

Seasonal Impact of Water Parameters Variation on Signal Propagation in Underwater Communication Systems

Funmilola Adeagbo^{1*}, Hammed Lasisi¹, Fatimat Aderinkola², Mubarak Asafa³, Olla Moses¹, Kehinde Alawode¹, Tolulope Awofolaju¹, Abdulsemiu Olawuyi¹

¹ Department of Electrical and Electronics Engineering,
Osun State University Osogbo, 230262, NIGERIA

² Federal Polytechnic Ede,
230262, NIGERIA

³ Bells University, Ota Ogun State,
230262, NIGERIA

*Corresponding Author: funmilola.adeagbo@uniosun.edu.ng

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Abstract

The study explores how environmental variations affect signal propagation in freshwater bodies, focusing on five key sites: Niger River, Asejire Dam, Ede Dam, Osun River, and Eti-Osa River. Employing laboratory-based quantitative analysis, parameters such as temperature, salinity, pH, turbidity, and total dissolved solids (TDS) were measured using standard instruments. Distinct seasonal trends emerged—temperature increased by an average of 8°C in the dry season, while turbidity and TDS rose notably during the rainy period, ranging from 30–150 NTU and 25–80 mg/L in the dry season to 41–200 NTU and 30–120 mg/L in the rainy season. These variations directly influenced acoustic signal performance. The data revealed that higher temperatures improve signal velocity and reduce attenuation, whereas increased turbidity, TDS, and salinity contribute to greater scattering and absorption losses. The novelty of this work lies in its integrated assessment of multi-parameter water quality influences on underwater signal transmission, emphasizing the dual-season comparative approach within tropical freshwater systems. Unlike prior studies that generalized oceanic models, this research contextualizes findings within inland aquatic environments relevant to Nigeria. The study contributes to the existing body of knowledge by quantitatively linking environmental conditions with communication efficiency, establishing that signal reliability in Underwater Communication Systems (UWCS) is seasonally dependent. In conclusion, the results underscore the necessity of adaptive communication models that account for local hydrological dynamics to minimize signal degradation and optimize transmission efficiency across varying aquatic conditions.

1. Introduction

The earth is covered with 70% of water, and there is need to investigate into how transmission of information can be done through this medium. Underwater Communication Systems (UWCS) are faced with challenges of poor signal, delayed communication, and high error rate due to complex underwater environment. UWCS are been

studied by various researchers from diverse areas of contributions, to reduce the poor signal quality [1]. The intricate relationship between underwater communication systems and water parameters has garnered increasing attention in recent research, underscoring the importance of these environmental factors [2]. Variations in salinity, temperature, pH, and TDS can significantly influence the propagation of signals and the overall effectiveness of communication technologies. These parameters not only affect sound speed and attenuation but also introduce challenges related to multipath propagation and signal distortion [3]. Understanding the extent of these variations is crucial for optimizing communication systems that can withstand environmental conditions [4]. This study focuses on the seasonal impacts of water parameter variations on signal transmission in UW environment using Nigerian Rivers as a case study, many researchers have conducted similar research but the geographical and climatic condition of the selected region is different from that of Nigeria, which can cause a major problem when such parameters were been used to model a communication system in Nigeria. The parameters from the selected river can be used as a benchmark value and the findings can give an insight to a better deployment of UWCS in underwater environments, a system which can withstand harsh condition for signal propagation. This analytical investigation aims to explore how these water parameters affect the reliability and efficiency of underwater communication, employing both theoretical models and empirical studies [5, 6]. Through this comprehensive examination, the research seeks to provide insights that will inform the design and implementation of more resilient underwater communication systems. Diverse communication technologies such as Electromagnetic waves (EM), Optical and Acoustic can be utilized for UWC [7]. The prototypes deployed for terrestrial networks cannot be functional in underwater environment owing to distinctive predictable hitches offered by underwater environs one of which is the parameter variations. The parameter affects each of the deployed technologies differently but collaboratively cause signal degradation in UWC [8].

1.1 Overview of Underwater Communication Systems and Their Importance

Effective underwater communication systems are essential for a range of applications, including military operations, environmental monitoring, and underwater exploration [9]. These systems face unique challenges due to the harsh environment, where factors like salinity, temperature, and turbidity can significantly impact signal propagation. Recent advancements have highlighted three main types of underwater communication waves: electromagnetic (EM), acoustic, and optical. Each has distinct advantages and disadvantages based on operational requirements and environmental conditions. For instance, while EM waves provide a higher data rate, they are particularly sensitive to seawater conductivity, as noted in [10]. Optical signals have the advantages of high transmission rates and low power consumption but suffer from short propagation distances, on the other hand, acoustic communication remains prevalent despite its limitations in bandwidth. An understanding of these variances is crucial, as they dictate the performance and reliability of underwater communication systems, thus underscoring their importance in advancing both technological solutions and scientific knowledge in underwater environments [11].

1.2 Key Water Parameters and Their Seasonal Variations

Seasons can cause variations in water parameters: such as salinity, temperature, pH, TDS and turbidity. These factors can be increased or decreased from one season to another, and this can inform the behavior of signal during each season and can in turns dictate the performance of UWCS. Parameters such as turbidity, Salinity and TDS are likely to get increased drastically during the rainy season due to run off surface, temperature and pH are slightly increased but within the range suitable for signal transmission. As indicated, seawaters' high conductivity can lead to substantial signal attenuation, challenging reliable data transmission. Notably, turbid conditions can further complicate communication efficacy, resulting in increased signal degradations which obstruct seamless signal retrieval and transmission. By understanding how these environmental variables interact and vary from one season to another, researchers can devise more robust communication system design and technologies tailored to optimal underwater signal propagation.

Underwater communication systems are significantly influenced by various water parameters, with salinity emerging as a critical factor. Variations in salinity can alter the density and sound speed of seawater, leading to changes in acoustic performance [3]. High salinity levels above 45‰ tend to increase sound speed, which can affect the propagation of signals and ultimately influence communication quality. Additionally, temperature plays an integral role in shaping signal characteristics, 1°C can increase sound speed to about 4m/s; warmer water can enhance signal transmission while colder temperatures may contribute to signal attenuation. These temperature-induced variations necessitate careful calibration of underwater communication devices to ensure reliable information transfer [10]. Furthermore, turbidity, characterized by the presence of suspended particles, can severely compromise visibility and signal clarity especially when it is above the threshold value of 150NTU, introducing noise that interferes with effective communication. Understanding these key parameters allows for the optimization of underwater systems, thereby improving their robustness and reliability in diverse aquatic environments [11].

1.3 Impact of Water Parameter Variations on Signal Propagation

Variations in water parameters such as salinity, temperature, and turbidity play a critical role in influencing signal propagation within underwater communication systems (UWCS) [8,10]. These variations directly affect the acoustic, optical, and electromagnetic properties of the water medium, thereby shaping signal range, fidelity, and transmission reliability. Understanding these environmental interactions is essential for designing and optimizing underwater systems that can operate efficiently in diverse aquatic conditions.

1.3.1 Types of Underwater Communication Systems (UWCS)

Underwater communication systems (UWCS) are designed to support data exchange between submerged devices, surface buoys, and offshore stations. They are widely applied in oceanographic monitoring, environmental sensing, and the control of unmanned underwater vehicles (UUVs). Generally, UWCS technologies are classified into three types: acoustic, optical, and electromagnetic (EM) systems. Acoustic communication remains the most prevalent method because sound waves travel efficiently through water over long distances. However, this approach suffers from limited bandwidth, long propagation delay, and multipath distortion due to the slow speed of sound underwater (approximately 1500 m/s). Optical communication, on the other hand, provides higher bandwidth and faster data transmission, but its performance degrades sharply in turbid or highly scattering waters. Electromagnetic communication offers short-range but high-data-rate connectivity; nevertheless, EM signals attenuate rapidly in conductive seawater, which restricts their effective range [9]. Recent innovations focus on hybrid communication models that integrate multiple techniques—such as acoustic–optical or acoustic–EM systems—to improve resilience against environmental variations. Such hybrid UWCS frameworks are particularly advantageous in tropical freshwater and coastal environments, where water quality parameters fluctuate seasonally. Their adaptability supports more stable communication for marine research, environmental management, and underwater surveillance [10].

1.3.2 Environmental Parameters Affecting Underwater Communication

The performance of UWCS is strongly influenced by the surrounding environmental parameters—notably salinity, temperature, and turbidity—which collectively determine sound velocity, signal attenuation, and propagation loss.

Salinity is a key determinant of water density and sound speed. Variations in salinity modify the refractive index and acoustic impedance of the medium, leading to changes in signal path and intensity. Studies show that salinity levels above 45 ‰ (parts per thousand) can increase the sound velocity, thereby affecting acoustic propagation and communication coverage [3]. Nevertheless, excessive salinity gradients can introduce impedance mismatches that degrade signal integrity. Continuous calibration of underwater transceivers is thus necessary to maintain transmission stability [8].

Temperature plays an equally important role. An increase of 1°C can raise the speed of sound in water by approximately 4 m/s [9]. Warm water enhances acoustic propagation efficiency, while cold water increases attenuation and scattering losses. These temperature-driven variations demand adaptive signal processing and calibration mechanisms to sustain consistent performance in variable thermal conditions [7].

Turbidity—the measure of suspended particulate concentration—affects both optical and acoustic systems. When turbidity exceeds 150 NTU, scattering and absorption significantly degrade signal strength, reduce the signal-to-noise ratio, and distort waveform integrity [11]. Such interference is common in estuarine and freshwater systems exposed to sediment runoff or organic matter. Hence, in turbid regions, optical systems often require acoustic backup channels to preserve data reliability.

In essence, the combined influence of salinity, temperature, and turbidity governs signal propagation characteristics. A holistic understanding of these parameters enables improved system design, error correction, and adaptive modulation strategies for robust underwater communication.

1.3.3 Knowledge Gaps in Tropical Freshwater Systems

Despite extensive global research on marine and deep-sea communication, knowledge gaps persist in tropical freshwater environments. Existing models predominantly target oceanic conditions characterized by relatively stable salinity and temperature, whereas tropical freshwater systems experience rapid and irregular changes in their physical and chemical properties [11]. This study focuses on Asejire Dam, Ede Dam, Niger River, and Eti-Osa River, which exhibit distinct environmental conditions. Asejire and Ede are located in cultivated agricultural zones; runoff during the rainy season introduces nutrients and chemicals that alter water conductivity, pH, and optical clarity. The Niger River, situated in a high-temperature zone, offers an ideal case to evaluate temperature-induced variations in signal speed and attenuation. Eti-Osa River, with comparatively higher salinity, serves as a contrasting site for assessing how salt concentration influences acoustic and electromagnetic communication. These site-specific differences emphasize the need for localized modeling and calibration of UWCS in tropical

regions. Unlike deep-sea environments, tropical freshwater systems are shallow, dynamic, and heavily influenced by seasonal rainfall and human activity. The lack of empirical data from such systems limits the development of accurate propagation models. Addressing this research gap will support the creation of adaptive communication frameworks tailored to the hydrographic variability of tropical freshwater ecosystems, particularly within West Africa [6, 7]. In summary, underwater communication performance is intricately linked to the physical and chemical properties of the aquatic environment. Variations in salinity, temperature, and turbidity alter the acoustic and optical pathways through which signals propagate, thus affecting transmission reliability and quality. Understanding these influences enables the development of robust UWCS capable of adapting to diverse and dynamic conditions. However, tropical freshwater systems remain underexplored, warranting focused research and field validation. The selection of rivers such as Asejire, Ede, Niger, and Eti-Osa provides a representative framework for investigating how environmental variability influences underwater communication efficiency in tropical contexts [3, 4, 6].

2. Materials and Methods

Study area: The study was carried out in five different locations with different water sample taken from each of the location during dry season between October- November 2023 and during raining season which range from June-August 2024.

Samples were taken with the respective longitude and latitudes: Niger River (N 8.050 Lat., E 6.770 Long.), Osun River (N 7.770 Lat., E 4.510 Long.), Asejire Dam (N 7.360 Lat., E 4.130 Long.), Ede dam (N 7.750 Lat., E 4.450 Long.) and Eti Osa River (N 6.480 Lat., E 3.5070 Long.)

2.1 Methodology for Environmental Parameter Evaluation

The methodology is structured to capture the spatiotemporal variability of selected parameters: salinity, temperature, TDS, pH and turbidity across representative freshwater and briny water environments [1, 2, 7]. A comparative experimental design was employed, combining quantitative field data with computational simulations to assess how variations in water properties affect signal behavior. The experimental setup was deployed across five distinct study sites Asejire Dam, Ede Dam, Niger River, Osun River and Eti-Osa River selected based on their differing hydrological and environmental characteristics. These sites provide a balanced representation of tropical freshwater and estuarine systems, characterized by seasonal and anthropogenic influences on water chemistry [10, 11].

The experimental design was developed in three stages:

1. On-site measurement of environmental parameter.
Real-time data collection was conducted at each site to record temperature, salinity, turbidity, pH, and electrical conductivity. Portable multi-parameter probes and acoustic sensors were used for on-site measurements, ensuring data consistency and reliability.
2. Controlled laboratory validation.
Water samples from each location were analyzed under controlled laboratory conditions to validate field readings and assess micro-scale variations affecting sound propagation. Controlled acoustic transmission experiments were performed using standard transducer pairs to evaluate the correlation between environmental variables and signal strength.
3. Simulation and modelling.
The empirical data collected were used to model acoustic propagation using MATLAB-based simulation frameworks. The Bellhop and URICK acoustic propagation models were implemented to evaluate path loss, attenuation, and delay spread under varying environmental inputs [9]. This multi-model approach provided comparative insights into the reliability of theoretical predictions against field measurements.

2.1.1 Data Collection Procedure

Field data were collected using a standardized protocol to minimize measurement inconsistencies across locations. Each parameter was measured at multiple depths (0.5 m, 1.5 m, and 3.0 m) to account for vertical stratification effects. Temporal variations were also recorded across three seasonal periods—pre-rainy, rainy, and post-rainy—to capture environmental fluctuations typical of tropical regions.

- Temperature (°C): Measured using calibrated digital thermometers with $\pm 0.1^\circ\text{C}$ accuracy.
- Salinity (ppt): Determined using a conductivity-salinity meter, with readings cross-validated using laboratory titration for chloride concentration [8].
- Turbidity (NTU): Assessed via a nephelometric turbidity meter. Threshold levels exceeding 150 NTU were identified as critical zones where optical scattering significantly affects communication [9].

- Conductivity ($\mu\text{S}/\text{cm}$): Recorded concurrently with salinity to assess ionic strength variations influencing electromagnetic signal attenuation.
- pH and Total Dissolved Solids (TDS): Supplementary indicators used to understand the physicochemical stability of the sampling sites.

Each dataset was recorded three times per location to ensure repeatability and reduce random error. The average values were subsequently analyzed for each parameter.

2.1.2 Signal Propagation Measurement

To evaluate the direct impact of environmental conditions on acoustic signal behavior, controlled transmission tests were conducted at each site. A signal generator emitted test pulses (10 kHz–50 kHz) through an underwater transducer. The received signals were recorded at distances ranging from 5 m to 50 m using a calibrated hydrophone array.

Measured variables included:

- Received Signal Strength (RSS): Captured using a digital oscilloscope and averaged over five consecutive trials.
- Signal-to-Noise Ratio (SNR): Computed from received signal data to quantify degradation caused by turbidity and temperature fluctuations.
- Path Loss (PL): Determined using the empirical relationship

$$PL(\text{dB}) = 10 \log_{10} \frac{P_t}{P_r} \quad (\text{Eq. 1})$$

where P_t is the transmitted power and P_r is the received power [3, 7].

- Attenuation Coefficient (α): Derived from the classical Thorp and Fisher equations to model frequency-dependent acoustic loss.

Data were analyzed to establish correlation patterns between environmental variations and the corresponding change in signal strength and delay. This enabled the identification of critical thresholds where parameter fluctuations begin to significantly impair communication quality.

2.1.3 Simulation Framework

The MATLAB simulation environment was employed to develop a predictive model of underwater acoustic performance under varying environmental conditions. The following sub modules were implemented:

- Sound Speed Calculation:
The empirical Mackenzie formula was used to determine sound velocity C as a function of temperature T , salinity S , and depth D :

$$c = (S\alpha - 35) (1.35 - 0.011T) + 0.0156D + 4.56T + 1450.0 + 0.00029T^3 - 0.056T^2 \quad (\text{Eq. 2})$$

This equation show how environmental parameter variations can alter/hinder propagation path [9].

- Path Loss Model:
Simulated path loss values were obtained by integrating both geometric spreading and absorption losses, given by:

$$PL(\text{dB}) = 20 \log_{10} + \alpha d \quad (\text{Eq. 3})$$

where α is the frequency dependent absorption coefficient and d is the transmission distance. [2]

- Performance Metrics Evaluation:
Statistical metrics including Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and R-squared (R^2) were employed to quantify the deviation between simulated and measured results. These performance indicators provided a robust basis for model validation [10].

2.1.4 Data Analysis and Validation

Post-collection, all datasets were processed using MATLAB and SPSS software. Descriptive and inferential analyses were carried out to examine correlations between water parameters and signal characteristics. The following analyses were conducted:

- Correlation Analysis: To identify the degree of association between salinity, temperature, turbidity, and acoustic performance.
- Regression Analysis: To model the predictive relationship between environmental parameters and communication efficiency.
- Comparative Simulation Analysis: To contrast field data with simulation outputs, thereby validating the accuracy of predictive models.

Model validation involved computing error metrics such as RMSE, MAE, and coefficient of determination (R^2). Results with RMSE values below 0.05 and R^2 above 0.90 were considered statistically acceptable for performance prediction accuracy. This methodology establishes a comprehensive framework for analyzing how environmental parameters affect underwater communication systems. By integrating empirical measurements, laboratory validation, and simulation modeling, it enables an in-depth understanding of the relationship between physical water properties and signal propagation behavior. The inclusion of diverse tropical freshwater and estuarine environments (Asejire, Ede, Niger, Osun and Eti-Osa) ensures that the study outcomes are regionally representative and scientifically reliable. The methodological approach thus provides a foundation for subsequent sections on results analysis and performance optimization strategies.

3. Result and Discussion

The result of the samples collected were analyzed from the laboratory and the values were recorded accordingly and the result from all samples were compared to the standard values required for each of the parameter to achieve a good communication via underwater. Six parameters were analyzed which are Temperature, Salinity, Turbidity, TDS, pH and Depth.

Each sample location is graphically analyzed based on the values of the parameters recorded and the result is as shown in Table 1 for raining season parameters and Table 2 shows dry season parameters. Figure 1 and 2 is the graphical representation of raining and dry season parameters respectively.

3.1.1 Analysis on Sample Collected During Rainy Season

The sample collected from different river during different season was analyzed in the laboratory and the following result was obtained.

Table 1 Analysis of samples collected during raining season

Parameters	Niger	Asejire	Ede	Osun	Eti Osa
Temp.(°c)	28	27	26	26	25
Salinity (%)	20	20	20	20	29
Turbidity (NTU)	191	41	155	160	200
TDS (mg/L)	30	100	120	110	30
pH	7.01	7.00	7.20	6.90	7.50
Depth (m)	100	24	20	20	66

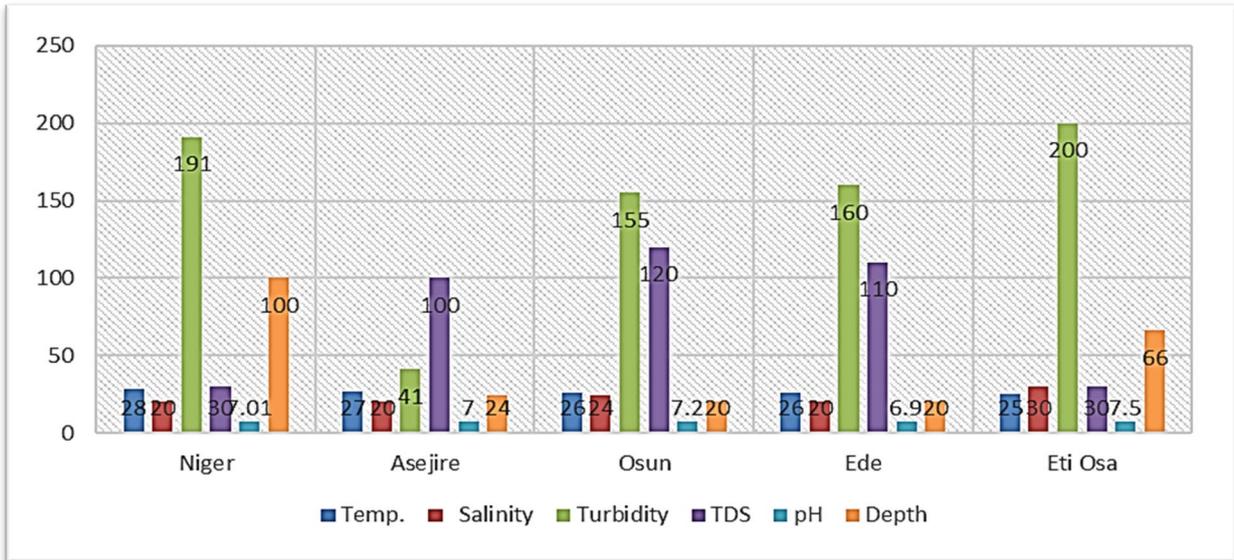


Fig. 1 Graphical representation of samples collected during raining season

Table 2 Analysis of samples collected during dry season

Parameters	Niger	Asejire	Ede	Osun	Eti Osa
Temp.(°c)	36	30	28	28	27
Salinity (%)	22	22	22	22	30
Turbidity (NTU)	140	30	100	110	150
TDS (mg/L)	25	70	80	85	20
pH	7.0	7.0	7.0	7.0	7.2
Depth (m)	100	24	20	20	66

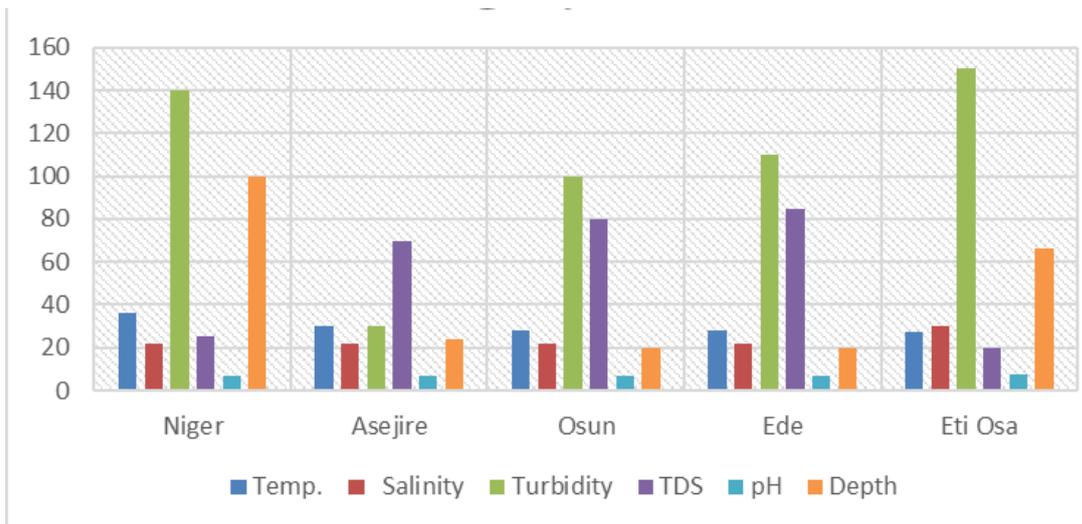


Fig. 2 Graphical representation of samples collected during dry season

The investigation into the impact of water parameter variations on underwater communication systems reveals significant insights into how environmental conditions influence communication efficacy. By analyzing samples from diverse locations, including Niger River, Asejire Dam, Ede Dam, Osun River, and Eti-Osa River, during both rainy and dry seasons, the study provides a comprehensive overview of key factors affecting signal propagation. These factors include temperature, salinity, turbidity, total dissolved solids (TDS), pH, and depth.

3.2 Findings

Note: when I quantify sound-speed sensitivity I use widely used practical rules of thumb: $\approx +4.0 \text{ m}\cdot\text{s}^{-1}$ per $+1^\circ\text{C}$ and $\approx +1.4 \text{ m}\cdot\text{s}^{-1}$ per $+1$ PSU salt, and pressure/depth effects $\approx +17 \text{ m}\cdot\text{s}^{-1}$ per 1,000 m (these rules are standard approximations used to estimate sound-speed changes). The analysis of water parameter variations reveals clear seasonal and spatial influences on underwater communication performance across sampled sites.

Temperature exhibits the most significant seasonal contrast, with dry season values up to 8°C higher than in the rainy season (e.g., Niger River: 36°C vs 28°C). Since sound speed in water increases by approximately $4 \text{ m}\cdot\text{s}^{-1}$ per $^\circ\text{C}$, this corresponds to an estimated rise of $32 \text{ m}\cdot\text{s}^{-1}$. Such variation meaningfully alters acoustic propagation paths, refraction, and Doppler effects. Hence, communication systems operating seasonally in these environments must recalibrate timing synchronization, equalization, and Doppler tracking to accommodate these dynamic sound-speed profiles.

Salinity differences, ranging from 20 PSU in inland waters to 30 PSU at Eti-Osa, also influence signal behavior. Each unit increase in salinity contributes roughly $1.4 \text{ m}\cdot\text{s}^{-1}$ to sound speed, meaning that Eti-Osa's elevated salinity could raise acoustic velocity by about $14 \text{ m}\cdot\text{s}^{-1}$ relative to inland sites. This variation affects acoustic ray bending and travel times, introducing modeling errors if uniform salinity assumptions are used. Additionally, higher salinity enhances conductivity, leading to greater attenuation of electromagnetic (EM) signals and minor increases in optical scattering. Consequently, saline environments demand acoustic-dominant communication systems and the inclusion of salinity data in channel calibration.

Turbidity demonstrates pronounced seasonal variation, with values exceeding 190 NTU during the rainy season in the Niger River and Eti-Osa. Since suspended particles primarily determine optical signal degradation, such levels severely restrict underwater optical wireless communication (UOWC) range and reliability. While acoustic propagation remains largely unaffected, optical links under these conditions are viable only over a few meters. Conversely, clearer waters at Asejire Dam (30–41 NTU) present moderate feasibility for short-range optical transmission.

Total Dissolved Solids (TDS) show localized increases in the rainy season (e.g., Ede: $80 \rightarrow 120 \text{ mg/L}$), which correlate with higher electrical conductivity. Elevated TDS increases EM attenuation and influences electrode impedance, posing challenges for near-field EM communication. For sites with TDS exceeding 100 mg/L , acoustic or hybrid wired links are recommended due to more stable transmission characteristics. Although TDS has limited acoustic impact at low frequencies, its correlation with ionic concentration may influence high-frequency absorption.

pH levels remain near neutral (6.9–7.5) with minimal variation, producing negligible immediate impact on acoustic or optical propagation. However, maintaining pH stability is vital for long-term sensor reliability and minimizing corrosion, drift, and fouling in transducers and optical instruments.

Depth remains largely constant across seasons, but it determines the propagation regime. Shallow sites (20–24 m) experience intense bottom reflections, stronger multipath, and greater temporal dispersion, requiring robust equalization in acoustic systems. Deeper sites like the Niger River (100 m) support longer propagation paths but exhibit thermocline-induced sound-speed gradients that vary seasonally.

In practice, site-specific communication strategies emerge. For the Niger River, high turbidity during the rainy season favors acoustic transmission, while dry-season temperature elevation necessitates updated timing and Doppler compensation. Asejire Dam's moderate depth and relatively low turbidity allow both optical and acoustic links depending on range. At Ede and Osun, higher TDS and moderate turbidity support short-range optical bursts only during clearer periods; otherwise, acoustic systems dominate. Eti-Osa's high salinity and turbidity severely limit optical and EM methods, making acoustics the only reliable approach. Overall, underwater communication system design must dynamically integrate temperature, salinity, and turbidity data into adaptive channel models to sustain performance across variable aquatic environments.

4. Conclusion

This study investigated how seasonal shifts in temperature, salinity, turbidity, TDS, pH, and depth affect underwater communication in Nigeria's freshwater systems. Results show that seasonal changes strongly impact signal strength, propagation, and reliability, for instance high turbidity $>150\text{NTU}$ and salinity $>25\%$ can affect signal propagation. Limited real-time and long-term data constrain accurate environmental modeling, as most findings stem from short-term laboratory analyses. Nonetheless, the research provides valuable insights for designing adaptive systems suited to local water conditions. Future efforts should emphasize continuous field monitoring, advanced modeling, and collaboration among researchers, technologists, and agencies to build reliable datasets, such coordinated approaches will enhance underwater networks for environmental management, hydro-surveying, and national security in Nigeria's aquatic environments. Building on these results, future studies should: Explore the interaction between multiple parameters (e.g., the combined effects of temperature and turbidity) to understand synergistic impacts on signal quality, Extend the research to include optical and acoustic communication systems, comparing their resilience to environmental changes, and

Investigate innovative materials and technologies, such as bio-inspired designs, to improve signal propagation under challenging conditions.

Recommendations

This study recommends collaboration among researchers, engineers, and agencies to enhance data sharing and modeling, and to integrate machine learning or hybrid communication methods that will improve system reliability, supporting environmental monitoring, resource management, and national security.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Adeagbo and Lasisi; **data collection:** Adeagbo, Aderinkola and Asafa; **analysis and interpretation of results:** Adeagbo, Moses and Alawode; **draft manuscript preparation:** Awofolaju and Olawuyi. All authors reviewed the results and approved the final version of the manuscript.

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