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Development Of Water Quality Index (WQI) Model for the Evaluation of Groundwater (Well) Status in Yakurr, South – South, Nigeria

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Abstract—This research assessed the condition of groundwater in the Yakurr Local Government Area of Cross River State, Nigeria, employing the Water Quality Index (WQI) approach. Water samples were obtained from 15 hand-dug wells located within three communities (Mkpani, Ekori, and Ugep) during both rainy and dry periods. A total of nineteen physical, chemical, and microbial indicators were examined, which include pH, turbidity, conductivity, TDS, TSS, chloride, nitrate, phosphate, hardness, sodium, calcium, magnesium, bicarbonate, dissolved oxygen, BOD5, iron, fluoride, and total coliform count. The weighted arithmetic index method was utilized to calculate the WQI. The findings indicated that WQI values varied between 117.1 and 811.4. Two wells were identified in the 'Poor' category (13.33%), four fell into the 'Very Poor' category (26.67%), and nine were marked as 'Unsuitable for Drinking' (60%). The WQI assessment indicated that Ugep was the most severely impacted area, whereas Ekori demonstrated comparatively better water quality. Elevated levels of iron, TCC, and phosphate significantly influenced the high WQI readings. The study concludes that numerous wells in Yakurr are not safe for direct use, highlighting the urgent need for treatment, enhanced sanitation, and ongoing monitoring to maintain public health safety.

Keywords — Groundwater; GIS, Well, WQI, Pollution, Seasonal Variation

I. INTRODUCTION

Water serves as an essential component of our ecosystem; however, the quality of both surface water and groundwater has been declining for a long time as a result of natural occurrences and human actions. Various natural elements that affect water quality include hydrology, weather patterns, climatic conditions, landforms, and geological characteristics [1, 48, 69, 70]. Some examples of human activities that negatively impact water quality include mining operations, animal farming, the creation and disposal of waste (industrial, municipal, and agricultural), increased soil erosion or sediment runoff due to changes in land use [2, 25,42], and contamination from heavy metals [26, 60].

Sustainable environmental methods, economic development, and human well-being all rely on access to clean and safe water [3,23, 24]. Recently, both poorer and wealthier countries have faced challenges in preserving or enhancing water quality due to issues linked to nutrient buildup in water and the eutrophication of water resources, alongside the need to meet the demands of a growing population [3, 17,26, 38). Nevertheless, the decline in groundwater quality has been worsened by poor waste management, agricultural expansion, and increasing population numbers. Various regions around the globe have encountered significant challenges regarding water supply and ensuring water quality and sanitation [1, 13, 33]. Assessing the quality of groundwater for human use is vital for the well-being of the rising population [37, 39], develop a water quality index (WQI) for Loktak Lake in India.

Groundwater management and planning profit from access to high-quality water, which is critical for effective groundwater conservation strategies [23, 24, 58] and [6, 53] emphasizes of the climate situation been very significant. Access to safe, clean water represents a significant challenge in many rural and semi-rural regions of Nigeria. Consequently, boreholes have become widespread throughout numerous cities in Nigeria, including Yakurr. The primary focus of this paper was to evaluate a Water Quality Index (WQI) model to assess the groundwater situation in Yakurr, located in Cross River State, South-South Nigeria, while critically assessing the most frequently utilized WQI models.
A Water Quality Index (WQI) includes four processes: selecting relevant water quality parameters, gathering real water quality data, converting the concentration of each parameter into a single dimensionless sub-index, and finally

calculating an overall water quality index by aggregating the sub-indices alongside their respective weighting factors [14, 32, 37, 70].

The water quality index serves as an effective tool for assessing the suitability of groundwater for a wide array of residential uses in a consolidated and restorative manner, providing vital information to decision-makers and stakeholders regarding water quality [8, 20, 21, 22, 54]. It evaluates groundwater quality through a straightforward mathematical equation that transforms extensive data on water quality parameters into one figure and offers a score representing the groundwater's condition [4, 28, 29, 52]. Similarly, [12] investigated WQI as a method for merging multiple data sets on water quality traits into a single metric for analyzing the water quality over time and across locations. This paper examines various published studies, through which we identified 21 WQI models employed internationally. Similarly, [2] discuss the water quality status around animal dung in Adiabo River Catchments of Odukpani Local Government Area of Cross River State, Nigeria. More so,[9,34], carried out anthropogenic impacts on the water quality of Kedong Stream in Idomi, Yakurr Local Government Area of Cross River State, Nigeria, [38] investigated water quality in Nkome Ekpache in Ikom Local Government Area of Cross River State.

II. REVIEW OF WQI MODELS

The graphic in Figure 1 presents the development history of the WQI models. Even though WQI models have only been created within the past 50 years, water quality indices have been utilized to classify water quality since the mid-1800s [1]. In the 1960s, Horton created the initial WQI model, which was founded on 10 key water quality parameters that were considered important in the majority of water bodies [30, 55]. Brown, with the backing of the National Sanitation Foundation, created an enhanced version of Horton's WQI model called NSF-WQI. This was done with input from 142 water quality experts who helped with the selection and prioritization of parameters [1, 5]. The NSF-WQI has served as the foundation for various other WQI models that have been developed subsequently.

The Scottish Research Development Department (SRDD) developed the SRDD-WQI in 1973, drawing on Brown's model, and utilized it to evaluate the quality of river water (reference). The Bascaron Index (1979), House Index (1986), and Dalmatian Index [63] are all subsequent variations of the SRDD-WQI. Steinhart and colleagues developed the Environmental Quality Index model in 1982 for assessing water quality in the Great Lakes ecosystems. The British Columbia Ministry for Environment, Lands and Parks introduced the British Columbia Water Quality Index (BCWQI) in the mid-90s as a significant advancement. This index was utilized to assess the quality of numerous water bodies across the province of British Columbia, Canada [61, 66].

2.1. Sub-indices

The main objective of the sub-index method is to transform parameter concentrations into values without units, referred to as parameter sub-indice. Various WQI models utilized established guideline values for water quality to create these sub-indices [40, 41, 43, 65]. Although most of the models analyzed incorporated this phase, the CCME model [46] and the Dojildo model did not include this phase and instead executed the final aggregation function using the actual parameter concentrations of sub-indices [18,57].

2.2. Parameter weighting

Typically, the weight value of parameters is determined by the relative significance of the water quality parameter and/or relevant water quality standards [5, 7, 10, 64]. Most WQI models employed methods of unequal weighting, ensuring that the sum of all parameter weight values equaled 1.

The Horton, Bascaron, and Almeida index models also utilized unequal weighting; however, the weights assigned were whole numbers, leading to totals that exceeded 1. Conversely, some models, like the Oregon model, adopted a system of equal weighting where each parameter was given the same weight. In contrast, the CCME index, Smith index, and Dojildo index models do not need weight values to calculate the final score [44], carryout a review of the Genesis and Evolution of Water Quality Index (WQI) and some future directions

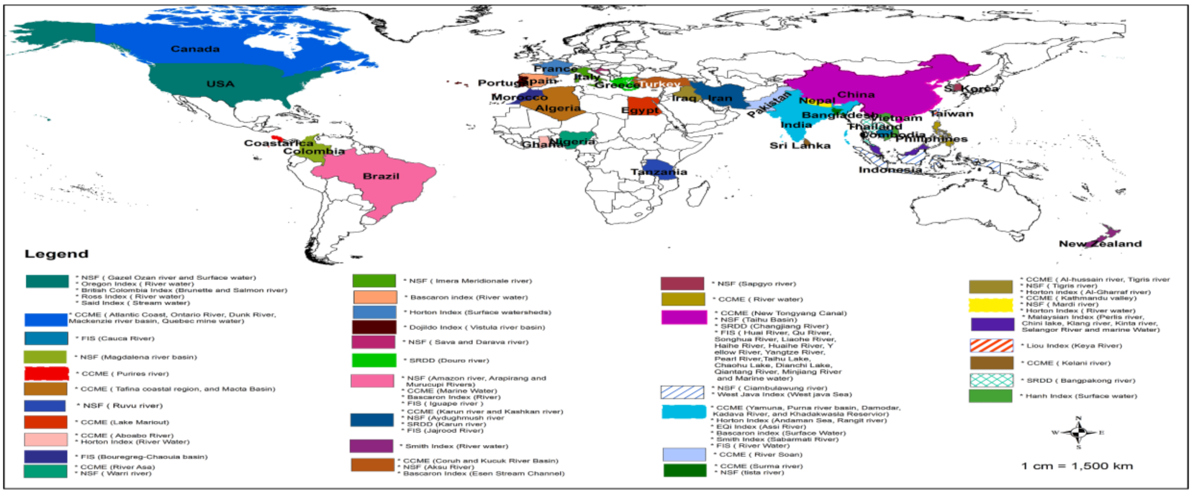


Fig. 1. Countries and types of water bodies in which WQIs have been applied globally, [44, 70]

The Delphi method was utilized for choosing water quality indicators in several applications of water quality index models [1. 19]. In this approach, essential indicators are chosen through the opinions of experts collected via interviews or surveys [31, 47]. The parameters for water quality indices were generally determined by the availability of data, the insights of specialists, or the ecological relevance of each water quality indicator. [16,50] Found that numerous water quality index models used only fundamental water quality indicators due to the unavailability of measurements for additional parameters [11, 15, 37]. A significant number of researchers adjusted the list of model parameters according to the accessibility and feasibility of data, and this sometimes made it unfeasible to incorporate vital water quality indicators into the model [45, 47, 67]. Several water quality index models excluded suspended sediments, pathogens, and harmful substances due to the expensive analysis costs and a lack of advanced laboratory capabilities.

III. MATERIALS AND METHODOLOGY

The study area is the Yakurr Local Government Area of Cross River State, South-South Nigeria. It is located approximately between latitude 5^0 48′ 3″N and longitude 8^0 4′5″E. The capital of Yakurr is Ugep. Yakurr Local Government Area is bounded in the North by Obubra, South by Biase, West by Abi and East by Akamkpa and Etung Local Government Area. According to the Nigerian census (2006), Yakurr has a population of about 196,450. The projected population as of 2022 is 298,900, with a total land mass of more than $670km^{2,}$ with a temperature range from 37^0 C to as low 21^0 C. The descriptive map of the study is presented in Figure 4, and the general structure of the WQI model is depicted in Figure 5.

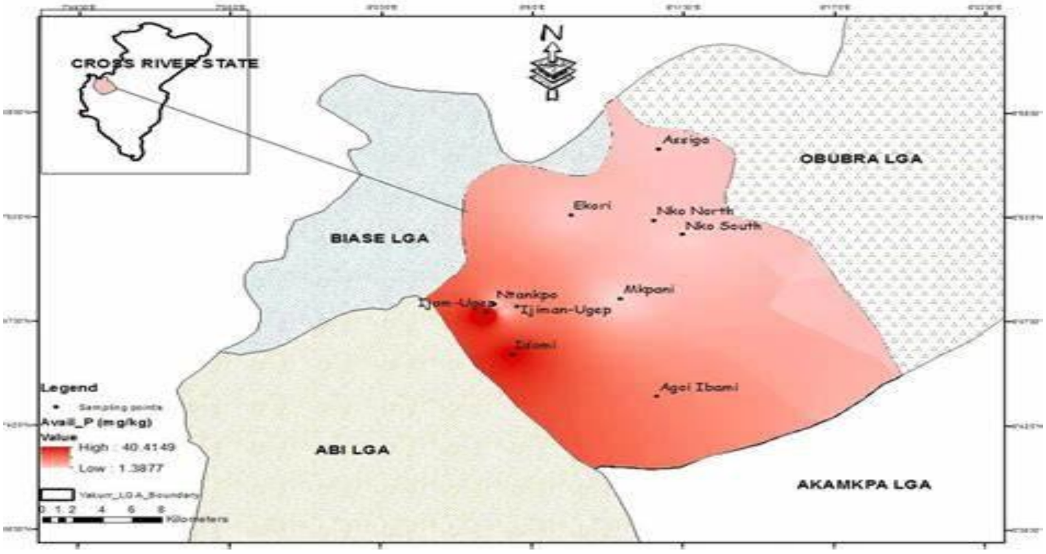


Fig.2.The map of the study area of Yakurr Local Government.

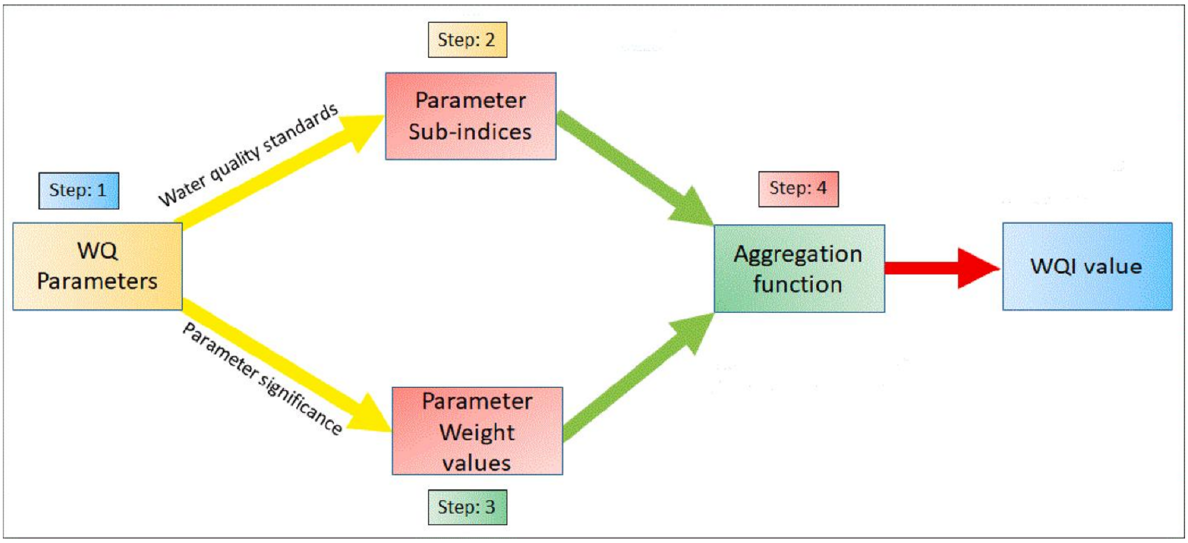
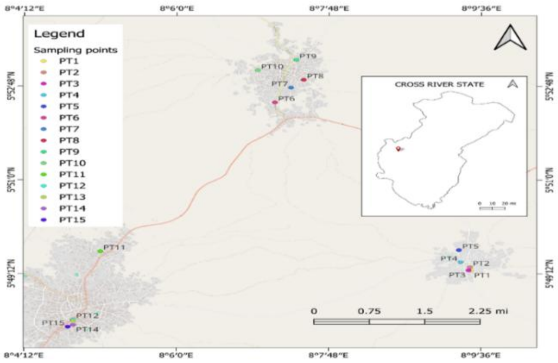
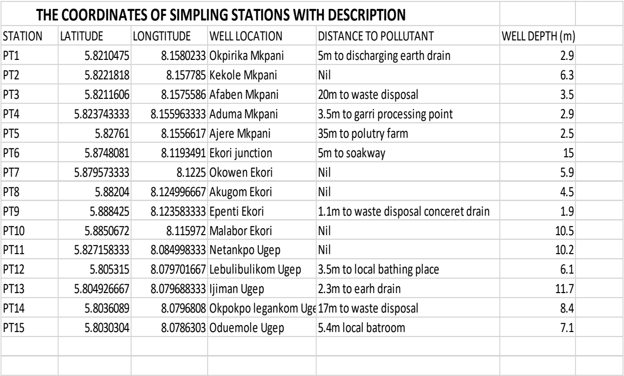


Fig. 3. General structure of WQI model.

3.2 Data Collection
During the reconnaissance survey, fifteen (15) productive wells from each of the following locations: Mkpani (PT1-PT5), Ekori (PT6-PT10), and Ugep (PT11-PT15). Thirty (30) water-filled sample bottles were gathered from the fifteen (15) sources, with two samples from each source. Before sample collection, the location of the various water sources was ascertained by GPS. One (1) liter plastic containers were used to collect water samples at several sampling locations. The sampling container was rinsed twice or three times with the water to be sampled. Additionally, upon sampling, the wells' depth was assessed. In compliance with international water and wastewater sampling protocols, the physicochemical and bacteriological analyses were carried out within 48 hours of the samples being collected from each well. The samples were tagged and transported to the laboratory in a cooler set at 40 °C.

A PH-2603 (a pH meter) was used to test the pH, EC, and Temperature in situ, while other parameters were measured in a laboratory.
QGIS 3.40.4 was the software utilized in the investigation. For the development of the research area's sample sites map. Using GIS and IDW interpolation techniques, the point data at each site was calculated to build the sample point's map.





THE COORDINATES OF SIMPLING STATIONS WITH DESCRIPTION

STATION	LATITUDE	LONGTITUDE	WELL LOCATION	DISTANCE TO POLLUTANT	WELL DEPTH (m)
PT1	5.8210475	8.1580233	Okpirika Mkpani	5m to discharging earth drain	2.9
PT2	5.8221818	8.157785	Kekole Mkpani	Nil	6.3
PT3	5.8211606	8.1575586	Afaben Mkpani	20m to waste disposal	3.5
PT4	5.823743333	8.155963333	Aduma Mkpani	3.5m to garri processing point	2.9
PT5	5.82761	8.1556617	Ajere Mkpani	35m to polutry farm	2.5
PT6	5.8748081	8.1193491	Ekori junction	5m to soakway	15
PT7	5.879573333	8.1225	Okowen Ekori	Nil	5.9
PT8	5.88204	8.124996667	Akugom Ekori	Nil	4.5
PT9	5.888425	8.123583333	Epenti Ekori	1.1m to waste disposal conceret drain	1.9
PT10	5.8850672	8.115972	Malabor Ekori	Nil	10.5
PT11	5.827158333	8.084998333	Netankpo Ugep	Nil	10.2
PT12	5.805315	8.079701667	Lebulibulikom Ugep	3.5m to local bathing place	6.1
PT13	5.804926667	8.079688333	Ijiman Ugep	2.3m to earh drain	11.7
PT14	5.8036089	8.0796808	Okpokpo legankom Uge	17m to waste disposal	8.4
PT15	5.8030304	8.0786303	Oduemole Ugep	5.4m local batroom	7.1

Fig: 4. Map showing the distribution of sampling points (wells) in the study area

Table 1. Water quality index range

Water quality index range	Water quality status
≤50	Very good water quality
51-100	Good water quality
101-200	Poor water quality
201-300	Very poor water quality
>300	Unsuitable for drinking

3.3. Data Analysis

The qualitative and quantitative evaluation of the parameters was carried out in strict accordance with the appropriate procedures. In the qualitative evaluation, various substances of interest were found, and in the quantitative evaluation, their concentrations were measured in milligrams per liter (mg/l). Water samples were collected following APHA (2017) standard procedures. A total of 19 parameters were analyzed: temperature, pH, turbidity, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), chloride, nitrate, phosphate, total hardness, sodium, calcium, magnesium, bicarbonate, dissolved oxygen (DO), biochemical oxygen demand (BOD_5), iron, fluoride, and total coliform count (TCC)

3.4. Formulation of the Water Quality Index (WQI)

The Water Quality Index has been established based on the drinking water standards suggested by the World Health Organization [71, 72, 73]. The assessment of groundwater (well) involved a desired level or defined water quality parameters, which aimed to provide insight into the extent of anthropogenic activity's impact on water quality. This study employed the Inverse Distance Weighting (IDW) method for the interpolation of the Water Quality Index (WQI). The three-stage process for determining the WQI of the measured groundwater. The initial phase involved assigning a weight (wi) to each water quality metric based on its significance in determining the overall quality of groundwater for drinking purposes. The subsequent phase involves the assignment of the relative weight (Wi) to each water quality parameter as follows

$$w_i = \frac{wi}{\sum_{n=1}^{n} \mathrm{wi}}$$

(1)

Where W_i represents the relative weight, wi denotes the weight allocated to each parameter, and n signifies the total number of parameters. In Stage 3, the quality rating scale (qi) for each parameter is calculated by dividing its concentration in each groundwater sample by the corresponding standard as per WHO guidelines[71,72]), and then multiplying the result by 100.

$$q_i = \frac{\mathrm{Vi-Vid}}{Si-Vid} * 100$$

(2)

Where q_i denotes the quality rating, and V_i represents the observed value of the ith parameter at a specified sample location. S_i represents the standard value of the ith parameter in pure water, whereas V_{id} denotes the ideal value of the ith parameter. All ideal values (V_{id}) of the drinking water parameters are set to zero, except for pH and dissolved oxygen [68]. The optimal pH for pure water is 7.0; however, the usual value for contaminated water is 8.5. The optimal dissolved oxygen level is 14.6 mg/l, although the standard for potable water is 5 mg/l.

Ultimately, the SLI is established for each physicochemical water quality indicator before calculating the WQI.

$$\mathrm{Sli=Wi} * \mathrm{qi}$$

(3)

Where S_{li} is the sub-index of the ith parameter, q_i is the rating based on the concentration of the ith parameter. The WQI can be determined by

$$\mathrm{WQI} = \sum_{n=1}^{n} \mathrm{SIi}$$

(4)

The Water Quality Index (WQI) is calculated as the summation of S_{li} for each parameter, where n is the total number of parameters. [54, 56, 62] The WQI classification standard was employed to assess the groundwater quality status at each site. According to [52], the groundwater quality in Calabar metropolitan is classified into four categories, ranging from "good" to "very poor," highlighting the necessity for prompt intervention. The NSF model used recommended parameter ranges from water quality standards to compute the sub-index values linearly [21, 42, 67]. The sub-index scale ranged between 0 and 100; when parameter concentrations were found below the recommended values, then the sub-index value was assigned 100; otherwise, 0 was registered automatically [32;42; 48,51]. The West Java WQI model used a simple linear interpolation function. In this instance, the sub-index value was calculated using equations (1) and (2).

3.5 Aggregating Functions

The WQI model uses an aggregation method as the final step. Several WQI models, such as the SRDD model, the Horton model NSF index earlier version, the House index, the Malaysian and Dlmatian index models utilizes a simple additive aggregation function expressed as,

$$WQI = \sum_{i=1}^{n} S_I \, w_I$$
(5)

Where S_i is the sub-index value for parameter I, $w_{i,}$ which ranges from 0 to 1, is the corresponding parameter weight value, and n is the number of parameters.

The West Java WQI model used a simple linear interpolation function. The sub-index was calculated using equations (6) and (7).

$$S_{i=} S_1 - \left[(S_1 - S_2)\left(\frac{X_i - X_1}{X_2 - X_1}\right)\right]$$
(6)

$$S_{i=} S_1 - \left[(S_1 - S_2)\left(\frac{X_1 - X_i}{X_1 - X_2}\right)\right]$$
(7)

Where Si is the sub-index value for water quality parameter *i* computed for the measured value *Xi*. S1 and S2 are the maximum and minimum sub-index values for the maximum and minimum guideline values (X1 and X2) for parameter *i*. Eq. (1) is used when the measured parameter value is higher than the upper guideline value; otherwise, Eq. (2) is used [19,41, 59,65] recommended equation (3) for obtaining the sub-index value for parameter *i*:

$$S_i = \frac{P_c}{M_{pl}}$$
(8)

Where *Pc* is the measured value, and *Mpl* is the maximum permissible guideline limit (mg/L) of the water quality parameter.

IV. RESULTS AND DISCUSSION

4.1 Comparison of groundwater quality with the NSDWQ and WHO.

This study presents the chosen parameters as illustrated in Tables 1, 2, 3 and 4, respectively. The paper discusses the many parameters evaluated. This study references the Nigerian Standard of Drinking Water Quality (NSDWQ 2016) and the [71, 72] drinking water standards.

The research revealed that the temperature values from Table 3 are 26.25°C and 27.45°C, with a mean value of 26.95°C. The majority of the wells have temperatures below the limits established by the WHO [71, 72]). The sub-index values derived from Table 4, ranging from 3.5 to 4.4, indicate that the temperature conditions in the groundwater of the research region comply with the acceptable limits set by WHO.

The pH is a fundamental parameter in evaluating the quality and pollution status of aquifer systems, owing to its strong association with other chemical constituents of water. It reflects the concentration of hydrogen ions, with pure water exhibiting a neutral pH that signifies equilibrium in hydrogen ion activity. From table 2 wells (points) PT11, PT12, PT13 and PT14 are below the WHO and NSDWQ standard of 6.5-8.5, indicating the acidic nature of groundwater, which may suggest anthropogenic influence, geochemical interactions with aquifer materials, or seasonal variations, all of which have implications for potability and overall water quality status.

The turbidity in groundwater indicates the presence of suspended and colloidal substances, including clay, silt, organic debris, and microbes. This study presents turbidity values in Table 3, ranging from 0.362 NTU to 2.241 NTU, with a mean concentration of 1.3915 NTU, far below the WHO [71,72] recommended level of 5.0 NTU for drinking water quality.

The seasonal fluctuation in turbidity stayed below acceptable limits, with somewhat elevated values seen during the dry season due to a decreased water table, particle resuspension, and diminished natural flushing. This indicates that, overall, the groundwater in this research region is visually acceptable and poses low danger for turbidity-related problems.

The conductivity quantifies a substance or solution's capacity to transmit electric current, which escalates in direct correlation with the concentration of dissolved substances in water. The conductivity in this investigation ranges from 44 µS/cm to 331.4 µS/cm, with an average of 187.75 µS/cm, as presented in Table 3. These values comply with the WHO (2011, 2017) threshold of 500 µS/cm and do not diminish dissolved oxygen (DO), hence preventing any disruption to aquatic species. Seasonal analysis indicated that conductivity is elevated during dry seasons owing to diminished recharge, reduced dilution, and heightened evapoconcentration, which intensify the concentration of dissolved salts and ions inside the aquifer. The extended contact between water and rock in stagnant groundwater increases mineral breakdown, whereas greater dependence on wells during arid months may lead to heightened ionic concentrations. From a water quality index (WQI) standpoint, this seasonal increase in conductivity, although predominantly remaining within WHO acceptable limits, elevates the WQI scores during the dry season by exacerbating the chemical stress on groundwater. The combination of consistently high total coliform count (TCC) with increased conductivity exacerbates the decline in water quality, rendering dry season groundwater more susceptible and less drinkable than during the rainy season.

The analysis in Table 3 showed TDS values ranging from 26.4mg/l and 171.9mg/l, with an average value of 99.7mg/l which is well below the WHO permissible limit. This indicates the water is safe and palatable, as lower TDS enhances drinking quality.

Seasonal variation showed that TDS levels were higher in the dry season owing to low recharge, limited dilution, and enhanced evaporation, which concentrated dissolved ions within shrinking aquifer volumes. Declining water tables increased water-rock interaction, promoting mineral dissolution, while intensified human reliance on wells further mobilized dissolved substances. Although still within WHO limits, the dry season rise in TDS contributed to elevated WQI scores, indicating greater chemical stress and confirming the heightened vulnerability of groundwater quality during this period.

The analysis revealed that TSS concentrations in wells PT5, PT7, PT11, PT13, and PT15 exceeded the NSDWQ (2016) and WHO (2011, 2017) permissible limit 1mg/l, with elevated values particularly evident during the dry season. This seasonal variation can be attributed to several hydrogeological and anthropogenic factors. During the dry season, declining groundwater levels enhance the mobility of fine sediments such as silt and clay, thereby increasing suspended particle load in well water. In addition, higher water abstraction during this period tends to disturb the aquifer matrix, releasing more particulate matter. Poorly constructed wells further exacerbate this condition by allowing the direct entry of sediments. Similarly, open wells and fractured zones provide pathways through which loose particles are easily transported into the aquifer system. Furthermore, during prolonged dry spells, aquifers may become more vulnerable to surface contamination and suspended solids intrusion through cracks or open recharge points.

From a water quality perspective, elevated TSS values have significant implications. High levels of suspended solids increase turbidity, which reduces water clarity and may impair its palatability. Beyond aesthetic concerns, excessive turbidity can shield pathogenic microorganisms from disinfection processes, thereby increasing the risk of microbial contamination. This condition compromises the safety of groundwater for domestic consumption and may pose potential health risks, especially in communities' dependent on untreated well water. Additionally, persistently high TSS concentrations may accelerate the clogging of water storage and distribution systems, increasing maintenance costs. Thus, the elevated TSS values observed in the study area during the dry season highlight both environmental vulnerability and public health concerns. The Chloride concentrations in the study region varied from 2.00 to 5.95 mg/l, with a mean value of 3.975 mg/l. These results are well beneath the World Health Organization (WHO) permitted threshold of 250 mg/l for potable water, as specified in the 2011 and 2017 recommendations. The reduced chloride concentrations suggest that the groundwater (wells) in this research location is not negatively affected by saline intrusion, residential wastewater, or industrial effluents. This indicates that the aquifer system is mostly unpolluted and chemically acceptable for home and agricultural use.

This research observed nitrate values between 2.53 and 7.8 mg/l, with an average of 5.165 mg/l. The measured levels are far lower than the WHO allowed limit of 50 mg/l for drinking water, suggesting that the groundwater is not substantially affected by nitrate pollution. The study found phosphate concentration in groundwater (well) in table 3 ranged from 4.1 mg/l and 8.8mg/l with an average or 6.45mg/l. These values exceeded WHO (2011, 2017) standard for drinking water quality limit of 50mg/l, all the wells have exceeded in multiple samples. The elevated level was mainly linked to anthropogenic pollution, such as fertilizer use on agricultural land, cattle feces, sediment accumulation and the influence of a high-water table, all contributing to reduced soil conditions. It noted as the key contamination to WQI of the study area. The Water hardness results from dissolved calcium and magnesium carried into the groundwater through soil and rock. In this study, hardness in table 3 ranged from 9.35 – 50.35 mg/l, with an average of 29.85mg/l, which is well within the permissible limit of 100mg/l. In the present study, sodium ranged between 0.83 to 3.2mg/l with a mean of 2.015mg/l in table 3 and very well below WHO permissible limit of 50 to 200mg/l.

The Calcium enters the aquifer through the leaching of calcium-bearing minerals. In this study, calcium concentration ranged from 4.1 to 16.5mg/l, which is within the permissible limit. The seasonal analysis revealed that calcium levels elevated during the dry season reflect both natural processes (evapoconcentration and rock dissolution) and seasonal hydrological imbalance (low recharge and dilution), making the aquifer more mineralized.

Magnesium in groundwater originates mainly from the dissolution of magnesium-bearing minerals. In this study, magnesium concentration ranges from 7.55 to 34.8mg/l with an average of 21.175mg/l below the WHO permissible limit, contributing to water hardness but not at levels harmful to health. Bicarbonate is derived from the dissolution of carbonate minerals and soil CO_2. This study ranges from 1.015 – 6.25mg/l within the WHO permissible limit indicate natural buffering capacity, helping to maintain pH stability and water alkalinity. The Dissolved Oxygen (DO) values reflect the aeration status of groundwater. In this study is from 7.0 to 12.5mg/l in Table 3 and is within the WHO permissible limit. The DO levels are moderate, indicating some degree of natural recharge and circulation, which support aerobic microbial activity.

The Biochemical Oxygen Demand (BOD_5) levels, which measure organic pollution. In this present study ranges from 5.5 to 11.0mg/l below the permissible limit, this suggest limited organic contamination and does not threaten portability. Iron in groundwater originates primarily from the weathering of iron-bearing rocks and minerals. It typically occurs in the soluble ferrous (Fe^{2+}) state, which is stable under reducing conditions. Upon exposure to atmospheric oxygen or microbial activity, Fe^{2+} oxidizes to insoluble ferric (Fe^{2+}) forms, often leading to precipitation as oxides and hydroxides. This process explains why iron concentrations in groundwater are usually higher than in surface waters. In the present study, measured iron concentration varied, ranging from 0.039 to 0.975mg/l, with a mean value of 0.502mg/l. This exceeds the NSDWQ permissible limit of 0.3mg/l for drinking water. The seasonal variation in table 1 and figures 1 to 15 showed that iron is higher in the dry season than raining season. The analysis revealed that some wells (e.g. PT2, PT3, PT5, and PT7, 1, 12, 13, 14 and 15) recorded higher contamination levels. The elevated iron concentrations are attributed to the dissolution of iron – bearing minerals in soil, coupled with percolation and the underground flow process. It is noted as the key contaminant contributing to very poor and unsuitable drinking water quality. The measured fluoride concentrations in the study groundwater ranged from 0.17 to 0.955mg/l, with an average of 0.5625mg/l. These values fall within the WHO (2011, 2017) permissible limit of 1.5mg/l, indicating that fluoride does not pose a risk of dental or skeletal fluorosis. The calcium availability in the aquifer likely contributes to maintaining low and safe fluoride concentrations in the groundwater.

The analysis of groundwater quality revealed elevated levels of TCC across all the sampling points (wells), ranging from 21-164cfu/100ml, far exceeding the WHO guideline of 1cfu/100ml, indicating widespread microbial contamination. The high TCC values can be attributed to a combination of hydrogeological, environmental, and anthropogenic factors that characterize the study area. The majority of wells are shallow, poorly constructed, with inadequate lining and covers; such wells are highly vulnerable to infiltration of surface contaminants, particularly during rainfall events. The problem is compounded by the proximity of many wells to pit latrines, refuse dumps, earth drains, and local bathrooms, which serve as direct sources of faecal matter leaching into groundwater. This supports the observation by Roza and Singh (2010), who noted that the interaction of hydrological conditions and anthropogenic activities often influences changes in groundwater quality.

The persistence of high TCC values is also linked to poor hygiene and sanitation practices within the study area. Open defecation, indiscriminate waste disposal, and the drawing of water with unclean containers all contribute to the direct introduction of bacteria into the wells. The seasonal evaluation revealed that TCC was significantly higher during the dry season. This indicates that microbial contamination is most severe when groundwater recharge is minimal and dilution capacity is low, leading to water stagnation in shallow aquifers. Interestingly, several key physicochemical parameters, including conductivity, turbidity, nitrate, and total dissolved solids (TDS), also exhibited elevated values during the dry season. These increases may be attributed to higher evaporation rates, reduced water levels, and greater concentration of dissolved minerals and suspended particles. Despite these seasonal rises, the values of nitrate, turbidity, TDS, and conductivity largely remained within WHO permissible limits, unlike TCC, which consistently exceeded the safe threshold. This pattern demonstrates that while both chemical and microbial parameters intensify in the dry season, the greatest health risk remains microbiological, making TCC the primary driver of poor Water Quality Index (WQI) outcomes in the study area. In this study, well water samples were taken during one hydrological year to evaluate their water quality, and the quality parameters were analyzed comparing with three indices, such as the Iran Surface Water Quality Index (IRWQIsc), the National Sanitation Foundation Water Quality Index (NSFWQI), and the Canadian Water Quality Index (CCMEWQI). The use of these three indices provides a comprehensive approach to water quality assessment and management, enabling us to better understand the health and sustainability of water resources. According to the results, the IRWQISC index ranges from 50 to 78.9, the NSFWQI index ranges from 57 to 73, and the CCME WQI index ranges from 30 to 42, indicating moderate to poor water quality in the wells. The main factors contributing to the low quality of water are the entry of pollutants from residential and agricultural areas, uncontrolled human activities, and land use changes along the river.

4.2 Relationship between groundwater parameters in Yakurr

The relationships between the parameters of groundwater were demonstrated using Pearson's correlation matrix (Table 2). Strong positive or negative relationships as well as moderate and weak relationships exist between the parameters of groundwater in Yakurr. Strong positive and negative relationships turbidity and TSS (r=0.942), EC and TDS (r=0.997), Magnesium (r=0.959). The remaining parameters have moderate to weak relationships. Well correlated pairs likely have common sources (Mouli et al., 2005).

4.3 Water quality of groundwater in Yakurr L.G.A.

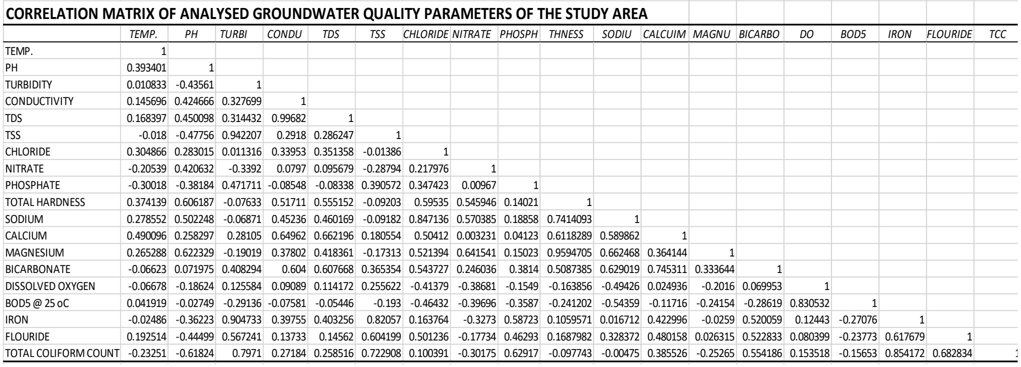
This study evaluated the WQI for Yakurr based on selected variables (Tables 1,2,3 and 4). The research also investigates the seasonal and WQI variability of the groundwater (well) quality across three communities in Yakurr L.G.A.: Mkpani (PT1-PT5), Ekori (PT6-PT10) and Ugep (PT11-PT15). It further identifies key pollutants contributing to water contamination, to model the spatial distribution of groundwater quality index map utilizing GIS and to hotspots where the most unsatisfactory (unsafe) groundwater is found, as well as a statistical approach in the study area. Also highlights public health implications and recommends a sustainable solution. The WQI values in fig15 ranged from 117.1 to 811.4 across the 15 wells. Based on WQI classification, 2 wells were categorized as "Poor," 4 as "Very Poor," and 9 as "Unsuitable for Drinking." Ugep recorded the highest contamination levels, with all wells falling into the "Unsuitable for Drinking" category. Ekori showed relatively better water quality.

WQI analysis revealed contamination hotspots in Ugep, well PT10 in Ekori and parts of Mkpani. Seasonal comparison showed higher pollution levels during the dry season due to lower recharge and concentration of pollutants. The most critical contaminants were iron, phosphate, and total coliform count, exceeding WHO guidelines in multiple samples.

The results show that groundwater (well) in Yakurr LGA is significantly affected by both anthropogenic and seasonal factors. Ugep's poor water quality is linked to higher population density, improper sanitation, and waste disposal near wells. The presence of iron, phosphate, and TCC at elevated levels indicates contamination from natural geological sources, agricultural runoff, and faecal matter.

Correlation analysis in the table revealed strong relationships between EC and TDS, and between nitrate and phosphate, suggesting common sources of contamination. GIS maps illustrated clear spatial trends, assisting in identifying critical areas requiring urgent intervention.
These findings raise serious public health concerns as the water is used directly for drinking without treatment, potentially exposing residents to gastrointestinal infections, heavy metal toxicity, and waterborne diseases.

Table 2. Correlation matrix



CORRELATION MATRIX OF ANALYSED GROUNDWATER QUALITY PARAMETERS OF THE STUDY AREA

	TEMP.	PH	TURBI	CONDU	TDS	TSS	CHLORIDE	NITRATE	PHOSPH	THNESS	SODIU	CALCUIM	MAGNU	BICARBO	DO	BOD5	IRON	FLOURIDE	TCC
TEMP.	1																		
PH	0.393401	1																	
TURBIDITY	0.010833	-0.43561	1																
CONDUCTIVITY	0.145696	0.424666	0.327699	1															
TDS	0.168397	0.450098	0.314432	0.99682	1														
TSS	-0.018	-0.47756	0.942207	0.2918	0.286247	1													
CHLORIDE	0.304866	0.283015	0.011316	0.33953	0.351358	-0.01386	1												
NITRATE	-0.20539	0.420632	-0.3392	0.0797	0.095679	-0.28794	0.217976	1											
PHOSPHATE	-0.30018	-0.38184	0.471711	-0.08548	-0.08338	0.390572	0.347423	0.00967	1										
TOTAL HARDNESS	0.374139	0.606187	-0.07633	0.51711	0.555152	-0.09203	0.59535	0.545946	0.14021	1									
SODIUM	0.278552	0.502248	-0.06871	0.45236	0.460169	-0.09182	0.847136	0.570385	0.18858	0.7414093	1								
CALCIUM	0.490096	0.258297	0.28105	0.64962	0.662196	0.180554	0.50412	0.003231	0.04123	0.6118289	0.589862	1							
MAGNESIUM	0.265288	0.622329	-0.19019	0.37802	0.418361	-0.17313	0.521394	0.641541	0.15023	0.9594705	0.662468	0.364144	1						
BICARBONATE	-0.06623	0.071975	0.408294	0.604	0.607668	0.365354	0.543727	0.246036	0.3814	0.5087385	0.629019	0.745311	0.333644	1					
DISSOLVED OXYGEN	-0.06678	-0.18624	0.125584	0.09089	0.114172	0.255622	-0.41379	-0.38681	-0.1549	-0.163856	-0.49426	0.024936	-0.2016	0.069953	1				
BOD5 @ 25 oC	0.041919	-0.02749	-0.29136	-0.07581	-0.05446	-0.193	-0.46432	-0.39696	-0.3587	-0.241202	-0.54359	-0.11716	-0.24154	-0.28619	0.830532	1			
IRON	-0.02486	-0.36223	0.904733	0.39755	0.403256	0.82057	0.163764	-0.3273	0.58723	0.1059571	0.016712	0.422996	-0.0259	0.520059	0.12443	-0.27076	1		
FLOURIDE	0.192514	-0.44499	0.567241	0.13733	0.14562	0.604199	0.501236	-0.17734	0.46293	0.1687982	0.328372	0.480158	0.026315	0.522833	0.080399	-0.23773	0.617679	1	
TOTAL COLIFORM COUNT	-0.23251	-0.61824	0.7971	0.27184	0.258516	0.722908	0.100391	-0.30175	0.62917	-0.097743	-0.00475	0.385526	-0.25265	0.554186	0.153518	-0.15653	0.854172	0.682834	1

Table 3: Statistical Analysis of Groundwater (Well) Quality Parameters and Its Coherence with NSDWQ and WHO Standards.

S/NO	Parameters /unit	Drinking water standards		Statistical analysis of Observed valued			
		NSDWQ 2016	WHO (2011), (2017)	MIN	MAX	MEAN	SD
1	TEMPERATURE (ºC)	Ambient	27-29	26.45	27.45	26.95	0.707106781
2	pH	6.5-8.5	7-8.5	5.5	7.4	6.45	1.343502884
3	TURBIDITY (NTU)	5	5	0.362	2.421	1.3915	1.455932862
4	CONDUCTIVITY (µs/cm)	500	500	44	331.5	187.75	203.2931996
5	TDS (mg/l)	500	600-1000	26.4	171.9	99.15	102.8840367
6	TSS (mg/l)	0.1	1	0.006	1.952	0.979	1.376029796
7	CHLORIDE (mg/l)	100	250	2	5.95	3.975	2.793071786
8	NITRATE (mg/l)	10	50	2.53	7.8	5.165	3.726452737
9	PHOSPHATE (mg/l)	100	5	4.1	8.8	6.45	3.323401872
10	TOTAL HARDNESS (mg/l)	100	100	9.35	50.35	29.85	28.99137803
11	SODIUM (mg/l)	100	50-200	0.83	3.2	2.015	1.675843071
12	CALCUIM (mg/l)	10	75	4.1	16.5	10.3	8.768124087
13	MAGNESIUM (mg/l)			7.55	34.8	21.175	19.26865979
14	BICARBONATE (mg/l)			1.015	6.25	3.6325	3.701704
15	DISSOLVED OXYGEN (mg/l)	14	5≥14	7	12.5	9.75	3.889087297
16	BOD_5 @ 25^0C			5.5	11	8.25	3.889087297
17	IRON (mg/l)	0.3	0.3	0.03	0.975	0.5025	0.668215908

18	FLOURIDE (mg/l)	1.5	1.5	0.17	0.955	0.5625	0.555078823
19	TOTAL COLIFORM COUNT /100ml (cfu)	0	1	21	164	92.5	101.1162697

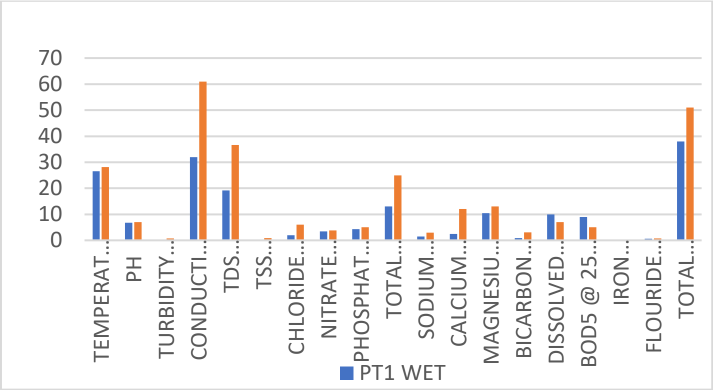


Fig 5. Comparison analysis for well and dry season for well 1.

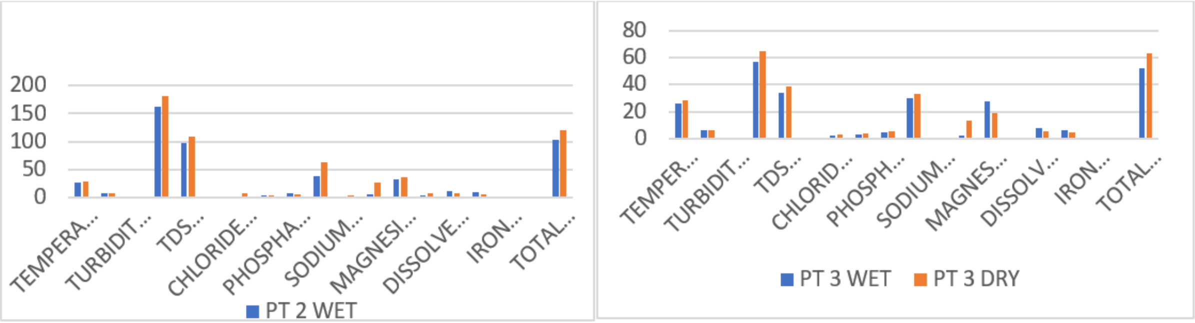


Fig. 6. Comparison analysis for wet and dry season for wells 2 and 3.

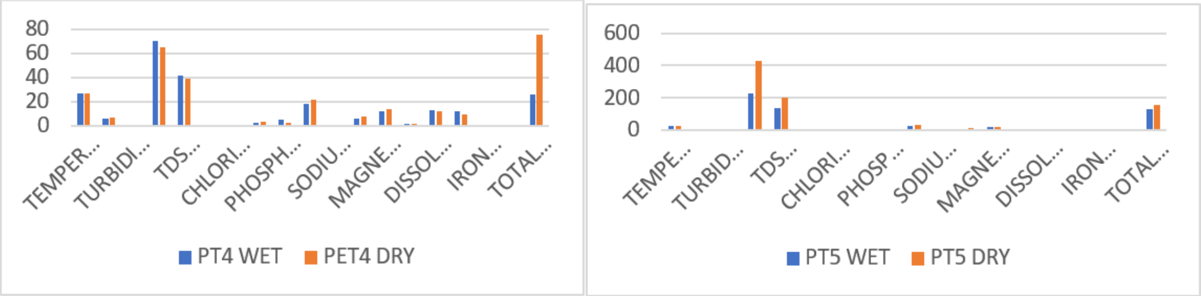


Fig. 7. Comparison analysis for wet and dry season for wells 4 and 5.

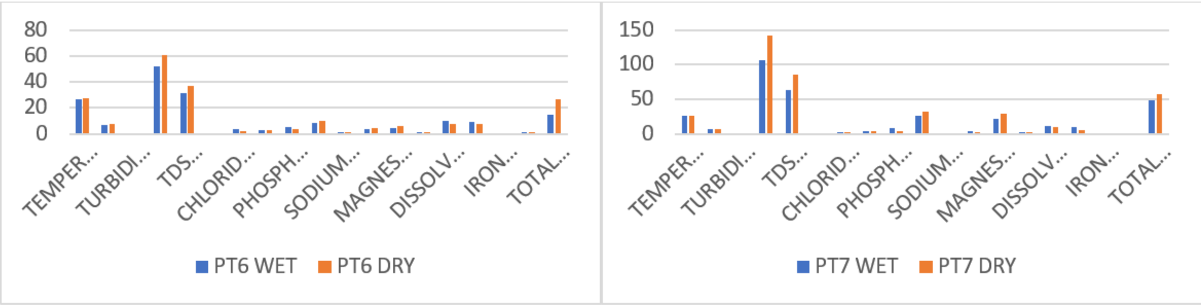


Fig. 8. Comparison analysis for wet and dry season for wells 6 and 7

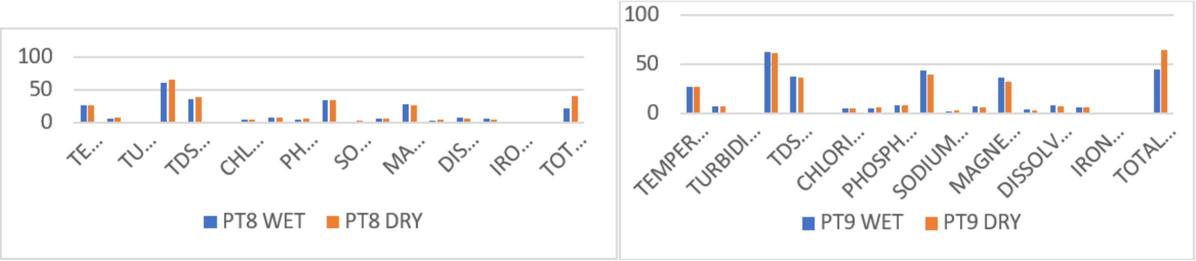


Fig. 9. Comparison analysis for wet and dry season for wells 8 and 9.

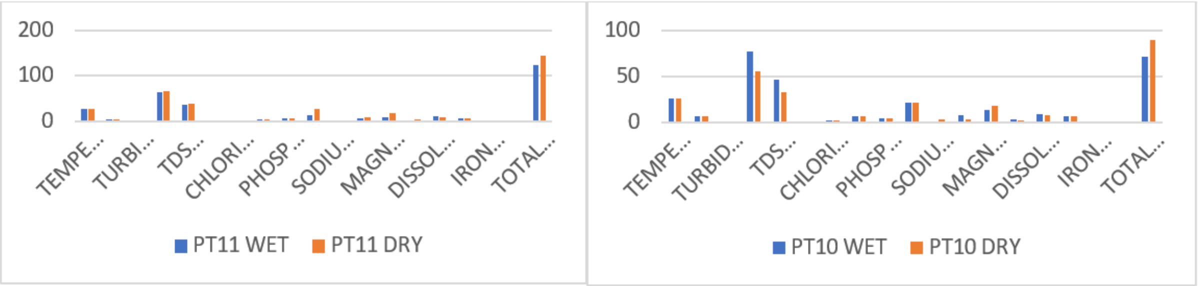


Fig. 10. Comparison analysis for wet and dry season for wells 10 and 11

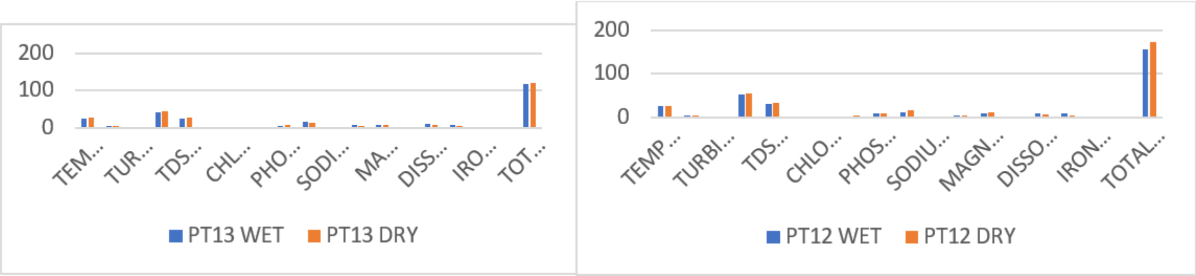


Fig. 11. Comparison analysis for wet and dry season for wells 12 and 13

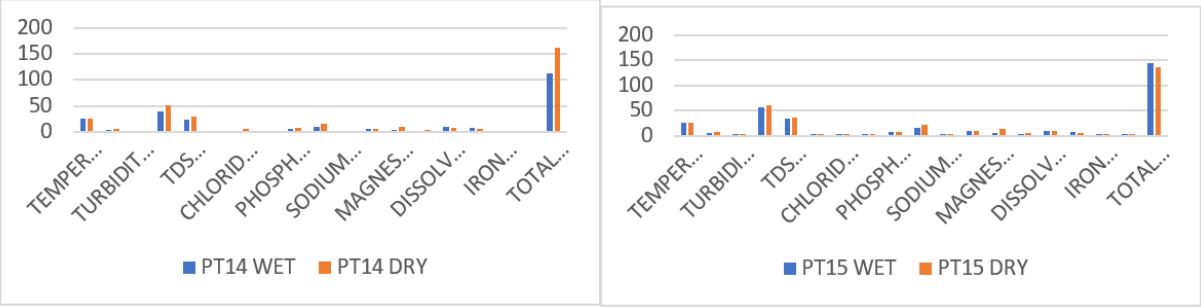


Fig. 12. Comparison analysis for wet and dry season for wells 14 and 15

Fig. 13. Groundwater Classification Index System of Yakurr Catchment Area

Table 4. WQI and rating for the water wells samples

Well Station	WQI Rate	Rating of Water Quality Classification
PT.1	233.7005	Very Poor
PT.2	575.6531	Unsuitable for drinking
PT.3	302.5427	unsuitable for drinking
PT.4	255.083	very poor
PT.5	724.9082	unsuitable for drinking
Pt.6	117.0638	Poor
Pt.7	289.4482	Very poor
Pt.8	169.336	Poor
Pt.9	285.56079	Very poor
Pt.10	397.6981	Unsuitable for drinking
Pt.11	670.3585	Unsuitable for drinking
Pt.12	811.4034	Unsuitable for drinking
Pt.13	594.2103	Unsuitable for drinking
Pt.14	671.5192	Unsuitable for drinking
Pt.15	702.2654	Unsuitable for drinking

V. CONCLUSION

This study developed and applied a Water Quality Index (WQI) to evaluate the status of well water in Yakurr Local Government Area. The findings indicate that most of the sampled wells are either very poor or unsuitable for drinking, with WQI values between 117.1 and 811.4. Ugep was identified as the most affected community, and key contaminants included iron, phosphate, and TCC. Most WQI models involve four stages: (1) selection of water quality parameters, (2) determination of parameter sub-indices, (3), determination of parameter weightings and (4) aggregation of the sub-indices to compute the overall water quality index. The water quality index (WQI) model is a popular tool for evaluating surface water quality. It uses aggregation techniques that allow conversion of extensive water quality data into a single value or index. Globally, the WQI model has been applied to evaluate water quality (surface water and groundwater) based on local water quality criteria. Since its development in the 1960s, it has become a popular tool due to its generalized structure and ease-of-use.

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