American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-5, Issue-12, pp-46-57
www.ajer.org
Research Paper Open Access

Produced Water Treatment Methods and Regulations: Lessons from the Gulf of Mexico and North Sea for Nigeria

Adaobi Stephenie Nwosi-Anele[1], Omowumi O. Iledare[2]
[1](Department of Petroleum and GasEngineering, Faculty of Engineering, University of Port Harcourt, Nigeria)
[2](Emerald Energy Institute, University of Port Harcourt, Nigeria)

ABSTRACT: *Discharge specifications are allowable effluent limits of constituents in produced water before being discharged into the environment. Environmental regulatory agencies in the North Sea, Gulf of Mexico, and Niger Delta regions have specified effluent limits for the constituents of produced water. These PW discharge limits may be specified for metals, solids, bacteria, oil/grease content, PH, temperature, process chemicals and dispersed hydrocarbon constituents. Recent environmental impact assessments show that contrary to the trend in Niger Delta, North Sea and Gulf of Mexico have continued to modify their effluent limits pursuant to ZERO effluent discharge. This contrasts sharply with the Niger Delta which has maintained its effluent discharge limits for a long time without review. This has left the region with discharged effluents that may fall short of the needed environmental friendliness level. This paper investigates produced water treatment methods used in North Sea and Gulf of Mexico and how these could be useful for produced water treatment in Niger Delta. Critical comparative evaluations of treatment processes used in North Sea and Gulf of Mexico are carried out considering the terrain, PW constituents and regulatory specifications analogous to the Niger Delta. Results show that these treatment processes may be adopted based on terrain similarities. Effluent discharge limits may be met and exceeded with a view to achieving ZERO discharge effluent in Niger Delta.*

Keywords: *Produced Water (PW), Total Dissolved Solids (TDS), Total Suspended Solids (TSS)*

I. INTRODUCTION

Produced water (PW) is a subsurface fluid just like crude oil and natural gas consisting of certain harmful substances. Water must be produced with oil and associated gas to the surface during hydrocarbon production activities. Oil field operators are particularly interested in producing crude oil but must find a way to handle the "necessary evil" (produced water) that comes with it in order to ensure efficiency in their operations. Due to this reality facing oil field operators, so many research works have been done to find a way to handle produced water around the world.

Discharge specifications are the allowable effluent limits of constituents of produced water. The constituents of produced water are characterized as follows: dissolved and dispersed oil compounds, dissolved, dispersed and suspended organic compounds, treatment chemicals (corrosion inhibitors, mud cuttings etc.), produced solids, bacteria, and metals.

Effluent limits are characterized as follows: pH, temperature, oil/grease content, salinity, turbidity, total dissolved solids (TDS), total suspended (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), lead, iron, copper, chromium, Zinc, sulphide, sulphate, mercury and turbidity. The effluent limits can be determined in the laboratory.

- Conductivity: Conductivity of a solution is a measure of the ionic content of the solution used to measure quality of the solution for salinity determinations. It is measured in ohms.
- Chloride (mg/l): Chloride content of a solution is determined using titration method. The pH value of chloride solution should be between 7 and 10.
- Hydrogen ion concentration (pH): This is the measure of the ionic concentration of hydrogen ions in a solution. It could be measured using pH meter.
- Turbidity: This can be measured using Jackson's candle turbid meter which consists of a long flat-bottom glass tube until the outline of the flame is no longer visible compared to the standard turbidity unit.
- Biochemical Oxygen Demand (BOD): Biochemical Oxygen Demand is the amount of oxygen required by aerobic microorganisms to decompose the organic matter in a sample of produced water. It is estimated as

the difference between the dissolved oxygen concentrations in water sample fixed immediately after sampling and its duplicate incubated in the dark at room temperature for 5 days.

- Chemical Oxygen Demand (COD): This is a measure of the capacity of produced water to consume oxygen during the decomposition of organic matter and oxidation of inorganic chemicals such as ammonia and nitrate. It is used to measure the degree of water pollution; it is measured in the laboratory, when a closed water sample is incubated with strong chemical oxidant under specific condition of temperature and for a period of time.
- Total dissolved solids: Total dissolved solids could be determined by filtering a well-mixed sample of produced water and the filtrate allowed to dry.
- Total suspended solids: Total suspended solids could be obtained through same method as total dissolved solids. It is usually suspended on the surface of the produced water and may be visible to the eyes.
- Nitrate: The Nitrate content of produced water can be measured using the spectrometric method.
- Phosphate: Phosphate in produced water is measured when the sample is acidic and heated such that it becomes organic, then calorimetric or spectrometer test is applied to the solution to determine the presence of phosphate.
- Oil and grease content: Sample of produced water is collected and poured into a beater rinsed with extraction solvent (usually 111 trichloroethane or carbon tetrachloride). 111 trichloroethanesolution is then poured into the beaker containing produced water and left to stand for 10 minutes to separate. A spectrometer is then used to measure the oil and grease content and is calibrated to Bonny Light Crude Oil.
- Metallic content of produced water (Cadmium, lead, copper, zinc, Iron): Metals present in produced water are determined by use of atomic absorption spectrometric method.

Surface water temperature: This is temperature of the surface water measured using a thermometer.

The effluent limit permitted varies for different regions around the world. The oil and grease content of produced water seems to be one universal effluent discharge parameter that is majorly used to judge the discharge of produced water into the environment while other constituents remain almost silent. This is so because other constituents of produced water may vary depending on the kind of chemicals used during exploration, well completion, and work over operations and production activities. Reservoir formation type also influences the salinity and $_{P}$H of produced water; limits are still set in the different regions for all constituents of produced water. Khalilpour (2014) lamented the regulatory gap for the Norwegian part of the North Sea, as the focus has remained on oil/grease content of produced water rather than other constituents of produced water which are the dissolved components of produced water and this has been the case all over the world [1].

Environment regulatory agencies are bodies set to ensure environmental safety for the lives of humans, plants and animals in different regions around the world. To achieve this, they ensure that harmful substances are not emitted into the environment; they set limits for discharge of some substances into the air, land and sea. The North Sea, Gulf of Mexico, and the Niger Delta have these environmental protection agencies that check emission of oil and gas industrial waste into the environment.

II. NIGER DELTA PRODUCED WATER REGULATION AND TREATMENT METHODS

The Niger Delta region is situated in the Southern part of Nigeria and bordered to the South by the Atlantic Ocean and to the East by Cameroon. It occupies a surface area of about 112,300 square kilometers and represents 12% of Nigeria's total surface area. Its wetlands of 70,000km^2 which are the largest in Africa form basically sediment depositions. The Niger Delta has a well-endowed ecosystem containing one of the highest concentrations of biodiversity on the planet. Its arable terrain can sustain a wide variety of crops, lumber of agricultural trees and many species of fresh water fish than any ecosystem in Africa. The Niger Delta is a sensitive environment with surrounding rivers and lakes linking the Atlantic Ocean as shown in fig 1.

The Niger Delta may lose 40% of its terrain in the next thirty years as a result of environmental negligence on the part of the oil industry players, as reported by the Nigerian National Petroleum Corporation (NNPC, 1983). Between 1983 and 2015 (32 years), a lot of degradation has been experienced in the Niger Delta environment. The slow poisoning of the waters in the Niger Delta and the destruction of the vegetation and agricultural land by oil spills and petroleum operations (like the disposal of improperly treated produced water) could be managed by oil field operators. The geographical map of the Niger Delta as shown in Fig 1 depicts a region surrounded by seas and rivers linking the Atlantic Ocean. Disposal of improperly treated industrial waste into swamps and rivers surrounding the Niger Delta is indeed harmful.

The Nigerian Ministry of Environment is saddled with the responsibility of ensuring a safe ecosystem for the good of all her citizens and there is also the National Environmental Standards and Regulations Enforcement Agency (NESREA). Aside the NESREA Act of 2007, there are so many other laws and regulations on the environment in Nigeria. These include the Environmental Impact Assessment Act, Harmful Waste Act, Hydrocarbon Oil Refineries Act, Associated Gas Re-injection Act, the Endangered Species Act, Water Resources Act and the Territorial Waters Act to mention a few.

The Constitution of the Federal Republic of Nigeria (1999) made provisions for environmental protection. Section 20 provides for the environmental objectives of the Nigerian State towards improving and protecting the air, land, water, forest and wildlife of Nigeria. Sections 33 and 34 are also linked to the environment. Under the NESREA Act 2007, two regulations are prominent. These are the National Effluent Limitation Regulations and the Federal Solid and Hazardous Waste Management Regulations of 1991. The Environmental Impact Assessment (EIA) Act of 2004 is geared towards assessment of potential impacts, whether positive or negative, of a proposed project on the natural environment. The Oil in Navigable Waters Act of 2004 is concerned with the discharge of oil from a ship into territorial waters or shorelines. There is also the National Oil Spill Detection and Response Agency (NOSDRA) which is mandated to play the lead role in ensuring timely, effective and appropriate response to oil spills, as well as ensuring clean up and remediation of all impacted sites to the best practical extent. According to the Ministry of Environment website, NOSDRA shall also identify high risk/priority areas in the oil-producing environment for protection as well as ensure compliance of the oil industry operators with all existing environmental legislations in the petroleum sector.

The philosophy behind the Nigerian Laws in the Petroleum Industry is that the licensee/lessee or Operator is expected to be responsible for hazardous materials, wastes and toxic chemicals from cradle to grave. It is against this backdrop that the Department of Petroleum Resources set the effluent discharge standard for discharge of produced water into the Niger Delta environment as shown in TABLE 2. The Department of Petroleum Resources in 1981 issued interim Guidelines concerning the monitoring, handling, treatment and disposal of effluents, oil spills and chemicals, drilling muds and drill cuttings by lessees /oil operators. Tentative allowable limits of waste discharges into fresh water, coastal water, and offshore areas of operations were also established. As one of the statutory functions of DPR, it must ensure that petroleum industry operators do not degrade the environment in the course of their operations. These guidelines are contained in a publication called Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN).

In order to make the oil and gas industry economically efficient, there must be an absolute elimination of all factors that constitute harm to the environment while exploiting the environment for the economy. Treating produced water properly before disposal is one of such ways to eliminate the harm done to the environment by the oil and gas industry. Ukpohor (2001) studied the impact of disposal of huge volumes of untreated produced water on the environment especially as the declining era of oil and gas production in Nigeria sets in [2]. He stated that more volumes of water would be produced because the Niger Delta is 82% water drive. He also observed that there were effects of produced water discharge on the ecosystem, man, and aquatic lives. He suggests that technologies should be put in place to minimize volume of water produced, re-inject produced water, re-use produced water for consumption, and ensure compliance with discharge regulations. Reducing the volume of water produced does not totally eliminate water disposal into the environment. It reduces the volume of produced water to be treated, thereby reducing cost of water treatment. Depending on the constituents of produced water and the purpose of re-injection, the water may be treated before re-injection. Water treatment cannot be totally ruled off in a field operation plan; therefore treatment techniques are a necessity for any field development plan.

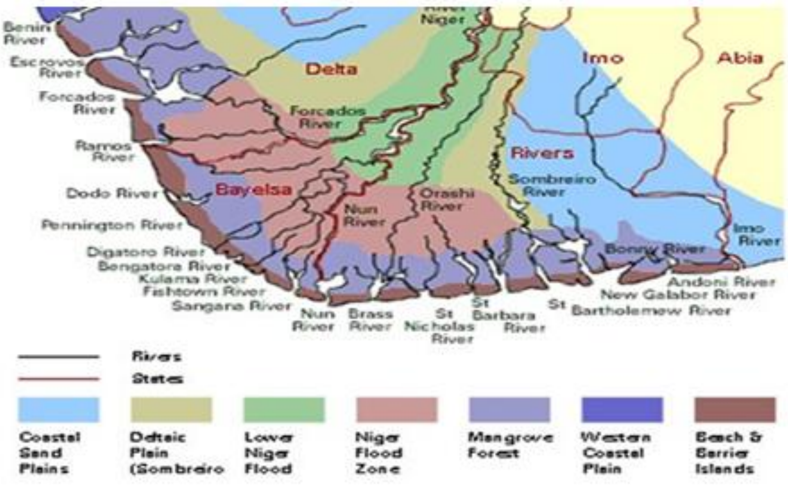

Figure 1: Niger Delta Region and Surrounding Rivers

Isehunwa and Onovae (2011) evaluated the physio-chemical properties and constituents of produced water from three (3) selected flow stations (onshore, swamp and offshore) and two (2) oil terminals (near shore) in the Niger Delta to determine the extent of compliance with standards and global best practices [3]. The results of their research show that the pH was within limits, oil and grease content were above discharge limits, iron concentration was high, chloride ion, total dissolved solids, and total suspended solids exceeded allowable limits in all stations as presented in TABLE 1.

Table 1: Constituents of produced water from fields in the Niger delta (Isehunwa and Onovae 2011)

Parameter	Allowed limit	Flow stations			Terminals	
		X	Y	Z	A	B
pH @75oF	6.5-8.5	8.12	8.53	7.88	8.10	8.43
Resistivity @ 65oF		0.45	0.68	1.58	0.37	8.40
Oil/grease content (mg/l)	10.00	65.00	42.00	64.00	80.00	40.00
Copper (mg/l)	1.00	0.25	0.01	0.37	0.44	0.08
Lead (mg/l)	0.05	0.05	0.03	ND	ND	0.04
Iron (mg/l)	1.00	0.40	0.15	0.35	0.17	0.13
Nickel (mg/l)	1.00	0.50	0.49	0.54	0.33	0.65
Barium (mg/l)	-	16.00	8.00	5.00	20.00	11.00
Zinc (mg/l)	1.00	0.10	1.80	0.98	0.09	0.85
Magnesium (mg/l)	-	56.00	34.40	165.00	4.86	14.75
Chloride (mg/l)	600.00	5,100.00	2,583.00	3,589.00	4,678.00	3,970.00
Sulphate (mg/l)	200.00	12.00	2.00	-	-	30.00
Carbonate mg/l)	-	16.00	220.00	200.00	180.00	110.00
Bicarbonate (mg/l)	-	2,000.00	980.00	4,720.00	1,036.00	710.00
Total dissolved solids	2,000.00	9,000.00	3,978.00	5,300.00	6,850.00	6,440.00
Total suspended solids	30.00	60.00	80.00	138.00	104.00	94.00
BOD (mg/l)	10.00	500.00	8.50	4.50	8.68	5.33
Discharge temp(oF)	-	85.00	84.00	92.00	85.00	82.00

It was observed that some flow stations lacked the basic gravity separation facility to treat produced water while for some other platforms treatment of produced water was mainly by dilution before over board disposal. They further compared produced water in the Niger Delta with that in Europe. Observation showed that barium, sodium and zinc were higher in Niger Delta than in Europe.

Total suspended solids exceeding required limit present in produced water as well as oil and grease content of produced water would result in discharge of oily water into the environment, polluting the environment and destroying the ecosystem and aquatic habitat. These could be very harmful because the important component in the marine and aquatic food web (phytoplankton, periphyton, sphergiral and zooplankton) would be destroyed. Respiration of aquatic animals would be hampered by the sealing caused by large oil droplets in aquatic habitats. This results in suffocation of aquatic animals. High ion and chloride concentration results in water hardness and acidity of the surrounding waters which may be harmful for rural dwellers depending on the rivers and lakes around them for water supply for their daily survival. Meeting discharge regulatory specifications is the only way out of this harm that may befall human lives, aquatic lives and the ecosystem.

It was observed that oil field operators in the Niger Delta complied with regulations in the 1900's until the 21st century when a back drop was noticed. The effluent discharge regulation of Nigeria as stipulated by the Department of Petroleum Resources (DPR) is yet to be met. These specifications are presented in TABLE 2. Research has shown that there are lessons to be learnt by Nigeria from the North Sea and the Gulf of Mexico.

Table 2: The Effluent Produced Water Discharge Limit in the Niger Delta (DPR)

Effluent characteristics	Inland	Near shore	Offshore
pH	6.5-8.5	6.5-8.5	No limit
Temperature °C	25	30	-
Oil/Grease Content	10	20	40
Salinity	600	2,000	-
Turbidity	>10	>15	-
Total dissolved Solids	2,000	5,000	-
Total suspended solids	>30	>50	-
Chemical Oxygen Demand	10	125	-
Biochemical Oxygen Demand	10	125	-
Lead	0	No limit	-
Iron	1	No limit	-
Copper	2	No limit	-
Chromium	0	0	-
Zinc	1	5	-
Sulphide mg/l	0	0	0
Sulphate SO4- mg/l	200	200	300
Mercury mg/l	0	-	-
Turbidity	10 NTU	10 NTU	10 NTU

III. NORTH SEA PRODUCED WATER REGULATION AND TREATMENT METHODS

The North Sea is an offshore exploration and production environment and is also a part of the Atlantic Ocean. The North Sea is bordered by Norway, Denmark, Germany, the Netherlands, Belgium, France and the United Kingdom. Of all the bordering countries, 95% of its oil production is from the United Kingdom, Denmark, the Netherlands and Norway. The North Sea produces three(3) billion barrels of oil yearly, is fed by many rivers and linked with the Atlantic Ocean making it a sensitive environment and similar to the Niger Delta. It is a hub for transport, merchandise and a major source of fish stock.

3.1 North Sea Discharge Regulatory Specifications

Produced water discharge regulatory specifications for the North Sea has a complex background. This is because the European Union (EU) bordering the North Sea has developed a regulatory framework dating back to the 1800's. Measures were taken to protect the North Sea by its bordering countries in the 1970's; this led to two major Conventions i.e. the Oslo Convention of 1972 and the Paris Convention of 1974. These two Conventions were merged to form the Convention for the Protection of the Marine Environment of the North Sea, nicknamed OSPAR after the Oslo and Paris Conventions, "OS" for Oslo and "PAR" for Paris; this came into force in 1998. Before the merger, the PW regulation was set as 40ppm under the Paris Convention in 1978. OSPAR changed the regulation to 40mg/l. In 2001, OSPAR adopted a recommendation for the management of produced water from offshore installations, making all oil field operators complete a review of the available technique in place on their fields. By 2006, performance standards for the dispersed hydrocarbons were reduced from 40mg/l to 30mg/l [4].

Produced water effluent limit discharged into the environment of the North Sea has been improved following the resolution of OSPAR. The Convention also recommends that:

- Further investigation should be made to check the extent and effects of pollution caused by hazardous constituents of produced water on the environment and also to develop appropriate technology to tackle and minimize such discharges.
- To review and adopt technologies for reduction of volume of water to be produced at the surface and consequently volume to be discharged into the environment (re injection, down-hole separation or water shut off).
- Study of long term effects of produced water on the North Sea environment.

3.2 Technologies Used In the North Sea to Meet Discharge Regulatory Specifications

These technologies were suggested by OSPAR as techniques suitable for produced water treatment in order to meet discharge effluent specifications. Technologies listed in TABLE 3 were suggested by OSPAR as techniques suitable for produced water treatment in order to meet discharge effluent specifications. They were classified into three:

Preventive techniques: These are used to prevent the surface production of water. This could be achieved by installing oil-water separation devices in situ.

Process integrated techniques: These are to be installed alongside the oil and gas production facilities for surface produced water treatment and control. The process integrated techniques function to eliminate water completely from oil samples produced and oil from water samples ensuring that water to be discharged into the environment does not contain oil. Hence oil in grease content and dissolved/ dispersed aromatic hydrocarbons in

PW are handled by this process. Depending on the constituents of produced water, some end of pipe techniques may be combined with the process integrated techniques to achieve better effluent.

End of pipe techniques: End of pipe techniques are to be used to treat produced water volumes produced to the surface, they are standalone facilities functioning as a process separate from the production platform. Produced water is made to go through the end of pipe process techniques when produced to the surface to achieve effluent discharge limit.

The conventional and biological techniques can handle the oil and grease content, total dissolved solids, and total suspended solids.

Membrane techniques are employed to handle metallic concentration of produced water as well as dissolved and dispersed hydrocarbon content of produced water.

Absorption/Adsorption, Oxidation and Stripping techniques are employed to handle little volume of produced water. They have proven inefficient when handling huge volumes of produced water.

In practice, where end of pipe techniques are used, conventional techniques combined with membrane techniques have proven very efficient in the North Sea.

As it stands today, discharge of produced water into the North Sea must meet the discharge specification of 30mg/l. Technologies for improvement have been suggested by OSPAR as shown in TABLE 3. The EU marine environment strategy has proposed a goal to be achieved by the year 2020 banning any discharge to the marine environment.

Table 3: List of potential measures to be used for produced water treatment as recommended by OSPAR Convention.[4]

PREVENTIVE TECHNIQUES	PROCESS INTEGRATED TECHNIQUES	END OF PIPE TECHNIQUES
• Down-hole oil-water separation and re-injection (DOWS) • Down-hole gas –water separation and re-injection (DGWS) • Mechanical water shut-off • Chemical water shut-off	• Methanol recovery unit • Glycol regeneration • Overhead vapour combustion • Macro porous polymer Extraction (MPPE) • C-tour • High pressure condensate-water separation • Steam stripping (glycol regeneration water) • Insulation of pipelines • Stainless steel lines and casks • Alternative methods of gas drying • Labyrinth type choke valve • Glycol overheads backflow to separator • Degasser	**Conventional techniques** • Skimming tanks • Corrugated plate interceptors • Hydro cyclones • Induced gas flotation units/ dissolved gas flotation units • Centrifuges • Plate coalsecers **Biological Techniques** • Aerobic • Bioreactor • Membrane Bioreactor • Enzyme reactor • Compost filter (glycol overhead) • Bacterial treatment **Membrane Techniques** • Micro-filtration • Ultra-filtration • Nano-filtration • Membrane separator • Reverse Osmosis • Pertraction • Emulsion Pertraction • Electrodialysis • Membrane assisted affinity sorption (MAAS) **Absorption/adsorption techniques** • Absorption filter • Granular active carbon • Powder carbon • Ion exchange • Centrifugal absorption techniques • Zeolites • MPPE • MPPS • Reusable oil adsorbent **Oxidation techniques** **Stripping techniques**

IV. GULF OF MEXICO PRODUCED WATER REGULATIONS AND TREATMENT METHODS

The Gulf of Mexico is also referred to as the Gulf in the United States of America. Its basin countries are the United States, Mexico, and Cuba. The North Sea has the United States of Texas, Louisiana, Mississippi, Alabama and Florida bordering on the north, Mexico on the southwest and Cuba on the southeast. It is connected to the Atlantic Ocean similar to the Niger Delta and the North Sea earlier discussed. The Gulf of Mexico accounts for total of 17% of U.S crude oil production with gas production and other refining activities taking place in this region. The Gulf of Mexico is a hub of oil and gas activities including fishing and other merchandise. It is not different in this regard from the Niger Delta and the North Sea.

4.1 Produced Water Discharge Regulatory Specification For Gulf Of Mexico

Produced water discharge regulatory specifications vary according to region. Authorities responsible for environmental protection in the United States (United States Environmental Protection Agency, USEPA) have stipulated regulatory specifications for the Gulf of Mexico. These regulations follow the U.S legal/ regulatory framework; other requirements may vary with regions. Specifically the requirements are in this order:

- National oil and grease limits
- Effluent toxicity testing requirements for species before discharge.
- Monitoring, studies, control measures to meet regional needs.

The Gulf of Mexico has the following regulations:

- Onshore - Zero discharge effluent.
- Agricultural and wildlife - Water must be good enough for wildlife, livestock and agricultural use, oil and grease limit in produced water should be 35mg/l maximum.
- Coastal wells- Zero discharge except in Cook Inlet and Alaska.
- Offshore wells - Oil and grease limit before discharge should be 29mg/l monthly average and 42mg/l daily maximum. Oil and grease content of produced water is the only parameter regulated by national standards. Other parameters vary according to region and constituents of produced water.
- Discharges in the Gulf of Mexico are regulated and checked through NPDES (National Pollutant Discharge Elimination System) general permits [5].
- Zero discharge specification is the target for the Gulf of Mexico as environmental regulatory agencies propose more stringent measures for produced water discharge.

4.2 Technologies Used In the Gulf of Mexico to Meet Discharge Regulatory Specification

Regulatory agencies in the Gulf of Mexico do not suggest ways to treat produced water in their regulation like OSPAR Convention does for the North Sea. Oil field operators are left to use best available techniques suitable at their convenience provided regulatory specifications are met. Godec*et al.*, (1994) presented methods that have been used to achieve the long standing discharge effluent of 29mg/l monthly average and 42mg/l daily average in the Gulf of Mexico [6]. They are:

- Hydro cyclone
- Centrifuges
- Plate Coalescers
- Induced/dissolved gas flotation units
- Re-injection of produced water for improved oil recovery
- Re-injection of produced water into abandoned wells.
- Combination of two or more techniques with chemicals (flocculants and scale inhibitors) to achieve better discharge effluents.

Godec*et al*., (1994) opines that zero discharge effluents in the Gulf of Mexico is anticipated but at a higher cost of PW treatment, lower net present value and lower tax returns to host government [6].

Table 4: Comparative Analysis of Produced water management approaches of North Sea and Gulf of Mexico.

North Sea	Gulf of Mexico	Niger Delta
Precautionary measures are put in place	Holistic effect of the effluent is the focus. Study is conducted of the potential effect of the discharge.	No specific goal to find effect of PW discharge on the environment.
Methods of PW treatment methods are suggested by OSPAR Convention. Best available techniques are used.	Methods of PW treatment methods are decided by the oil field operators to ensure regulatory specification is met.	Methods of PW treatment are decided by oil field operators.
OSPAR Convention decides regulatory specification, it may vary with location	NDPES regulates oil in grease content in PW, other parameters vary with region	DPR regulates effluent discharge limits of PW.

but all meet baseline requirements of oil/grease limit.	and constituents of PW in the United States but regional EPAs regulate regional discharges.	
Polluters pay, use of risk assessment approach to authorize discharge limit.	Limit is on the volumes of PW to be discharged into the environment per day.	No penalty for violation, no limits on volume of water to be discharged into the environment.
Long standing oil/grease limit of 40mg/l was modified to 30mg/l in 2006. No discharge permitted onshore and shallow waters, sensitive areas such as rivers, parks and wild life area	Oil/grease limit is 29mg/l monthly average. 42mg/l daily average. Zero discharge on onshore platforms, water to be discharged to coastal region must be suitable for agricultural purposes. No discharge within dredge sites and shallow waters, no discharge within 1000 meters of areas of biological concern.	Long standing 40mg/l for deep offshore, 20mg/l for shallow waters, 10mg/l for onshore. No prohibited discharge areas.
Chemicals to be used are tested and must be approved before they can be used. Specific chemicals are banned and cannot be used.	-	-
By year 2006, 15% reduction in the total oil present in produced water, compared with year 2000.	-	-
EU goal of ban of discharges into the marine environment is proposed for year 2020	Zero discharge effluent is set as next target.	-

The regulations in the North Sea vary with the Gulf of Mexico but they all work towards mitigating environmental pollution by produced water. In the North Sea and Gulf of Mexico, produced water treatment has been successful. However, reasons for the variation are:

- Number of offshore wells in the region.
- Period of offshore production
- National and regional politics
- Different analytical methods
- Human nature

V. APPLICATION OF PRODUCED WATER TREATMENT METHODS IN THE NIGER DELTA

In order to make the Niger Delta environment safe for lives, produced water treatment methods that have been used in the Gulf of Mexico and North Sea are suggested for the Niger Delta, especially the end of pipe PW treatment method. End of pipe methods are suggested because our aim is to ***meet discharge regulatory specifications.***

5.1 End of Pipe Processes Of Produced Water Treatment

Conventional end of pipe PW treatment techniques are adopted for this work because they are cheaper, available in the market, no patent needed and easy to use. It was observed by Isehunwa and Onovae (2011) that these conventional treatment equipment were lacking on the platforms investigated [3]. However hydro cyclone is major gravity separating equipment and cannot be used on a floating production platform (offshore) as standalone equipment, if discharge regulatory specification must be met. Hence, processes of produced water treatment would be developed to ensure that produced water meets effluent limit before discharge.

Conventional end of pipe treatment technique includes:

- Skimming tanks
- Corrugated plate interceptors
- Hydro cyclones
- Induced gas flotation units/ dissolved gas flotation units
- Centrifuges
- Plate coalsecers
- Flocculants and scale inhibitors
- Media filter units

5.2 Processes of Produced Water Treatment

Produced water is made to go through the treatment process with the aid of a pump. Scale inhibitors are injected into the produced water with the aid of the chemical injection system. The scale inhibitor forms a thin film in the wall of the metal facility to inhibit scale formation and corrosion as the treatment process goes on.

The scale inhibitor also reduces the physio-chemical properties of the produced water inhibiting chemical reaction between metallic constituents of the produced water.

Process A

As in Fig. 2, the skimmer acts like a gravity separator; oil and grease content of produced water reduces to 150 microns from an initial state of oily water. When produced water from the skimmer gets into the plate coalescer, oil droplets coalesce to form larger droplets. Flocculants are injected into the stream of produced water in the plate coalescer to aid further separation. It reduces the oil droplets to about 40 micron size before passage into the hydro cyclone with the aid of a pump. The hydro cyclone further reduces it to 10-5 microns; the media filter further absorbs almost all oily droplets of produced water, reducing to about 5 microns and increases the pH of the initially acid feed water, making produced water friendly for the environment before disposal overboard [7].

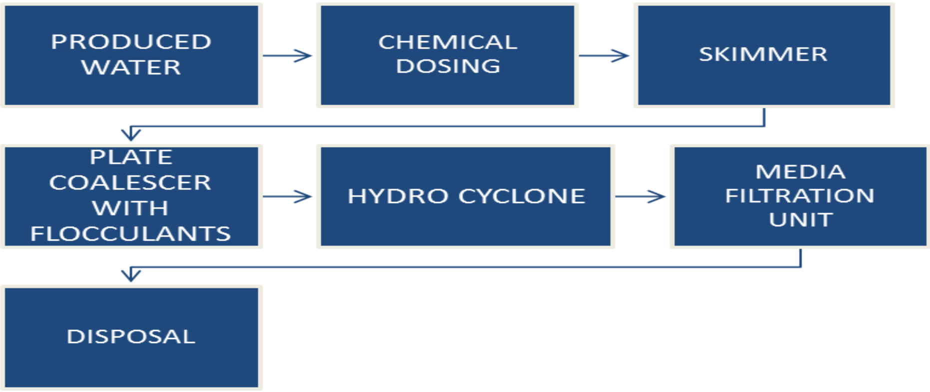

Figure 2: PROCESS A - Produced water treatment using Combination of Skimmer, Plate coalescer, Hydro cyclone and Media filtration unit.

Process B

After chemical dosing with scale inhibitor, produced water is sent into the gas flotation unit where it is dosed with flocculants to aid coagulation of oil droplets, after which the skimmer aids to separate the coagulated oil droplets by means of gravity separation. The media filter receives the produced water from the skimmer and further absorbs almost all oily droplets of produced water, reducing to about 2 microns per liter and meeting/ exceeding specification of 10mg/l before disposal overboard. The media filter is able to convert the acidic feed water to alkaline depending on the media used. The media of the filter may be sand, gravel or walnut shells that have the ability to increase the pH of the produced water as shown in Fig. 3. Gas flotation units have been the leading choice for offshore operators. This process can be used in any field location [7].

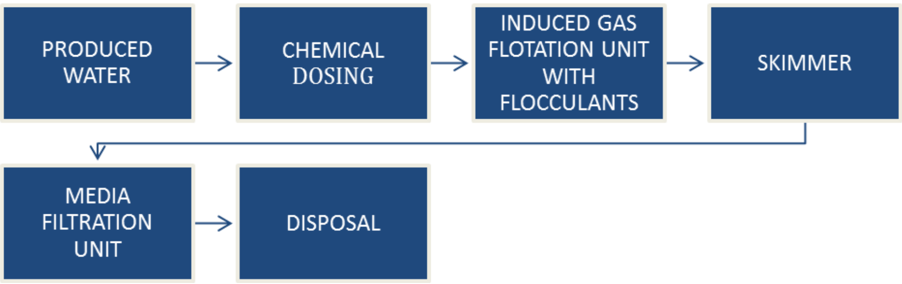

Figure 3: PROCESS B - Produced water treatment using Combination of Induced gas flotation unit, Skimmer and Media filtration unit.

Process C

As in Fig. 4, Produced water is made to go through the treatment process with the aid of a pump. Scale inhibitor and corrosion inhibitors are injected with produced water, the scale and corrosion inhibitors form a thin film in the wall of the metal facility to inhibit scale formation and corrosion as the treatment process goes on, the scale inhibitor also reduces the physio-chemical properties of the produced water inhibiting chemical reaction between metallic constituents of the produced water. Flocculants are not needed for process C, because the centrifuge is very efficient, the only chemicals needed are the scale and corrosion inhibitors. The skimmer acts is a gravity separator reducing oil and grease content of produced water to 150 microns from an initial state of oily water. The centrifuges work with a rotational force stronger than the hydro cyclone, its efficiency is seen as it can reduce oil and grease droplets to 2 microns meeting discharge specification of 10mg/l content in produced water. It functions effectively on floating platform; it is insensitive to external motion, portable in size and can be used for offshore operations. Media filter does little further removal of oil droplets by absorbing oil droplets in the granular media and increases the P^H of the acidic feed water with the aid of its filtering media turning it to alkaline before overboard disposal. However in a floating production platform the media filter may not be suitable because of its size, weight and the media filter plugs often leading to frequent change of the filter, hence this is optional depending on the constituents of the produced water. This process is short and faster compared with processes A and B, but the centrifuge needs energy to operate unlike the hydro cyclone.[7].

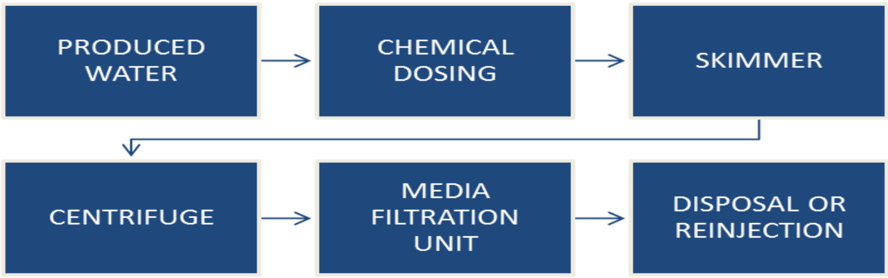

Figure 4: PROCESS C -Produced water treatment using combination of Skimmer, Centrifuge and Media filtration unit.

Chemical Dosing

Produced water that goes through treatment process is dosed with chemicals such as flocculants and scale inhibitors. Flocculants are used to aid coagulation of oil droplets thereby enhancing produced water purification. Scale inhibitors are used to inhibit scale formation in the produced water flow stream forming a thin film around the metal facility. Chemicals are dosed as follows: 200mg/l for flocculants and 60mg/l for scale inhibitors [8]. Since produced water is measured in barrels and volume of chemicals are in tons, the required dosage of chemicals for a barrel of produced water is 0.0000035ton of flocculants and 0.00001094ton of scale inhibitor is required per barrel of produced water. The feed stream of the produced water treatment plant is properly dosed with flocculants and scale inhibitors before treatment commences. Processes A&B require both scale inhibitors and flocculants while process C requires scale inhibitors alone because centrifuges are capable of removing oil in water up to about 10mg/l as standalone treatment facility.

Table 5: Comparison of three processes of produced water treatment

CRITERIA	DESCRIPTION
Oil removal technology	Process A is capable of treating produced water to about 10mg/l and even exceed disposal limit. Process C exceeds disposal limit of 10mg/l due to the efficiency of centrifuges. Process B can be used to meet disposal specification.
Industrial status	All three processes are widely used in the North sea and Gulf of Mexico for produced water treatment. Process C is more efficient for floating platforms because it is insensitive to sea motion. Process A may not be efficient for deep offshore location because of space and platform motion.
Product Water quality	Processes A&B discharge good quality feed water that meets discharge requirements. Process C discharges better quality feed water because of the high efficiency of centrifuges.
Energy Use	Process B requires no energy except that a forwarding pump is required to aid flow of produced water. Process C requires more energy due to the force used by the centrifuge. Process A requires little energy for pressurized flotation unit.
Expected lifetime of critical component	Process A has no moving parts and may suffer from abrasion. Skimmer is durable and is expected to exhaust useful life. Filtering media should be frequently changed. Process C requires frequent maintenance to ensure full useful life of facility. Process B is same as Process A (no moving parts) and may suffer from abrasion. Filtering media should be frequently changed.
Operating and Maintenance cost and considerations	Scale and corrosion inhibitors and flocculants costs increase operating cost for processes A&B. Frequent changing of filtering media adds to operating costs for all three processes. Operating costs for Process C may be higher due to frequent maintenance needed for centrifuges and need for energy to run the centrifuges. Hydrocyclones require frequent cleaning to avoid plugging by solids. Hydrocyclone does not need electric energy but Centrifuges need

	electrical energy to enable its high rotation frequency; it is a more expensive device than the hydro cyclone. Operating costs for processes A&C is estimated as 5% of capital cost in the model. Operating cost of process B is 15% of capital cost.
Pretreatment of feed water	Pretreatment of feed water is not required for all three processes expect that chemical dosing is required to avoid scale formation and corrosion.
Concentrate Management and Waste disposal	All three processes produce slurry depending on the quality of the feed water. Slurry should be disposed properly.
Infrastructure considerations	Processes A and C require external pressure tank for flotation units and plate coalescers. All processes require installation of residence tanks. All three processes require installation and connection of pump and systems.
Overall Costs	Vendor was contacted for costs of facilities and chemicals; construction of tanks was estimated. The cost for each of the processes of produced water was computed in the MS excel spread sheet model. Cost of Process A is affected by cost of chemicals. Cost of Process B is influenced by cost of maintenance and operation of centrifuges and cost of inhibitors.

VI. LESSONS FROM THE NORTH SEA AND GULF OF MEXICO

Applying the methods used in the North Sea and Gulf of Mexico, produced water treatment can be achieved in the Niger Delta. They can be applied as follows:

- End of pipe produced water treatment methods can meet discharge regulatory specifications and are useful for surface disposal of PW.
- Preventive techniques can be used in the Niger Delta, installing down hole oil/water separation techniques to ensure water is separated in-situ. This would reduce the huge volumes of water produced at the surface especially as the Niger Delta is almost 80% water drive.
- Dispersed aromatic hydrocarbons are very harmful constituents of produced water and should be removed from produced water before surface discharge. This can be achieved by using process integrated techniques like the Macro Porous Polymer Extraction (MPPE) and C-tour process.
- Membrane technology (Nano filtration, ultrafiltration, reverse osmosis and electrodiaylsis) can be used to increase PH of PW from acidic to alkaline.
- Zero discharge can be achieved onshore either by total reinjection of PW into an abandoned well or used for secondary oil recovery. Zero effluents discharge can also be achieved by use of conventional techniques combining centrifuge, plate coalesce and media filtration.
- 10mg/l can be achieved as the new oil/grease allowable limit for produced water in the deep offshore by use of conventional techniques. Combining the facilities to form a chain process with the aid of flocculants and scale inhibitors.
- Host governments should ensure that there are collaborative efforts of all environmental protection agencies (Federal and state ministries of environment, Directorate of Petroleum resources and other stakeholders) in Nigeria to review regulatory specification for oil and gas industry as well as monitor the industries to ensure regulations are met.
- Polluters pay principle could be adopted as a check measure.
- Discharge effluents should be reviewed and modified until ZERO discharge effluent is possible in Nigeria.
- There should be collaboration of all environmentally concerned bodies as is the case in the North Sea and Gulf of Mexico to ensure that produced water in Nigeria is properly managed.

VII. CONCLUSION

It was observed that oil and grease content, dissolved solids, dispersed solids, iron and chloride concentrations were high, exceeding required effluent limit. It was noticed that the facilities to be used for PW treatment were lacking on some platform, some other platforms practice dilution of PW before disposal. Routine supervisions of samples of PW were not regular. Lessons were learnt from the existing treatment methods and regulatory enforcement pattern in the North Sea and Gulf of Mexico that can be applied in Nigeria to ensure that discharge regulatory specifications are met and may be gradually modified to achieve zero effluent. The following recommendations were made based on lessons learnt:

- The regulatory agencies can ensure strict compliance by routine supervision of samples of produced water to be discharged and treatment facilities used for produced water treatment.
- The Federal Ministry of Environment, State ministries of Environment, Directorate of Petroleum Resources, Federal Environmental Protection Agency (FEPA) and all concerned stakeholders may come

together to form a collaborative effort backed by law to ensure that discharge regulatory specifications are met.

- Chemicals to be used for exploration and production activities should be examined to assess toxicity level
- Environmental protection should be part of the conditions stated in the agreements by government to oil and gas operators before granting licenses for operation in Nigeria's oil and gas industry.
- All platforms in Nigeria should have the basic surface produced water treatment technology on the field. In-situ PW treatment facilities are good but end of pipe treatment method should always be on site for contingency purposes.

REFERENCES

[1] Khalilpour R., 2014 Produced Water Management: An example of a Regulatory Gap. *SPE conference paper -171000-MS*., 21-22 April, 2014.

[2] Ukpohor T.O. 2001. Produced Water: Environmental Issues/ Technological solution of the Nigeria depletion Era. *SPE conference paper 71437,* 30 September -3 October, 2001.

[3] Isehunwa S.O and Onovae S., Evaluation of Produced Water discharge in the Niger Delta. *Asian Research publishing Network (ARPN) Journal of Engineering and Applied Sciences.* 6 (8), 2011. 66-72.

[4] Garland Emmanuel and Hjelde Erik, 2003. *Discharge of produced water: New challenges in Europe*. SPE conference paper 80585, 10-13 March 2003.

[5] Veil J. A. *Why are produced water discharge standards different throughout the world?* Presented at 13th IPEC. San Antonio. Texas, 2006.

[6] Godec, Tracey Sturat-Paul, BundhrigKosowki, and G.E. Smith. *Economic Impacts of Alternative Produced Water Treatment and Disposal Practices on Oil and Gas Resources in the Gulf of Mexico.* Offshore Technology Conference Paper 7404, 2-5 May 1994.

[7] Nwosi-Anele Adaobi Stephenie. *Economic implication of produced water treatment methods (with due consideration of discharge regulatory specification)*. Masters dissertation, University of Port Harcourt 2016.

[8] Hackney John and Mark R. Wiesner. Cost assessment of produced water treatment. 2016. *(accessed online on 24 Aug, 2015)*