LAUTECH Journal of Engineering and Technology 20 (1) 2026: 66-76
10.36108/laujet/6202.02.0160

Fuzzy Synthetic Evaluation of the Level of Service of Agba Dam Water Treatment Plant

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Article Info

Article history:

Received: Dec 21, 2025
Revised: Jan 7, 2026
Accepted: Jan 20, 2026

Keywords:

Fuzzy synthetic evaluation, Water treatment plant, Water supply, Water supply infrastructures, Water quality

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ABSTRACT

This study addresses the critical need for a robust evaluation of water treatment plant performance, with a focus on the level of service at the Agba Dam Water Treatment Plant in Nigeria. The objective was to apply fuzzy set theory for objective assessment. The methodology involved collecting 1664 water quality parameter measurements, including pH, conductivity, turbidity, and total dissolved solids. Of these, 354 valid entries served as performance indicators. These data were integrated into a fuzzy synthetic evaluation model assessing service level against prescribed regulatory and expert limits. The key result showed water quality across all sampled parameters was consistently within limits, with mean values: pH = 7.15, conductivity = 176.62 µS/cm, turbidity = 1.23 NTU, and total dissolved solids = 87.18 mg/L. Consequently, it's concluded that the Agba Dam Water Treatment Plant delivers an excellent level of service, scoring 2.75 on a defined 3-point fuzzy evaluation scale. This scale was explicitly defined using a Likert-type system with linguistic terms 'Poor', 'Good', and 'Excellent', and was validated by expert biochemists and principal scientists from the plant.

INTRODUCTION

Clean water provision is fundamental for public health and socio-economic development, with water treatment plants (WTPs) serving as critical infrastructure for rendering water safe for consumption. A conventional WTP typically comprises a series of units, including intake, aeration, coagulation, flocculation, sedimentation, filtration, and disinfection, culminating in clear water storage tanks (Spellman, 2013). Each unit performs distinct functions to ensure water quality parameters, such as physicochemical indicators (e.g., pH, conductivity, total dissolved solids (TDS), iron) and biological parameters (e.g., Escherichia coli), are within allowable ranges defined by international bodies like the World Health Organization (WHO) and national standards such as the Nigerian Industrial Standard for Drinking Water Quality (NIS 554:2015).

In many developing nations, including Nigeria, urban water supply systems face significant challenges like intermittent provision, poor infrastructure, and increasing demand, leading to a substantial gap between water supply and demand (Adah and Abok, 2017; Okeola and Sule, 2002). These issues underscore the critical importance of ensuring the optimal performance and reliable "level of service" from existing water treatment facilities.

Evaluation of WTP performance is crucial and can involve assessing efficiency from raw to treated water quality or comparing treated water parameters against potable water standards (Spellman, 2013). Regardless of the method, such evaluations inherently involve multiple criteria and complex decision-making processes. However, a robust multi-criteria evaluation framework for comprehensively assessing the "level of service" of water treatment plants, particularly one that can effectively handle the inherent imprecision and subjectivity of water quality data, remains largely underexplored. This gap limits the ability to provide a nuanced and holistic performance assessment.

To address this, this study aimed to develop and apply a fuzzy synthetic evaluation model based on fuzzy set theory for assessing the level of service of the Agba Dam Water Treatment Plant in Nigeria, leveraging fuzzy logic's ability to integrate multiple, potentially imprecise, performance indicators into a comprehensive evaluation score. The methodology involved collecting 1664 water quality parameter measurements, including pH, conductivity, turbidity, and total dissolved solids. Of these, 354 valid entries served as performance indicators. These data were integrated into the fuzzy synthetic evaluation model that assesses the level of service against prescribed regulatory and expert limits. The key result showed water quality across all sampled parameters was consistently within limits, with mean values: pH = 6.23, conductivity = 154.10 µS/cm, turbidity = 0.72 NTU, and total dissolved solids = 75.82 mg/L. Consequently, it's concluded the Agba Dam Water Treatment Plant delivers an excellent level of service, scoring 2.65 on a defined 3-point fuzzy evaluation scale. This scale was explicitly defined using a Likert-type system with linguistic terms 'Poor', 'Good', and 'Excellent', and was validated by expert biochemists and principal scientists from the plant.

LITERATURE REVIEW

Globally, about 2 billion people still lack access to safely managed drinking water services (World Bank, 2022). Water supply infrastructure is responsible for distributing potable water to consumers. The development of water systems has been most notable in industrialized societies, and it has been widely asserted that the use and availability of water infrastructure are essential factors of economic growth and development (Cecilia, 2014).

A global problem with water supply can be attributed to inadequate maintenance of water supply infrastructures. The rapidly declining freshwater resources and ageing water infrastructure globally create hardship for many water utilities addressing the regular water demand (Salehi, 2022). Dangui and Jia (2022) report the relationship between water infrastructures and economic growth, corroborated by other researchers' work; Frone and Frone (2014) established the relationship between water supply and wastewater investment as positively and significantly correlated with the economic growth in Romania.

Nigeria has an estimated 267 billion cubic metres of surface water and 92 billion cubic metres of groundwater per annum, with over 200 dams with a combined storage capacity of 34 billion cubic metres, yet Nigeria is still classified as 'water short' because of its inability to meet the challenge of the domestic demand for potable water (Egbinola, 2017). Investigations have revealed that many of the rural communities in Nigeria do not have improved water supply systems, such as piped water networks or boreholes. Where such facilities exist, they are either malfunctioning or completely broken down, forcing households to rely on available sources for domestic purposes (Ishaku et al., 2011).

In Kwara State, the Kwara State Water Corporation (KWWC) is responsible for the treatment and distribution of water to the entire state. The KWWC is tasked with the operation and maintenance of water infrastructures in the state, which also includes the supply of water to different parts of the state from water works stationed strategically within the state. The Ilorin metropolis comprises several water supply infrastructures some of which include

Asa dam water works, Agba dam water works, and Sobi water works.

According to Ajadi (2010), the level of service by the Kwara State Water Corporation (KWWC) was reported to be unsatisfactory, specifically in the areas of coverage, service connections, and regularity of water supply. This report is further supported by Ibrahim et al. (2020), who also reported the corporation's inability to pump clean water sufficiently to the residents to meet the rising demand for domestic potable water.

Generally, the public sector has not been successful in meeting the demand of residential and commercial users. Water supply services are unreliable and of low quality, and are not sustainable owing to the difficulties in management. Many water supply systems are extensively deteriorated and underutilized due to under-maintenance and lack of funds for operations (Ishaku et al., 2011). Epileptic power supply is also a major hindrance to water supply efforts within the country (Egbinola, 2017).

The level of water supply across the country differs from state to state. For example, in Lagos state, only 10% of its population is served by public water supply (World Bank, 2019), and over 60% of the households in Ibadan lack potable water and adequate sanitary facilities (Olanrewaju and Afolabi, 2020). In Kano state, 35% of the residents suffer from the inaccessibility to clean water (UNICEF, 2019). Bature et al. (2021) in their study discuss the major water supply problems faced by households, which include inadequate water supply from the Kaduna state water board.

Recognizing non-revenue water (NRW) as a barrier to sustainable water development, Farouk et al. (2023) utilized a fuzzy synthetic evaluation (FSE) method to assess the effectiveness of water distribution network (WDN) rehabilitation approaches. Through a systematic review, 21 potential rehabilitation approaches were identified and grouped into seven key components (zoning network, programs, simulation, trenchless, algorithm, significance index, and resin transfer molding). The study employed a questionnaire survey with a 5-point Likert scale, collecting 176 valid responses from screened water industry experts. After validating internal consistency with Cronbach's alpha, FSE was applied to determine component significance, overall effectiveness, and suitable weightings and membership functions. Their findings indicated that the zoning network component was the most effective approach for reducing NRW, showing an impact level of 4.23. This study highlights the utility of FSE in evaluating complex water infrastructure challenges.

METHODOLOGY

Study area

Ilorin is in the North-Central geopolitical zone of Nigeria. It lies between latitude 8°30'N and 4°33'E. The city, in its geological setting,s consists of a Pre-Cambrian basement complex with an elevation of between 273m and 333m above sea level. There is an isolated hill (Sobi Hills) of about 394m above sea level towards the north of the western part and from 200m to 346m in the east (Ibrahim et al., 2018).

Ilorin metropolis has a tropical wet – dry climate, days are very hot during the dry season from November to January, while temperatures typically range from 33°C to 37°C. The main river in Ilorin is the Asa River, which divides the city into two parts, the western part representing the core indigenous area and the eastern part consisting of the modern residential areas and the GRA (Ajadi, 2010).

The first water supply scheme completed in Ilorin was the Agba dam project in 1952, even before the water corporation was created, with an output of 3,100m3. The output was raised to 4542m3 per day in 1974 (Ifabiyi and Ashaolu, 2013). Ilorin metropolis currently comprises three water works: Asa dam water works located in Ilorin West LGA, Agba dam water works in Ilorin South LGA, and Sobi water works in Moro LGA, which are responsible for distributing water in the city.

Theoretical framework

The methodological approach for this study was designed to systematically evaluate the level of service of the Agba Dam Water Treatment Plant using a robust, multi-criteria framework. This involved three key stages: a comprehensive review of relevant literature to establish foundational knowledge and identify pertinent evaluation criteria; the application of standard data analysis techniques for processing raw water quality data; and the development and implementation of a fuzzy synthetic evaluation (FSE) model. This integrated approach was selected because traditional evaluation methods often struggle with the inherent subjectivity and imprecision of real-world water quality data, where fuzzy logic provides a suitable tool to translate qualitative assessments into quantifiable results for a holistic performance evaluation.

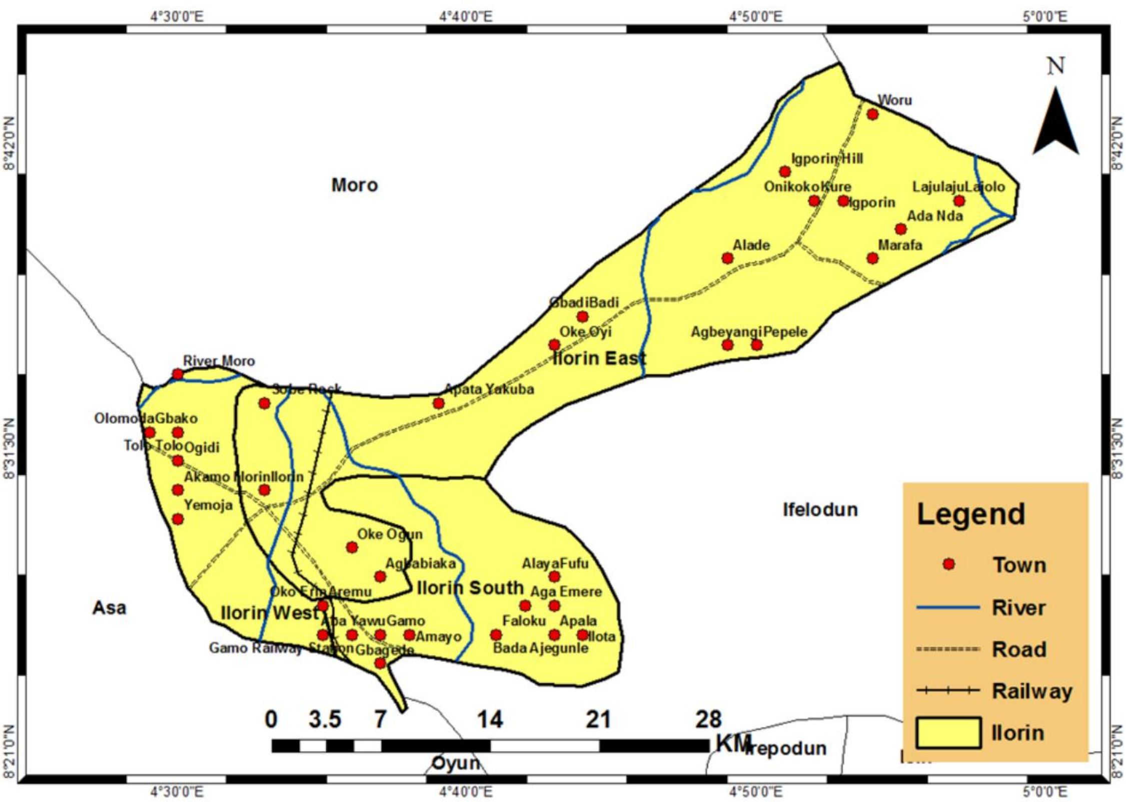

Figure 1: Map of Ilorin (Fajemidagba, 2018)

Performance indicators

Performance indicators (PIs) are quantifiable metrics used to evaluate the condition and performance of a water treatment plant. For this study, the selection of performance indicators was based on parameters routinely used in water quality testing, including pH, conductivity, turbidity, and total dissolved solids (TDS). These specific parameters were chosen due to their critical role in assessing drinking water safety and treatment efficiency, and their relevance was further validated by expert biochemists and principal scientists from the Agba Dam Water Treatment Plant.

Data analysis

The collected data for this study underwent descriptive analysis. For each of the identified performance indicators (pH, conductivity, turbidity, and total dissolved solids), the mean value was computed. The mean ($\underline{x}$) for an individual performance indicator (x_i) was calculated by dividing the sum of its values by the total number of valid entries (n) for that indicator, as shown in Equation (1):

$$\underline{x} = \frac{\sum_{i=1}^{n} \quad x_i}{n} \tag{1}$$

Where:

- x_i represents the value of each performance indicator.
- n is the total number of values for that performance indicator.

Additionally, a 'Total Mean' was calculated, representing the cumulative sum of the mean values obtained for each individual performance indicator. This cumulative mean provides an aggregated perspective across all parameters, as depicted in Equation (2):

$$Total\ Mean = \sum_{i=1}^{k} \quad \underline{X_i} \tag{2}$$

Where:

- $\underline{X_i}$ represents the mean value of each individual performance indicator.
- k is the total number of performance indicators (in this study, k=4: pH, conductivity, turbidity, TDS).

Fuzzy synthetic evaluation

Fuzzy Synthetic Evaluation (FSE) is a powerful method rooted in fuzzy set theory, first introduced by Zadeh (1965). This approach is particularly effective for decision-making problems that involve multiple criteria or qualitative information, where traditional, precise numerical methods may fall short. Its ability to handle imprecision and uncertainty makes FSE well-suited for evaluating complex systems like water treatment plants, where water quality parameters often have varying degrees of satisfaction rather than strict pass/fail thresholds.

Fuzzy sets

At the core of FSE are fuzzy sets, which allow for the representation of vague or imprecise concepts, unlike classical sets, where an element is either entirely in or entirely out of a set. A fuzzy set is defined by its membership function, which maps each element in the domain of interest onto the interval (0, 1) (Dahiya et al., 2007). This value, known as the degree of membership or weighting, indicates the extent to which an element belongs to the fuzzy set (Dahiya et al., 2007). For example, a water quality parameter might be "partially good" or "mostly excellent." The membership function contains all the information regarding a fuzzy set (Ross, 2009) and typically comprises three conceptual zones: core, support, and boundary (Zadeh, 1965).

A fuzzy set X is defined in terms of its membership function by Eq. (3) and Eq. (4).

$$\mu_x = \{1 \ \in (0,1) \ 1 \quad x \ is \ a \ full \ member \ of \ X \tag{3}$$

$$x \ is \ a \ partial \ member \ of \ X \ x \ is \ not \ a \ member \ of \ X$$

$$X = \sum_{i=1}^{n} \quad \frac{\mu_X(x_i)}{x_i} \tag{4}$$

Fuzzy matrix

A fuzzy matrix or fuzzy relational matrix R), serves to define the relationship between sets in a fuzzy evaluation. In the context of this study, this matrix effectively links the performance indicators (e.g., pH, conductivity, turbidity, TDS) with the defined linguistic evaluation grades ('Poor', 'Good', 'Excellent'). Each element, r_{ij}, within the matrix represents the degree of membership—a value between 0 and 1—that a specific performance indicator i belongs to a particular evaluation grade j. (Hsiao, 1998). This structure allows for a comprehensive representation of how each water quality parameter aligns with the established levels of service. The fuzzy matrix is formally expressed as shown in Equations (5) and (6)

$$R = [r_{11}\, r_{12} \dots r_{1n}\, r_{21}\, r_{22} \dots r_{2n} \dots r_{m1}\, r_{m2} \cdot\cdot \quad (5)$$

$$r_{ij} = \mu_{R(x_i, y_i)}, \qquad X \times Y \rightarrow [0, 1] \quad (6)$$

Fuzzy operator

A fuzzy operator is essential for making fuzzy decisions by aggregating the degrees of membership. A robust fuzzy synthetic evaluation method leverages membership functions and fuzzy operators to accurately determine the overall evaluation result (Dahiya et al., 2007). In this study, the fuzzy "OR" operator, as defined by Zadeh, was employed. This operator selects the maximum of the membership grades across different evaluation categories ('Poor', 'Good', 'Excellent') to determine the resulting overall membership (Dahiya et al., 2007). The choice of the fuzzy "OR" operator implies that the highest degree of satisfaction (i.e., the most positive assessment) for any of the performance indicators towards a particular service level contributes most significantly to the overall fuzzy decision. This approach ensures that a strong performance in one aspect can elevate the overall perceived level of service. The fuzzy "OR" operator is formally represented as shown in Equation (7):

$$\mu c\,(x) = \max\,(\mu_{poor}\,(x), \mu_{good}\,(x), \mu_{excellent}\,(x)) \quad (7)$$

Fuzzification

Fuzzification is the critical process of converting precise, or "crisp," numerical inputs (such as your measured pH, conductivity, turbidity, and TDS values) into fuzzy values or linguistic variables. This involves translating the input values into linguistic concepts, which are then represented by fuzzy sets. Membership functions are subsequently applied to these fuzzy sets to determine the degree of truth for each defined linguistic variable (Arabacioglu, 2010). The resulting fuzzy values typically range between 0 and 1. For the performance indicators in this study, the membership functions were defined to represent the degree of satisfaction for individual parameters (Hsiao, 1998; Ameyaw and Chan, 2015).

Let the fuzzy evaluation set V be defined as:

$$V = \left\{\frac{1}{poor}, \frac{2}{Good}, \frac{3}{Excellent}\right\} \quad (8)$$

The membership function for the individual performance indicator is obtained using the following equation, Ameyaw & Chan (2015):

$$MF_i = (x_1, x_2, x_3) \quad (9)$$

where MF_i is the membership function for a performance indicator i , and x_1, x_2, and x_3 represent the percentage of values that fall within the poor, good, and excellent range. Equation (10) is used to determine the relative importance or influence of each performance indicator (such as pH, conductivity, turbidity, or total dissolved solids) within the overall water treatment plant evaluation. These weighting values are crucial because they allow the model to prioritize or de-prioritize certain parameters based on their contribution to the overall assessment. The equation is as follows:

$$W = (w_1, w_2, \dots, w_n) = (w_i) = \frac{M_i}{\sum_{j=1}^{n} M_j} \quad (1$$

Where

- $\boldsymbol{w_i}$ is the weight of the i[th] performance indicator
- $\boldsymbol{M_i}$ is the mean of the i[th] performance indicator
- M_j is the sum of all performance indicators

Fuzzy decision

The fuzzy decision module is where the actual evaluation occurs, synthesizing the fuzzified input data with the relationships defined in the fuzzy matrix (Hsiao, 1998). The fuzzy synthetic evaluation set (Hsiao, 1998) is given as:

$$F = W \circ R = \{e_1, e_2, e_3\} \quad (11)$$

Where:

- W is the weighting set
- R is the fuzzy relational matrix.

The symbol "∘ " represents the composite operation defined by the generalized weighted mean method Hsiao (1998), and can be written mathematically as

$$e_j = \left(\sum_{j=1}^{m} W_i \times r_{ij}\right),\ \mathrm{j} = 1, 2, \ldots, \mathrm{n} \quad (12)$$

Subsequently, the fuzzy OR operator (from Equation (7)) is applied to the result of the composite operation, which is the fuzzy synthetic evaluation matrix. The outcome from the OR operation reveals the level of service defined by the linguistic variable and a crisp value is gotten from the defuzzification of the fuzzy synthetic evaluation set.

Defuzzification

Defuzzification is the final stage in the fuzzy synthetic evaluation process, serving to translate the fuzzy output from the fuzzy decision step into a single, quantifiable value. This step is crucial for practical interpretation and actionable decision-making, as fuzzy values, while comprehensive, are not immediately intuitive for applied researchers or stakeholders.

The crisp value for the level of service (LOS) of the water treatment plant's fuzzy synthetic evaluation set can be determined by adopting the gradings from the evaluation set (Equation 8) as weights for the memberships of the fuzzy synthetic evaluation set (Sadiq and Rodriguez, 2004). The method employed in this study is based on this principle, effectively calculating a weighted average of the fuzzy output set to yield a precise numerical score. This crisp score, such as 2.65 on a 3-point scale, then directly represents the overall level of service. The calculation is shown in Equation (13):

$$\mathrm{LOS} = 1\mu_{poor} + 2\mu_{good} + 3\mu_{excellent} \quad (13)$$

Outline of the evaluation model

The procedures involved in the fuzzy synthetic evaluation adopted for this study involve the following steps:

1. Fuzzification: Define membership functions and weighting values for individual performance indicators.
2. Fuzzy decision making: Compute the fuzzy relationship matrix and fuzzy synthetic evaluation set to determine the overall level of service of the water treatment plant.
3. Defuzzification: Transform fuzzy decision output to a crisp value.

RESULTS AND DISCUSSION

Performance indicators

The performance indicators used in this study are water quality parameters, viz., pH, conductivity, turbidity, and total dissolved solids (TDS). These performance indicators have been grouped into three cadres based on the allowable limits defined by the World Health Organization, Nigerian Standards for Drinking Water Quality, and expert judgement, and are shown in Table 1.

Table 1: The limits defined by WHO and NSDWQ for the water quality parameters used in this study.

Indicator	Poor	Good	Excellent
pH	< 6.5 & > 8.5	6.5 − 8.5	7.0 − 7.5
Conductivity (µS/cm)	> 1000	200 − 300	< 200
TDS (mg/L)	> 500	300 − 500	< 300
Turbidity (NTU)	> 5	1 − 5	< 1

Data analysis

In this study, the data used were retrieved from Kwara State Water Corporation (KWWC), and for each performance indicator, 1664 entries were recorded for a span of ten years (2014 – 2024), with only 354 valid entries. The recorded parameters were subjected to descriptive analysis, where their mean values were computed, as well as the cumulative mean of individual performance indicators, as shown in Table 3.

Table 2: Mean values and total mean values of performance indicators

Performance indicator	Mean, $\underline{x} = \frac{\sum_{i=1}^{n} x_i}{n}$
pH	7.15
Conductivity (µS/cm)	176.62
Total Dissolved Solids (mg/L)	87.18
Turbidity	1.23
Total mean (Sum of all performance indicator mean) $\sum_{i=1}^{n} \underline{x_i}$	272.18

Each of the performance indicators listed in Table 2 has a mean value of 272.18. The total mean (Equation (2)) is used in the calculation of the weighting values of performance indicators (Equation (10)).

Fuzzy synthetic evaluation

The application of the FSE method allowed for the determination of the level of service of the water treatment plant by combining the fuzzification, decision-making, and defuzzification steps.

Fuzzification

The membership functions of each of the performance indicator is calculated using Eq. (9). The membership in each membership function is a percentage value for poor, good, and excellent, respectively. As an example, the pH performance indicator as an example, the classified pH values are recorded as: 15% poor, 58% good, and 27% excellent. The membership function is written as (Eq. 8):

$$MF_{pH} = \frac{0.45}{poor} + \frac{0.28}{good} + \frac{0.27}{excellent}$$

The membership function is written through Eq. (9) as: (0.15, 0.58, 0.27). Using the same approach, the membership function for the remaining performance indicators is derived and is shown in Table 3 and in Figure 2.

Table 3: Membership function for individual performance indicator

Performance indicator	Membership function
pH	(0.15, 0.58, 0.27)
Conductivity	(0.0, 0.33, 0.67)
Turbidity	(0.09, 0.25, 0.66)
TDS	(0.00, 0.02, 0.98)

The weighting values obtained for individual performance indicators using Eq. (10) are shown in Table 4.

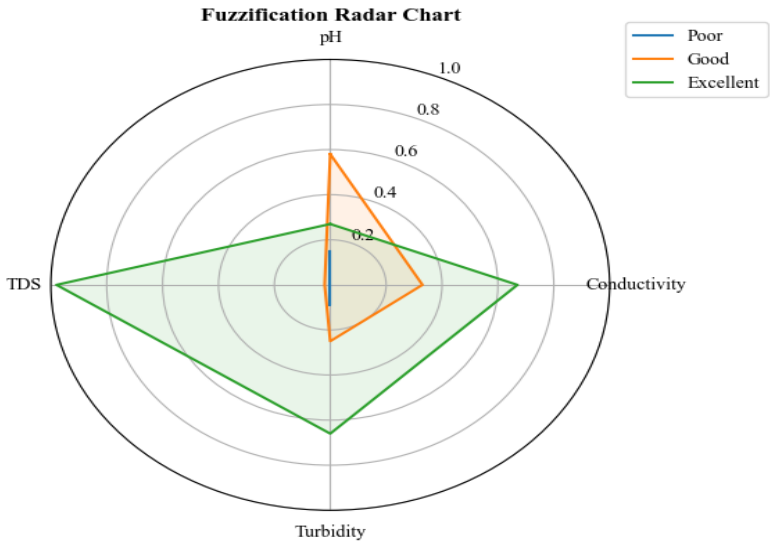

Figure 2: Fuzzification Result Radar Chart

The weighting values obtained for individual performance indicators using Eq. (10) are shown in Table 4.

Table 4: Weighting value for individual performance indicator

Performance indicator	Weighting value
pH	0.0263
Conductivity	0.6489
TDS	0.0045
Turbidity	0.3203

Fuzzy decision

For the fuzzy decision, the fuzzy relational matrix R is defined using Eq. (5) and the weighting set W is defined using Eq. (10) :

$$R = \begin{bmatrix} 0.15\ 0.58\ 0.27\ 0.0\ 0.33\ 0.67\ 0.09\ 0.25 \\ 0.66\ 0.00\ 0.02\ 0.98 \end{bmatrix}$$

$$W = (0.0263, 0.6489, 0.0045, 0.3203)$$

The fuzzy synthetic evaluation set is then computed from Eq. (11) as:

$$F = W \circ R = [0.0044\ 0.2369\ 0.7587\ ]$$

The fuzzy OR operator is applied to the fuzzy synthetic evaluation set using Eq. (7):

$$\mu_F = (0.0044, 0.2369, 0.7587) \ = 0.7587$$

The result from the OR operator returns the membership value 0.7587 as the maximum membership, which also falls under the excellent category by definitions in Eq. (8) and Eq. (9). Therefore, the level of service of the water treatment plant in terms of water quality from the fuzzy decision is excellent.

Defuzzification

The crisp value for the level of service (LOS) is computed using Eq. (13) as:

$$LOS = 1(0.0044) + 2(0.2369) + 3(0.7587) = 2.75$$

The level of service for the water treatment plant has a crisp value of 2.75/3, which is a high value and is ranked excellent by the FSE model applied.

The level of service calculated and validated by the FSE model applies to the water quality treated by the Agba dam water treatment plant. The mean values of performance indicators are inline with the acceptable WHO and NSDWQ values for safe drinking water. This indicates that the components of the water treatment plant (aerator, flocculation chambers, chlorination chamber) are in great condition.

A direct comparison of the Agba Dam Water Treatment Plant's level of service with other similar facilities is challenging due to the lack of publicly available, comparable FSE-based assessments for other Nigerian or regional plants. Future research could benefit from applying this standardized FSE methodology across multiple plants to facilitate benchmarking and identify best practices or common challenges.

CONCLUSION

This paper successfully evaluated the level of service of the Agba Dam Water Treatment Plant using a fuzzy synthetic evaluation (FSE) method, assessing key physicochemical water quality parameters (pH, conductivity, turbidity, TDS) against established standards. The FSE methodology effectively handled data imprecision, yielding an "Excellent" service level with a crisp value of 2.75 on a 3-point scale. This high score indicates robust overall performance, synthesizing varied individual parameter contributions into a holistic assessment.

However, the study has limitations: it focused on only four physicochemical parameters, excluding crucial biological metrics or heavy metals. The reliance on historical data also limits insights into real-time fluctuations. Despite these, the findings offer significant policy and operational implications, validating current practices and providing a quantitative benchmark for performance. The model's detailed insights can guide targeted interventions for continuous improvement and resource optimization.

For future studies, expanding parameters to include bacteriological data and heavy metals is recommended. Integrating real-time monitoring with IoT sensors would enable dynamic evaluations. Comparative studies across other treatment facilities would facilitate benchmarking, while further validation and uncertainty analysis could strengthen model confidence and applicability.

ACKNOWLEDGEMENTS

Author Contributions: Conceptualization, OG and AA; Analysis, AA, OG; Initial Draft. A.A; writing-review and editing, OG; Oversight, AW and TS. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: The authors maintain confidentiality of data.

Conflict of interest: The corresponding author states that there is no conflict of interest on behalf of all authors.

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