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## Characterization of Oil Field Formation Water and its Effect on Tap Water Dilution for Eco-Friendly Environment

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### Abstract:

The research work examined the effect of the dilution factor of Formation water (FW) by tap water to be discharged into the environment in an eco-friendly way pertaining to the Minimal National Standards (MINAS). The FW from oil fields discharges large volume of liquid wastes containing complex mixture of organic and inorganic compounds with both toxic and non toxic elements which adversely effects the both the biotic and aquatic life. Therefore, proper treatment, management and reuse of the FW are important for a sustainable eco-friendly environment. In this paper the FWs were collected from the different depths of the producing horizons oil fields of Upper Assam Basin and a complete evaluation and characterization were attempted. Various physical and chemical properties of the pollutants of FWs were determined and their effects on tap water dilution were assessed. The dilution is an attempt to safely dispose FW with environmental regulations. The evaluation of FW in this paper includes the analysis of pH, Specific gravity, Salinity, Total Dissolved Solids (TDS), Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Turbidity, organics, inorganics, minerals, metals and ions such as Sodium (Na), Potassium (K), Lithium (Li) and Chloride (Cl). It was observed that the pollutants decreased with increased dilution factor. Characterization and evaluation of FW is essential in petroleum industries is to mitigate the adverse environmental impacts on the ecosystem.

**Key words:** FW, Upper Assam Basin, Pollutants, Dilution, Characterization, Evaluation.

### 1. Introduction

FW is water trapped in underground formations that is brought to the surface during oil and gas exploration and production. In traditional oil and gas, FW is brought to the surface along with oil or gas [1, 2]. FW has been in contact with the hydrocarbon bearing formation for centuries; it has some of the chemical characteristics of the reservoir rocks and fluids. The American Petroleum Institute estimates that in stripper oil well (oil well that is nearing the end of its economically useful life) operations approximately 34.07 L (0.214 bbl) of FW are recovered for each 1 L (0.0063 bbl) of oil [3]. As on 2014, about 2226- 2862 L (14-18 bbl) FW are generated each year with the production of oil and gas in the U.S. [4]. The rise in water cut is also observed in many producing oil fields of Upper Assam Basin [5]. The FW may include, water and chemicals injected into the formation during drilling operation, production and worker operations [6-8]. This water is sometimes referred to as Produced Water (PW) but in this study it is referred as FW [2, 9, 10]. Sources of this water may include flow from above or below the hydrocarbon zone, flow from within the hydrocarbon zone, or flow from injected fluids and additives resulting from production activities [1, 10]. The physical and chemical properties of FW and the type of hydrocarbon product being produced vary considerably depending on the geographic location of the field and the geochemistry of the producing formation [2, 3, 5, 11, 12]. Several developing countries like India are facing the problem of fresh water scarcity, therefore proper management, treatment and reuse of the FW for the beneficial purpose of mankind and environment has become a necessity to mitigate the scarcity of fresh water problem. The adopted option for management of FW by E&P companies are the injection of FW for Improved Oil Recovery (IOR) and injection into the non pay zones for mere disposal [1, 9, 13]. FW properties and volume vary throughout the lifetime of a reservoir. The following Table 1 shows the disposal of waste water permissible limits according to MINAS specification.

**Table 1: Parameters Specification of on-shore disposal wastewater according to MINAS**

[ref. Environment (Protection) Rules, 1986]

SN	Parameters	Permissible limit
1	pH	6.0 to 9.0
2	Temperature ( <sup>o</sup> C)	Shall not exceed 5 <sup>o</sup> C above the ambient temperature of the receiving body
3	Oil & Grease (O & G)	10 mg/L
4	Suspended Solids	100 mg/L
5	Chlorine (Cl)	1.0 mg/L
6	Zinc (Zn)	5.0 mg/L
8	Chromium (Cr)	2.0 mg/L
9	Copper ( Cu)	3.0 mg/L
10	Lead (Pb)	0.1 mg/L
11	Iron (Fe)	3.0 mg/L
12	Total Metal	10.0 mg/L
13	TDS	24.59 X 10 <sup>4</sup> mg/L
14	DO	7 mg/L
15	Salinity	2-4 X 10 <sup>8</sup> mg/L
16	Conductivity	0.25-0.75 mS
17	Turbidity	5-10 NTU
18	BOD	30 mg/L
19	Alkalinity	200 mg/L
20	Hardness	300 mg/L
21	Chloride	250 mg/L

## 2. Experimental

### 2.1 Materials

The following materials were used to conduct the experimental works.

**Table 2: Showing the Materials used in the experiments**

SN	Sample	Specifications	Source
1	FW-1	Barail/ depth 3250 m	Oil E & P
2	FW-2	Tipam/ depth 2502m	Oil E & P
3	EDTA (Ethylene Diamine Tetra Acetic Acid)	0.01M	RFCL Limited
4	Erichrome black indicator	0.5g in 100ml	RFCL Limited
5	pH	pH 10	WTW
6	Potassium Chloride ( KCl)	M.W. 74.56 g/mol	Avantor Performance Materials India Limited
7	Sodium Chloride (NaCl)	M.W. 58.44 g/mol	RFCL Limited
8	Calcium Carbonate (CaCO <sub>3</sub> )	M.W. 100.09 g/mol	Merck Specialities Pvt. Ltd.
9	Lithium Carbonate (Li <sub>2</sub> CO <sub>3</sub> )	M.W. 73.89 g/mol	Spectrochem Pt. Ltd. Mumbai (India)
10	Hydrochloric Acid (HCl)	M.W. 36.46 g/mol, Sp. Gr. at 25 <sup>o</sup> C is about 1.18	RFCL Limited
11	Petroleum Ether	Wt. per ml at 20 <sup>o</sup> C, 0.630-0.645g	Fisher Scientific
12	Phenolphthalein	pH range 8.2-10 (colourless to pink)	RFCL Limited
13	Methyl Orange	-	Human Diagnostics & Surgichem
14	Tap water	-	Laboratory water supply

## 2.2 Instruments used during experimental work

**Table 3: Showing the Instruments used in the experiments**

SN	Name of the instrument	Parameters	Model	Make
1	Water Analyser	pH, TDS, Conductivity, Salinity, Turbidity, DO	Water Analyser 371	Systronics, Ahmedabad
2	Atomic Adsorption Spectrometer(AAS)	Fe, Cu, Mn & Cr	AAS Analyst 200	Perkin Elmer(India) Pvt. Ltd.
3	Gas Chromatography (GC)	Organics	Gas Chromatograph Clarus 480	Perkin Elmer(India) Pvt. Ltd.
4	Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES)	Fe, Zn, Mg, Pb & Sr	OPTIMA 2100DV	PERKIN ELMER,USA
5	Flame Photometer	Na, K, Li & Ca	Flame photometer 128; Compressor 126	SYSTRONICS Ahmedabad
6	BOD Incubator	Biochemical Oxygen Demand	FOC cooling incubator	VELP Scientifica
7	Scanning Electron Microscope (SEM)	-	-	-

## 2.3 Design of experiments (DOE)

DOE refers to the process of planning, designing and analyzing the experiment so that valid and objective conclusions can be drawn effectively and efficiently. Two FWs were used to determine the physical and chemical properties. The physical properties salinity, TDS, pH, Conductivity, Turbidity and DO were determined by the Water analyzer. And other physical properties hardness and alkalinity were determined by titration process. Oil and grease were determined by the separation process. The ions Na, K, Ca and Li were determined by Flame Photometer and Chloride ion was determined by titration. The metals Iron (Fe), Chromium (Cr), Manganese (Mn) and Copper (Cu) were determined by AAS. And also the organics and inorganics were determined by GC and ICP-OES respectively. To understand the relationship of the components in FW samples with the subsurface geology, SEM examinations were done.

## 2.4 Experimental

### 2.4.1 Water Analyser

The physical properties of FW were determined by Water Analyser such as Salinity, Conductivity, TDS, pH, Turbidity and DO. These results were directly shown at the display screen of the instrument. Another two physiochemical properties alkalinity and hardness were determined by titration.

### 2.4.2 Titration methods

*Alkalinity:* 50 ml sample water + methyl orange titrated with 0.05 N HCl = T

$$H_3 \text{ in gm/L} = \frac{T \times 0.05 \times 50 \times 1000}{\text{sample}}$$

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Total Alkalinity =  $HCO_3^- \times 0.82$

Total hardness: 50 ml sample water + buffer solution 10 (3-4 drops) + Erichrome black indicator, then titrated with EDTA 0.01 M or 0.02N. A change to ink colour was observed after titration.

$$\text{Total hardness} = \frac{EDTA \times 1000}{\text{sample}} \text{ mg/L}$$

#### 2.4.3 O & G

20 ml sample water + 20 ml petroleum ether in separating funnel was mixed and shaken for a half an hour. Appearance of two layers was observed where the lower layer was separated out in the beaker then dried in the oven and weighed = y, x = wt of the empty beaker.

$$O \& G = \frac{(y - x) \times 10^6}{\text{sample}} \text{ mg/l}$$

#### 2.4.4 Flame Photometer

Flame Photometer is a microcontroller based unit designed to provide automation in operation, measurements and end result presentation. It can do the estimation of Na, K, Li and Ca in single aspiration of a sample.

Preparation of stock standard solution

1. Na: A standard solution of 1000 ppm is prepared by dissolving 2.5416g NaCl in one litre of distilled water.
2. K: A standard solution of 1000 ppm is prepared by dissolving 1.9070 g KCl or 2.5869 g KNO<sub>3</sub> in one litre of distilled water.
3. Ca: A standard solution of 1000 ppm is prepared by dissolving 2.497 g CaCO<sub>3</sub> in approx 300 ml glass distilled water and adding 10 ml conc. HCl in one litre of distilled water.
4. Li: A standard solution of 2000 ppm is prepared by dissolving 4.945 g Li<sub>2</sub>CO<sub>3</sub> in approx 300 ml glass distilled water and adding 15 ml conc. HCl in one litre of distilled water.

#### 2.4.5 AAS

Determination of Fe, Cu, Mn and Cr in FW was conducted in the instrument AAS. Prior to the determination of the amount present, the AAS equipment was calibrated and analyzed using blank solution of 2% Nitric acid (HNO<sub>3</sub>) solution and standard solutions of 1ppm, 2ppm, 3ppm and 4ppm of Fe solution for Fe test. Similarly for Cr, Mn and Cu 1ppm, 2ppm, 3ppm and 4ppm of Cr, Mn and Cu standards samples were made respectively. After calibration samples were aspirated, the results were obtained.

#### 2.4.6 GC

The organics were determined by GC. The samples were prepared by dissolving in solvent ethyl acetate until the clear solution obtained.

#### 2.4.7 ICP-OES

The inorganics were determined by ICP-OES. The samples were prepared with Petroleum Diethyl ether in the ratio 1:1 and kept in a separating funnel and shake vigorously for an half an hour. Separated lower part was taken for ICP-OES.

#### 2.4.8 Test for Ammonium (NH<sub>4</sub>) cation

Aqueous solution + Nessler's reagent = reddish brown precipitate was present, indicated the presence of ammonium ion.

#### 2.4.9 Test for Phosphate (PO<sub>4</sub>) anion

Aqueous solution + concentrated nitric acid + ammonium molybdenum and heated = yellow precipitate is present and confirmed.

#### 2.4.10 Test for Sulphate (SO<sub>4</sub>) anion

Aqueous solution +Ba(NO<sub>3</sub>)<sub>2</sub> solution = white precipitate is present and insoluble in HNO<sub>3</sub> indicated the presence of SO<sub>4</sub> ions.

#### 2.4.11 SEM

The SEM consists of an electron optics column and an electronics console. The coated SEM sample is placed in the sample chamber, in the electron optics column and evacuated to high vacuum (approximately  $2 \times 10^{-6}$  torr). The three dimensional cross sectional view of minerals, pores and grain fabrics and textures were determined from SEM.

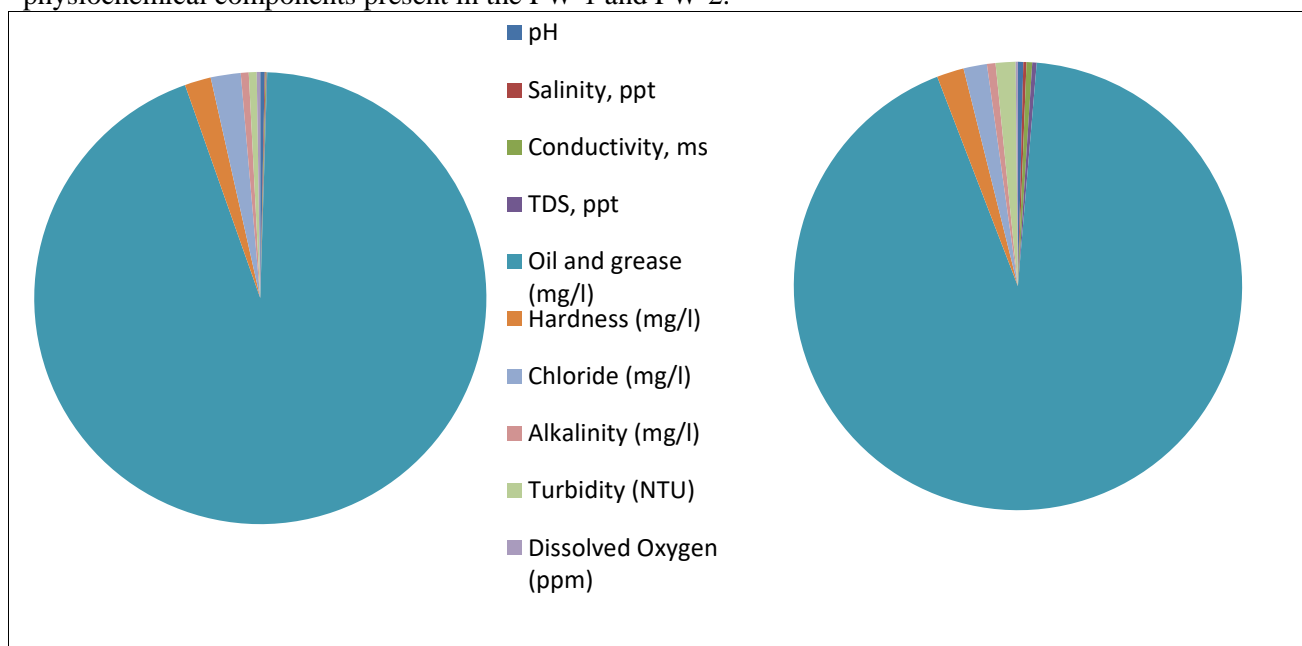
### 3 Results and Discussions

#### 3.1 Characterization of Physico-bio-chemical properties of FWs

**Table 4: Physico-bio-chemical qualities of PW, tap water and PW dilution with tap water**

SN	Parameters	FW-2			FW-1			Tap water
		0% dilution with tap water	50% dilution with tap water (1:1)	90% dilution with tap water (1:9)	0% dilution with tap water	50% dilution with tap water (1:1)	90% dilution with tap water (1:9)	
1	pH	6.72	6.15	5.48	8.1	7.54	6.87	5.62
2	Salinity, ppm	12000	6700	2100	51200	34700	9300	800
3	Conductivity, ms	1.76	0.973	0.310	8.98	5.16	1.39	0.109
4	TDS, ppm	9.7X10 <sup>3</sup>	5.4X10 <sup>3</sup>	1.7X10 <sup>3</sup>	6.47X10 <sup>4</sup>	2.77X10 <sup>4</sup>	0.74X10 <sup>4</sup>	7.7X10 <sup>4</sup>
5	O & G (mg/L)	2000	1000	500	2000	1000	5000	0
6	Hardness (mg/L)	40	25	15	42	25	17.5	60
7	SO <sub>4</sub> anion (mg/L)	0	0	0	0	0	0	0
8	Chloride (mg/L)	45.495	37.609	12.132	36.396	29.116	23.050	8.492
9	Alkalinity (mg/L)	12	9	6	13.5	10.5	6.7	1.200
10	NH <sub>4</sub> cation (mg/L)	0	0	0	0	0	0	0
11	PO <sub>4</sub> anion (mg/L)	0	0	0	0	0	0	0
12	Turbidity (NTU)	12	5.3	1.3	31	12	6.7	-0.21
13	DO (ppm)	5.3	3.9	3.1	3.3	3.1	2.9	2.9

Table 4 indicates that most of the parameters showed lower or no values with tap water while it was found to be higher and significant in pure FW samples. TDS for FW-2 was found to be 0.97 ppt. On further diluting it to 50% and 90% with tap water, the parameters decreased to 5420 ppm and 1700 ppm respectively. This could be attributed to suspended and dissolved solids inherent in the FW. O & G was found to be 2000 mg/L for pure formation while it decreased to 1000 mg/L and 500 mg/L on further dilution. Conductivity was 1.76237 ms while it decreased to 0.973 ms and 0.310 ms on further dilution. Hardness for pure FW-2 sample was 40 mg/L whereas it decreased to 25mg/L and 15 mg/L on further dilution. Similar decreasing trend was observed for FW-1. These experimental data showed nearest value of tap water and hence is safe to dispose the produced water in to the environment. The below Figure 1 and Figure 2, both showed the Pi chart of the bio physiochemical components present in the FW-1 and FW-2.



**Figure 1: Physico-bio-chemical experimental data of FW-2**

**Figure2:Physico-bio-chemical experimental data of FW-1**

**Table 5: Biochemical Oxygen Demand (BOD) of FW**

SN	Sample (ml)	D1 (at time zero), ppm	D2 (after 3 days incubation), ppm	BOD, ppm
1.	FW-2	5.3	5.9	0.6
2.	FW-1	3.3	5	1.7

Table 5 showed the BOD present in the FWs. Initially DO value of FW-2 was 5.3 ppm and FW-1 was 3.3 ppm respectively. After 3 days incubation the DO value of FWs were increased to 5.9 ppm and 5 ppm respectively. Thereby, we obtained the BOD of 0.6 ppm and 1.7 ppm of the respective FWs by the BOD. The low value of BOD means abnormally high levels of aerobic bacterial activity.

### 3.2 Characterization of inorganics present in FW

**Table 6: Inorganics present determined by ICP-OES**

SN	Parameters	FW-2			FW-1			Tap water
		0% dilution with tap water	50% dilution with tap water (1:1)	90% dilution with tap water (1:9)	0% dilution with tap water	50% dilution with tap water (1:1)	90% dilution with tap water (1:9)	
1	Fe (mg/L)	0.331	0.016	0	0.447	0.139	0	0.072
2	Zn (mg/L)	0.514	0.217	0.006	0.624	0.137	0.012	0.0058
3	Mg (mg/L)	4.912	2.285	2.016	5.598	4.982	4.123	3.077
4	Pb (mg/L)	1.244	0.895	0.72	0.664	0.482	0.210	0.099
5	St (mg/L)	0.402	0.297	0.193	0.581	0.287	0.178	0.087

Table 6 indicates the various heavy metals like Fe, Zn, Mg, Pb and St were detected in the FW-1 and FW-2 samples. The presence of Mg was found to be the highest as compared to other heavy metals. The presents of Ca and Mg indicates the hardness of the FW.

### 3.3 Characterizations of heavy metals in FW

**Table 7: Iron, Chromium, Manganese, Copper are the metals determination by AAS**

SN	Parameters	FW-2			FW-1		
		0% dilution with tap water	50% dilution with tap water (1:1)	90% dilution with tap water (1:9)	0% dilution with tap water	50% dilution with tap water (1:1)	90% dilution with tap water (1:9)
1	Fe, ppm	-0.149	-0.160	-0.152	-0.097	-0.127	-0.150
2	Cr, ppm	-0.594	-0.518	-0.532	-0.539	-0.575	-0.553
3	Mn, ppm	0.070	0.063	0.061	0.075	0.065	0.065
4	Cu, ppm	-0.032	-0.036	-0.039	-0.024	-0.013	-0.026

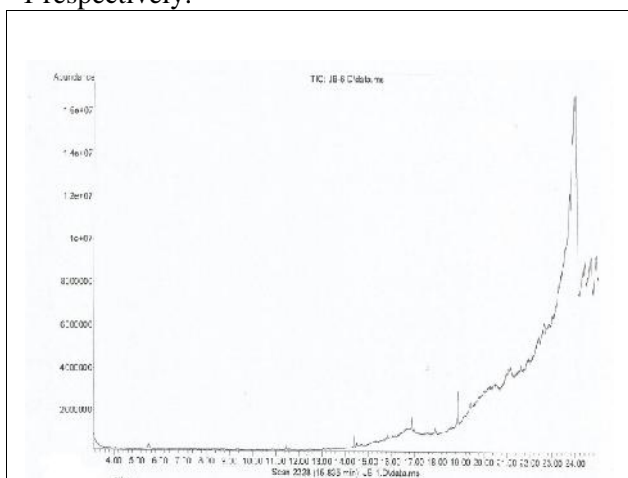
The table 7 shows the presence of heavy metals namely Fe, Cr, Mn and Cu in the FWs. The above results showed the negative results implicate absence of heavy metals.

### 3.4 Characterization of Organics in FW

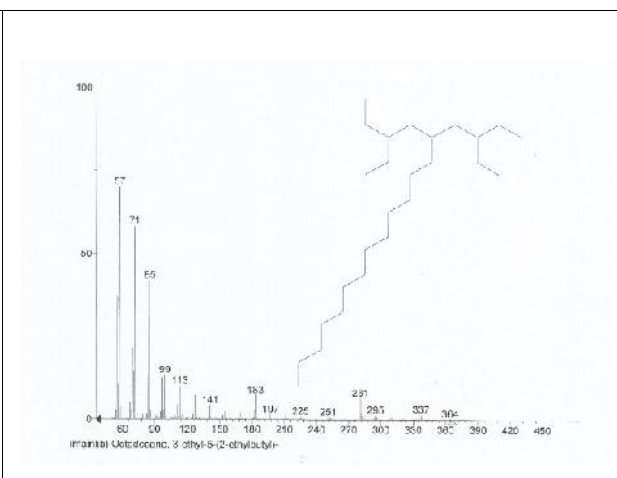
**Table 8: Organics determination by GC**

Serial no.	Produced water sample	Organics present
1	FW-2	Octadecane, 3-ethyl-5(2-ethylbutyl)-
2	FW-1	Pentadecane, 2, 6, 10, 14- tetramethyl-

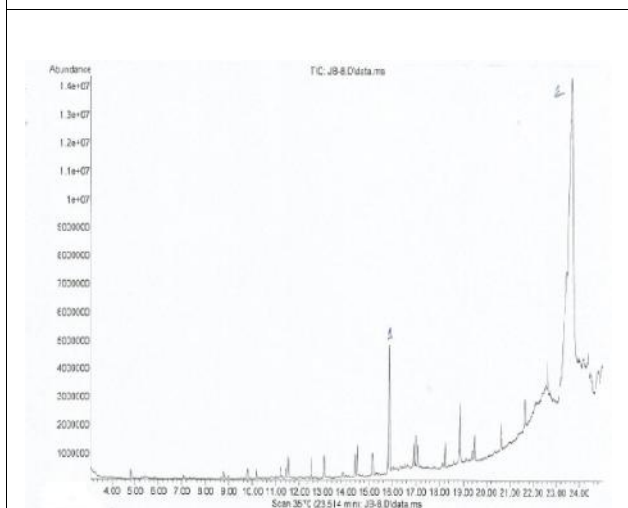
The table 8 showed the probable organics found in FWs. Octadecane, 3-ethyl-5(2-ethylbutyl) - and Pentadecane, 2, 6, 10, 14- tetramethyl- were the organics found in FW-2 and FW-1 respectively after GC peak analysis. The below figures 3(a & c) showed the finger prints of GC of organics found in FWs and figures 3 (b & d) showed the analysis of peak and determined the probable organics found in the particular FW-2 and FW-1 respectively.



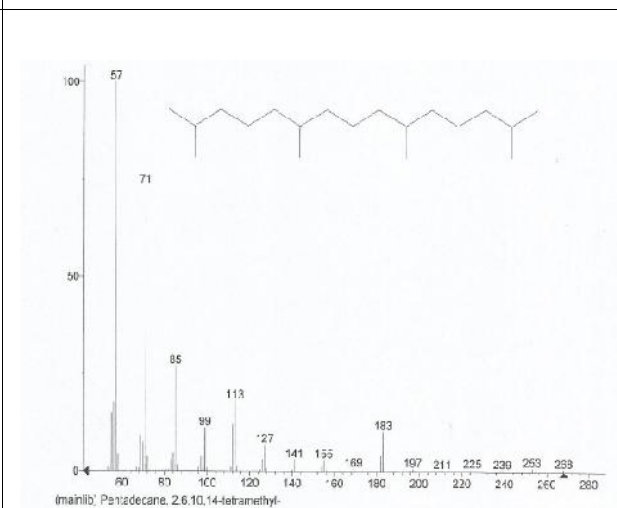
**Figure 3(a): Finger prints of FW-2**



**Figure 3(b): Octadecane, 3-ethyl-5(2-ethylbutyl)- probable organics found by GC peak analysis of FW-2.**



**Figure 3(c): Finger prints of FW-1**



**Figure 3(d): Pentadecane, 2, 6, 10, 14-tetramethyl- probable organics found by GC peak analysis of FW-1.**

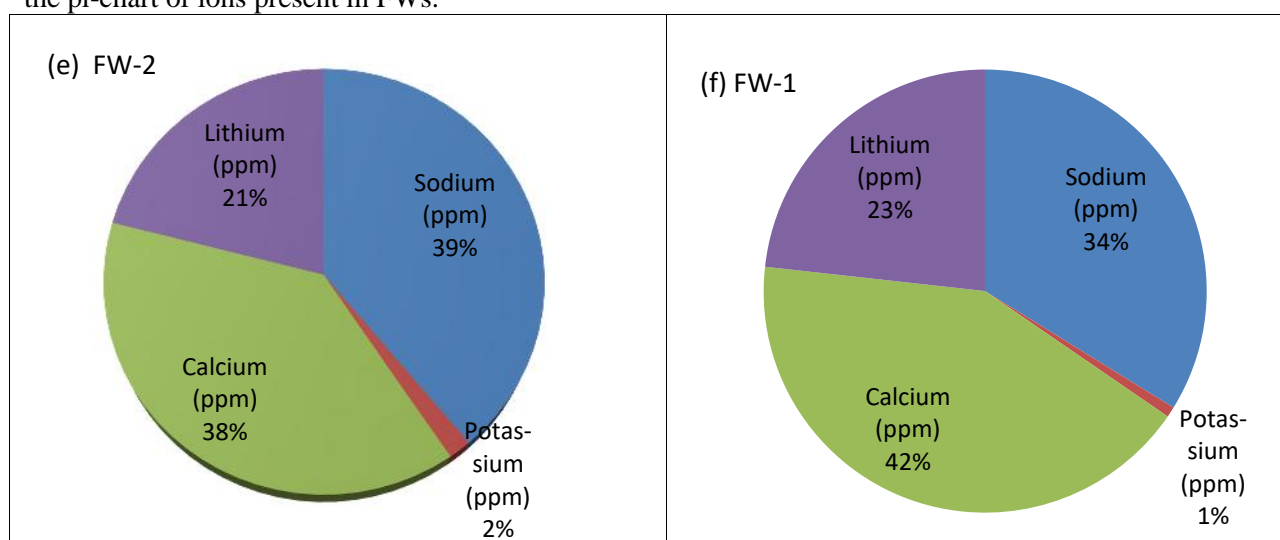


### 3.5 Characterization of Ions present in FW

**Table 9: Ions obtained from Flame photometer**

SN	Parameters	FW-2 D.F. = 10			FW-1 D.F.= 100			Tap water
		0% dilution with tap water	50% dilution with tap water (1:1)	90% dilution with tap water (1:9)	0% dilution with tap water	50% dilution with tap water (1:1)	90% dilution with tap water (1:9)	
1	Na, ppm	92.46	45.52	12	72.70	37.44	12.67	11.67
2	K, ppm	3.91	1.8	0.54	1.65	0.69	0.27	00.90
3	Ca, ppm	91.19	94.40	97.46	90.62	94.64	98.00	99.19
4	Li, ppm	49.91	49.93	49.95	49.95	49.96	49.97	49.97

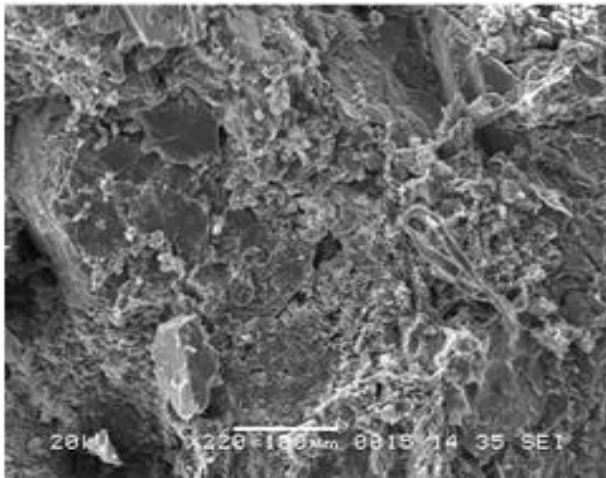
The table 9 showed the ions Na, K, Ca and Li present in FWs. Among these ions, Na was found to be highest in FW-2 and Ca found highest in FW-1. After diluting the FWs 50% and 90% with tap water, concentration of ions decreased and almost equaled to the value of ions found in tap water. The below figure 3 (e & f) showed the pi-chart of ions present in FWs.



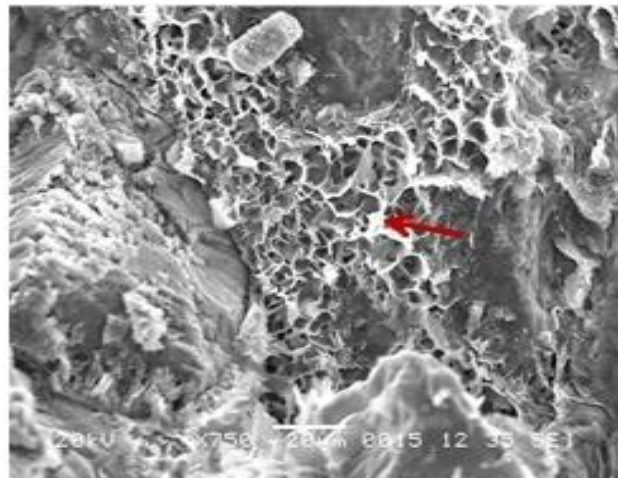
**Figure 3: Pi -chart of ions present (e) FW-2 (DF=10) and (f) FW-1 (DF=100)**

### 3.6 Characterization of minerals present in the porous media of Barail (FW-1) and Tipam (FW-2) formation

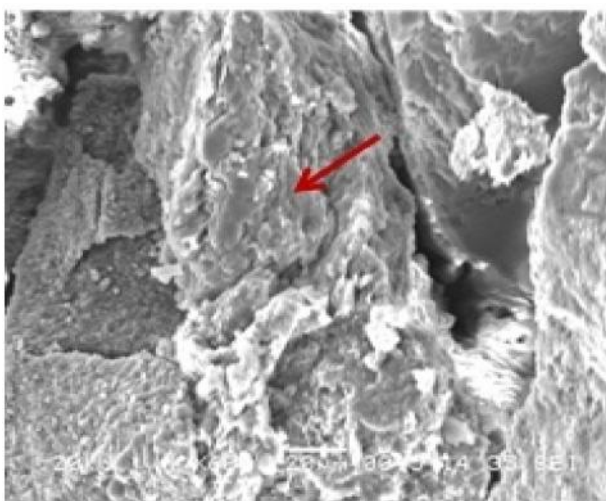
#### 3.6.1 SEM study of the conventional core of the Barail (FW-1) formation (3250 m)



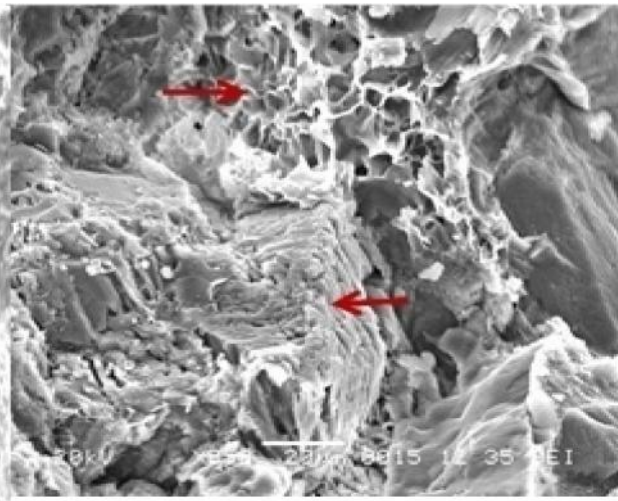
**Figure 3(g): SEM photomicrograph showing sparry (crystallized) type of calcite cement.**



**Figure 3(h): SEM photomicrograph showing well-sorted grains showing intermediate porosity and permeability; intragranular fracturing of framework of grains indicate development of secondary porosity**



**Figure 3(i): SEM photomicrograph showing kaolinite clay.**

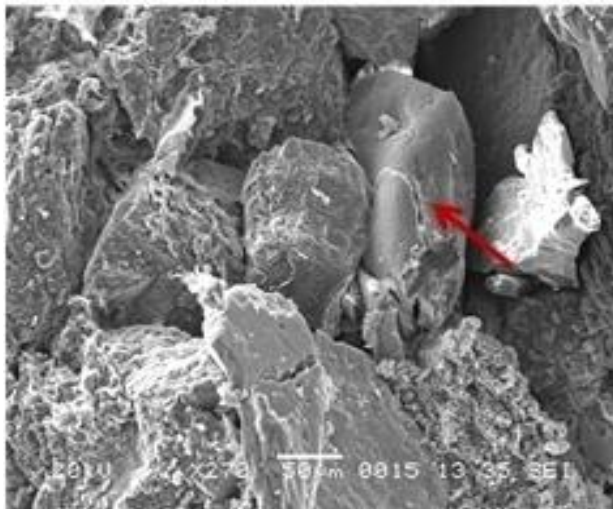


**Figure 3(j): SEM photomicrograph showing framework grains (quartz) coated with clay as well as finer minerals does not favour precipitation of silicious overgrowth**

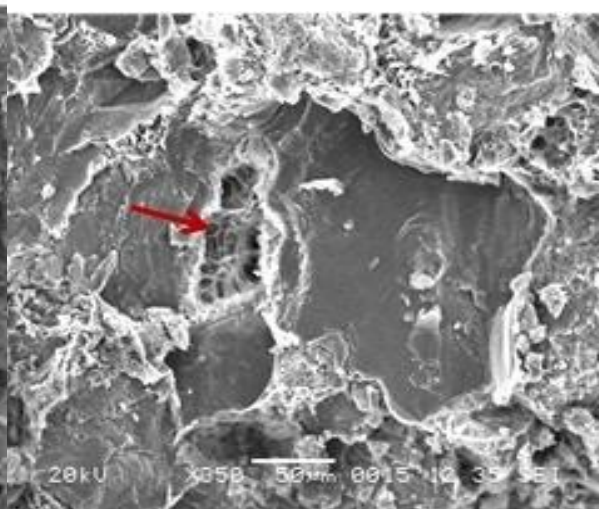
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above four figures 3(g, h, i & j) are the SEM photomicrograph of conventional core FW-1 (Barial formation).

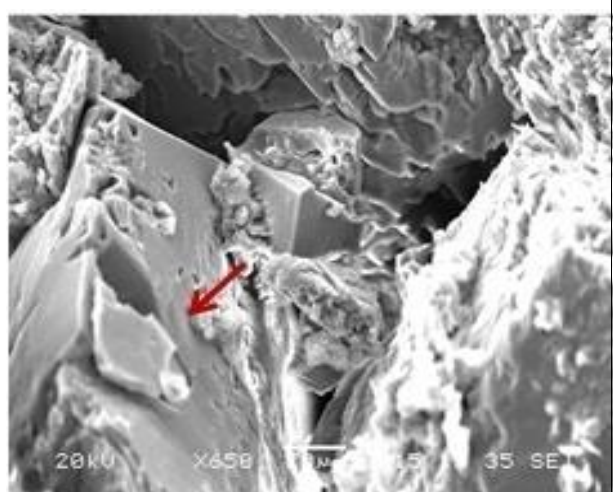
### 3.6.2 SEM study of the conventional core of the Tipam (FW-1) formation (2502m)



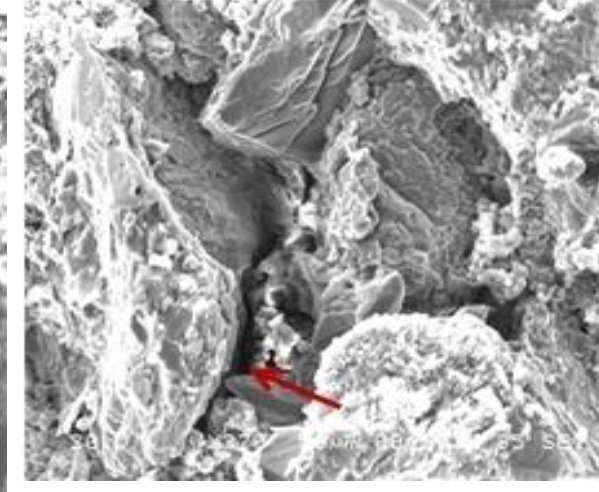
**Figure 3(k): SEM photomicrograph showing kaolinite (bookish structure) and smectite (honeycomb structure) clay distribution.**



**Figure 3(l): SEM photomicrograph showing smectite clay deposition the clay matrix.**



**Figure 3(m): SEM photomicrograph showing tightly packed grains deposition over the in smectite clay intergranular pore spaces.**



**Figure 3(n): SEM photomicrograph showing surface weathering of quartz.**

The SEM photomicrograph of FW-1 oilfield belonging to the Barail formation in Figure 3(g) showed sparry (crystallized) type of calcite cement. Calcite concretions generate a complex porous system which influences fluid flow, oil productivity and recovery efficiency [14] and suggested two main sources of calcite cement: marine water for diagenetic microcrystalline calcite and compactional water sourced from the underlying carbonates of the Barail formation for the mesodiagenetic sparry calcite [15]. It also showed well-sorted grains with intermediate porosity and permeability having intragranular fractures of framework of grains indicating development of secondary porosity in Figure 3(h). The close relationship between depositional lithofacies in each bed, diagenesis, permeability, and porosity demonstrates that each influences the other, and in turn how understanding of reservoir properties is enhanced by integration of paleoenvironmental reconstruction, stratigraphy, mineralogy, and geostatistics [16]. Secondary porosity development occurred due to partial to complete dissolution of early calcite cements and feldspar grains. The new data presented in this paper suggest

the reservoir quality is strongly linked to their diagenetic history; hence, the reservoir quality is reduced by clay minerals, calcite and silica cements but is enhanced by the dissolution of the unstable grains, in addition to partial or complete dissolution of calcite cements and unstable grains. [17]. In Figure 3(i) showed the SEM photomicrograph kaolinite clay and Figure 3(j) showed framework grains (quartz) coated with clay as well as finer minerals does not favour precipitation of silicious overgrowth. Kaolinite covers a fractured quartz grain and fills porosity in wavy -bedded inter-ridge sandstone and minor amount of illitic clay are present as “wispy” coatings on grains and kaolinite [18].

The SEM photomicrograph of FW-2 oilfield belonging to the Tipam formation in Figure 3(k) showed kaolinite (bookish structure) and smectite (honeycomb structure) clay distribution and figure 3(l) showed smectite clay deposition the clay matrix. Aquifer support porous media in a

part of oil bearing horizon belonging to Tipam sandstone formation at depths 2483-2487m and 2504-2506m of reservoir formation with temperature 72-76<sup>0</sup>C belonging to some high water cut wells of Upper Assam Basin [19]. In Figure 3(m) showed the SEM photomicrograph of tightly packed grains deposition over smectite clay intergranular pore space and in Figure 3(n) also showed surface weathering of quartz. The clay size fraction of the weathering rinds indicates that Si, Al and Fe are principal elements in the clay –size fraction. The small amount of Ti and bases (Mg, Ca, Na, and K) present are probably from small remnants of primary minerals in the clay –size fraction [20].

#### 4. Conclusion

FW analysis is very much important for Petroleum engineering industry from both upstream and downstream activities. The presence of heavy metals and the toxic substances in produced water may cause serious threat to the environment when disposed without proper treatment. The physico-chemical characteristics of the FW such as Salinity, TDS, Conductivity, Turbidity and Chloride, ions like Na, K, Ca and Li and also heavy metals like Fe, Mn, Cu and Cr increases with increasing oilfield depth i.e. vary considerably depending on the geographical location of the field. Dilution effect due to tap water is seen to reduction of concentrations of parameters and therefore, is safe to dispose FW in compliance with environmental regulations as per MINAS.

#### Acknowledgement

We would like to acknowledge DBT’s Twinning Project no. BT/485/NE/TBP/09/04/2013 entitled “**Remediation of produced water from NE oil field by microbial and membrane intervention with modeling of an effluent unit for the recovery of usable water**”.

#### Nomenclature

FW	Formation water
PW	Produced water
DO	Dissolved oxygen
BOD	Biochemical oxygen demand
TDS	Total dissolved solid
NE	North East
AAS	Atomic adsorption Spectrometer
GC	Gas chromatography
ICP-OES	Inductively Coupled Plasma- Optical Emission Spectrometry
SEM	Scanning Electronic microscope
MINAS	Minimal National Standards
Na	Sodium

Ca	Calcium
K	Potassium
Li	Lithium
Cl	Chloride
Mn	Manganese
St	Strontium
Fe	Iron
Cu	Copper
Cr	Chromium
Zn	Zinc
Pb	Lead
RFCL	Ranbxy Fine Chemical Limited
IOR	Improved Oil Recovery
O & G	Oil and Grease
EDTA	Ethylene Diamine tetra acetic acid
M.W.	Molecular Weight
KCl	Potassium Chloride
NaCl	Sodium chloride
CaCO <sub>3</sub>	Calcium carbonate
Li <sub>2</sub> CO <sub>3</sub>	Lithium carbonate
HCl	Hydrochloric acid
DOE	Design of Experiments
HCO <sub>3</sub>	Bicarbonate
HNO <sub>3</sub>	Nitric Acid
NH <sub>4</sub>	Ammonium cation
SO <sub>4</sub>	Sulphate anion
Ba(NO <sub>3</sub> ) <sub>2</sub>	Barium Nitrate
ppm	Parts per million

### References

1. Subrata Borgohain Gogoi Ramkrishna Sen, Amarjit Rajbongshi, Kalpajit Hazarika “Characterization of Oil field Produced waters of Upper Assam Basin, India” *International Journal of New Technologies in Science and Engineering* Vol. 2, Issue. 1, 2015, Issn 2349-0780.
2. Joel; Amajuoyi; Nwokoye (2010) “Characterisation of formation water constituents and effect of fresh water dilution from Land Rig Location of Niger Delta, Nigeria”. *J. Appl. Sci. Environ. Manage.* June, 2010. JASEM ISSN 1119-8362 Vol. 14 (2) 37 – 41
3. Yang, M. and Nel, T. *SPE Annual Technical Conference and Exhibition, 2006. San Antonio, Texas, USA.*
4. Veil, J. A. and Clark, C.E. *SPE, Presented at the International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Rio de Janeiro, 2010.*
5. S.B. Gogoi, and A.S. Tamuli, “Recent Advances in Treating Oil Field Produced Water: A Review,” *J. of Petroleum Engineering & Technology*, vol. 4, no. 2, pp. 366-370, 2014.
6. J.A. Veil, M.G. Pruder, D. Elcock, and R.J. Redweik, “A White Paper Describing Produced Water from Production of Crude Oil, Natural Gas, and Coal Bed Methane prepared by Argonne National Laboratory for U.S. Department of Energy,” *National Energy Technology Laboratory, Jan., 2004.*

7. A.A. Al-Haleem, H.H. Abdulah, and E.A. Saeed, J, “Components and treatments of oilfield produced water,” *Al-Khwarizmi Engineering Journal*, vol. 6, no. 1, pp. 24 – 30, 2010.
8. Eman A. Emam, Taha M. Moawad, Noha A. K. Aboul- Gheit “Evaluating the characteristics of offshore oil field of produced water” *Petroleum & Coal* 56(4) 363-372, 2014.
9. B. Stone, “Management of Produced water,” *Oxford publications*, Washington, 37-41, 2003.
10. Onojake M.C. et al., “Evaluation and management of produced water from selected oil fields in Niger Delta, Nigeria” *Archives of Applied Science Research*, 2012, 4 (1):39-47.
11. O.F. Joel, C.A. Amajuoyi, and C.U. Nwokoye, “Characterization of formation water constituents and the effect of fresh water dilution from land rig location of the Niger Delta, Nigeria,” *J. Applied Sci. Environ. Management*, vol.14, no. 2, pp. 37 – 41, 2010.
12. R.P.W.M. Jacobs, E. Grant, J. Kwant, J. M. Marqueine and E. Mentzer, “ The composition of produced water from shell operated oil and gas production in the North Sea,” In: J.P. Ray and F.R. Englehart, Eds., *Produced Water, Technological /Environmental Issues and Solutions*, Plenum Press, New York, pp. 13-21, 1992.
13. H. Patel, D. Borgohain, and S. Jena, “Hydro geochemistry of Upper Assam Oil field,” *J. of Petroleum Technology*, vol. 2, pp. 11 – 14, 2003.
14. Neyda M. Abreu and Emma S. Bullock “Opaque assemblages in CR2 Graves Nunataks (GRA) 06100 as indicators of shock-driven hydrothermal alteration in the CR chondrite parent body” DOI: 10.1111/maps.12227.
15. R.S. De. Souza and C.M. De Assis Silva, “Origin and timing of carbonate cementation of the Namorado Sandstone (Cretaceous), Albacora Field, Beazil: implications for oil recovery” *Spec. Publs inl. Ass. Sediment.* (1998)26, 309-325.
16. J. M. McKinley, P. M. Atkinson, C. D. Lloyd, A. H. Ruffell, R. H. Worden, “How Porosity and Permeability Vary Spatially With Grain Size, Sorting, Cement Volume, and Mineral Dissolution In Fluvial Triassic Sandstones: The Value of Geostatistics and Local Regression” DOI: 10.2110/jsr.2011.71 Published on December 2011; 81 (12)
17. Nabil M. Al Areeq, Mohamed A. Soliman, Mahmoud A. Essa, Nabeel A. Al- Azazi “Diagenesis and reservoir quality analysis in the Lower Cretaceous Qishn sandstones from Masila oilfields in the Sayun–Masila Basin”, eastern Yemen DOI: 10.1002/gj.2639 Published: 23 January 2015.
18. Debra K. Higley, “Petrology and Reservoir Paragenesis in the Sussex "B" Sandstone of the upper cretaceous cody shale, House Creek and Porcupine fields, Powder river basin, whyoming. Issue 1917” Page no. 67
19. Dhruvajyoti Neog and Pradip Borgohain, “Porous Media Characterization for Feasibility Study of Oil Well Water Production Control” *International Journal of Innovative Research in Science, Engineering and Technology*, An ISO 3297: 2007 Certified Organization. Vol. 5, Issue 12, December 2016.
20. Bruce LaVerne Foxworthy, “Volcanic eruptions of 1980 at Mount St. Helens: the first 100 days”, *Mary Hill, Geological Survey (U.S.)*, page no. 7.
21. Dusan Spornjak, Ajay K. Prasad, Suresh G. Advani, “Experimental investigation of liquid water formation and transport in a transparent single-serpentine PEM fuel cell” *Elsevier Journal of Power Sources* 170 (2007) 334–344.
22. Y. Du, L. Guan, and H. Liang, “Advances of produced water management,” *Canadian International Petroleum Conference*, 7-9 June, Calgary, Alberta, 2005.
23. ASTM (1979). *Annual Book of America Society for Testing and Materials Standards*, 1527, Philadelphia.
24. Bansal, KM; Caudle, DD (1999). “Interferences with Processing Production Water for Disposal”, *9<sup>th</sup> Produced Water Seminar*, Houston, TX, Jan. 21-22.
25. Brendehaug, J; Johnsen, S; Bryne, KH; Gjose, AL; Eide, TH (1992). “Toxicity Testing and Chemical Characterization of Produced Water – A Preliminary Study, in *Produced Water*”, J.P. Ray.
26. Clair, N.S. Perry, L.M. and Gene, F.P. “*Chemistry of Environmental engineering and science*”, 5th ed. 2003, McGraw- Hill companies Inc.
27. Cline J.T. “*API Produced Water Management Technical Forum and Exhibition*”, 1998. Lafayette, LA, USA.
28. Duffus, J.H. *Environmental Toxicology*. 2nd ed. 1980, Edward Arnold Publishers Limited, London. P 21 – 103.
29. Durell G. et al., 2000. *5<sup>th</sup> SPE International Conference on “Health, Safety, and Environment in Oil and Gas Exploration and Production”*. 26-28 June 2000. Stavanger, Norway.
30. Egereonu, U. Dike, R. *Journal of Chemical Society Nigeria* 2007 32:59 –166
31. *Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPI 2000)*
32. Franson, M.A. “*Standard Methods for the Examination of Water and Wastewater*” 14<sup>th</sup> 1995, New York, USA, p150-152.

- 
33. Johnsen, S. et al., *Seventh SPE International Conference on Health, "Safety and Environment in Oil and Gas Exploration and Production"*, 2004, Calgary, Society of Petroleum Engineers, Richardson, Texas.
  34. Neff, J. M. Elsevier "Applied Science Publishers", 1987, London p. 469-538.
  35. Osuji, L.C. and Onojake, C.M. *Chemistry and Biodiversity*. 2004. 1:1708 – 1715
  36. Smith J.P. et al., "Environmental Toxicology and Water Quality". 1998. 13(4): 323-336.
  37. Tobonimi, J.K.I. et al., *Sciencia. Africana*. 2010, 9: 154 – 165
  38. Z. Khatib, and P. Verbeek, "Water to Value – Produced Water Management for Sustainable Field Development of Mature and Green Fields," *J. of Petroleum Technology*, pp. 26-28, Jan., 2003. World Health Organization. *Guidelines for drinking water quality*. 2nd ed. 1998, p188.
  39. K. Guerra, K. Dahm, and S. Dunderf, "Oil and gas produced water management and beneficial use in the Western United States," U.S. Department of the Interior Bureau of Reclamation, *Science and Technology Program Report No. 157, Technical Service Center*. Sep. 2011.