion Susceptibility Trends

The consistency between the parameter weights and PCI outcomes highlights the key deterioration mechanisms in the Edo Polytechnic network. Junctions with the lowest PCI values (like the, J32, J34, and J35) correspond to areas where aging pipes intersect with highly aggressive soils of low resistivity. This confirms that material aging and soil aggressiveness are the primary drivers of external corrosion in the system. Burial depth also contributed to the observed variation: shallow sections experienced fluctuating wet–dry cycles, while deeper sections remained exposed to persistently moist conditions, sustaining continuous corrosion. These trends reinforce that the interaction of age-related deterioration with geochemical aggressiveness defines the corrosion susceptibility of the buried pipelines.

Implications for practice emerge directly from these findings. The PCI framework clearly identifies critical junctions such as J32, J34, and J35 for urgent rehabilitation or replacement, while also highlighting the broader need for preventive maintenance across moderately deteriorated segments. By providing a structured and transparent measure of risk, PCI allows operators to prioritize limited resources toward the most vulnerable parts of the network. Moreover, integration of PCI with GIS platforms could enable the development of spatial corrosion-risk maps, thereby improving visualization and planning for infrastructure managers, as demonstrated in related studies (Farh *et al*., 2023; Taiwo *et al*. 2023). Figure 4. Pipe Condition Index (PCI) values for pipeline segments J1–J45. Red bars denote junctions with PCI <0.30 (low risk), while blue bars represent PCI values between 0.30 and 0.60 (moderate risk). The analysis shows no segment exceeded the 0.60 safety threshold, indicating overall susceptibility of the network to corrosion-related failures.

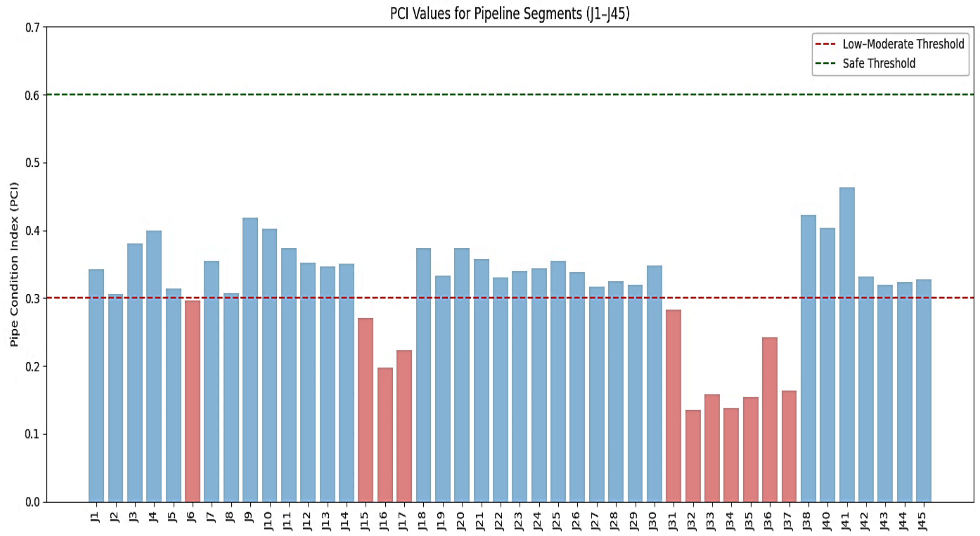

Figure 4: Risk Assessment Level of Water Pipelines

Discussion of Findings

The analysis identified pipe age, soil resistivity, and burial depth as the most influential drivers of corrosion risk, while attributes such as pipe diameter and length were comparatively less significant. This confirms that external corrosion is primarily governed by material deterioration and soil aggressiveness rather than geometric properties. Similar findings have been reported in recent reviews: Hussain *et al*. (2024) and Zhu (2023) emphasize that pipeline aging accelerates coating degradation and reduces cathodic protection effectiveness, leaving pipelines more vulnerable to soil-driven corrosion.

The high influence of soil resistivity observed in this study aligns with electrochemical theory, as low-resistivity soils facilitate ionic movement and accelerate corrosion reactions. This has been highlighted in pipeline deterioration modeling by Farh *et al.* (2023), who ranked soil resistivity as the dominant external factor using fuzzy AHP, and by Ba *et al.* (2021) in natural gas pipeline risk assessments. The strong role of resistivity in the present study reinforces its value as a practical proxy for soil aggressiveness in contexts where advanced geochemical analyses may be unavailable.

Burial depth emerged as the third most important factor, reflecting the dual effect of shallow burial (greater exposure to environmental fluctuations) and deeper burial (persistent contact with moist soils). Experimental evidence by Macêdo *et al*. (2024) demonstrated that oxygen diffusion and soil moisture retention at different depths both significantly influence long-term corrosion rates, a trend consistent with the findings here.

In contrast, attributes such as pipe diameter and length carried relatively lower weights. While these parameters influence hydraulic performance and operational capacity, their direct role in external corrosion is limited. This agrees with the conclusions of Macêdo *et al*. (2024), who found geometric parameters to be secondary to soil and material properties in pipeline deterioration assessments.

Beyond individual parameters, the results highlight the practical utility of the Pipe Condition Index (PCI) as a decision-support tool. By condensing multiple attributes into a single interpretable score, PCI provides a transparent framework for prioritizing interventions. Similar applications of condition indices have been reported in water and wastewater infrastructure management, where indices supported resource allocation under data-scarce conditions (Betgeri & Kumar, 2023; Taiwo *et al.,* 2023). Importantly, the integration of PCI within an AHP-based multi-criteria framework ensures that judgments remain logically consistent, as evidenced by the acceptable Consistency Ratio achieved in this study.

These findings carry important implications for infrastructure management in Nigeria and similar developing regions. First, they show the urgency of targeting maintenance toward older pipeline sections and those located in low-resistivity soils. Again The PCI values derived for the 45 junctions (J1–J45) are shown in Figure 4. Values below 0.30 were classified as high risk, while 0.30–0.60 indicated moderate risk, consistent with AWWA guidelines and ElAbbasy *et al.* (2014). None of the pipeline segments exceeded 0.60, showing that the entire distribution network falls below internationally accepted performance standards.

Critical hotspots such as J32, J34, and J35 recorded the lowest PCI values (as low as 0.135) and should be prioritized for rehabilitation or replacement. Eleven junctions, including J6, J15–J17, and J31–J37, fell in the high-risk category (0.135–0.297), suggesting severe deterioration driven by aggressive soils and pipe aging. The remaining junctions were in the moderate category (0.306–0.463), with J38 (0.423) and J41 (0.463) achieving the highest scores, though still below the safety threshold.

These findings are consistent with prior studies showing that buried pipelines in corrosive soils rarely achieve high condition indices (Revie, 2008; Roberge, 2012). ElAbbasy *et al.* (2014) similarly found that most Canadian water mains clustered within moderate risk ranges, while more recent studies reaffirm the role of soil aggressiveness and pipe age as dominant drivers (Moura & Santos, 2022; Macêdo, 2024). , they demonstrate the feasibility of adopting AHP–PCI frameworks where inspection data are limited, providing a structured basis for prioritization. Finally, integrating PCI outputs into GIS platforms could enhance visualization of corrosion hot spots, as recommended in recent geospatially-enabled asset management studies (Liu & Li, 2023; Abdelkader *et al*., 2024). Such integration would support not only engineering decisions but also policy-level strategies for sustainable water distribution infrastructure.

By these case-specific findings, this study demonstrates the adaptability of an AHP–PCI framework in sub-Saharan Africa, where data scarcity, poorly mapped utilities, and limited inspection technology pose significant challenges. By applying a context-specific and replicable methodology, the research advances corrosion risk management in developing regions and offers a model that can be extended to similar water distribution systems across African and other resource-constrained settings.

CONCLUSION

This study demonstrates that an Analytic Hierarchy Process (AHP)–based Multi-Criteria Decision Analysis (MCDA) framework provides a structured and transferable approach for assessing corrosion risk in buried pipelines under data-scarce conditions. By integrating pipeline and soil parameters into a locally adapted Pipe Condition Index (PCI), the research advances methodological practice in sub-Saharan Africa, where systematic corrosion risk assessments remain limited.

The practical significance of this framework extends beyond the Edo State Polytechnic case study. The PCI offers a transparent tool for prioritizing pipeline maintenance at the local level, while also informing broader decision-making at national and regional scales. By supporting resource allocation toward high-risk segments, the framework contributes to more sustainable water infrastructure planning and policy.

Looking forward, the approach offers a foundation for methodological expansion. Integration with Geographic Information System (GIS) platforms would enable spatial visualization of corrosion hot spots, while coupling with artificial intelligence and machine learning models could improve predictive capacity for proactive asset management. Future studies should also incorporate additional parameters such as coating condition and soil moisture to further strengthen the robustness of the framework.

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