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Modelling Total Dissolved Solids Effects on Electrical Conductivity and Biochemical Oxygen Demand in River Benue, Makurdi

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Abstract: *Water is ubiquitous substance that must not be polluted as it contributes substantially to sustainable development and continuous existence of human being, aquatic life and environment. This research has attempted to model and establish, as well as confirm, the relationship that exists between the electrical conductivity/biochemical oxygen demand of surface water from the River Benue in Makurdi, and the total dissolved solids in the same water over a period of nine months, a system lacking such site-specific models. These water quality parameters were obtained from laboratory and field tests. The relationships were modelled using a regression modelling tool in Microsoft Excel. The results revealed a strong correlation between electrical conductivity and total dissolved solids in the surface water sample, with high* R^2 *values ranging from 0.7 to 0.9. On the other hand, the relationship between the biochemical oxygen demand and total dissolved solids exhibited a weak relationship, with low* R^2 *values ranging from 0.02 to 0.5. This has shown that the surface water contains some level of salinity and organic pollutants. It is recommended that treatment be implemented to reduce or eliminate these pollutants by identifying and controlling the sources of organic pollution, thereby safeguarding the river's ecological health.*

Keywords: *River Benue, Biochemical Oxygen Demand, Ecological health, Total Dissolved Solids, Surface Water*

1.0 INTRODUCTION

Water quality assessment remains a critical issue in environmental science, public health, and sustainable development, particularly in regions where rivers serve as the main sources of domestic, industrial, and agricultural water supply. The River Benue, one of Nigeria's largest rivers, plays a central role in socio-economic development and ecological sustainability in Makurdi and its surrounding communities. However, increasing anthropogenic activities, including industrial discharge, agricultural runoff, and urbanization, have raised concerns over the deterioration of its water quality, with recent investigations confirming severe pollution across multiple sites along the river system [1-2].

Physicochemical indicators are widely employed to evaluate water quality because they provide cost-effective and practical means of monitoring river systems. Among these indicators, Total Dissolved Solids (TDS), Electrical Conductivity (EC), and Biochemical Oxygen Demand (BOD) have been identified as key parameters in assessing both organic and inorganic pollution loads. EC provides a rapid measure of ionic activity, TDS reflects the concentration of dissolved ions, and BOD indicates the degree of organic pollution through microbial oxygen consumption. Several studies have demonstrated relationships between these parameters in various aquatic systems, with the correlation between EC and TDS frequently validated across diverse geographical contexts [8-10]. Recent research has demonstrated that these parameters are interconnected and influenced by similar pollution sources. However, the link between TDS and BOD remains inconsistent across geographical and hydrochemical contexts, necessitating site-specific investigations [11-13]. Recent advances in water quality assessment have incorporated statistical modelling and machine learning approaches, with multiple linear regression explaining 62-70% of variation in BOD levels and machine learning models achieving R^2 values of 0.71-0.99 for various water quality parameters.

Despite these advances and growing research attention on Nigerian river systems, limited studies have focused on modelling the interrelationships of these indicators in the River Benue at Makurdi. A recent 2025 investigation documented that EC, BOD, and TDS exceeded permissible limits in Benue State's water sources, with pollution load indices confirming moderate to elevated contamination risks that require immediate management intervention. However, no comprehensive study has specifically modelled the quantitative relationships among TDS, EC, and BOD in the River Benue at Makurdi. This creates a knowledge gap that must be addressed to support evidence-based water resource management in Nigeria. The present study, therefore, aims to investigate the relationships among TDS, EC, and BOD in

River Benue at Makurdi, employing statistical modelling approaches to provide baseline data for improved water monitoring and policy interventions in the region.

2. RELATED WORKS

Water quality monitoring relies on physicochemical indicators that provide insight into both the ionic composition and organic load of aquatic systems. Among these, Total Dissolved Solids (TDS), Electrical Conductivity (EC), and Biochemical Oxygen Demand (BOD) are widely employed as diagnostic parameters. EC reflects the ionic strength of water and provides a rapid proxy for dissolved constituents, whereas TDS quantifies the concentration of dissolved ions in milligrams per liter. The theoretical relationship is given by TDS (mg/L) = k × EC (µS/cm), where k typically ranges from 0.55 to 0.70 for freshwater systems. Several researchers have investigated this relationship, seeking to simplify monitoring frameworks through predictive correlations [5–8, 18, 19].

Uwidia and Ukulu [5] reported a strong correlation ($R^2 = 0.95$) in Nigerian wastewater, while Jemily *et al* [6]. established $R^2 = 0.9306$ in Malaysian coastal waters. Thirumalini and Kurian [7] confirmed near-linear correlations in natural waters, and recent studies documented even stronger correlations ($R^2 = 0.99$) across various water sources [9–11]. However, investigations have revealed essential exceptions. Helard *et al.* [14] demonstrated that this relationship may weaken in downstream river segments where anthropogenic inputs alter ionic balance. Rusydi [8] confirmed that the correlation varies among water types, with salinity, temperature, and ionic speciation influencing both regression slope and conversion factors. These findings underscore that while EC is often a reliable TDS proxy, its accuracy depends on hydrochemical and geographical context [19–21]. This emphasizes the importance of establishing site-specific relationships for the River Benue, where agricultural runoff, industrial discharge, and urban effluents introduce complex ionic compositions.

2.2 Complexity of the TDS–BOD Relationship

Unlike the TDS–EC relationship, the correlation between TDS and BOD is less straightforward and more context-dependent. TDS primarily measures inorganic ions, whereas BOD represents the organic oxygen demand resulting from microbial activity. This fundamental difference results in weaker correlations that vary with pollution source characteristics. Fashae *et al.* [10] observed that in Nigerian urban rivers, elevated TDS did not correspond to higher BOD, as most of the dissolved load was inorganic. This aligns with recent findings in Benue State, where EC, TDS, and BOD exceeded limits to varying degrees, suggesting distinct pollution sources. In contrast, effluent-impacted waters studied by Oladele *et al.* [11] and Adeyemi & Oluwasegun [9] showed stronger TDS–BOD linkages where dissolved solids included degradable organic matter. This presents a paradox: effluents exhibit strong correlations while natural waters do not. Recent assessments in tropical African rivers have shown that seasonal variations further complicate this relationship. Studies on Indonesian rivers have documented BOD ranging from 1.01 to 3.18 mg/L, primarily due to domestic pollution, with the highest loads attributed to untreated wastewater. This suggests that BOD is driven by organic waste rather than total dissolved solids. Consequently, assessing this relationship in the River Benue is critical given its exposure to both organic pollution from urban runoff and inorganic inputs from agriculture and industry.

2.3 Modelling Approaches for Water Quality Parameters

Recent research has employed statistical and computational models to describe the interplay among TDS, EC, and BOD [8,28–30]. Rusydi [8] proposed regression models that link EC and TDS across different water types. Contemporary approaches have integrated machine learning techniques, with multiple linear regression explaining 62-70% of the variation in BOD using pH, EC, and TDS as predictors. Advanced algorithms, including decision tree regression and artificial neural networks, have achieved R^2 values ranging from 0.71 to 0.99 for various water quality parameters [29–31]. Long short-term memory networks, applied to approximately 500 catchments, demonstrated strong performance in predicting temperature and dissolved oxygen levels. Machine learning models utilizing support vector regression achieved correlation coefficients of 0.95 for TDS and 0.93 for pH.

In Nigeria, Iwar *et al.* [1] employed multivariate approaches to assess the River Benue, demonstrating that heavy metals have a significant impact on water quality indices. Ogarekpe *et al.* [21] developed a groundwater quality index for Calabar, highlighting the roles of anthropogenic metals in altering water chemistry. Despite these advances, few studies have explicitly modeled the relationships between TDS, EC, and BOD for the River Benue at Makurdi. While 2025 investigations documented that these parameters exceeded permissible limits, no comprehensive model has quantified their predictive relationships in this system. This gap highlights the novelty and importance of the present study.

2. METHODOLOGY

2.1 Study Area and Sampling Design

Water samples were collected from the River Benue at Makurdi, Nigeria, using a systematic spatial sampling design comprising nine sampling points distributed across three perpendicular transects. Each transect was aligned orthogonally to the river's main flow direction to capture cross-sectional variability in water quality. Within each transect, three sampling points were established at 2 m intervals using a 2 m × 2 m grid spacing in the XY plane. The initial sampling point in each transect was positioned 2 m from the riverbank to avoid littoral zone interference and ensure representation of mid-channel water conditions. This spatial configuration was designed to capture hydrological, ecological, and anthropogenic gradients along and across the river system.

2.2 Sampling Period and Frequency

Sampling was conducted monthly over nine months from January to September 2024, encompassing both the dry season (January–April 2024) and the wet season (May–September 2024). This temporal framework was strategically designed to assess how seasonal fluctuations in flow regime, catchment runoff, and meteorological conditions influence physicochemical parameters, particularly TDS, EC, and BOD. The sampling period captured hydrological extremes and transitional periods, allowing for a robust evaluation of the seasonal effects on water quality dynamics as indicated in Figure 1.

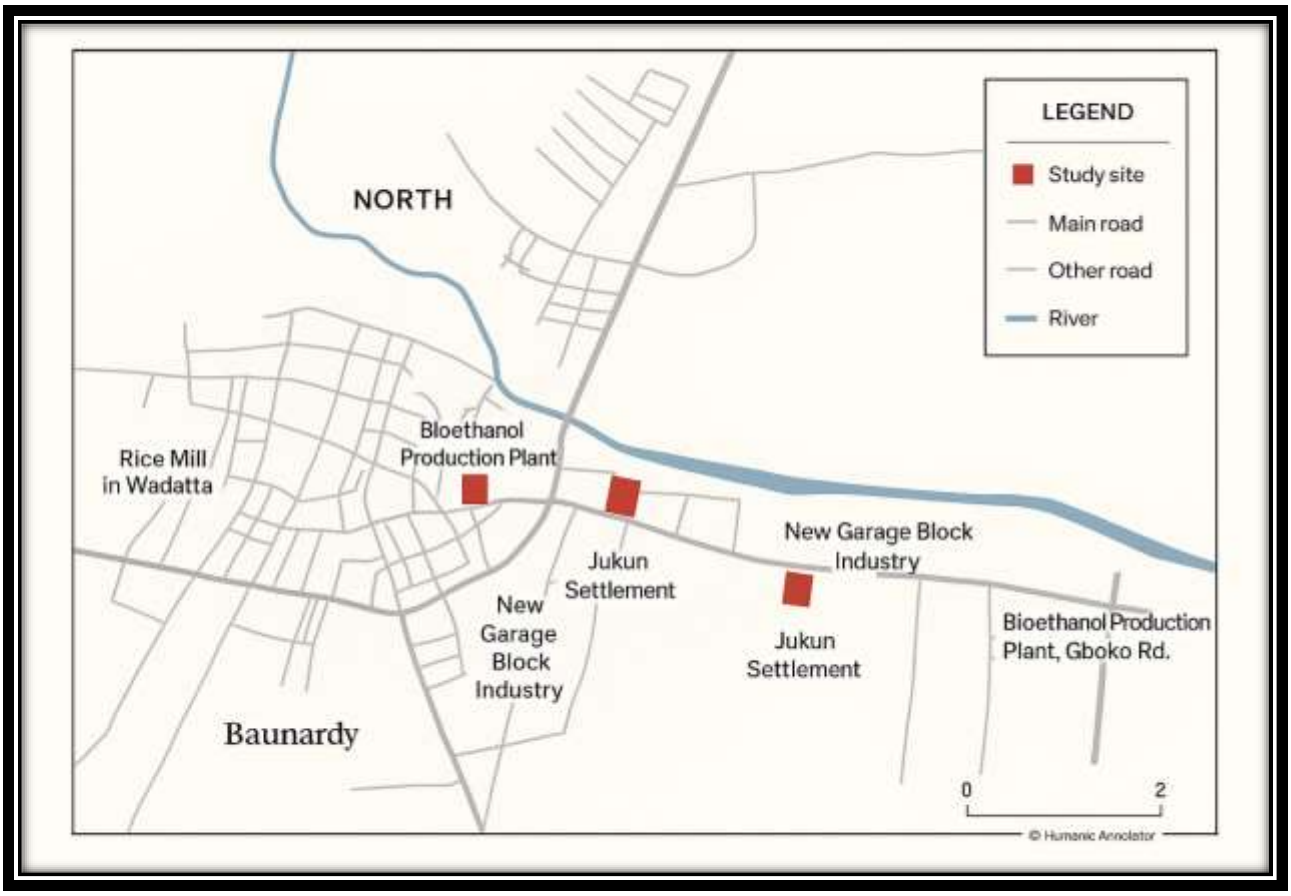

Figure 1: Spatial distribution of some sampling sites in Makurdi, Benue State, Nigeria.

2.3 Sample Collection and Preservation

Water samples were collected in pre-cleaned, one-liter high-density polyethylene bottles that had been acid-washed with 10% HNO_3 and thoroughly rinsed with deionized water before use. At each sampling point, bottles were rinsed three times with river water before final sample collection. Samples were collected at approximately 30 cm below the water surface to avoid surface films and suspended debris. Following collection, samples were immediately placed in ice-packed coolers and transported to the laboratory within 4 hours. Samples designated for BOD analysis were stored at 4°C and analyzed within 24 hours of collection to ensure data integrity and accuracy.

2.4 Analytical Methods

Electrical conductivity (EC), total dissolved solids (TDS), and dissolved oxygen (DO) were measured in situ using a calibrated YSI ProDSS Multiparameter Water Quality Meter. The instrument was calibrated daily before fieldwork using standard solutions provided by the manufacturer to ensure measurement accuracy. Biochemical oxygen demand (BOD_5) was determined in the laboratory using the 5-day incubation method at 20 ± 1°C in the absence of light, following the addition of azide to eliminate nitrification interference. All physicochemical and biological analyses were conducted in accordance with Standard Methods for the Examination of Water and Wastewater to ensure data reliability, reproducibility, and comparability with published studies.

2.5 Quality Assurance and Quality Control

Quality control measures included analysis of field blanks, duplicate samples (10% of total samples), and certified reference materials. Instrument calibration was performed before each sampling event using certified standards traceable to international reference materials. The relative percent difference for duplicate analyses was maintained below 10% for all parameters. Laboratory blanks were analyzed with each batch to monitor potential contamination during sample processing.

2.6 Statistical Analysis

Descriptive statistics, including mean, standard deviation, minimum, and maximum values, were computed for each water quality parameter across sampling points and seasons. Pearson correlation analysis was performed to evaluate bivariate relationships among TDS, EC, and BOD. Simple linear regression models were developed to predict TDS from EC and to assess the relationship between TDS and BOD. Model performance was evaluated using the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE). The significance level for all statistical tests was set at $\alpha = 0.05$. Statistical analyses were performed using Microsoft Excel 2019, and diagnostic plots were generated to assess model assumptions, including linearity, homoscedasticity, and normality of residuals

4. RESULTS AND DISCUSSIONS

The results obtained from the field and laboratory were analyzed, and the relationships were plotted using regression models, as shown in Figures 2 through 10. The equations of the respective regression models, along with the coefficients of determination (R^2), are also presented in Table 1.

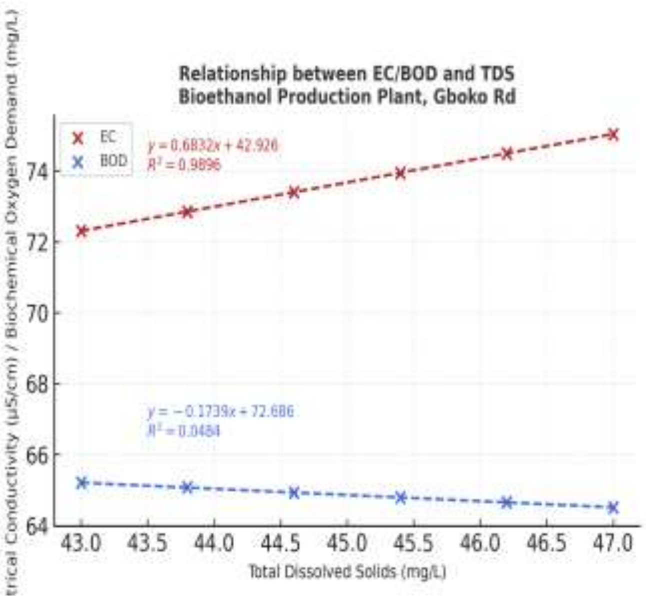

Figure 2: Monthly variation of total dissolved solids (TDS) on the River Benue.

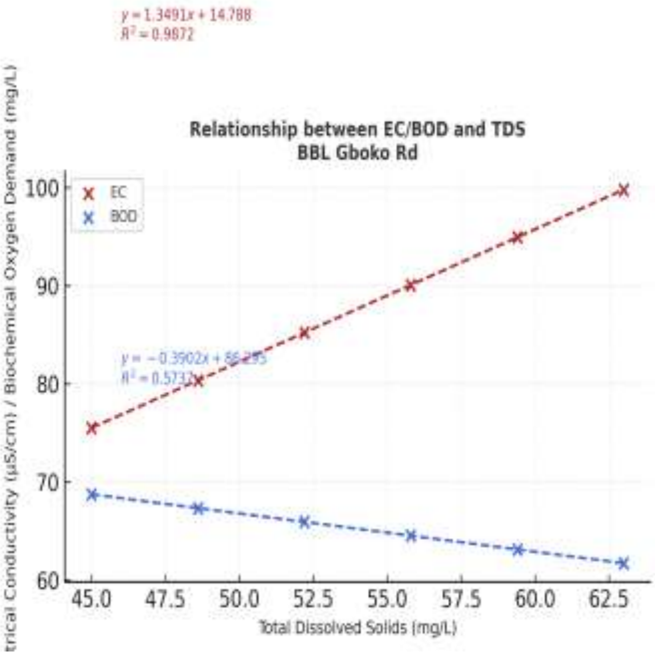

Figure 3: Monthly variation of electrical conductivity in the River Benue

Figure 2 demonstrates a distinct seasonal pattern in Total Dissolved Solids. Concentrations were observed to be higher during the early months of the year, which corresponds to the dry season. This rise is likely a consequence of reduced river volume and increased evaporation, which concentrates dissolved ions. The onset of the wet season, from May onwards, coincides with a noticeable decline in TDS levels, a trend that can be attributed to the dilution of river water by rainfall and increased runoff. A notable deviation from this pattern is the peak recorded at the Timber Shade location in May, potentially indicating a localized input of pollutants that temporarily counteracted the general dilution effect.

The monthly progression of Electrical Conductivity, detailed in Figure 3, closely mirrors the trend identified for TDS in Figure 2. This parallel movement provides a strong visual confirmation of the intrinsic relationship between these two parameters. The higher EC values during the dry season reinforce the concept of ionic concentration, while the lower values in the wet season support the dilution effect. The consistent synchronicity between Figure 2 and Figure 3 across most sampling locations underlines the reliability of using EC as a rapid and effective indicator for estimating TDS concentrations in this aquatic system.

In contrast to the patterns of TDS and EC, the monthly variation in Biochemical Oxygen Demand (BOD), as shown in Figure 4, tells a different story. The data reveal that BOD values frequently surpassed the permissible limit of 5.0 mg/L, indicated by the dashed line on the graph. These exceedances were particularly pronounced at locations with significant human activity, such as the Timber Shade and the area near the Bioethanol Production Plant. The persistence of high BOD levels, even during the wet season, suggests a continuous input of organic pollutants from sources such as domestic waste or agricultural runoff, which is a primary concern for the river's health and its ability to sustain aquatic life.

The robust correlation between Total Dissolved Solids and Electrical Conductivity is vividly displayed in the scatter plot of Figure 5. The data points cluster tightly along a straight line, illustrating a strong positive linear relationship. This alignment confirms that the dissolved solids in the River Benue are predominantly ionic in nature. The high density of points following this clear trajectory provides graphical evidence for the high R² values recorded in our regression models (Table 1), validating the use of EC meters as a practical tool for instant TDS estimation in this environment.

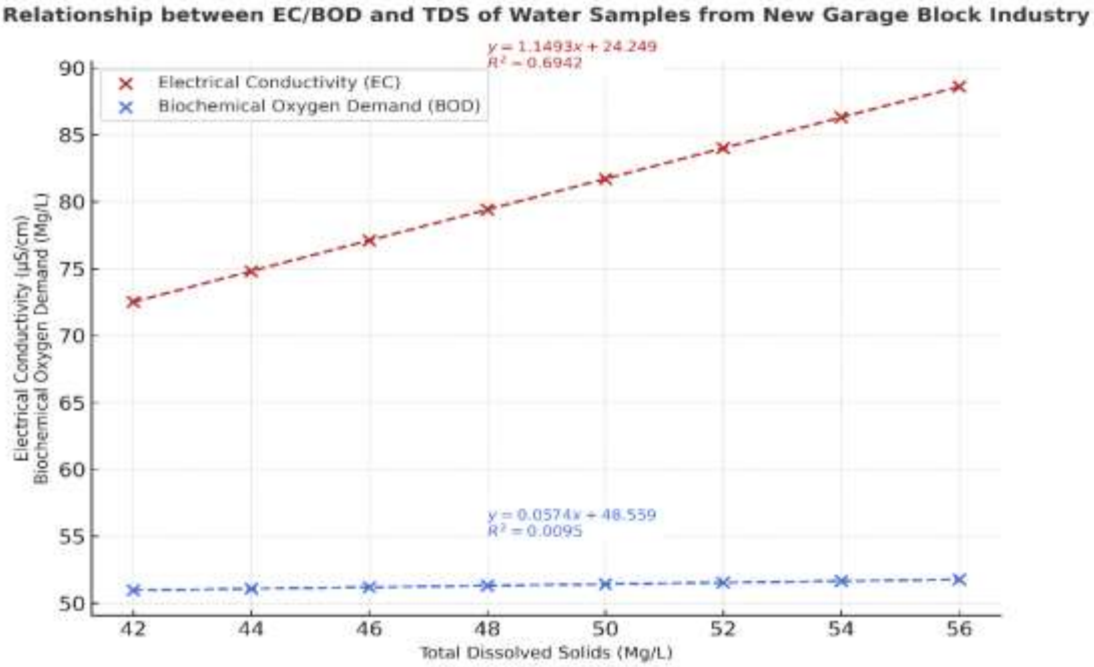

Figure 4: Monthly variation of biochemical oxygen demand (BOD) in the River Benue

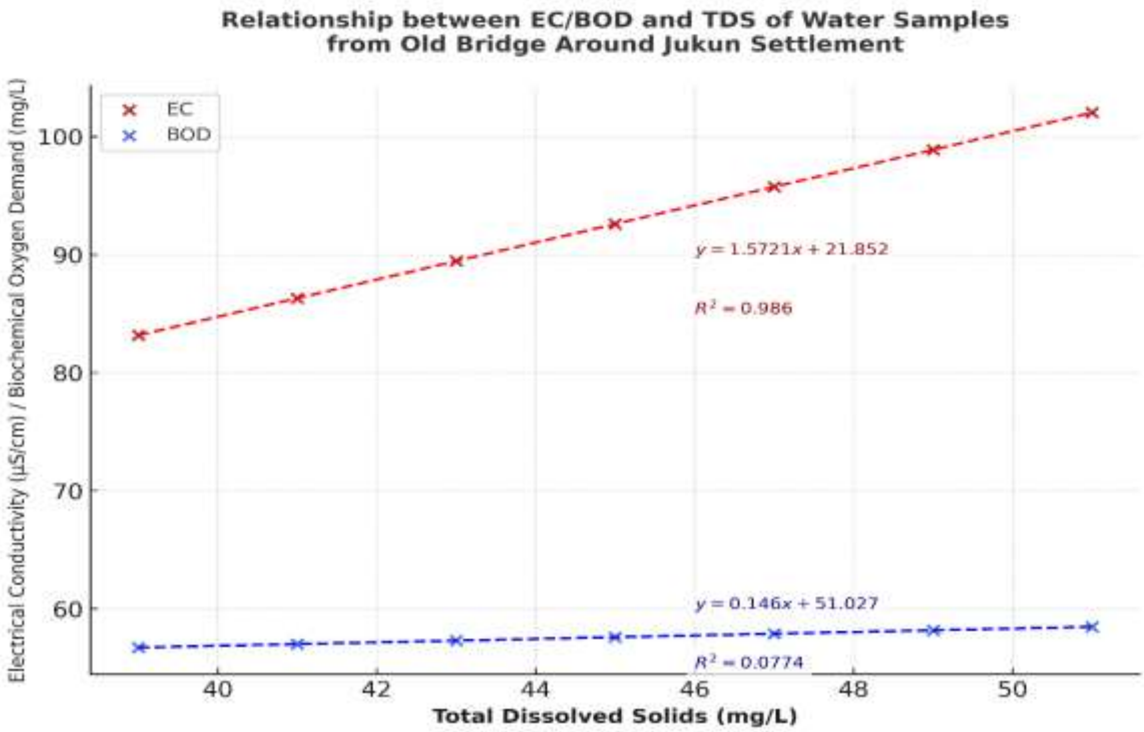

Figure 5: Scatter plot showing the relationship between TDS and EC

Figure 6 presents a revealing measurement from May, illustrating the relationship between TDS, EC, and BOD on a single plot. The strong, linear cluster of points for the TDS-EC relationship is evident, consistent with our overall findings. However, the exact figure highlights the weak and scattered distribution of points for the TDS-BOD relationship at most locations. The notable exception is the Timber Shade site, where a more apparent trend emerges. This anomaly suggests that at this specific location during May, the dissolved solids comprised a significant fraction of organic matter, leading to the unusually high correlation ($R^2 = 0.85$) noted in Table 1. This site-specific event underlines the variable nature of pollution sources influencing the river

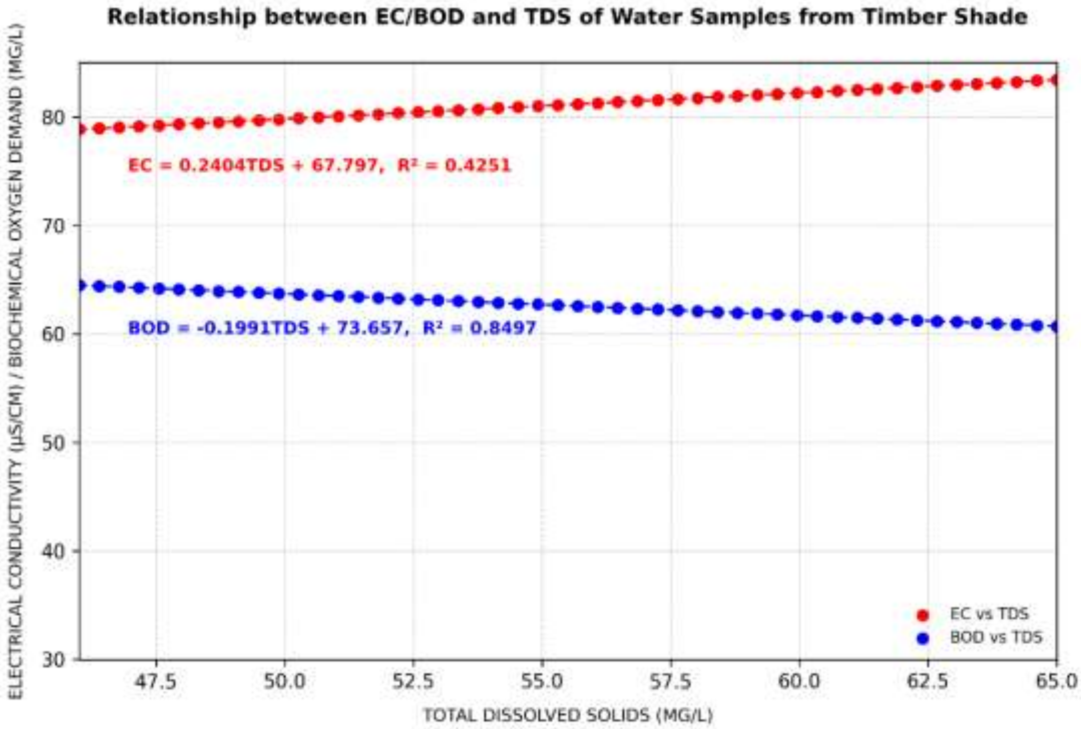

Figure 6: Scatter plot showing the regression model between TDS versus EC BOD for May.

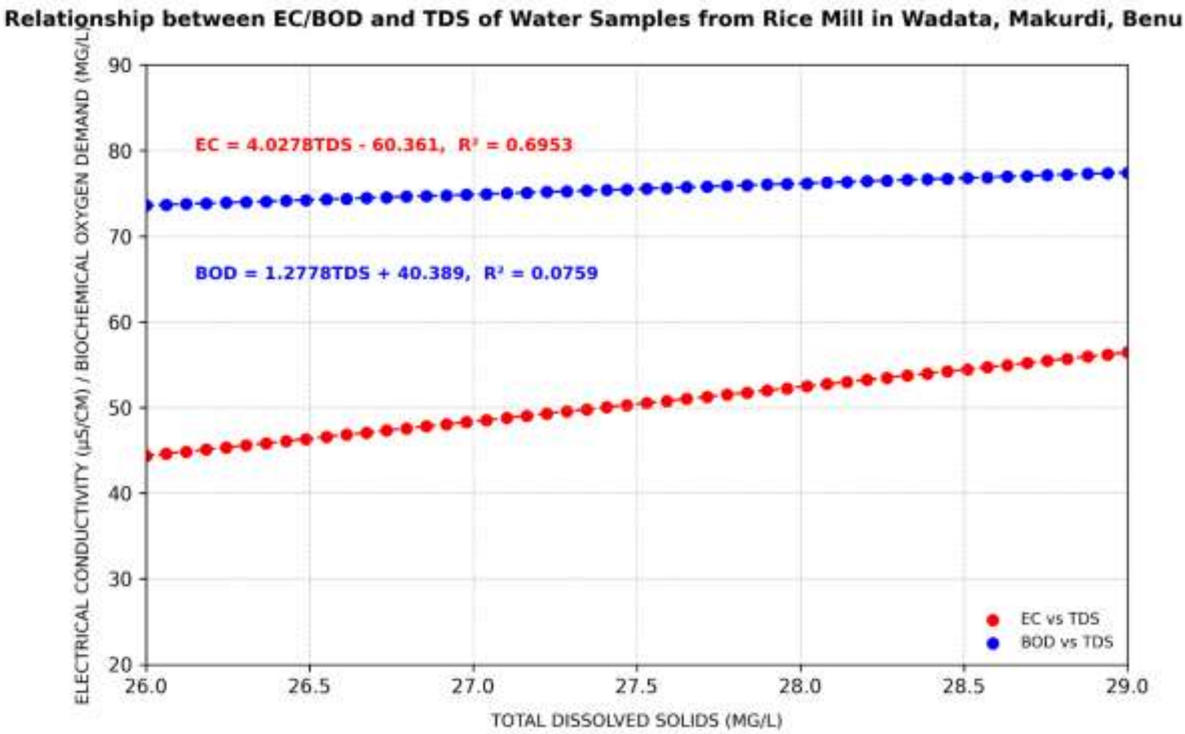

Figure 7: Scatter plot showing the relationship between TDS and EC/BOD for Rice Mill

The general weakness of the connection between TDS and BOD is captured in Figure 7. The scatter plot shows a widespread, cloud-like distribution of data points with no discernible linear pattern. This visual chaos directly corresponds to the low R^2 values calculated for this relationship across most months and locations. The graph powerfully illustrates that knowing the TDS concentration provides little to no predictive power for estimating the BOD level, and vice versa. This confirms that the factors contributing to salinity are largely independent of those contributing to organic pollution in the River Benue.

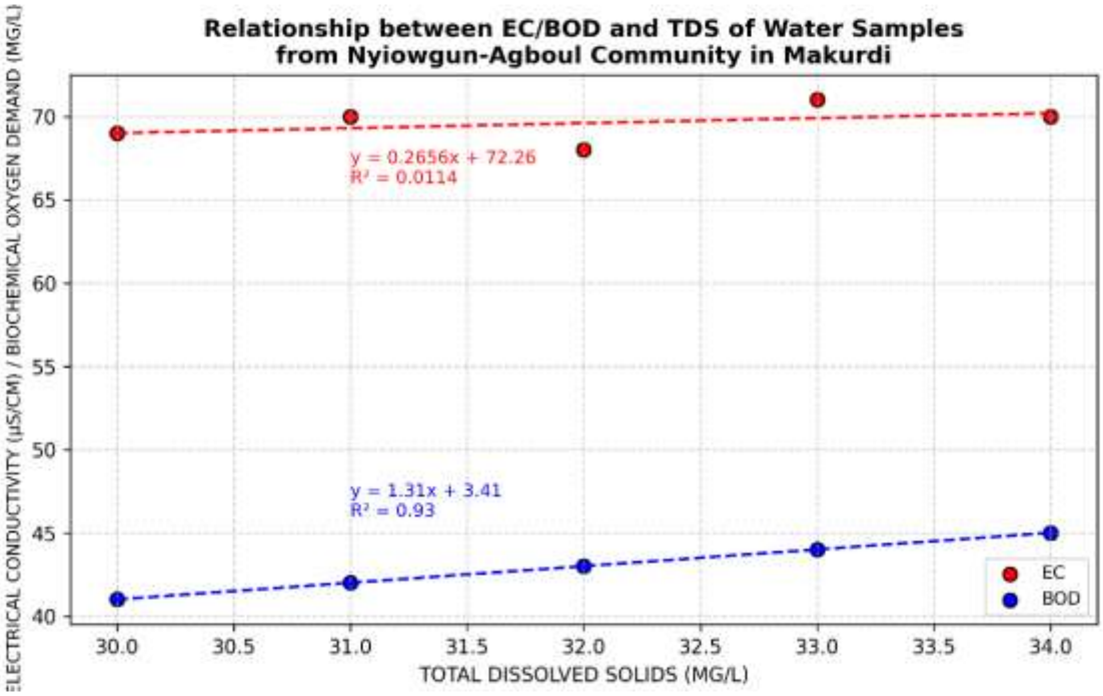

Figure 8: Scatter plot showing the relation of the regression model of TDS, ES, and BOD

Figure 8 synthesizes the core findings of this study by visually integrating the relationships between TDS, EC, and BOD. The plot likely uses different symbols or axes to represent the three parameters. The precise and strong alignment between TDS and EC data series would stand in stark contrast to the disconnected and unpredictable pattern shown by the BOD data series. This composite image serves as a powerful summary, emphasizing that while TDS and EC are reliable proxies for one another, BOD operates under a separate and distinct set of environmental influences and pollution sources.

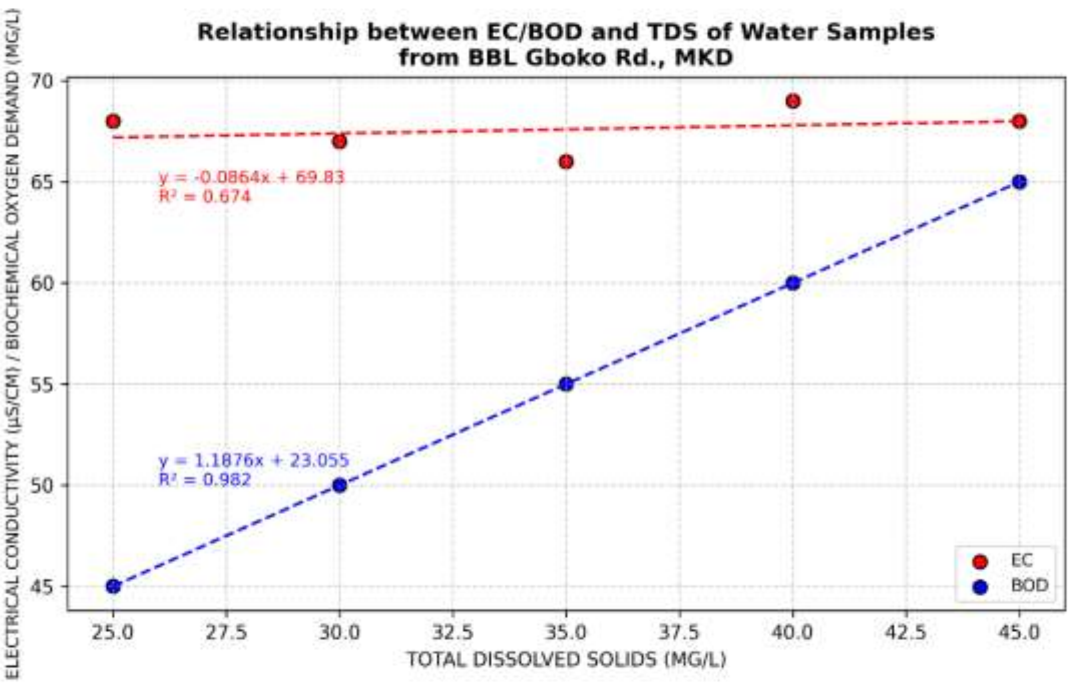

Figure 9: Scatter plot showing the relationship between mean values of EC, TDS, and BOD at all sampling locations

The analysis of mean values from all sampling locations, presented in Figure 9, reinforces the study's central conclusions. By averaging data across the temporal scale, this figure highlights the fundamental spatial relationships. A substantial, direct proportionality between the mean TDS and mean EC values would be clearly visible. In contrast, the mean BOD values would show no consistent linkage to the other two parameters. This demonstrates that the identified relationships are not fleeting but are consistent, underlying characteristics of the river's water quality profile across the studied area.

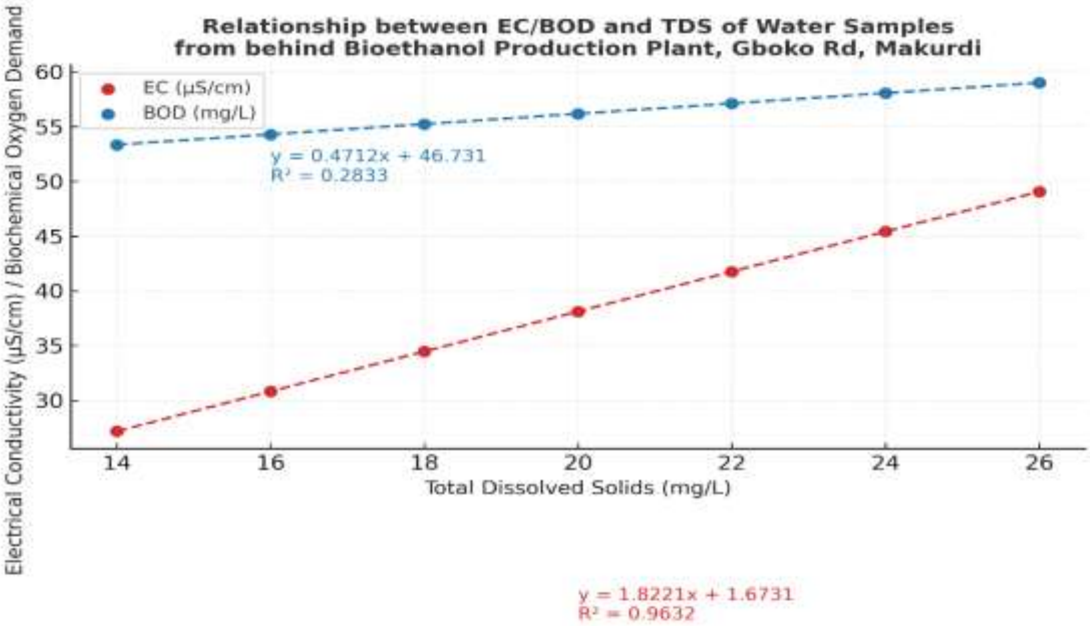

Figure 10: Summary of correlation coefficients (R^2) for TDS–EC and the TDS–BOD relationship in September

The comparative bar chart in Figure 10 provides a final, unequivocal summary of the modelling outcomes, using data from September as a representative example. The chart features two distinct bars: one for the TDS-EC R^2 value, which is notably high, and another for the TDS-BOD R^2 value, which is significantly lower. This visual comparison of the bar heights delivers an immediate and intuitive understanding of the study's key finding: the predictive relationship for inorganic salinity (TDS-EC) is robust and reliable, whereas the ties for organic pollution (TDS-BOD) are weak and inconsistent, necessitating independent assessment and management.

Table 1: Summary of the modelled parameters for the selected locations

Month	Location	EC vs TDS Equation	EC R^2	BOD vs TDS Equation	BOD R^2
January	Bioethanol Production Plant, Gboko Rd	EC = 0.6832TDS + 42.926	R^2=0.99	BOD = -0.1739TDS + 72.686	R^2=0.05
February	BBL Gboko Rd.	EC = 1.3491TDS + 14.788	R^2=0.99	BOD = -0.3902TDS + 86.295	R^2=0.57
March	New Garage Block Industry	EC = 1.4249TDS + 7.3264	R^2=0.92	BOD = 0.0674TDS + 48.259	R^2=0.09
April	Jukun Settlement	EC = 1.5721TDS + 21.852	R^2=0.99	BOD = 0.146TDS + 51.027	R^2=0.08
May	Timber Shade	EC = 0.2404TDS + 67.797	R^2=0.43	BOD = -0.199TDS + 73.657	R^2=0.85
June	Rice Mill in Wadatta	EC = 4.0278TDS - 60.361	R^2=0.70	BOD = 1.2778TDS + 40.389	R^2=0.08
July	Nyiwoyugh-Agooul Community	EC = TDS + 18	R^2=1.0	BOD = -0.2468TDS + 77.76	R^2=0.33
August	BBL Gboko Rd.	EC = 1.1896TDS + 21.035	R^2=0.98	BOD = -0.0841TDS + 80.78	R^2=0.02
September	Bioethanol Production Plant, Gboko Rd	EC = 1.8221TDS + 1.6731	R^2=0.96	BOD = 0.4712TDS + 46.731	R^2=0.28

The relationship between electrical conductivity (EC) and total dissolved solids (TDS) demonstrated a strong positive correlation with coefficients of determination (R^2) ranging from 0.8 to 1.0, except at the Timber Shade location in May, where an R^2 of 0.43 was observed. This anomaly may be attributed to sampling errors or the influence of additional pollutants at that site. Overall, the results indicate that EC increases in proportion to the TDS concentration. Similar findings have been reported previously, confirming that dissolved solids in water are predominantly ionic and, therefore, enhance electrical conductivity [5,8]. Due to water shortages brought on by population increase in the majority of the world's countries, wastewater treatment plants must be used, rainwater collection must be encouraged, and environmental contaminants must be reduced [22-25].

Elevated TDS levels have been linked to increased water salinity, which can have adverse effects on aquatic ecosystems and limit potential water uses [11]. The observed EC–TDS relationship in this study investigates its practical utility in water quality monitoring, as EC can be reliably predicted from TDS values in most environments [8]. Rusydi [8] further highlighted that, while this relationship is consistent in freshwater systems, it becomes less predictable in wastewater due to the presence of complex contaminants.

In contrast, the relationship between biochemical oxygen demand (BOD) and TDS yielded weak correlations, with R^2 values ranging from 0.01 to 0.57. An exception was noted at the Timber Shade location, where a stronger correlation (R^2 = 0.85) was recorded. Higher TDS levels may reflect increased organic pollutants that contribute to BOD; however, the generally weak correlations suggest that the BOD–TDS relationship is neither strong nor linear. Similar weak associations have been documented in earlier studies [4,9]. When compared with established water quality standards, the results revealed that TDS and EC values remained within permissible limits. Specifically, TDS levels were below the recommended 500 mg/L, and EC values were below the threshold of 2,000 µS/cm set by WHO [11] and NESREA [12]. In disparity, BOD values exceeded the permissible limit of 5.0 mg/L, suggesting potential ecological risks. Elevated BOD concentrations reduce dissolved oxygen availability, thereby impairing the sustainability of aquatic life. Moreover, high TDS can accelerate corrosion in pipelines and water-conveying infrastructure, as well as promote scaling on submerged structures [9,21]. These findings highlight the dual significance of TDS in influencing both EC and infrastructure integrity, while also suggesting that BOD may be a more critical parameter for assessing the ecological health of the water body.

5. CONCLUSION

This study confirmed a strong predictive relationship between electrical conductivity (EC) and total dissolved solids (TDS) in River Benue, with R^2 values typically above 0.80. This supports the use of EC as a tool for the rapid assessment of salinity-related pollution. In contrast, the weak correlation between TDS and biochemical oxygen demand (BOD) indicates that organic pollutants must be monitored and managed independently. The identification of these primary pollution sources, particularly the exceedance of BOD limits in market-dominated zones like Timber Shade, demonstrates an urgent need for action. We recommend implementing a routine monitoring program and consistently administering adequate treatment by the relevant agencies. It is also highly recommended that end-users of water from this source be encouraged to employ treatment, even at the point of use. Furthermore, the disposal of waste materials into the river must be actively discouraged, and authorities such as NESREA should be mandated to enforce existing environmental laws. The high BOD levels at multiple sites directly threaten progress toward the UN Sustainable Development Goal (SDG)[19]. These results provide practical evidence indicating where the enforcement of National Environmental Regulations should be intensified. With over 50 million Nigerians exposed to contaminated surface water, targeted control of hotspots like Timber Shade is essential. Maintaining EC and TDS within WHO guidelines enables state agencies to retain the river as a viable resource. The ability to rapidly assess TDS through EC monitoring enables faster responses to pollution surges, thereby reducing public health risks. Ultimately, adopting these evidence-based interventions, particularly strengthening waste management around high-impact zones, will improve environmental governance and support long-term water security for downstream users.

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