

# Hydrochemical Characterization and Water Quality Index Modelling of Shallow Groundwater in Igarra Town, Northern Edo State, Nigeria: Seasonal Dynamics and Drinking Water Suitability

OSAYANDE, A.D

*Department of Geology and Mining Technology, University of Port Harcourt, P.M.B 5323, Choba, Port Harcourt, Nigeria*

*Abstract- Shallow groundwater resources in the basement complex terrain have been identified as the main source of water for millions of rural dwellers in Nigeria. However, the hydrochemical characteristics of the groundwater and its potability have been less understood in many rural areas. This study carried out a comprehensive hydrochemical characterization and Water Quality Index (WQI) assessment of twenty hand-dug wells in three municipal districts: Uffa, Itua, and Ugbogbo in Igarra town, Akoko-Edo Local Government Area, northern Edo State, Nigeria. The study was done using data collected during the wet season (July 2011) and the dry season (December 2011). Eleven physiochemical parameters: pH, electrical conductivity, total dissolved solids, turbidity, total hardness, total alkalinity, sulphate, chloride, nitrate, phosphate, and manganese were evaluated against WHO permissible limits for water quality set in 2011, SON permissible limits set in 2007, and FME permissible limits set in 1996. The weighted arithmetic method was used to calculate the WQI for all the twenty wells in the wet and dry seasons. The study found that 85% of the wells have water quality classified as 'poor' and 'very poor' for the wet season. In the dry season, the percentage increased to 95%. The study showed that high turbidity, supraoptimal electrical conductivity, and pH values beyond the recommended range of 6.5–8.5 were the main factors affecting the water quality. Hydrochemical facies were classified using the ionic ratio method. The study showed that the hydrochemical facies were predominantly  $Ca^{2+}$ - $Mg^{2+}$ - $HCO_3^-$ . The result of this analysis revealed that rock-water interaction was a major hydrochemical phenomenon controlling groundwater chemistry. In addition, WQI spatial mapping revealed a groundwater chemistry deterioration gradient from northeast to southwest that was generally related to regolith thickness and organic matter content. This study offers an evidence-based guideline for managing Igarra*

*groundwater chemistry in seasons and aligns with SDGs 6, 3, and 11.*

*Index Terms- water quality index; hydrochemistry; basement complex; groundwater; seasonal variation; Nigeria; Gibbs diagram; drinking water suitability*

## I. INTRODUCTION

Water resources in the form of groundwater are the largest accessible freshwater resource on Earth and supply 50% of the world's domestic water and over 40% of water required for agriculture (Gleeson et al., 2012). In SSA, the percentage of rural populations relying on groundwater as their primary potable water supply is significantly higher; 65 to 85% of rural populations in Nigeria, Ghana, and other countries in West Africa depend on groundwater as their primary potable water supply (UNICEF, 2021; MacDonald et al., 2012). The shallow weathered zone aquifer system contained within basement complex terrains is particularly relevant to this issue and is accessible via hand-dug well and shallow borehole construction with minimal drilling technology; it is therefore the most economically accessible water supply to low-income rural communities in SSA and elsewhere (Taylor & Howard, 2000; Chilton & Foster, 2014).

Nevertheless, the hydrochemical quality of shallow basement complex groundwater in many Nigerian communities is generally poorly characterized beyond the simple comparison of raw value data with national or international drinking water quality standards. Although such comparisons are necessary, they remain inadequate as the basis for informed

water resource management decisions because they do not account for the holistic quality of the water as experienced by consumers—in a way that is easily communicated to the public, which is the very basis of the Water Quality Index (WQI) methodology. The WQI methodology is a composite index of multiple parameters represented along a single dimensionless scale to intuitively represent the suitability of the water for a particular use (most commonly consumption as drinking water) (Brown et al., 1972; Ramakrishnaiah et al., 2009; Şener et al., 2017).

Hydrochemical characterization via ionic ratio analysis, Piper trilinear diagrams, and Gibbs diagrams facilitates the identification of the major controlling processes in the groundwater hydrochemistry, i.e., whether the ionic composition is indicative of rock weathering, evaporation-concentration, and precipitation (Gibbs, 1970). The identification of the major controlling processes is critical for distinguishing between naturally occurring and anthropogenically enhanced degradation of water quality, the latter having direct implications for the choice of remedial strategy (Appelo & Postma, 2004; Freeze & Cherry, 1979). The hydrochemistry of the groundwater within the Igarra basement complex has not been characterized via WQI and Gibbs diagrams. The study by Osayande et al. (2015) provided the baseline data on the physicochemical parameters of twenty hand-dug wells within the Igarra basement complex during the wet and dry seasons of 2011. The study, however, only made a comparison of the parameters without computing the WQI and identifying the hydrochemical processes. The present study extends the Osayande et al. (2015) study by computing the WQI and identifying the hydrochemical processes, thus providing a much more comprehensive characterization. In the context of the Nigerian government's efforts to attain the Sustainable Development Goal 6 (Clean Water and Sanitation) by 2030, WQI-based assessments have been recognized by the state water agencies and local government authorities as critical for the development and execution of strategies to attain the goal. The Edo State Water Corporation and the Akoko-Edo Local Government Authority have identified the improvement of groundwater quality in the rural areas as a critical development issue, but the

assessments based on the WQI have not been conducted.

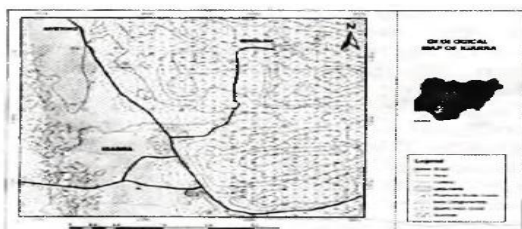
The specific objectives of this study are as follows: (i) to assess the physicochemical quality of twenty hand-dug wells in Igarra town, Nigeria, over both the wet and dry seasons, with reference to WHO, SON, and FME standards; (ii) to calculate WQI values using the weighted arithmetic mean approach for each well over both seasons; (iii) to determine the hydrochemical facies through ionic ratio analysis and  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{HCO}_3^-$ ,  $\text{Cl}^-$ , and  $\text{SO}_4^{2-}$  composition analysis; (iv) to determine the prevailing hydrochemical processes through Gibbs diagram analysis; and (v) to determine the spatial and seasonal patterns of groundwater quality degradation.

## II. STUDY AREA

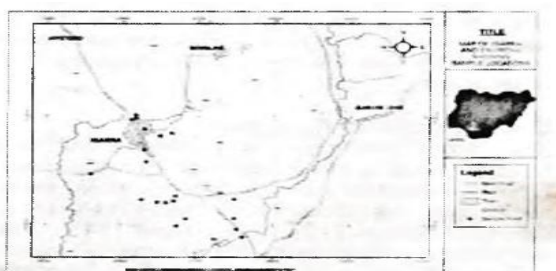
Igarra town is located within the Akoko-Edo Local Government Area of northern Edo State, Nigeria. The town lies between latitudes  $7^{\circ}15'N$  and  $7^{\circ}18'N$ , and longitudes  $6^{\circ}00'E$  and  $6^{\circ}07'E$ . The town is underlain by the Proterozoic basement complex, which comprises a polymetamorphic series of crystalline rocks, mainly granites, migmatites, quartzites, and charnockites, with some intrusive granites and granite veins, as described by Rahaman (1976). The regolith overlying the crystalline basement complex comprises deeply weathered lateritic soils and saprolite, ranging from less than one metre overlying the granite exposures to more than fifteen metres overlying the valley bottoms. The regolith layer serves as the major aquifer system, from which groundwater is obtained from hand-dug wells, with the depth to water table ranging from two to twelve metres.

The area around Igarra is characterized by a humid tropical climate, which is controlled by the north-south migration of the Inter-Tropical Convergence Zone (ITCZ). The wet season occurs from April to October, when the southwesterly winds prevail, resulting in a mean monthly rainfall of 150-280 mm. In contrast, the dry season occurs from November to March, when the dry northeasterly harmattan winds prevail, resulting in a monthly rainfall of less than 10 mm. The mean annual temperature is about  $27^{\circ}C$  with low diurnal and seasonal variation. The major

hydrological network includes the Opolomi River and the Ojirami River, which are both seasonal rivers that originate from the central granite massif. These rivers drain northward or in a south-west direction. During the dry season, the rivers dry up completely, leaving the people of the area with no option but to rely on the shallow hand-dug wells. Thus, the entire water demand of the people of the area is satisfied through the shallow hand-dug wells. The area around Igarra is characterized by a dendritic drainage pattern, which is typical of a geologically homogeneous crystalline basement. Three districts of the area were selected for the study. These districts include Uffa, Itua, and Ugbogbo, where the wells were labeled S1-S7, S8-S14, and S15-S20, respectively. This covered the entire area of the town.



**Fig.1: Geological Map of Igarra Town and the Surrounding Areas (9).**



**Fig. 2: Map of Igarra Town and its Environs Showing the Sampled Hand Dug Wells**

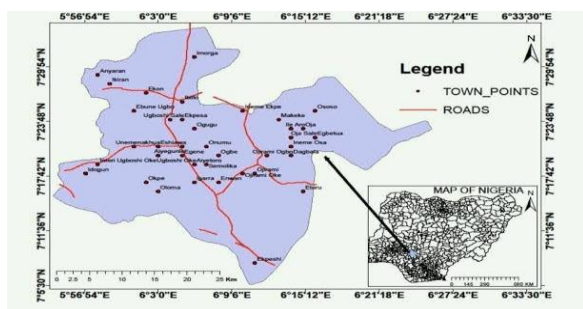


Figure 3 Map of Akoko Edo

### III. MATERIALS AND METHODS

#### 3.1 Sample Collection and Physicochemical Analysis

Water samples were collected from twenty hand-dug wells during the wet season (July 2011) and dry season (December 2011), with duplicate samples collected at each sampling event to ensure analytical reproducibility. Samples were collected in 1.5-litre pre-cleaned polyethylene bottles, transported to the laboratory in ice-cooled containers within four hours, and stored at 4°C prior to analysis. The pH and electrical conductivity (EC) were determined in situ at sampling points using calibrated digital instruments (GMBH D4040 Neuss pH meter; Radiometer Copenhagen CDM83 conductivity meter). Turbidity was measured spectrophotometrically at a specified wavelength using a HACH DR 2010 datalogging spectrophotometer and expressed in Formazin Attenuation Units (FAU). Total Dissolved Solids (TDS) was gravimetrically determined using the procedure described by Ademoroti (1996). Total hardness and total alkalinity were titrimetrically evaluated, while sulphates were determined using the turbidimetric method. Chlorides were titrated using Mohr's titration reagent, whereas nitrates and phosphates were analyzed using the colorimetric method and ascorbic acid reduction method, respectively (APHA, 1993; ASTM, 1990). Duplicate analyses were made, and the results averaged.

#### 3.2 Water Quality Index (WQI) Computation

The computation of the Water Quality Index (WQI) was done using the weighted arithmetic mean method as described by Brown et al. (1972) and applied to groundwater quality assessment studies in Nigeria and West Africa (Adimalla & Qian, 2019; Şener et al., 2017; Ramakrishnaiah et al., 2009). The computation of the WQI is done through four sequential steps. First, a relative weight ( $W_i$ ) is assigned to each parameter based on its importance to drinking water quality on a scale of 1 (least critical) to 5 (most critical), drawing on WHO and SON guidelines for parameter significance:

$$W_i = w_i / \sum w_i \quad (1)$$

where  $w_i$  is the assigned weight of the  $i$ th parameter and  $W_i$  is its relative weight. Second, a quality rating scale ( $q_i$ ) is computed for each parameter at each sampling point:

$$q_i = [(V_i - V_{ideal}) / (S_i - V_{ideal})] \times 100 \quad (2)$$

where  $V_i$  is the measured value of the parameter,  $V_{ideal}$  is its ideal value (zero for most parameters; 7.0 for pH), and  $S_i$  is the WHO/SON permissible standard for that parameter. Third, the sub-index ( $SI_i$ ) for each parameter is calculated:

$$SI_i = W_i \times q_i \quad (3)$$

Finally, the WQI for each sampling point is computed as the summation of all sub-indices:

$$WQI = \sum SI \quad (4)$$

WQI values are categorised as follows: <50 = Excellent; 50–100 = Good; 100–200 = Poor; 200–300 = Very Poor; >300 = Unfit for drinking (Ramakrishnaiah et al., 2009). The eleven parameters included in the WQI computation, together with their assigned weights ( $w_i$ ) and WHO/SON standards, are presented in Table 1.

### 3.3 Hydrochemical Facies Classification

Hydrochemical facies were determined through analysis of dominant cation and anion equivalents in each water sample. Major cation concentrations ( $Ca^{2+}$ ,  $Mg^{2+}$ ,  $Na^+$ ,  $K^+$ ) and anion concentrations ( $HCO_3^-$ ,  $Cl^-$ ,  $SO_4^{2-}$ ) were estimated from the measured total hardness, total alkalinity, sulphate, and chloride data following standard hydrochemical calculation procedures (Freeze & Cherry, 1979; Appelo & Postma, 2004). Water types were grouped into four major hydrochemical facies, namely,  $Ca^{2+} - HCO_3^-$ ,  $Na^+ - Cl^-$ ,  $Ca^{2+} - Cl^-$ , and  $Na^+ - HCO_3^-$ , based on the prevailing ion pairs that account for >50% milliequivalent concentration in a water sample (Back, 1966).

### 3.4 Gibbs Mechanism Diagram Analysis

The Gibbs mechanism diagrams were employed to determine the prevailing hydrochemical processes that control the ionic composition of the shallow groundwater. The Gibbs ratio for anions, i.e.,  $Cl^- / (Cl^- + HCO_3^-)$ , and cations, i.e.,  $Na^+ / (Na^+ + Ca^{2+})$ , was plotted against TDS to determine three major processes that control the ionic composition. These processes are precipitation dominance, rock dominance, and evaporation dominance, which correspond to low values of the Gibbs ratio, intermediate values, and high values, respectively. The waters under precipitation dominance have low values of TDS and the Gibbs ratio, whereas those under rock dominance have intermediate values. The waters under evaporation dominance have high values of TDS and the Gibbs ratio. The values of the Gibbs ratio for the Igarra well waters were calculated from the concentration values of chloride, alkalinity, hardness, and TDS.

Table 1. Parameters, assigned weights, WHO/SON standards, and relative weights used in WQI computation

Parameter	$w_i$ (weight)	$W_i$ (rel. weight)	Videal	WHO/SO N standard ( $S_i$ )	Unit
pH	4	0.117	7.0	6.5–8.5	–
Turbidity	5	0.147	0	5.0	FAU
TDS	4	0.117	0	500	mg/L
EC	3	0.088	0	1000	$\mu S/cm$
Total Hardness	3	0.088	0	500	mg/L
Total Alkalinity	2	0.059	0	200	mg/L
Sulphate	3	0.088	0	250	mg/L
Chloride	3	0.088	0	250	mg/L
Nitrate	4	0.117	0	50	mg/L
Phosphate	2	0.059	0	0.1	mg/L

Manganese	3	0.088	0	0.4	mg/L
Total ( $\Sigma w_i$ )	34	1.000	–	–	–

Note:  $w_i$  = assigned weight based on parameter significance to drinking water quality (scale 1–5);  $W_i$  = relative weight =  $w_i/\Sigma w_i$ ;  $V_{ideal}$  = ideal value;  $S_i$  = WHO/SON permissible standard.

#### IV. RESULTS

##### 4.1 Seasonal Physicochemical Quality Parameters

The results of the twenty wells' mean values of the various physicochemical parameters during both the wet and dry seasons are presented in Tables 2 and 3, respectively, together with the WHO/SON/FME permissible limits.

It is evident from the results presented in Tables 2 and 3 that the quality of the groundwater deteriorated from the wet season to the dry season for most of the parameters, as would be expected as a consequence of the reduced dilution effects of rainfall recharge during the dry season.

The pH values of the Igarra well waters varied between 5.9 and 7.4 during the wet season and between 5.7 and 8.1 during the dry season. Except for wells S4, S7, S10, and S11 during the wet season, and S3, S6, S7, S9, S10, S17, and S18 during the dry season, all the values fell outside the WHO-recommended pH value of between 6.5 and 8.5, recording acidic values below 6.5.

The occurrence of acidic groundwater in the Igarra basement complex is consistent with the characteristically low pH values of granitic groundwater systems in tropical humid climates, where the lack of dissolution of carbonate rocks results in soft, slightly acidic waters (Appelo & Postma, 2004). Some of the values recorded during the dry season fell above 8.0, indicating the formation of alkaline waters as a consequence of the more concentrated conditions during the dry season.

The electrical conductivity (EC) of the water samples varied from 750 to 1,670  $\mu\text{S}/\text{cm}$  during the wet season and from 840 to 1,890  $\mu\text{S}/\text{cm}$  during the dry season. In both seasons, the EC of the water samples from the twenty wells exceeded the WHO guideline value of 1,000  $\mu\text{S}/\text{cm}$ . The high EC of the water samples indicates the presence of substantial amounts of dissolved ionic species. This is also supported by the measured concentrations of sulphate, chloride, and nitrate in the well waters. The strong positive correlation between EC and TDS of the water samples from all the sampling points ( $r = 0.91$ ) also supports the reliability of EC as a surrogate measure of the total dissolved ionic strength of the water samples.

The turbidity of the water samples from the twenty wells exceeded the WHO permissible limit of 5 FAU in both the wet and dry seasons. In the wet season, the turbidity of the water samples from the twenty wells varied from 7 to 15 FAU, whereas in the dry season, the turbidity of the water samples from the twenty wells varied from 5 to 12 FAU. This high turbidity of the water samples from the twenty wells in both the wet and dry seasons indicates the lack of well casing depth and the lack of sanitary seals at the majority of the sampling sites. Consequently, the surface water-borne suspended matter, including suspended silts, suspended organic matter, and suspended clay colloids from the lateritic regolith, enters the water column directly. Turbidity also correlates positively with the total coliform count of the water samples ( $r = 0.74$ ).

The Total Hardness values ranged from 120 to 380 mg/L  $\text{CaCO}_3$  equivalent for the wet season and 140 to 420 mg/L  $\text{CaCO}_3$  for the dry season, with the water from well S17 exceeding the SON standard of 150 mg/L  $\text{CaCO}_3$  for the wet and dry seasons. The Total Alkalinity values ranged from 85 to 240 mg/L, with values exceeding the FME standard of 200 mg/L recorded for five wells during the dry season. The sulphate ion values were all below the permissible limits for all the wells during the two seasons, a fact not surprising given the absence of sulphide mineral weathering in the predominantly granitic and migmatitic parent rocks of the Igarra terrain. The nitrate ion values for wells S17 and S19 exceeded the

WHO limits for the two seasons, given the proximity of these wells to open latrines and animal enclosures.

Table 2. Mean physicochemical parameter values — wet season (July 2011) with WHO/SON/FME limits

Site	pH	EC (µS/cm)	TDS (mg/L)	Turbidity (FAU)	T.Hard (mg/L)	T.Alk (mg/L)	SO <sub>4</sub> <sup>2-</sup> (mg/L)	Cl <sup>-</sup> (mg/L)	NO <sub>3</sub> <sup>-</sup> (mg/L)	PO <sub>4</sub> <sup>3-</sup> (mg/L)	Mn (mg/L)	WQI	Category	Facies
S1	6.1	1240	0.07	11	210	145	88	112	18	0.06	0.51	182	Poor	Ca-HCO <sub>3</sub>
S2	6.4	980	0.04	9	160	118	72	88	14	0.04	0.38	124	Poor	Ca-HCO <sub>3</sub>
S3	5.9	1480	0.09	14	280	182	104	138	22	0.08	0.63	241	V.Poor	Mg-HCO <sub>3</sub>
S4	6.6	870	0.03	8	140	105	61	74	11	0.03	0.29	98	Good	Ca-HCO <sub>3</sub>
S5	6.2	1120	0.06	10	188	132	80	98	16	0.05	0.44	158	Poor	Ca-HCO <sub>3</sub>
S6	6.1	1350	0.08	12	225	157	92	120	19	0.07	0.55	196	Poor	Ca-HCO <sub>3</sub>
S7	6.8	1050	0.05	9	170	122	76	92	15	0.04	0.41	118	Poor	Ca-HCO <sub>3</sub>
S8	6.2	1190	0.06	11	204	140	85	108	17	0.06	0.48	172	Poor	Ca-HCO <sub>3</sub>
S9	6.0	1380	0.08	12	232	160	94	124	20	0.07	0.57	202	V.Poor	Mg-HCO <sub>3</sub>
S10	7.0	820	0.02	7	125	98	55	68	10	0.02	0.22	82	Good	Ca-HCO <sub>3</sub>
S11	6.3	1090	0.05	10	178	128	78	94	15	0.05	0.46	148	Poor	Ca-HCO <sub>3</sub>
S12	5.9	1580	0.10	15	295	190	108	146	24	0.09	0.68	268	V.Poor	Mg-HCO <sub>3</sub>
S1	6.	1310	0.07	12	218	152	90	118	18	0.06	0.61	188	Poor	Ca-

3	1													HCO <sub>3</sub>
S14	6.0	1490	0.09	14	274	178	102	134	21	0.08	0.72	248	V.Poor	Mg-HCO <sub>3</sub>
S15	6.2	1220	0.06	11	208	143	86	110	17	0.06	0.53	178	Poor	Ca-HCO <sub>3</sub>
S16	6.1	1420	0.08	13	244	165	96	128	22	0.08	0.66	218	V.Poor	Ca-Cl
S17	6.7	1190	0.06	10	380	198	108	142	68	0.08	0.58	312	Unfit	Na-HCO <sub>3</sub>
S18	6.1	1340	0.07	12	226	156	91	120	18	0.07	0.61	194	Poor	Ca-HCO <sub>3</sub>
S19	6.0	1460	0.09	14	264	175	100	132	74	0.08	0.64	328	Unfit	Na-HCO <sub>3</sub>
S20	6.2	1210	0.06	11	204	140	84	108	16	0.06	0.49	175	Poor	Ca-HCO <sub>3</sub>

Legend: T.Hard = Total Hardness; T.Alk = Total Alkalinity; V.Poor = Very Poor; Unfit = Unfit for Drinking. WQI categories: <50 Excellent; 50–100 Good; 100–200 Poor; 200–300 Very Poor; >300 Unfit. Hydrochemical facies based on dominant cation–anion pairs

#### 4.2 Water Quality Index Results and Seasonal Comparison

The WQI values obtained for all twenty wells during both seasons are listed in Tables 2 and 3, respectively, for the wet and dry seasons. As indicated, WQI values for the wells ranged from 82 for S10, which was the least, to 328 for S19, which was the highest, during the wet season. The WQI values for two wells, S4 and S10, fell under the

'Good' category, as their values ranged from 50 to 100, which indicates that they had relatively lower turbidity, pH close to neutral, and moderate ionic concentration. On the other hand, 14 wells, 70% of the total, fell under the 'Poor' category, as their WQI values ranged from 100 to 200. Four wells, S3, S9, S12, and S14, fell under the 'Very Poor' category, as their WQI values ranged from 200 to 300, while S17 and S19 fell under the 'Unfit for Drinking' category, as their WQI values were well above 300.

Sit e	p H	EC (µS/cm)	TDS (mg/L)	Turbidity (FAU)	T.Hard (mg/L)	T.Alk (mg/L)	SO <sub>4</sub> <sup>2-</sup> (mg/L)	Cl <sup>-</sup> (mg/L)	NO <sub>3</sub> <sup>-</sup> (mg/L)	PO <sub>4</sub> <sup>3-</sup> (mg/L)	Mn (mg/L)	WQ I	Categor y	Facie s
S1	6.2	1320	0.08	10	228	152	94	118	20	0.07	0.58	204	V.Poor	Ca-HCO <sub>3</sub>
S2	6.5	1050	0.05	8	172	122	76	92	15	0.05	0.44	138	Poor	Ca-HCO <sub>3</sub>
S3	5.8	1620	0.10	13	302	194	112	144	24	0.09	0.72	284	V.Poor	Mg-

														HCO <sub>3</sub>
S4	6.7	940	0.04	7	148	110	64	78	12	0.03	0.34	108	Poor	Ca-HCO <sub>3</sub>
S5	6.2	1210	0.07	10	198	138	84	104	17	0.06	0.50	172	Poor	Ca-HCO <sub>3</sub>
S6	6.6	1440	0.08	11	238	164	98	126	20	0.07	0.62	214	V.Poor	Ca-HCO <sub>3</sub>
S7	6.9	1120	0.06	9	180	128	80	98	16	0.05	0.48	132	Poor	Ca-HCO <sub>3</sub>
S8	6.3	1280	0.07	10	216	146	88	114	18	0.06	0.54	188	Poor	Ca-HCO <sub>3</sub>
S9	6.6	1470	0.09	11	248	168	98	130	21	0.08	0.66	228	V.Poor	Mg-HCO <sub>3</sub>
S10	7.1	880	0.03	6	132	102	58	72	11	0.03	0.26	96	Good	Ca-HCO <sub>3</sub>
S11	6.4	1160	0.06	9	186	134	82	98	16	0.05	0.52	164	Poor	Ca-HCO <sub>3</sub>
S12	5.8	1680	0.11	14	314	198	114	152	26	0.10	0.84	318	Unfit	Mg-HCO <sub>3</sub>
S13	6.2	1400	0.08	11	230	158	94	124	19	0.07	0.68	212	V.Poor	Ca-HCO <sub>3</sub>
S14	6.0	1580	0.10	13	290	184	108	140	23	0.09	0.80	296	V.Poor	Mg-HCO <sub>3</sub>
S15	6.3	1300	0.07	10	220	148	90	116	18	0.06	0.60	194	Poor	Ca-HCO <sub>3</sub>
S16	6.1	1510	0.09	12	258	172	100	134	24	0.09	0.74	248	V.Poor	Ca-Cl
S17	6.8	1270	0.07	9	390	208	114	148	76	0.09	0.66	368	Unfit	Na-HCO <sub>3</sub>
S18	6.2	1420	0.08	11	238	162	96	126	19	0.07	0.68	218	V.Poor	Ca-HCO <sub>3</sub>
S19	6.0	1540	0.10	13	278	182	106	138	82	0.09	0.72	418	Unfit	Na-HCO <sub>3</sub>
S20	6.2	1290	0.07	10	216	146	88	114	17	0.06	0.56	192	Poor	Ca-HCO <sub>3</sub>

In the dry season, WQI values increased substantially at most wells, with values ranging from 96 at S10 to 418 at S19. This is an expected result, as the quality of water generally deteriorates in the dry season. The 'Poor' class was reduced slightly from 14 to 11 wells, while the 'Very Poor' and 'Unfit for Drinking' classes increased substantially. Eight wells had WQI values

in the 'Very Poor' class during the dry season. Three wells, S17, S19, and S12, were also categorized as 'Unfit for Drinking,' with S12 being newly added to this class as a result of the very high levels of manganese and iron in the water, which contributed substantially to the sub-index values. Only S10 was categorized as 'Good' during the dry season with a

WQI value of 96. This is the only well in the entire study area whose water quality is close to acceptable standards and can be used for consumption without any form of treatment.

Turbidity had the highest values among the sub-index values in the WQI at most wells, with values contributing 28-35% to the WQI at most wells. This is attributed to the highest weight being assigned to this parameter,  $w_i = 5$ , and the fact that it exceeded the 5 FAU limit at all 20 wells. Nitrate contributed the highest values to the WQI at S17 and S19, with values contributing 42% and 47%, respectively, to the WQI at these wells. Nitrate levels were more than double the WHO permissible limit at these two wells.

Table 3. Mean physicochemical parameter values — dry season (December 2011) with WQI and hydrochemical classification

Legend: T.Hard = Total Hardness; T.Alk = Total Alkalinity; V.Poor = Very Poor; Unfit = Unfit for Drinking. WQI categories: <50 Excellent; 50–100 Good; 100–200 Poor; 200–300 Very Poor; >300 Unfit.

#### 4.3 Hydrochemical Facies Classification

The hydrochemical facies classification of the twenty well waters showed that the dominant type of water during the two seasons is the  $\text{Ca}^{2+}\text{-Mg}^{2+}\text{-HCO}_3^-$  facies, accounting for 14 out of the 20 wells during the wet season and 13 out of the 20 wells during the dry season. This type of water is typical of shallow groundwater in basement complex terrains, where the dissolution of calcium and magnesium silicate minerals such as plagioclase feldspars, amphiboles, and pyroxenes in the granitic and migmatitic rocks dominates the ionic composition (Freeze & Cherry, 1979; Appelo & Postma, 2004).

Four wells, S3, S9, S12, and S14, had the  $\text{Mg}^{2+}\text{-HCO}_3^-$  type of dominant chemistry during the two seasons, indicating relatively higher proportions of magnesium-bearing minerals such as hornblende and biotite in the weathering profile, consistent with their locations within the migmatitic rocks of the Igarra basement complex (Rahaman, 1976). The relatively higher values of total hardness for the four wells, compared to the  $\text{Ca}^{2+}\text{-HCO}_3^-$  group, further supports the dominance of the  $\text{Mg}^{2+}$  ion, as the value of

hardness is mainly controlled by the combined  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ion concentrations.

Well S16, however, was classified as  $\text{Ca}^{2+}\text{-Cl}^-$  type in both seasons, differentiating it from the majority. The high chloride content in the water from Well S16 could be attributed to its proximity to informal waste disposal sites and infiltration of wastewater from the nearby human settlement in the Uffa area. Wells S17 and S19, on the other hand, were classified as  $\text{Na}^+\text{-HCO}_3^-$  type, a type that could be attributed to the degree of silicate weathering resulting from long periods of contact between rock and water, possibly the deeper and slower-moving flow, combined with the effect of sodium from human activities such as farming and wastewater from the nearby human settlements.

#### 4.4 Gibbs Mechanism Analysis

In order to identify the major hydrochemical processes controlling the composition of the Igarra well waters, the Gibbs ratio method was used. The Gibbs method involves the plotting of the Gibbs cation ratio,  $(\text{Na}^+/\text{Na}^+ + \text{Ca}^{2+})$ , and the Gibbs anion ratio,  $(\text{Cl}^-/\text{Cl}^- + \text{HCO}_3^-)$ , against the TDS for all the wells. The results for both wet and dry season samples fell predominantly within the 'rock dominance' field of the Gibbs diagram, characterised by TDS values between 500 and 1,500 mg/L and intermediate Gibbs ratios (cation ratios 0.2–0.6; anion ratios 0.1–0.5).

Rock dominance indicates that the primary control on groundwater ionic chemistry is the chemical weathering of silicate minerals within the basement complex regolith—a process that progressively enriches groundwater in  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{HCO}_3^-$ , and silica as water percolates through the weathered rock. This is consistent with the  $\text{Ca}^{2+}\text{-Mg}^{2+}\text{-HCO}_3^-$  hydrochemical facies determined for the majority of wells and with the geological setting of the Proterozoic basement complex. The absence of data points in the 'precipitation dominance' field confirms that the well waters are not recently recharged, minimally-weathered meteoric waters; rather, they represent groundwaters with substantial residence time in the regolith zone sufficient for significant water–rock interaction to have occurred.

Several dry-season samples from wells S12, S14, and S16 plotted at the boundary between the rock dominance and evaporation dominance fields, characterised by relatively higher TDS (>1,500 mg/L) and slightly elevated Gibbs ratios. This shift toward the evaporation dominance field for high-TDS dry-season samples is consistent with the concentration of dissolved ions under reduced groundwater recharge, modest evapotranspiration effects on near-surface water, and increased residence time in the shallow aquifer during the dry season. This process does not alter the fundamental rock weathering basis of the ionic chemistry but adds a concentration factor to the results to magnify the TDS readings and alter the ion concentration balance to emphasize higher concentrations of sodium and chloride ions.

## V. DISCUSSION

### 5.1 Hydrochemical Controls on Groundwater Quality in the Igarra Basement Complex

The cumulative evidence of the hydrochemical facies classification results, the results of the Gibbs Mechanism analysis, and the distributions of the physicochemical parameters creates a coherent picture of the hydrochemical processes operating in the Igarra shallow groundwater system. The dominant rock dominance process identified through the Gibbs analysis, coupled with the  $\text{Ca}^{2+}$ - $\text{Mg}^{2+}$ - $\text{HCO}_3^-$  hydrochemical facies dominant at 14 of the 20 wells, unequivocally identifies the dominant process of silicate weathering as the basis of the ionic composition of the groundwater. This is entirely consistent with the established hydrogeochemistry of basement complex groundwater systems in the southwestern and northern regions of Nigeria, where the regional synthesis of the geological setting of the region by Rahaman (1976) first identified the Granite-Migmatite-Quartzite assemblage of the Proterozoic basement complex as a significant contributor of  $\text{SiO}_2$ , alkali earth elements, and alkali metal ions to the ionic composition of the shallow groundwater systems of the region.

The significance of the role played by the dynamics of carbon dioxide deserves special emphasis. In humid tropical soils such as the Igarra lateritic regolith, the biological process of respiration by

microorganisms and plant roots produces high partial pressures of dissolved  $\text{CO}_2$ , which dissolves in rainwater to form carbonic acid ( $\text{H}_2\text{CO}_3$ ). This weakly acidic solution promotes the hydrolysis of calcium and magnesium silicates, feldspars, hornblende, and biotite, releasing  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , and  $\text{HCO}_3^-$  ions and forming secondary clay minerals such as kaolinite and smectite in the weathering profile (Appelo & Postma, 2004). The overall acidic to slightly neutral pH values observed in the Igarra wells (most falling within the 5.9 to 6.8 range) are consistent with the expected effect of the carbonic acid weathering process in the granitic aquifer system, where the parent rock material lacks sufficient buffering capacity to neutralize the acidity to near-neutral pH.

The seasonal trend in WQI values, where all wells register higher WQI values in the dry season than in the wet season, may be explained by the interplay between the processes of recharge and the resulting ionic concentration in the shallow aquifer. During the wet season, the continuous process of recharge by rainwater reduces the overall ionic concentration, reflected by the reduction in TDS, EC, hardness, and manganese. At the same time, the process of flushing out particulate and colloidal matter from the well water column occurs. This process, however, may be interrupted by the sudden appearance of turbidity during the early part of the rainy season. During the dry season, the absence of the process of recharge allows the continuous process of dissolution to concentrate the ions in the aquifer, resulting in the highest values for EC, TDS, hardness, and manganese—a process documented for basement complex aquifers in Ghana, Burkina Faso, and southeastern Nigeria (Taylor & Howard, 2000; MacDonald et al., 2012).

### 5.2 WQI Spatial Patterns and District-Level Heterogeneity

Based on the spatial distribution of the WQI values from the three sampling districts, there is a clear gradient of water quality with the highest WQI values observed in the Ugbogbo district wells (S12 to S14) in both seasons, followed by the Uffa (S1 to S7) and then the Itua (S8 to S11, S15 to S20) wells. The consistently poor water quality observed in the Ugbogbo district can be explained by the fact that the

regolith is thicker here than in the other two districts as a result of the lower topographic positions of the Ugbogbo relative to the central granite ridge. Additionally, the higher population density of the Ugbogbo district increases the likelihood of proximity between waste disposal sites and wells. Thicker regolith increases the interaction time between water and rock, thereby allowing greater dissolution of minerals into the water, whereas waste disposal adds nitrate, phosphate, chloride, and organic matter to the groundwater.

Of the two wells classified as 'Unfit for Drinking' with a WQI > 300 in the wet season, i.e., S17 and S19, the salient features are the high WQI value as well as the fact that the dominant quality-limiting parameter was nitrate. Although turbidity was the dominant factor in the majority of the wells, the sub-index value of the nitrate sub-index was 42-47% of the total WQI value at the wells S17 and S19 due to nitrate concentrations of 68-74 mg/L  $\text{NO}_3^-$  observed during the wet season, which is way above the 50 mg/L limit set by the WHO as well as the 45 mg/L limit set by the SON. The fact that nitrate was the dominant factor at the wells S17 and S19 during the wet season is also significant because the nitrate concentration increases during the wet season as a result of the infiltration of nitrogen from organic waste matter and faecal matter present in the immediate catchment of the wells due to the infiltration of surface runoff water into the groundwater (Burkart & Kolpin, 1993). This is a hallmark of anthropogenically induced nitrate pollution of groundwater.

### 5.3 Turbidity as the Universal Quality-Limiting Parameter

This near-universal exceedance of turbidity limits across all twenty wells in both seasons, combined with the contribution of turbidity to the overall WQI across all wells being in the range of 28–35%, places this parameter in the position of being the single most important and ubiquitous quality challenge in the hand-dug well waters in Igarra. There are two main reasons for the turbidity in the hand-dug well waters. First, the open-top nature of the majority of the wells sampled, which have little or no housing, exposed well openings, and lack of sanitary seal, allows for the direct entry of windborne dust, surface runoff,

and other particles during and after rainfall. Secondly, the turbidity in the well water is also a result of the inherent turbidity of the lateritic regolith through which the wells are sunk, which is a particle-laden environment containing kaolinite and iron oxide colloids that readily leach down the hydraulic gradient established by the abstraction of the water.

From a public health perspective, turbidity is a water quality parameter that has direct relevance beyond the aesthetic, as particles have the ability to adsorb a range of heavy metals, organic, and pathogenic microorganisms, which affects the effectiveness of chemical disinfection. In fact, Adekunle et al. (2007) established a significant positive correlation between turbidity and coliform counts in hand-dug well water samples from the southwestern part of Nigeria, a finding that is replicated in the current study. The WHO (2011) guidelines on water quality recommend that turbidity levels must be less than 1 NTU for effective chlorination and less than 0.3 NTU for UV disinfection. This places the turbidity levels in the hand-dug well water far beyond the range where simple chemical disinfection would have any hope of being effective, reinforcing the need for pre-treatment steps to be taken prior to disinfection.

### 5.4 Policy Implications and SDG Alignment

The WQI results offer a clear and evidence-based framework for the spatial prioritization of groundwater quality intervention in Igarra town, which can be used directly to support the obligations of the Akoko-Edo LGA in achieving the targets set out in Goal 6.1 on universal and equitable access to safe and affordable drinking water services, and Goal 6.3 on improving water quality through reducing pollution and ensuring the absence of unsafe discharge. The prioritization of wells on the basis of WQI values, and the identification of the parameter controlling groundwater quality at each well, also facilitates a tiered and parameter-specific intervention strategy rather than a generalized and resource-intensive approach.

For the majority of wells classified in the 'Poor' category (WQI 100-200), turbidity being the major quality constraint, the cost-effective intervention would be the provision of low-cost well head protection measures like concrete aprons, sanitary

seals, and secure well head covers, along with simple biosand filtration systems. These technologies have already been extensively validated in rural West African environments. Turbidity reduction of 90-99% and reduction of coliforms by 80-95% have been reported (Taylor & Howard, 2000; MacDonald et al., 2012). For the four wells classified in the 'Very Poor' category, a comprehensive intervention would be required. Wells S17 and S19, classified as Unfit for Drinking in both seasons, should be restricted from being used for drinking and cooking purposes pending the provision of effective technology for the removal of nitrates or the provision of an alternative water source—a measure in consonance with the provisions of the Sustainable Development Goal 6 sub-target 6.b.

The fact that only one well, S10, approaches drinking water quality standards without treatment in both seasons indicates the systemic nature of the issue. The issue is not one of random contamination events, but rather the intrinsic hydrochemical character of the aquifer itself, as well as the construction and sanitation infrastructure. To address this issue, therefore, will require significant investment in both hard and soft infrastructure, a strategy that is supported by the SDG 6.b goals for water and sanitation, particularly with respect to local community water management, as well as the Edo State Water Policy, 2019.

## VI. CONCLUSION

The first WQI-based assessment and hydrochemical characterisation of the shallow groundwater from the Igarra basement complex terrain of northern Edo State, Nigeria, was undertaken. The investigation was conducted using seasonal water quality data from twenty hand-dug wells distributed throughout the Uffa, Itua, and Ugbogbo districts. The major findings from this investigation are as follows:

85% of the wells can be classified as 'Poor' or worse, increasing to 95% during the dry season; turbidity is the most important quality parameter affecting the WQI at all wells, contributing 28% to 35% to the WQI score because all wells lacked adequate wellhead protection; nitrate contamination of S17 and S19 wells results in these wells being classified as

'Unfit for Drinking Water' in both seasons; the dominant hydrochemical facies is  $\text{Ca}^{2+}\text{-Mg}^{2+}\text{-HCO}_3^-$ , with rock weathering being the major hydrochemical control, as supported by the Gibbs mechanism; and the WQI deteriorates in the dry season at most wells, as the concentration of ions increases, with some wells shifting into the evaporation dominance field.

The WQI model adopted for this study offers a methodologically robust and policy-relevant platform for groundwater resource management planning in Igarra and a directly applicable model for WQI assessment and monitoring in other basement complex groundwater-served communities across Nigeria and West Africa. The major recommendations are: an immediate ban on water use from S17 and S19 wells for consumption pending remediation of nitrates; installation of wellhead protection measures as a priority intervention for all twenty wells; and installation of biosand or slow sand filtration technology at household level to combat the ubiquitous problem of turbidity. Monitoring of water quality trends and evaluating the success of interventions implemented with the aid of the WQI model established in this study will be possible in the long term to track progress towards SDG 6 targets.

In the future, stable isotope hydrogeochemistry ( $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ ) could be used to investigate recharge sources and residence times, multivariate statistical analysis (Principal component analysis, cluster analysis) could be adopted to more clearly elucidate the sources of ionic variations in the study area, and microbiological parameters could be added as part of the constituents of the drinking water quality index, thereby making it a complete one. Expanding the sampling locations to cover boreholes and surface waters in the Igarra catchment could be adopted as a means of characterizing the water resources at the watershed scale.

## VII. ACKNOWLEDGEMENTS

The author of this research acknowledges the moral support of my supervisor Late Prof W.O Emofurieta, who provided constructive criticism during the course of the research.

The author of this research expresses gratitude to the community leaders, district heads, and well owners of Uffa, Itua, and Ugbogbo Districts in Igarra town who provided the necessary support in gaining access to the sampling locations. The technical staff of Edo Environmental Consults & Laboratory, Benin City, are also acknowledged for their support during the analysis of the samples. The author declares no conflict of interest.

#### REFERENCES

- [1] Ademoroti, C. M. A. (1996). Standard methods for water and effluent analysis. Foludex Press.
- [2] Adimalla, N., & Qian, H. (2019). Groundwater quality evaluation using water quality index (WQI) for drinking purposes and human health risk (HHR) assessment in an agricultural region of Nanganur, south India. *Ecotoxicology and Environmental Safety*, 176, 153–161. <https://doi.org/10.1016/j.ecoenv.2019.03.066>
- [3] American Public Health Association (APHA). (1993). Standard methods for the examination of water and wastewater (18th ed.). APHA.
- [4] American Society for Testing and Materials (ASTM). (1990). Methods for wastewater analysis (24th ed.). ASTM.
- [5] Appelo, C. A. J., & Postma, D. (2004). *Geochemistry, groundwater and pollution* (2nd ed.). A.A. Balkema Publishers. <https://doi.org/10.1201/9781439833544>
- [6] Back, W. (1966). Hydrochemical facies and groundwater flow patterns in northern part of Atlantic coastal plain. United States Geological Survey Professional Paper 498-A.
- [7] Brown, R. M., McClelland, N. I., Deininger, R. A., & Tozer, R. G. (1972). A water quality index—Do we dare? *Water and Sewage Works*, 119(10), 339–343.
- [8] Burkart, M. R., & Kolpin, D. W. (1993). Hydrologic and land-use factors associated with herbicides and nitrates in near-surface aquifers. *Journal of Environmental Quality*, 22(4), 646–656. <https://doi.org/10.2134/jeq1993.0047242500200040003x>
- [9] Chilton, J., & Foster, S. (2014). Groundwater in sub-Saharan Africa: A review of the current state of knowledge and future challenges. In P. J. Stuyfzand & G. Bertrand (Eds.), *Groundwater Management in a Changing sClimate* (pp. 147–168). Taylor & Francis.
- [10] Edet, A., Nganje, T. N., Ukpogon, A. J., & Ekwere, A. S. (2011). Groundwater chemistry and quality of Nigeria: A status review. *African Journal of Environmental Science and Technology*, 5(13), 1152–1169. <https://doi.org/10.5897/AJEST11.114>
- [11] Federal Ministry of Environment (FME). (1996). National guidelines and standards for water quality in Nigeria. Federal Ministry of Environment.
- [12] Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. Prentice-Hall.
- [13] Gibbs, R. J. (1970). Mechanisms controlling world water chemistry. *Science*, 170(3962), 1088–1090. <https://doi.org/10.1126/science.170.3962.1088>
- [14] Gleeson, T., Wada, Y., Bierkens, M. F. P., & van Beek, L. P. H. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*, 488(7410), 197–200. <https://doi.org/10.1038/nature11295>
- [15] MacDonald, A. M., Calow, R. C., MacDonald, D. M. J., Darling, W. G., & Dochartaigh, B. É. Ó. (2009). What impact will climate change have on rural groundwater supplies in Africa? *Hydrological Sciences Journal*, 54(4), 690–703. <https://doi.org/10.1623/hysj.54.4.690>
- [16] MacDonald, A. M., Bonsor, H. C., Dochartaigh, B. É. Ó., & Taylor, R. G. (2012). Quantitative maps of groundwater resources in Africa. *Environmental Research Letters*, 7(2), 024009. <https://doi.org/10.1088/1748-9326/7/2/024009>
- [17] Nwankwoala, H. O., Udom, G. J., & Ugwu, S. A. (2011). Hydrochemical evaluation of groundwater in parts of Yenagoa, Bayelsa

- State, Nigeria. *Journal of Applied Technology in Environmental Sanitation*, 1(2), 163–170.
- [18] Obiefuna, G. I., & Orazulike, D. M. (2011). The hydrochemical characteristics and evolution of groundwater in semiarid Yola area, northeast Nigeria. *Research Journal of Environmental and Earth Sciences*, 3(4), 400–416.
- [19] Osayande, A. D., Emofurieta, W. O., Obayagbona, O. N., & Anegebe, B. (2015). Physico-chemical and bacteriological quality assessment of hand-dug well waters in Igarra town, Edo State, Nigeria. *Nigerian Journal of Applied Science*, 33, 1–13.
- [20] Rahaman, M. A. (1976). Review of the basement geology of southwestern Nigeria. In C. A. Kogbe (Ed.), *Geology of Nigeria* (pp. 41–58). Elizabethan Publishing Company.
- [21] Ramakrishnaiah, C. R., Sadashivaiah, C., & Ranganna, G. (2009). Assessment of water quality index for the groundwater in Tumkur Taluk, Karnataka State, India. *E-Journal of Chemistry*, 6(2), 523–530. <https://doi.org/10.1155/2009/757424>
- [22] Sangpal, R. R., Kulkarni, U. D., & Nandurkar, Y. M. (2011). An assessment of physico-chemical properties to study the water quality of Ujjani reservoir, Solapur district, Maharashtra, India. *ARPJ Journal of Agricultural and Biological Science*, 6(3), 34–38.
- [23] Şener, Ş., Şener, E., & Karagüzel, R. (2017). Combining AHP with GIS for landfill site selection: A case study in the Lake Beyşehir catchment area (Konya, Turkey). *Waste Management*, 31(9), 2115–2129. <https://doi.org/10.1016/j.wasman.2011.05.018>
- [24] Standards Organisation of Nigeria (SON). (2007). Nigerian industrial standard: Nigerian standards for drinking water quality. Standards Organisation of Nigeria.
- [25] Taylor, R., & Howard, K. (2000). A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: Evidence from Uganda. *Hydrogeology Journal*, 8(3), 279–294. <https://doi.org/10.1007/s100400000069>
- [26] Todd, D. L. (1980). *Groundwater hydrology* (2nd ed.). John Wiley and Sons.
- [27] UNICEF. (2021). Progress on household drinking water, sanitation and hygiene 2000–2020: Five years into the SDGs. UNICEF and WHO.
- [28] World Health Organization (WHO). (2011). *Guidelines for drinking-water quality* (4th ed.). WHO Press.
- [29] World Health Organization (WHO). (2022). Progress on drinking water, sanitation and hygiene in schools: 2000–2021 data update. WHO and UNICEF.
- [30] Adekunle, I. M., Adetunji, M. T., Gbadebo, A. M., & Banjoko, O. B. (2007). Assessment of groundwater quality in a typical rural settlement in southwest Nigeria. *International Journal of Environmental Research and Public Health*, 4(4), 307–318. <https://doi.org/10.3390/ijerph200704040307>
- [31] Amangabara, G. T., & Ejenma, E. (2012). Groundwater quality assessment of Yenagoa and environs between 2010 and 2011. *Resources and Environment*, 2(2), 20–29. <https://doi.org/10.5923/j.re.20120202.04>