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FUZZY SYNTHETIC EVALUATION OF THE LEVEL OF SERVICE OF AGBA DAM WATER TREATMENT PLANT

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Abstract: This paper reports the application of fuzzy set theory for evaluating the level of service of Agba dam water treatment plant in Nigeria. The methodology is based on data analysis and fuzzy set theory used to express the level of service. The fuzzy synthetic evaluation model gives the level of service of the water treatment plant based on the prescribed limits of the water quality parameter of the treated water by various regulatory bodies and experts from the field of water treatment. The fuzzy model was applied to 1664 water quality parameters viz pH, conductivity, turbidity, and total dissolved solids which also served as performance indicators for the evaluation. The analysis showed that the water quality levels of these samples were within the prescribed limits; thus, the water treatment's level of service is excellent with a score of 2.65 on a 3–point scale.

Keywords: Fuzzy synthetic evaluation, water treatment plant, water supply, water supply infrastructures, water quality

INTRODUCTION

Water is essential to sustaining human life and health. Water covers about 71% of the Earth's surface, forming vast water bodies, and plays an essential part in our day–to–day activity; domestic and industrial purposes as well as in different sectors: agriculture, medicine, and engineering. Water contributes to improvements in the social well–being of human and environmental health via food and energy security (WWDR, 2015).

A water treatment plant is a water supply infrastructure used to treat water to make it safe for consumption. A conventional water treatment plant comprises the intake, the aerator, coagulation and flocculation units, sedimentation basin, filtration units, disinfection unit and the clear water tanks. Each of these units perform distinctive functions in ensuring water quality parameters such as the physiochemical parameters (pH, conductivity, total dissolved solids (TDS), Iron), and biological parameters such as Escherichia coli (E.coli) are within the allowable range for consumption as defined by WHO and individual state limits.

A water treatment plant can be evaluated by virtue of its efficiency in the improvement of water quality parameters from raw water to treated water or by evaluating the water quality parameters of the treated water by comparing the values with the acceptable defined ranges for potable water. Irrespective of the method used, it involves multiple criteria for the evaluation and decision–making.

The two important sources of water in most of the urban cities are piped water and groundwater. In developing countries like Nigeria, piped water supply is intermittent with unacceptable pressures, high leakage rates, and poor maintenance of the system from source to consumer with large gap between supply and demand. The government is primarily responsible for designing and implementing urban water systems which includes pipe distribution networks, treatment plans, and reservoirs to various consumer points. Some of the challenges of urban water management highlighted by Adah and Abok (2017) include the lack of effective compliance to water management policies, urbanization challenge and poor state of infrastructure.

In Nigeria, larger percentage of the populace do not enjoy potable water supply due to the poor performance level of water supply projects (Okeola and Sule, 2002). The Kwara State Water Board (KWSB) for example, whose responsibility is to pump and distribute sufficient clean water to the residents is seriously constrained due to its inability to meet the rising demand for domestic potable water (Ibrahim et al., 2020).

The fuzzy synthetic evaluation (FSE) method is based on fuzzy set theory which is designed to handle multicriteria problems (Jianhu and Mingfang, 2016) and in evaluating problems where uncertainties affect the decision–making process. The nature of the FSE method makes it a perfect fit for the evaluation of a water treatment plant whose criteria are the water quality parameters.

LITERATURE REVIEW

Globally, about 2 billion people still lack access to safely managed drinking water services (World bank, 2022). Water supply infrastructures are responsible for handling the distribution of 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 aging water infrastructure globally creates hardship for many water utilities addressing the regular water demand (Salehi, 2022). Dangui and Jia (2022) reports 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 ground water 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 part 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), 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 his study, discusses the major water supply problems faced by households as the include inadequate water supply from the Kaduna state water board.

Farouk et al. (2023) identified non–revenue water (NRW) as one of the barriers facing sustainable water development. As a result, they conducted a study aimed at solving the identified problem by evaluating the effectiveness of water distribution network (WDN) rehabilitation approaches using the fuzzy synthetic evaluation method. Potential WDN rehabilitation approaches were identified through a systematic review of articles.

The researchers began their study by evaluating 21 approaches retrieved from a systematic review of 327 articles which were regrouped into 7 components which are the zoning network, programs, simulation, trenchless, algorithm, significance index, resin transfer molding. A questionnaire survey based on a 5–point Likert scale to measure identified approaches was designed and sent to respondents. To avoid the possibility of bias, the respondents were subjected to screening to ensure they have experience in the water industry. The questionnaire results from the respondents after vetting produced 176 valid responses. The valid responses were subjected to Cronbach's alpha test to check for internal consistency. The result from the test indicated an excellent reliability good enough for fuzzy synthetic evaluation.

The fuzzy synthetic evaluation (FSE) process involved the assessment of various WDN approaches, determination of the significance of the 7 components evaluated earlier, and the overall effectiveness level of WDN rehabilitation approaches. The suitable weightings for the main seven components were first determined and as well as the membership functions. The overall effectiveness of the WDN approaches was calculated by multiplying the weighting of each component by the degree of the membership function of the said component and the grade points 1 – 5.

The results from the FSE approach used in the study showed that the most effective approach is the zoning network component with an impact level of 4.23. Farouk et al. (2023) praised the zoning network due to its effectiveness in reducing non–revenue water.

Lu et al. (1999) applied Fuzzy Synthetic Evaluation (FSE) to conduct a trophic status assessment for Fei–Tsui reservoir in Taiwan. The objective of this study was to determine the cause of the long–term change of water quality and the overturn phenomena observed from 1987 to 1992. The FSE process involved gathering historical data from the management of Fei–Tsui reservoir from 1987 to 1996, identifying the classification factors (CF) and designing the membership functions of the 3 factors which are more applicable to Taiwan. The classification factors used are total phosphorous present in the water, chlorophyll a, and the Secchi disk depth. The result shows that the water quality was unstable, which was caused by the short–term overturn effect and recommended that expert systems may be developed for providing valuable information and for aiding reservoirs management.

METHODOLOGICAL FRAMEWORK

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 settings 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 the 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 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).

Ilorin is a diverse community, comprising people from various ethnicities and cultural backgrounds with the Yorubas being the dominant ethnic group. Beyond its cultural and historical significance, Ilorin is also a thriving hub of economic activity. The city is home to bustling markets, commercial centers, and industrial estates that drives its economy and sustain livelihoods. Ilorin is one of the fastest growing urban cities in Nigeria.

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.

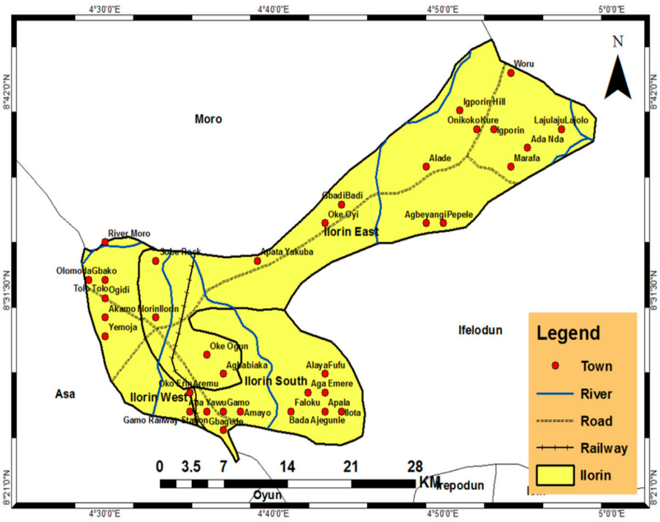

Figure 1: Map of Ilorin (Fajemidagba, 2018)

Theoretical framework

The methodological approach involved the review of literature, development of data analysis techniques and development of fuzzy synthetic evaluation model.

— **Performance indicators**

Performance indicators (PIs) are quantifiable metrics used to evaluate the condition and performance of the water treatment plant.

— **Data analysis**

The data used for this study was subjected to a descriptive analysis to calculate the mean of individual parameters and total mean of the performance indicators. The mean value for a performance indicator will be calculated by dividing the sum of all values by the total number of values as shown in Eq. (1).

$$\text{Mean, } \bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \quad (1)$$

Where: x_i represents the value of each performance indicator,
n is the total number of performance indicators.

The total mean value for a water supply infrastructure will be calculated by summing the mean values for each of its performance indicator as shown in Eq. (2):

$$\text{Total mean, } \sum_{i=1}^{n} X_i \quad (2)$$

where x_i represents the value of each performance indicator.

— **Fuzzy synthetic evaluation**

Fuzzy synthetic evaluation is based on the fuzzy set theory developed by Zadeh (Zadeh, 1965) and is applied in various decision–making problems involving multiple criteria or imprecise information.

≡ **Fuzzy sets**

A fuzzy set is defined in terms of its membership function which maps the domain of interest onto the interval (0, 1) Dahiya et. al (2007). The membership function contains all the information regarding a fuzzy set (Ross, 2009) and represents the degree, or weighting, that the specified value belongs to a set (Dahiya et. Al., 2007). A membership function comprises three zones viz. core, support, and boundary (Zadeh, 1965).

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

$$\mu_x = \begin{cases} 1 & \text{x is a full member of X} \\ \in (0,1) & \text{x is a partial member of X} \\ 1 & \text{x is not a member of X} \end{cases} \quad (3)$$

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

≡ **Fuzzy matrix**

A fuzzy matrix or fuzzy relational matrix R is a matrix defined by the relation on the sets X and Y, and X has m elements and Y has n elements. The elements r_{ij} of the matrix are defined by a membership function of the pair of elements from the sets X and Y whose result is in the range of 0 and 1 (Eq. 5 and Eq. 6) Hsiao (1998).

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \quad (5)$$

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

≡ **Fuzzy operator**

A fuzzy operator is used to make fuzzy decisions. A well designed fuzzy synthetic evaluation method makes use of the membership function and fuzzy operator to properly decide the result of an evaluation (Dahiya et al., 2007). The fuzzy operator used in this paper is the fuzzy “OR” operator (Dahiya et al., 2007) defined by Zadeh where the maximum of the membership grades is taken as the result of the evaluation (Eq. 7).

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

≡ **Fuzzification**

The fuzzification of the crisp input values into linguistic variables involves two processes: the input values are translated into linguistic concepts represented by fuzzy sets and membership functions are then applied to them to get the degree of truth in each defined linguistic variable Arabacioglu (2010). The membership functions for the performance indicators will be defined as the degree of satisfaction of 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 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.

The weighting value for each indicator is also calculated using the equation:

$$W = (w_1, w_2, \dots, w_n) \; = \; (w_i) = \frac{M_i}{\sum_{j=1}^{n} M_j} \qquad (10)$$

≡ **Fuzzy decision**

In the fuzzy decision stage, a fuzzy operator is applied to the membership functions to provide a result. In making a fuzzy decision, the fuzzy synthetic evaluation set (Hsiao, 1998) is given as:

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

where W is the weighting set and 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

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

The fuzzy OR operator (Eq. 7) is applied to the result of the composite operation which is the fuzzy synthetic evaluation matrix. The result 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**

The level of service of the water treatment plant's crisp value of the fuzzy synthetic evaluations set can be determined using Eq. (13) below by adopting the gradings from the evaluation set in Eq. (8) as weights for the memberships of the fuzzy synthetic evaluation set (Sadiq and Rodriguez, 2004).

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

Outline of the evaluation model

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

- Fuzzification: Define membership functions and weighting values for individual performance indicators.
- 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.
- 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 World Health Organization, Nigerian Standards for Drinking Water Quality, and expert judgement and are shown in Table 2.

Table 2. 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 was retrieved from Kwara State Water Corporation (KWWC) and for each performance indicator, 1664 entries were recorded for a span of ten years (2014 – 2024). 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 3. Mean values and total mean values of performance indicators

Performance indicator	Mean, $\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$
pH	4.45
Conductivity (μS/cm)	150.39
Total Dissolved Solids (mg/L)	91.86
Turbidity	1.47
Total mean, $\sum_{i=1}^{n} \bar{x}_i$	248.17

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: 45% poor, 28% 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: (0.45, 0.28, 0.27). Using the same approach, the membership function for the remaining performance indicators is derived and is shown in Table 4.

Table 4. Membership function for individual performance indicator

Performance indicator	Membership function
pH	(0.45, 0.28, 0.27)
Conductivity	(0.1, 0.33, 0.57)
Turbidity	(0.09, 0.25, 0.66)
TDS	(0.00, 0.02, 0.98)

The weighting values obtained for individual performance indicator using Eq. (10) is shown in Table 5.

Table 5. Weighting value for individual performance indicator

Performance indicator	Weighting value
pH	0.0179
Conductivity	0.6060
TDS	0.3701
Turbidity	0.0060

— **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) :

$$R = \begin{bmatrix} 0.45 & 0.28 & 0.27 \\ 0.1 & 0.33 & 0.57 \\ 0.09 & 0.25 & 0.66 \\ 0.00 & 0.02 & 0.98 \end{bmatrix}$$

$$W = (0.0179, 0.6060, 0.3701, 0.0060)$$

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

$$F = W \circ R = [0.0692 \quad 0.2139 \quad 0.7166]$$

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

$$\mu_F = \max(0.0692, 0.2139, 0.7166) = 0.7166$$

The result from the OR operator returns the membership value 0.7166 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 from the fuzzy decision is excellent.

— **Defuzzification**

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

$$LOS = 1(0.0692) + 2(0.2139) + 3(0.7166) = 2.65$$

The level of service for the water treatment plant has a crisp value of 2.65/3 which is a high value and is ranked excellent by the FSE model applied.

CONCLUSION

This paper evaluates the level of service of the Agba dam water treatment plant in Ilorin, Nigeria.

The evaluation of the water treatment plant involved the identification of performance indicators which are functions of the water drinking standards as prescribed by the World Health Organisation (WHO) and the Nigerian Standards for Drinking Water Quality (NSDWQ and the evaluation of these parameters using the fuzzy synthetic evaluation method.

The fuzzy synthetic evaluation method involved the retrieval, classification, and processing of data on each defined performance indicator carried out in three steps viz. fuzzification, fuzzy decision making and defuzzification. The result from the fuzzy synthetic evaluation reveals an excellent level of service with a crisp value of 2.65 rating on a 3–point Likert scale.

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