DESIGN OF A WATER TREATMENT SYSTEM FOR BENEFICIAL USE OF THE PRODUCED WATER IN A GAS FIELD IN BANGLADESH

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A Project

By

MD. MEHEDI HASAN

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Submitted to the

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RECOMMENDATION OF THE BOARD OF EXAMINERS

The undersigned certify that they have read and recommended to the department of Petroleum and Mineral Resources Engineering (PMRE) for acceptance of the project entitled "**DESIGN OF A WATER TREATMENT SYSTEM FOR BENEFICIAL USE OF THE PRODUCED WATER IN A GAS FIELD IN BANGLADESH"** Submitted by **MD. MEHEDI HASAN**, Reg No. **0413142013**; in partial fulfillment of the requirements for the degree of Master of Engineering in Petroleum Engineering.

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DECLARATION

I declare that this project entitled **"DESIGN OF A WATER TREATMENT SYSTEM FOR BENEFICIAL USE OF THE PRODUCED WATER IN A GAS FIELD IN BANGLADESH"** is the result of my own research except as cited in the references. The project has not been accepted for any degree and is not concurrently submitted in candidature of any other degree .

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Date : 10/03/18

Dedicated, in thankful appreciation for support,
encouragement and understanding to my beloved family,
friends and my supervisor

ABSTRACT

Produced water is water trapped in underground formations that is brought to the surface along with oil or gas. It is by far the largest volume byproduct or waste stream associated with oil and gas production. Produced water handling has been an issue of concern for oil and gas producers as it is one of the major factors that cause abandonment of the producing well. The development of effective produced water management strategies poses a big challenge to the oil and gas industry today. The conversion of produced water into irrigation or fresh water provides a cost-effective tool to handle excessive amounts of the produced water. There are more than 150 methods for produced water treatment. In this research, we proposed on-site produced water treatment units configured to achieve maximum processing throughput for Bangladesh. We tested the produced water sample collected from a Gas field in Bangladesh in BASF Bangladesh Ltd. construction chemical Lab. The lab test result showing that the Dissolved oil, EC, TDS, Na^+, Cl^-, HCO_3^- , COD, Ca^{2+}, and other parameters of produced water are much higher than the acceptable limit define by Environment and Forest Ministry of Bangladesh. We also studied various advanced separation techniques to remove oil and dissolved solids from the produced water. We selected media filtration as the oil removing technique and Reverse Osmosis (RO) as the dissolved solids removing technique along with three stage separators as being the best for Bangladesh based on produced water property.

The study results show that the media filtration remove more than 90% of the oil and grease and water recovery nearly 100%. The RO units remove more than 95% of total dissolved solids from the produced water and it is the most used technology in the world (> 60% of worldwide seawater desalination installed capacity). The proper integration and configuration of media filtration and RO units can provide up to 80% efficiency for a processing throughput of 6-8 gallons per minute of produced water.

Finally a water treatment system designed considering a gas field producing 600 bbl equals 95400 litters water per day. The system is flexible and can be modified for the applications such as rangeland restoration, reservoir recharge and agricultural use and household use.

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The Author

Md. Mehedi Hasan

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CHAPTER 01

INTRODUCTION

1.1 Introduction

The role of oil and natural gas in modern civilization is well known. Nevertheless, like most production activities, oil and gas production processes also produce large volumes of liquid waste like produced water (*Spiegler KS, Kedem O.1996*).

Produced water is the water trapped in underground formations that is brought to the surface during oil and gas exploration and production. In traditional oil and gas wells, produced water is brought to the surface along with oil or gas. In coal bed methane production, wells are drilled into coal seams, and the water located there is pumped to the surface to allow gas to release from the coal seams. Because the water has been in contact with the hydrocarbon-bearing formation for a very long time, it has some of the chemical characteristics of the formation and the hydrocarbon itself. Produced water may include water from the reservoir, water injected into the formation, and any chemicals added during the drilling, production, and treatment processes. Produced water can also be called "brine", "saltwater", or "formation water." (Ahmadun, F. R., Pendashteh, A., Abdullah, L. C., Awang Biak, D. R., Madaeni, S. S., Abidin, Z. Z. 2009 ; Daniel A. J, Langhus BG, Patel C. 2005)

1.2 Source of Produced Water

Subsurface formations are generally permeated with fluids such as water and oil, or gas or mixtures of these substances. There is a hypothesis that the rocks that constitute most oil-bearing formations were completely filled with water prior to the deposit and accumulation of petroleum (Dores R.;,Hussain A.; Katebah M.;Adham 2012). Gradually over time, hydrocarbons migrated to cracks and trap locations, displacing some of the water from the formation and became hydrocarbon reservoirs. Hence, Reservoir rocks normally contain both

petroleum hydrocarbons (liquid and gas) and water. Sources of this water may include flow from water filled formation above or below the hydrocarbon zone, flow from within the hydrocarbon zone, or flow from injected fluids and additives resulting from production activities (Ahmadun, F. R. et al 2009;ALL Consulting 2003). This Water is frequently referred to as “connate water” or “formation water” and becomes produced water when the reservoir is produced and these fluids are brought to the surface [Ahmadun, F. R.et al. 2009; Igunnu E.T;Chen G.Z . 2014)

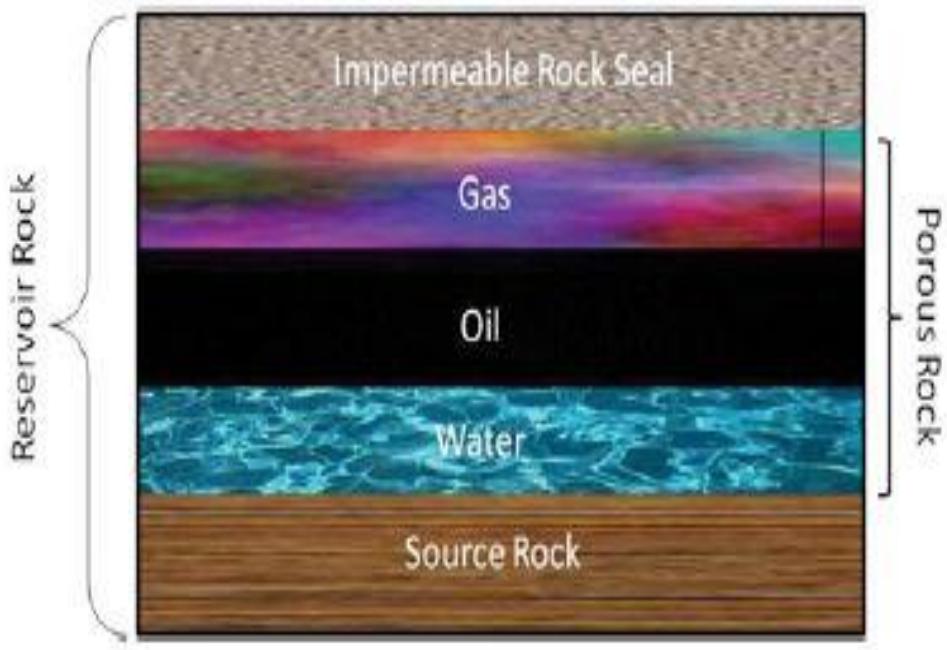

Figure 1.1: Sketch of a typical reservoir [Igunnu E.T. et al. 2014)

Crude oil has a lower density (between 790 – 873kg/m3) than water (1000kg/m3)and as such, floats above the natural water layer/formation water. In addition to the large volumes of water these reservoirs contain, more water is injected to help force the oil to the surface and achieve maximum oil recovery. When hydrocarbons are extracted, they are brought to the surface as a mixture of produced fluids. The composition of this produced fluid is largely dependent on whether crude oil or natural gas is being extracted and generally includes a mixture of either liquid or gaseous hydrocarbons, produced water, dissolved or suspended solids, produced

solids such as sand or silt, and injected fluids and additives that may have been placed in the formation because of exploration and production activities (Ahmadun, F. R.et al. 2009; all, Buller AT, Johnsen S, Frost K 2003)

1.3 Why produced water is a concern

PW represents the highest volume liquid waste stream for the petroleum industry. The cost of managing produced water is a significant factor in the profitability of wells and excessive water production is one of the main reasons to abandon an oil or gas well, leaving behind large volumes of hydrocarbons. Published data indicate that the volumes of PW generated worldwide are steadily increasing day by day (e.g. 70 billion barrels in 2007; 100 billion barrels in 2011). For instance, the American Petroleum Institute (API) estimated that in 1995, 18 billion of barrels of PW were generated in the US only from onshore facilities (Godshall NA. 2006).

Global produced water production is estimated at around 250 million barrels per day compared with around 80 million barrels per day of oil. Published figures from 2007 seem to agree on a worldwide WOR of 3:1 (Godshall NA.2006; B. Ferro, M. Smith 2007) while data from 2011 attributes for onshore crude oil operations in the US a WOR of approximately 8:1 and 12:1 for 2007 and 2025 respectively (Produced Water Market, 2011) considering water cut 70%. In addition, per the International Energy Agency (IEA) 2011 World Energy Outlook, both oil and gas will still represent a significant fraction of the energy consumption by 2035 (**Figure 1.2**), further contributing to the increase in PW volumes.

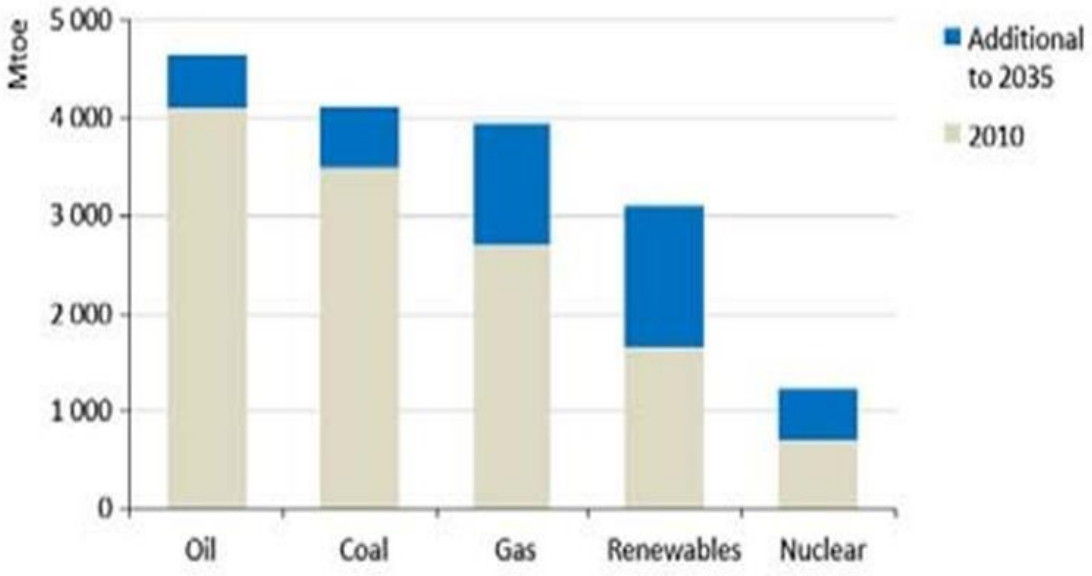

Figure 1.2 **:** World primary energy demand [Hoeven van der M. 2012**]**

Produced water contains various organic and inorganic components also naturally occurring radioactive material (NORM) and salts. Discharging produced water can pollute surface and underground water and soil (Buller AT et al. 2003; Dores R. 2012; Igunnu E.T 2014)

Some of the options available to the oil and gas operator for managing produced water might include the following:

1. Avoid production of water onto the surface – Using polymer gels that block water contributing fissures or fractures or downhole water separators which separate water from oil or gas streams downhole and reinject it into suitable formations. This option eliminates waste water and is one of the more elegant solutions, but is not always possible.
2. Inject produced water – Inject the produced water into the same formation or another suitable formation; involves transportation of produced water from the producing to the injection site. Treatment of the injectate to reduce fouling and scaling agents and bacteria might be necessary. While waste water is generated in this option, the waste is placed back underground.

3. Discharge produced water – Treat the produced water to meet onshore or offshore discharge regulations. In some cases, the treatment of produced water might not be necessary.
4. Reuse in oil and gas operations – Treat the produced water to meet the quality required to use it for drilling, stimulation, and workover operations.
5. Consume in beneficial use – In some cases, significant treatment of produced water is required to meet the quality required for beneficial uses such as irrigation, rangeland restoration, cattle and animal consumption, and drinking water for private use or in public water systems.

The operation selectin for produced water management depends on government rules, country economic condition, geological condition, technology availability, produced water quality and awareness about produced water management.

1.4 Produced water management system in Bangladesh

There are 26 discovered gas field in Bangladesh out of them 21 are at operating condition , producing nearly 2700 MMSCFD gas and 13000 BBL condensate and huge amount of water daily. The gas water ratio in SGFL is 1:12 (for 1MMscf gas production, produced water 12 BBL.) which is 1:1.65 in BGFCL. If the gas production and water production ratio consider as 1:7, total amount of water production nearly 18,900 bbl equals 30,05,100 litter per day [BAPEX website May 2017; SGFL website May 2017; BGFCL website June 2017]. According to PSC and government rules, the IOC's inject the produced water back into suitable formation. The local company under Petrobangla use API tank known as skimming pit for produced water management.

The rapid growth of the population poses a great challenge to our drinking water supply. Agriculture and energy production draws more and more freshwater, while producing more contamination of the already scarce freshwater resource. It is therefore very much relevant and important to study the produced water from our gas fields. Such study should aim to select the

most appropriate treatment processes such that the produced water can be put to beneficial use. The objectives of this work are in line with the above discussion and outlined as follows

I. Examine the treatment processes and technologies available for produced water in gas fields.

II. Design a treatment facility for beneficial use of the produced water in Bangladesh

In order to attain these objectives following methodology will be applied

1. Collect information on produced water in a selected gas field in Bangladesh.
2. Collect water sample and conduct physical and chemical analysis
3. Study the water treatment processes and technology.
4. Study the govt. rules regarding water quality
5. Select the most appropriate procedure to be implemented
6. Design the water treatment facility.

CHAPTER 02

PRODUCED WATER PROPERTY IN BANGLADESH

Produced water is the main wastage in gas filed during gas production. Sylhet Gas Filed ltd.(SGFL) and Bangladesh Gas Field Company Ltd (BGFCL) are producing nearly 3000 bbl or 4,77,000 litters water every day [SGFL website May 2017; BGFCL website June 2017]. Sample of produced water were collected from a gas field in Bangladesh. The following parameters of sample water was estimated from lab test at QC Lab, BASF Bangladesh Ltd**.**

1. Physical Properties (Temperature, Density)
2. Hydrogen Ion Concentration (pH)
3. Electric Conductivity (EC)
4. Turbidity
5. Total solids (TS)
6. Total Dissolved Solids (TDS):
7. Suspended Solids (SS)
8. Iron (Fe^{2+} & Fe^{3+})
9. Bicarbonate (HCO_3^-)
10. Calcium (Ca^{2+}):
11. Magnesium (Mg^{2+}):
12. Sodium (Na^+)
13. Chloride (Cl^-)
14. Biochemical Oxygen Demand (BOD)
15. Chemical Oxygen Demand (COD)
16. Dissolved Gas

The concentration of different parameter discussed as below

2.1 Physical Properties

Physical parameters define those characteristics of water that respond to the senses of sight, touch, taste or smell. The sample water has oily odor and its density is higher than normal water (1020 kg/m3). The lab room temperature was 77° F or 25° C during all the tests performed.

2.2 Hydrogen Ion Concentration (pH)

P^{H} is a measure of the hydrogen ion concentration in water and indicates whether the water is acidic or alkaline in nature**.** It ranges from 0 to 14 with a value of 7 indicating neutral water**.** The values within 7 to 0 are increasingly acid and within 7 to 14 is increasingly alkaline water**.** P^{H} is also an indicator of the existence of biological life as most of them thrive in a quite narrow and critical P^{H} range [Aziz, M.A. 1975].

The pH of the samples water are measured by a portable pH and temperature meter (HANNA HI98107 pocket pH meter)

Figure 2.1: Portable pH and temperature meter (HANNA Instruments)

The P^H value of the sample water is 7.44 where the National Standards is 6-9 for all discharge points. (inland surface water, public sewer and irrigated land) [Guide for Assessment of Effluent Treatment Plants (2008]

2.3 Electric Conductivity (EC)

Conductivity indicates the presence of ions within the water.

EC meter (HANNA HI99301 meter) was used to measure this parameter. Immersing a conductance cell in water samples the EC was measured and recorded from the digital display of the EC meter

Figure 2.2: EC and TDS meter (HANNA Instruments)

The EC value of the sample water is 11230 µs/cm which is much higher than national standards for all disposal points. (inland surface water -1200 µs/cm, Public sewer-1200 µs/cm and Irrigated land-1200 µs/cm) (Figure 2.3) [Guide for Assessment of Effluent Treatment Plants ,2008]

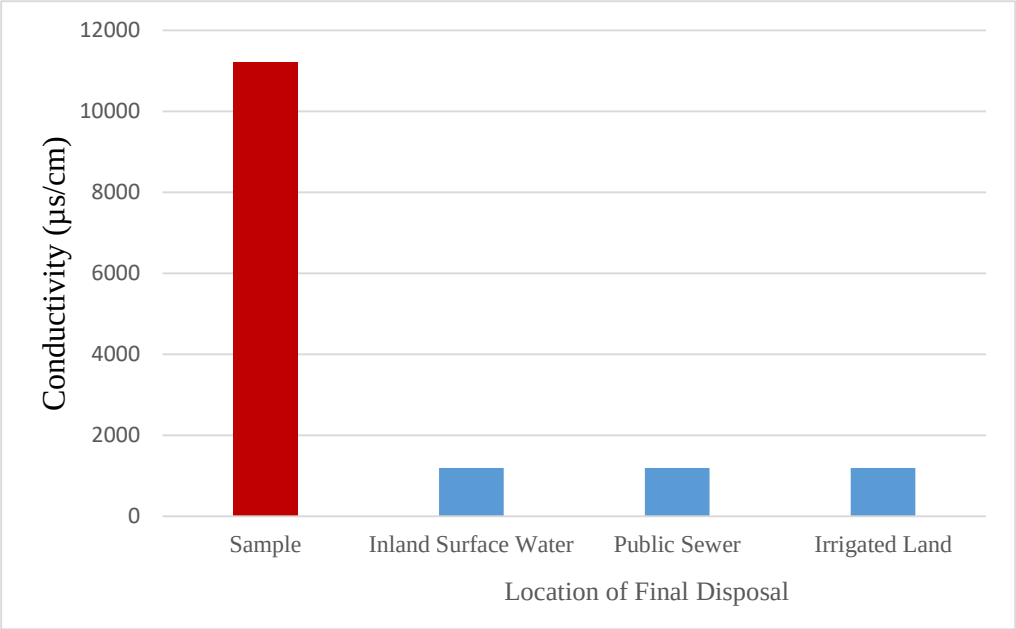

Figure 2.3**:** Conductivity of the sample water and national standards for disposal at different location

2.4 Turbidity

Turbidity is a measure of the extent to which light is either absorbed or scattered by suspended material in water. Because absorption and scattering are influenced by both size and surface characteristics of the suspended material, turbidity is not a direct quantitative measurement of suspended solids. Most turbidity in surface water results from the erosion of colloidal materials such as clay, silt, rock fragments and metal oxides from the soil. Vegetables fibers and microorganism may also contribute to turbidity. The disinfection of turbid water is difficult because of the adsorptive characteristic of some colloids and because of the solids that partially shield organism from the disinfection [Aziz M.A. (1975); Dara S.S. (1995)].

If turbidity is largely due to organic particles, dissolved oxygen depletion may occur in the water body. The excess nutrients available will encourage microbial breakdown, a process that requires dissolved oxygen. In addition, excess nutrients may result in algal growth. Although photosynthetic by day, algae respire at night, using valuable dissolved oxygen. Fish kills often result from extensive oxygen depletion.

The turbidity of the sample water was measured by HACH portable turbidimeter (HACH-2100Q)

Turbidity of the sample water is 70 NTU

Figure 2.4: Portable turbidity meter (HACH)

2.5 Total solids (TS)

The total solids (TS) in water consist of inorganic salts and dissolved materials. In natural waters, salts are chemical compounds comprised of anions such as carbonates, chlorides, sulphates, and nitrates (primarily in ground water), and cations such as potassium (K), magnesium (Mg), calcium (Ca), and sodium (Na). In ambient conditions, these compounds are present in proportions that create a balanced solution. If there are additional inputs of dissolved solids to the system, the balance is altered and detrimental effects may be seen. Inputs include both natural and anthropogenic source [Aziz M.A. 1975; Dara S.S. 1995].

The TS, TDS, TSS of the sample water was measured by a HANNA -HI99301 meter

The value of total solids of water sample is 13214 ppm which are mainly for dissolve particles like potassium (K), magnesium (Mg), calcium (Ca), and sodium (Na), Iron, Chlorine etc. The Total Solids(TS) of the sample water and national standards for disposal at different location given at figure 2.5 [Guide for Assessment of Effluent Treatment Plants (2008)]

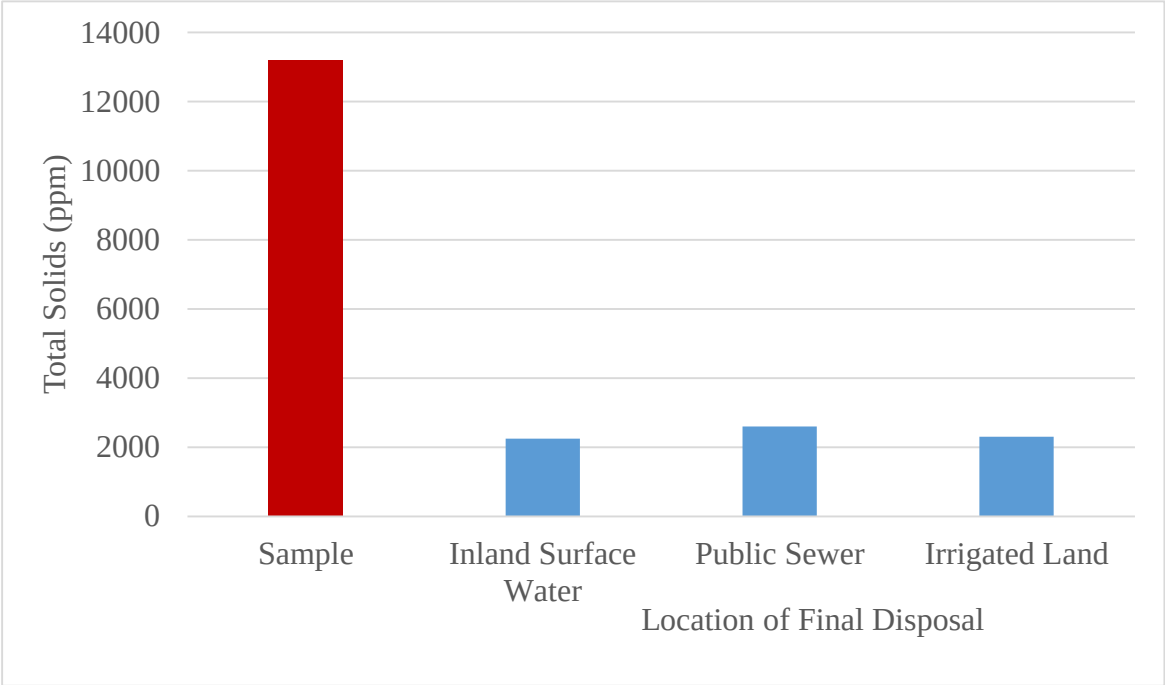

Figure 2.5**:** Total Solids **(**TS**)** of the sample water and national standards for disposal at different location

2.6 Total Dissolved Solids (TDS)

Total Dissolved Solids (often abbreviated TDS) is a measure of the combined content of all inorganic and organic substances contained in a liquid in: molecular, ionized or micro-granular suspended form. Generally, the operational definition is that the solids must be small enough to survive filtration through a sieve the size of two micrometers. Dissolved solids can produce hard water, which leaves deposits and films on fixtures, and on the insides of hot water pipes and boilers. [Dara S.S. 1995].

The dissolved solids content in the sample water is 12543 ppm. The national standards quality at different discharge point given at figure 2.6[Guide for Assessment of Effluent Treatment Plants ,2008]

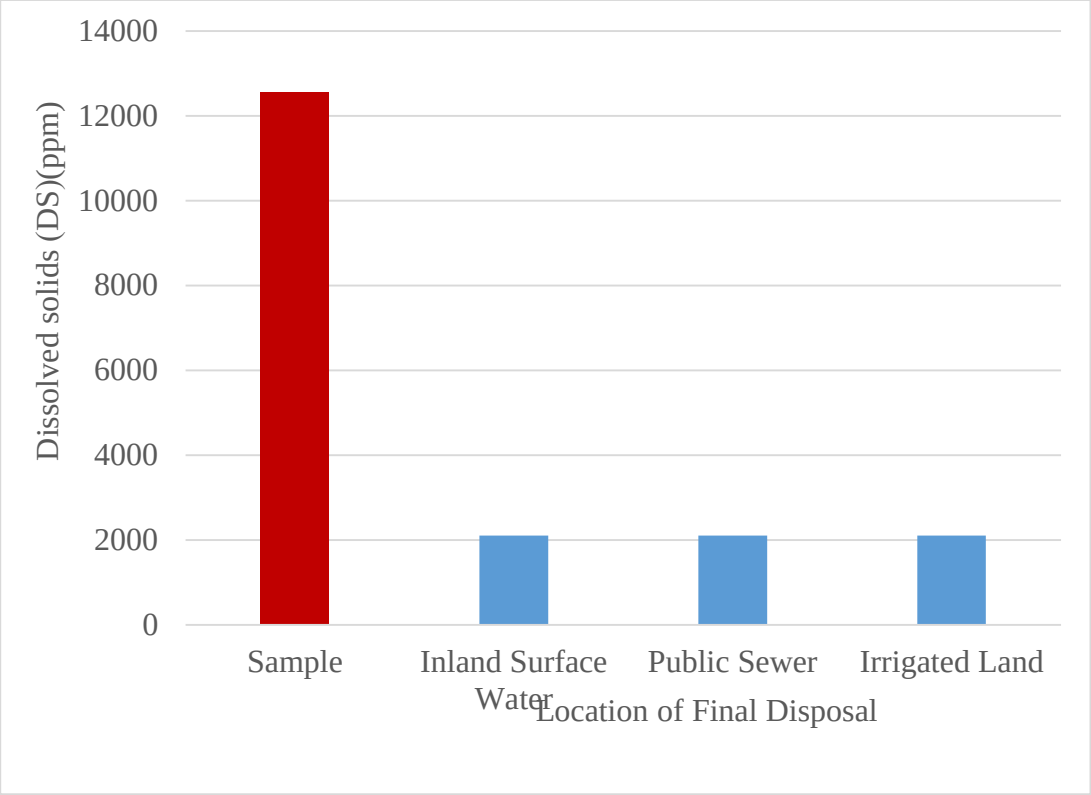

Figure 2.6**:** Dissolved Solids**(**DS**)** of the sample water and national standards for disposal at different location

2.7 Suspended Solids (SS)

Suspended materials consist of particles larger than molecular size that are supported by buoyant and viscous forces within the matter. These are sometimes referred to as non-filterable. Solids suspended in water may consist of inorganic or organic particles or of immiscible liquids. Inorganic solids such as clay silt and other soil constituents are common in surface water [Dara S.S. 1995].

Suspended solid is an indication of the amount of erosion that took place nearby or upstream. This parameter would be the most significant measurement as it would depict the effective and compliance of control measures e.g. riparian reserve along the waterways [Aziz M.A. 1975]. The values of suspended solids of the sample water is 671 ppm which mainly sand or other organic and inorganic particles. Suspended solids **(**SS**)** of the sample water and national standards for disposal at different location given at figure 2.7 [Guide for Assessment of Effluent Treatment Plants ,2008]

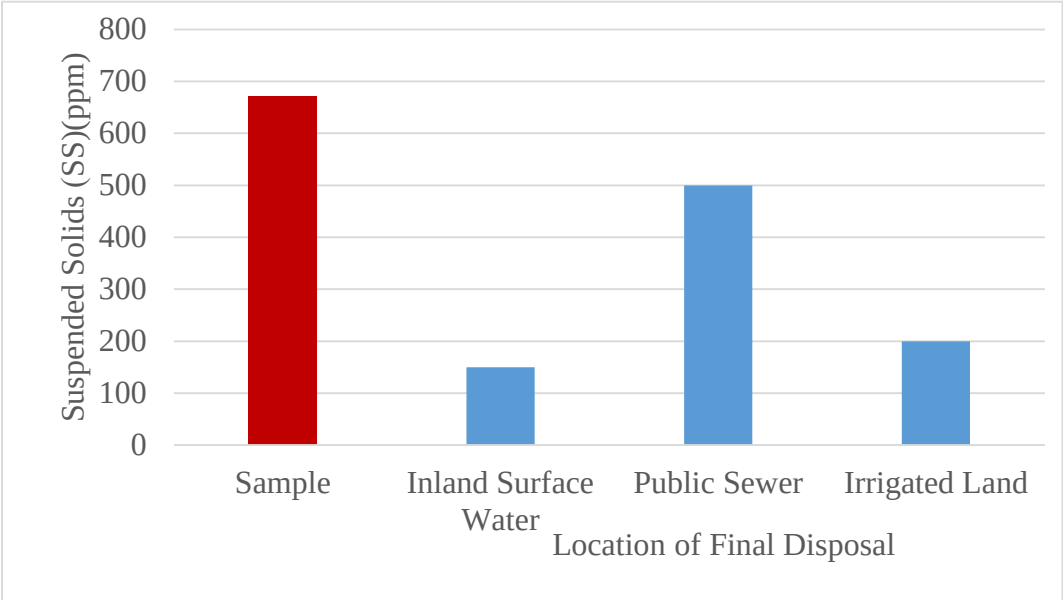

Figure 2.7**:** Suspended Solids **(**SS**)** of the sample water and national standards for disposal at different location

2.8 Iron (Fe^{2+} & Fe^{3+})

Ingestion of excessive amounts of iron results in the inhibition of activity of many enzymes. Water becomes deficient in oxygen by ferric iron [Dara S.S. 1995]. Such poisoning of steams is reckoned to be one of the main causes of fish kill. Water containing less than 2 ppm Fe cause staining of clothes and imparts a bitter taste [Aziz M.A. 1975].

For determining the iron contain UV-visible spectrophotometer was used.

The iron concentration in the sample water is 10.32 ppm and 20.36 ppm as Ferrous (**Fe^{2+}**) and Ferric (**Fe^{3+}**) respectively. The iron concentration of the sample water and national standards for disposal at different location given at figure 2.8[Guide for Assessment of Effluent Treatment Plants ,2008]

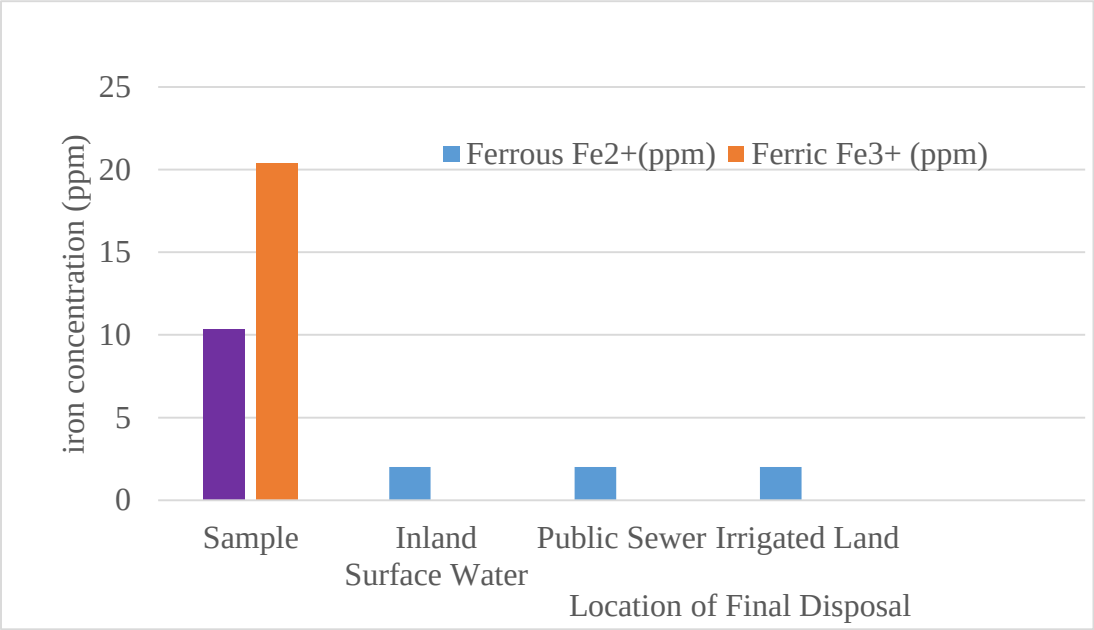

Figure 2.8**:** Iron concentration of the sample water and national standards for disposal at different location

2.9 Bicarbonate (HCO_3^-)

HCO_3^-, the bicarbonate ion, is the main alkaline factor in almost all water. Alkalinity serves as a buffer, neutralizing acids. Alkalinity is a measure of the capacity of water or any solution to neutralize or "buffer" acids. This measure of acid neutralizing capacity is important in figuring out how "buffered" the water is against sudden changes in pH [Aziz M.A. 1975]. The most important compounds in water that determine alkalinity include the carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ions.

There are many methods available to determine hardness. Soda reagent method applied to determine the alkanity of the sample water.

The concentration of Bicarbonate (HCO_3^-) in the sample water is 3356.83 ppm.

2.10 Calcium (Ca^{2+})

Calcium is normally present in natural water in dissociated form, as bivalent ions and is mostly responsible for causing hardness in water. Presence of calcium in water is excess of about 100 ppm decrease the cleaning and lathering properties of soap [Aziz M.A. 1975]. Higher calcium concentration than maximum acceptable limit of some samples may be due to the presence of plagioclase feldspar (Anorthite) in the sediment.

The complex metric titration method used to find the calcium content of the water sample.
The concentration of calcium ion in sample water is 20.71 ppm which is much higher than the acceptable limit by environmental organization.

2.11 Magnesium (Mg^{2+})

Magnesium is common constituent of natural water. It has an important contribution to the hardness of water. Magnesium salt breaks down when heated and form scale in boilers. Concentration greater than 125 ppm also can have a cathartic and diuretic effect. Chemicals softening reverse osmosis, electro dialysis or ion exchange reduces the magnesium and associated hardness to acceptable levels. The magnesium concentration may vary from zero to 100 ppm, depending on the source and treatment of the water [Aziz M.A. 1975; Dara S.S. 1995].

The volumetric method applied for determining the concentration magnesium of the sample water.

The magnesium concentration in sample water is 26.31 ppm.

2.12 Sodium (Na^{+})

Sodium is the sixth most abundant element on earth and is widely distributed in soils, plants, water and foods. Most of the world has significant deposits of sodium-containing minerals, most notably sodium chloride (salt) [Aziz M.A. 1975]. Sodium and chloride occur naturally in

water because of erosion or salt water intrusion (when salt water from the ocean seeps into underground water supplies). Sodium may reach both ground and surface water supplies because of residential, commercial and industrial activity, such as road salting.

Produced water is mainly brain where concentration of sodium is much higher than the sea water. The concentration of Na+ in sample water is 3525.43 ppm which is much higher than normal drinking water.

2.13 Chloride (Cl^-)

Chloride is widely distributed in nature, generally in the form of sodium chloride (NaCl), potassium chloride (KCl) and calcium chloride ($CaCl_2$) [Aziz M.A. 1975]. Chlorides occur in natural waters in widely varying concentrations. Upland and mountain supplies are quite low in chlorides, whereas rivers and ground water usually have a considerable amount. Sea and ocean water represents the residuals resulting from partial evaporation of neutral waters that flow into them and chloride levels are very high.

For determining the chloride in sample water Mohr method used.

The chloride concentration of the sample water is 3423 ppm which is five times higher than the acceptable limit by department of Environment Ministry of Environment and Forest, Bangladesh for different disposal locations. The chloride concentration of the sample water and national standards for disposal at different location given at figure 2.9 [Guide for Assessment of Effluent Treatment Plants ,2008]

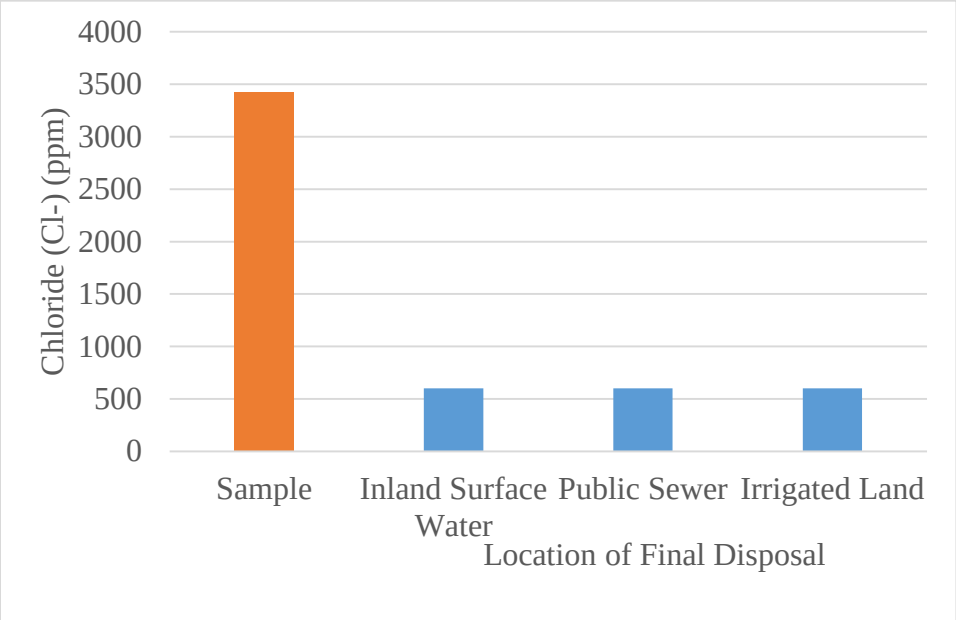

Figure 2.9: Chloride concentration of the sample water and national standards for disposal at different location

2.14 Biochemical Oxygen Demand (BOD)

Biochemical Oxygen Demand or BOD is a chemical procedure for determining the amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down organic material present in a given water sample at certain temperature over a specific time period. It is not a precise quantitative test, although it is widely used as an indication of the organic quality of water. It is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days (BOD_5) of incubation at 20°C and is often used as a robust surrogate of the degree of organic pollution of water.

BOD directly affects the amount of dissolved oxygen in rivers and streams. The rate of oxygen consumption is affected by several variables: temperature, pH, the presence of certain kinds of microorganisms, and the type of organic and inorganic material in the water.

The greater the BOD, the more rapidly oxygen is depleted in the stream. This means less oxygen is available to higher forms of aquatic life. The consequences of high BOD are the same as those for low dissolved oxygen: aquatic organisms become stressed, suffocate, and die

As the sample water is saline water, concentration of Na and Cl^- and other salt are higher than the acceptable limit no microorganisms can grow in the water. So, the value of BOD is not measurable.

2.15 Chemical Oxygen Demand (COD)

Chemical Oxygen Demand or COD is a measurement of the oxygen required to oxidize soluble and particulate organic matter in water. Chemical oxygen demand is an important water quality parameter because, similar to BOD, it provides an index to assess the effect discharged wastewater will have on the receiving environment. Higher COD levels mean a greater amount of oxidizable organic material in the sample, which will reduce dissolved oxygen (DO) levels. A reduction in DO can lead to anaerobic conditions, which is deleterious to higher aquatic life forms. The COD test is often used as an alternate to BOD due to shorter length of testing time.

The COD of the sample water measured by using MD 200 COD vario instrument

Figure 2.10:COD measuring device (Lovibond® Water Testing)

The COD in sample water is 730 mg/L which is much higher than the acceptable limit by environment and Forest Ministry of Bangladesh for different location [Guide for Assessment of Effluent Treatment Plants ,2008].

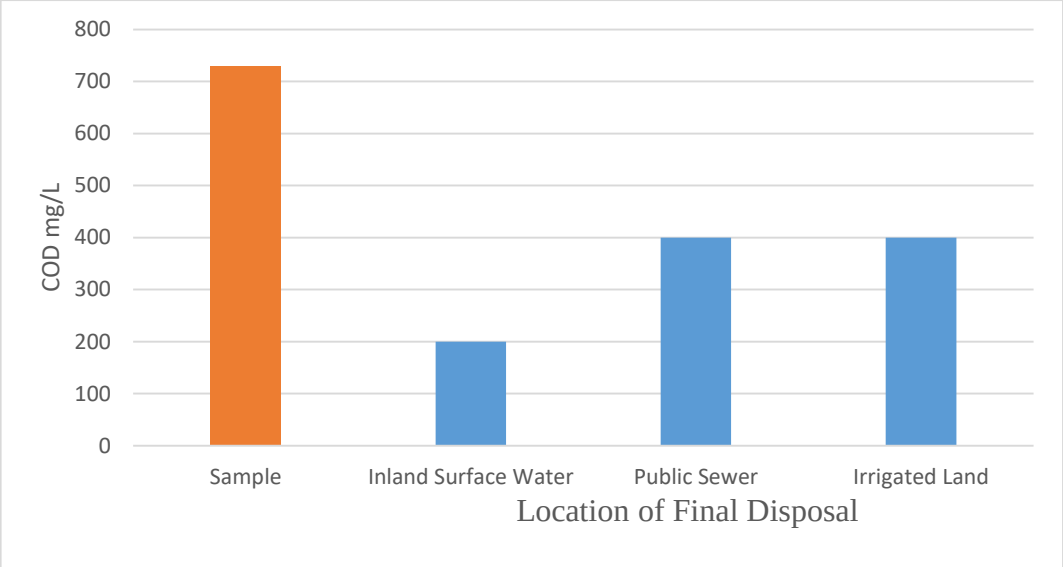

Figure 2.11: COD of the sample water and national standards for disposal at different location

2.16 Dissolved Gases:

The major dissolved gases in produced water are carbon dioxide, oxygen and hydrogen sulphide. They are formed naturally, by the activities of bacterial or by chemical reactions in the water [Ahmadun, F. R.et al. 2009; Dores R. et al, 2012; Igunnu E.T. et al. 2014]

The result from the laboratory analysis presented above are summarized in table 2.1.

The higher concentrated (iron , sodium , magnesium, P^H , chlorine etc) produced water mixed with subsurface water and its pollute the water bearing zone.

Table 2.1: Produced water property and acceptable limit of waste water disposal at different location by Ministry of Environment and Forest, Bangladesh [Guide for Assessment of Effluent Treatment Plants, 2008]

Parameters	Gas Field Produced Water	**Location of Final Disposal**			
		Inland Surface Water*	**Public Sewer****	**Irrigated Land*****	Remarks
Physical Appearance	Water with oily odor				
Temperature	77° F or 25° C (Lab temperature)				
P^{H}	7.44	6-9	6-9	6-9	Within limit
Density (kg/m^3)	1020				
Turbidity NTU	70				
TS (ppm)	13214	2250	2600	2300	Higher than limit
TDS (ppm)	12543	2100	2100	2100	Higher than limit
TSS (ppm)	671	150	500	200	Higher than limit
Conductivity (µs/cm)	11230	1200	1200	1200	Higher than limit
Chloride (Cl^-) (ppm)	3423	600	600	600	Higher than limit
Bicarbonate HCO_3^-(ppm)	3356.83				
Calcium Ca^{2+} (ppm)	20.71				
Magnesium Mg^{2+} (ppm)	26.31				
Ferrous Fe^{2+}(ppm)	10.32	2	2	2	Higher than limit
Ferric Fe^{3+} (ppm)	20.36				
Sodium Na^+ (ppm)	3525.43				
BOD mg/L	Not measurable	50	250	100	
COD mg/L	730	200	400	400	Higher than limit

Notes: (*) ***Land Surface Water*** refers to any pond, tank, water body, water hole, canal, river, spring or estuary

****Public Sewer*** refers to any sewer connected with fully combined processing plant including primary and secondary treatment

*****Irrigated Land*** refers to an appropriately irrigated plantation area of specified crops based on quantity and quality of wastewater

CHAPTER -3

PRODUCED WATER MANAGEMENT TECHNOLOGIES

The general objectives for operators treating produced water are: de-oiling (removal of dispersed oil and grease), desalination, removal of suspended particles and sand, removal of soluble organics, removal of dissolved gases, removal of naturally occurring radioactive materials (NORM), disinfection and softening (to remove excess water hardness) [Colorado School of Mines 2009, Daniel Arthur J. et al. 2005]. To meet up with these objectives, operators have applied many standalone and combined physical, biological and chemical treatment processes for produced water management. More than 150 methods are available for produced water management [Colorado School of Mines 2009]. Most used methods are

1. Membrane Filtration Technology (microfiltration (MF), ultrafiltration (UF), reverse osmosis (RO) and nanofiltration (NF)
2. Thermal Technologies (Multistage flash (MSF) distillation, vapour compression distillation (VCD) and multieffect distillation (MED))
3. Biological Aerated Filters
4. Hydro cyclones
5. Flotation Separation
6. Evaporation Pond
7. Adsorption
8. Ion Exchange Technology
9. Media Filtration
10. Chemical Oxidation
11. Electrodialysis (ED)/Electrodialysis Reversal (EDR)
12. Freeze-Thaw/Evaporation (FTE®)
13. Dew vaporation: Altelarain^{sm} Process

14. Macro-Porous Polymer Extraction Technology

Some of these technologies are reviewed in this section.

3.1 Membrane Filtration Technology

Membranes are microporous films with specific pore ratings, which selectively separate a fluid from its components. There are four established membrane separation processes, including microfiltration (MF), ultrafiltration (UF), reverse osmosis (RO) and nanofiltration (NF) [Igunnu E.T. et al. 2014; Xu P, Drewes JE. 2006].

3.1.1 Microfiltration/Ultrafiltration

Microfiltration (MF) has the largest pore size (0.1-3 μm) of the wide variety of membrane filtration systems. Ultrafiltration (UF) pore sizes range from 0.01 to 0.1 μm [Colorado School of Mines ,2009]. In terms of pore size, MF fills in the gap between ultrafiltration and granular media filtration. In terms of characteristic particle size, MF range covers the lower portion of the conventional clays and the upper half of the range for humic acids. This is smaller than the size range for bacteria, algae, and cysts, and larger than that of viruses. MF is also typically used for turbidity reduction, removal of suspended solids, *Giardia*, and Cryptosporidium. UF membranes are used to remove viruses, color, odor, and some colloidal natural organic matter [Igunnu E.T et al. 2014; OSPAR Commission (2008)]. Both processes require low trans membrane pressure (1-30 psi) to operate, and both are now used as a pretreatment to desalination technologies such as reverse osmosis, nanofiltration, and electrodialysis, but cannot remove salt themselves [Colorado School of Mines ,2009]

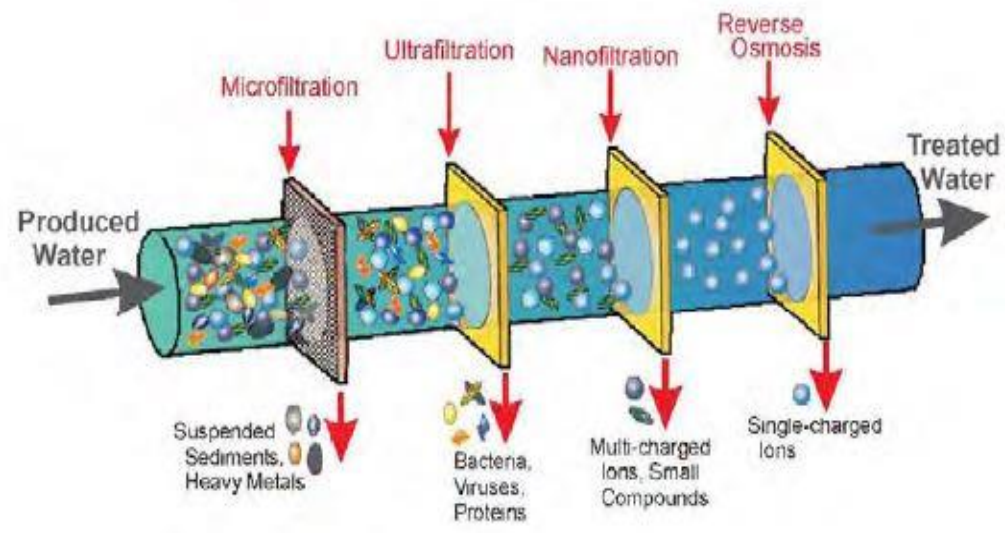

Figure 3.1: Schematic of different membrane filtration technology

Advantages:

a. Product water is totally free of suspended solids

b. It can be operated in cross-flow or dead-end filtration mode

c. Product water recovery range from 90% to 100%

d. Ceramic membranes have a longer lifespan than polymeric membranes

Disadvantages:

a. Irreversible membrane fouling can occur with significant amount of iron concentration in feed water

b. Membrane requires periodic cleaning

c. Waste generated during backwash and cleaning processes require disposal/ recycling or further treatment

3.1.2. Reverse Osmosis and Nanofiltration

Reverse Osmosis (RO) and Nanofiltration (NF) are pressure-driven membrane processes. Osmotic pressure of the feed solution suppressed by applying hydraulic pressure which forces permeate (clean water) to diffuse through a dense, non-porous membrane [Spiegler KS et al.

1966]. Seawater RO can remove contaminants as small as 0.0001 mm, but its major disadvantage is membrane fouling and scaling [Colorado School of Mines ,2009; Mark W. 2007]. Early studies on using RO to treat produced water failed due to insufficient process integration and poor treatment [Mondal S, Wickramasinghe SR 2008].

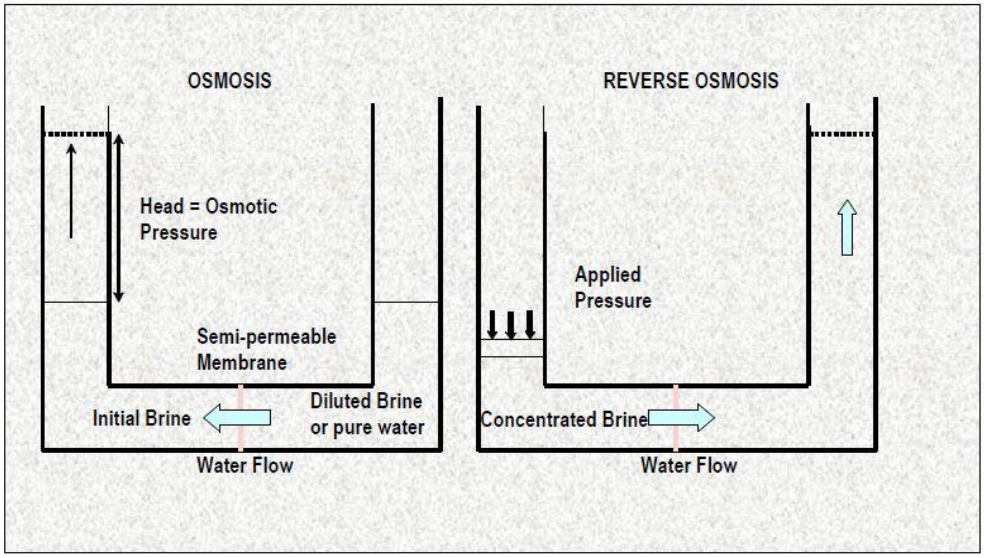

Figure 3.2: Schematic of osmosis and reverse osmosis [Nicolaisen B, Lien L. (2003)]

Experiments indicated that RO membrane technology would be excellent for oilfield produced water treatment with appropriate pre-treatment technology [Mondal S. et al. 2008, U.S. Bureau of Reclamation, 2003]. Capital costs of RO membrane systems vary depending on the size of rejection required, materials of construction and site location. Operating costs depend on energy price and total dissolved solid (TDS) level in the feed water. RO membrane systems generally have a life expectancy of 3–7 years [Colorado School of Mines , 2009; Science and Technology Research Report , 2014]. NF is a robust technology for water softening and metals removal and is designed to remove contaminants as small as 0.001 mm [Igunnu E.T et al. 2014 ; Meijer DT, Madin C. 2010]. It is applicable for treating water containing TDS in the range of 500–25 000 ppm. This technology is similar to RO [Colorado School of Mines , 2009]. NF membranes were employed for produced water treatment on both bench and pilot scales [Dores R. et al. 2012, Nicolaisen B, Lien L. 2003].

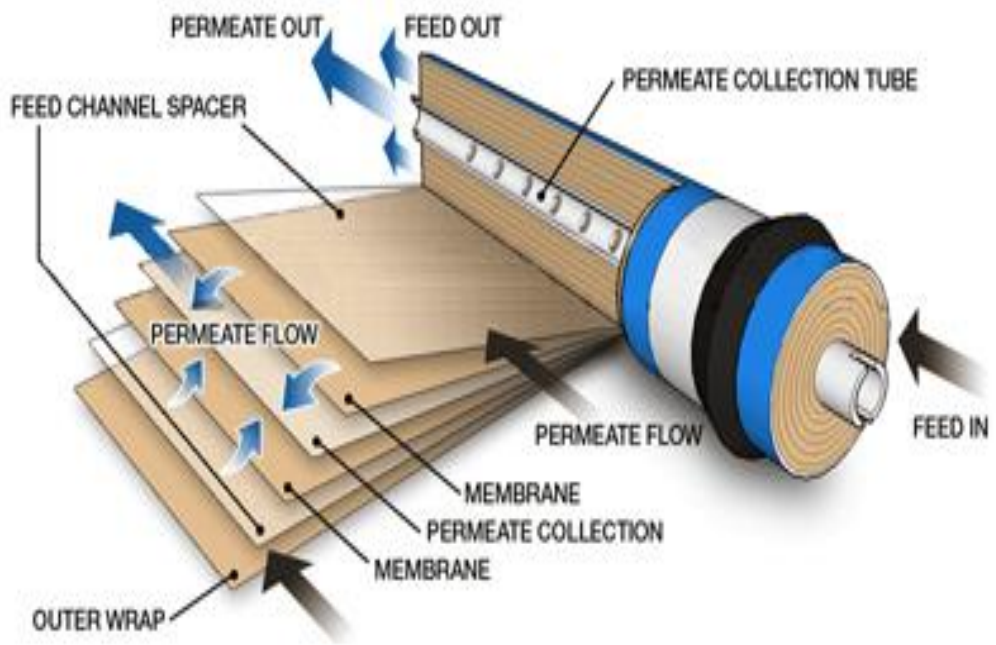

Figure 3.3: Schematic of reverse osmosis (RO) membrane element

[www.freshwatersytems.com]

Advantage:

a. It has high pH tolerance
b. System can be operated automatically leading to less demand of skilled workers
c. Energy costs can be reduced by implementing energy recovery subsystems
d. It performs excellently for produced water treatment with appropriate pre-treatment
e. It does not require concentrate treatment as brine generated is usually disposed into sea

Disadvantage:

a. It is highly sensitive to organic and inorganic constituents in the feed water
b. Membranes cannot withstand feed temperatures in excess of 45^0C

Comparison between different Membrane filtration technology given at Appendix Section Appendix-**A**

3.2 Thermal Technologies

Thermal treatment technologies of water are employed in regions where the cost of energy is relatively cheap. Thermal separation process was the technology of choice for water desalination before the development of membrane technology. Multistage flash (MSF) distillation, vapour compression distillation (VCD) and multieffect distillation (MED) are the major thermal desalination technologies [Igunnu E.T et al. 2014]. Hybrid thermal desalination plants, such as MED–VCD, have been used to achieve higher efficiency . Although membrane technologies are typically preferred to thermal technologies, recent innovations in thermal process engineering make thermal process more attractive and competitive in treating highly contaminated water [Colorado School of Mines 2009; GWI.2006].

3.2.1 Multistage Flash Distillation

Multistage flash distillation converts water to steam at low temperatures in a vacuum. At vacuum pressures, the boiling point of water is lower than at atmospheric pressure, requiring less energy. Water recovery from MSF treatment is ~20 % and often requires post -treatment because it typical contains 2-10 mg/l of TDS [Ahmadun, F. R et al 2009; Colorado School of Mines 2009]. The water is preheated and then subjected to a vacuum pressure that causes vapor to flash off the warm liquid. The vapor then is condensed to form fresh water while the remaining concentrated brine that does not flash is sent to the next chamber where a similar process takes place. The multiple stages are designed to improve the recovery of the process. Many of the older seawater desalination plants use the multistage flash distillation process.Its energy requirement is between 3.35 and 4.70kwh/bbl [Ahmadun, F. R et al. 2009; Darwish MA, Al Asfour F, Al-Najem N. 2003]

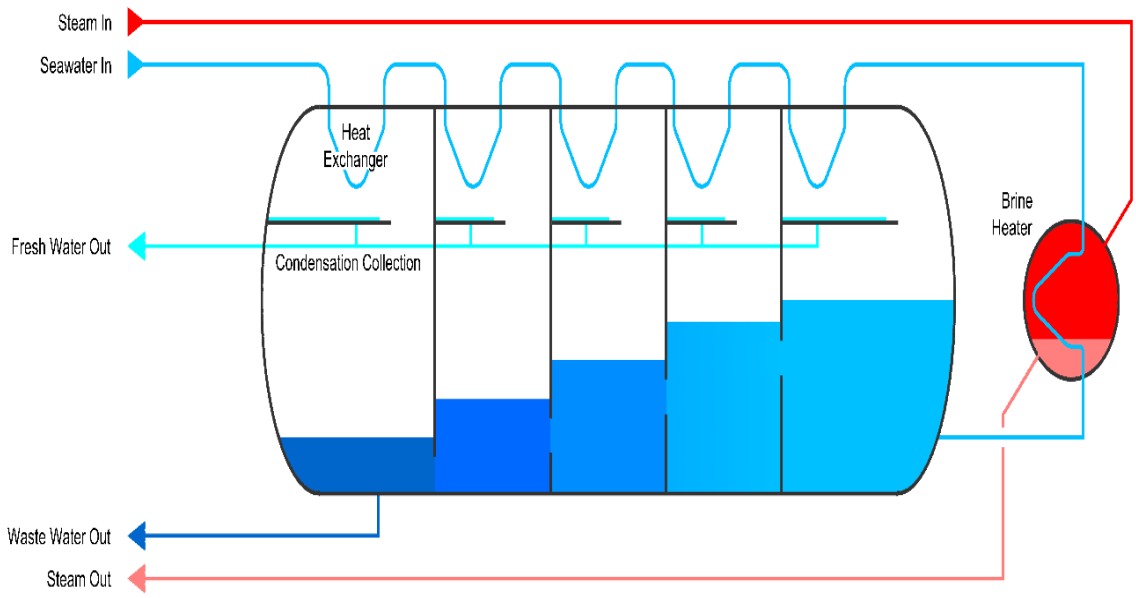

Figure 3.4: Schematic of Multistage Flash Distillation [**www.beggcousland.co.uk**]

Advantages:

a. It has a significantly long lifespan.

b. MSF system can withstand harsh conditions

c. It can easily be adapted to highly varying water quality

d. Cost of labour is cheaper than using membrane technology

e. Good for high TDS produced water treatment

f. Product water quality is high with TDS levels between 2 mg/l and 10 mg/l

Disadvantage:

a. Low product water recovery usually between 10 and 20%

b. It is not flexible for varying water flow rates

c. Scaling and corrosion can be a problem

3.2.2 Multieffect Distillation

MED process involves application of sufficient energy that converts saline water to steam, which is condensed and recovered as pure water. Multiple effects are employed in order to improve the efficiency and minimize energy consumption (Figure 3.5). A major advantage of

this system is the energy efficiency gained through the combination of several evaporator systems. Product water recovery from MED systems are in the range of 20–67% depending on the type of the evaporator design employed [Ahmadun, F. R. et al. 2009; U.S. Bureau of Reclamation 2003,]. Despite the high-water recovery from MED systems, it has not been extensively used for water production like MSF because of scaling problem associated with old designs. Recently, falling film evaporators have been introduced to improve heat transfer rates and reduce the rate of scale formation [U.S. Bureau of Reclamation, 2003].

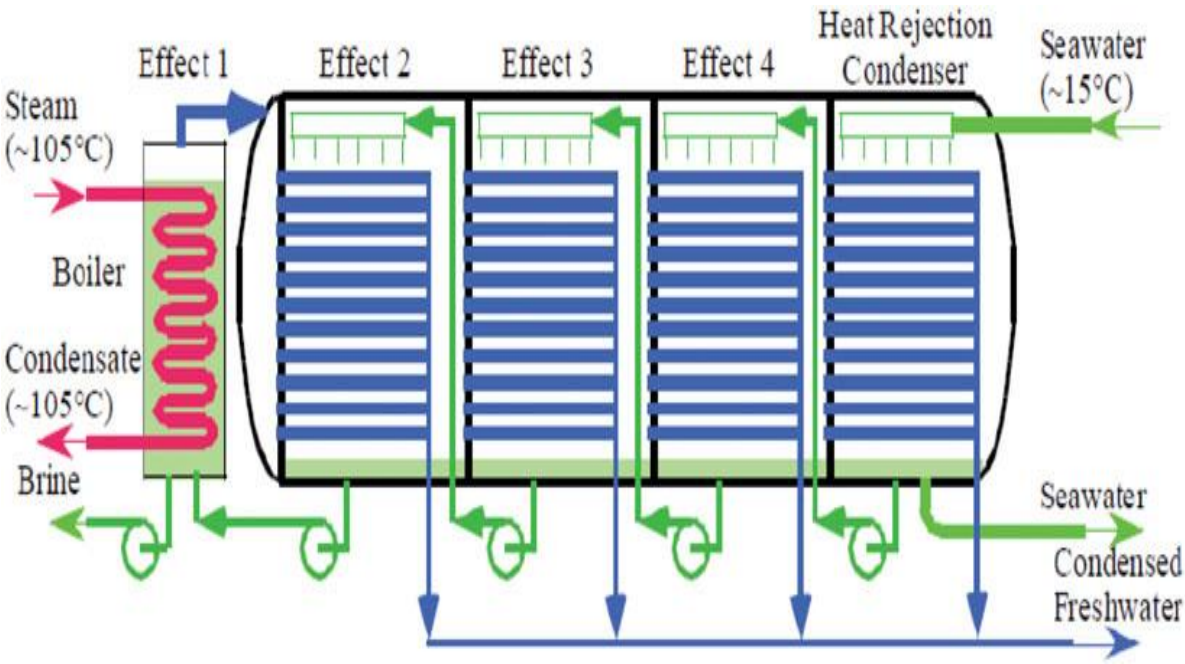

Figure 3.5: Schematic diagram of a conventional MED system [Igunnu E.T. et al. 2014]

MED has a life cycle of 20 years and can be applied to a wide range of feed water quality like MSF. It is good for high TDS produced water treatment . Scale inhibitors and acids may be required to prevent scaling and pH control is essential to prevent corrosion. Power energy consumption is in the range of 1.3–1.9 kWh/bbl [Darwish MA, Al Asfour F, Al-Najem N. 2003], operating cost is $0.11/bbl and total unit cost is $0.16/bbl [Ettouney HM, El-Dessouky HT, Gowin PJ 2002].

Advantage:

a. It has a long lifespan.

b. Energy requirement is cheaper than using MSF

c. It can easily be adapted to highly varying water quality

d. Cost of labour is cheaper than using MSF or membrane technology

e. Good for high TDS produced water treatment

f. Product water quality is high

Disadvantage:

a. Typically low product water recovery usually between 20% and 35%

b. It is not flexible for varying water flow rates

c. Scaling and corrosion can be a problem

d. High level of skilled labour Required

3.2.3 Vapor Compression

In the vapor compression process, the feed water is preheated in a heat exchanger by the product and reject streams from the process. This process uses a still that contains tubes [Colorado School of Mines 2009]. The water then is fed to the inside of the tubes, and the vapors then are fed to the outside of the tubes to condense. The gases that do not condense are removed from the steam-condensation space by a vent pump or ejector. The mechanical pump or ejector is a requirement of this process and is necessary to increase the pressure of the vapor to cause condensation. Vapor compression has been used for produced water treatment, and commercially available products currently are marketed for this application [Aziz, M.A. (1975); Igunnu E.T et al.2014].

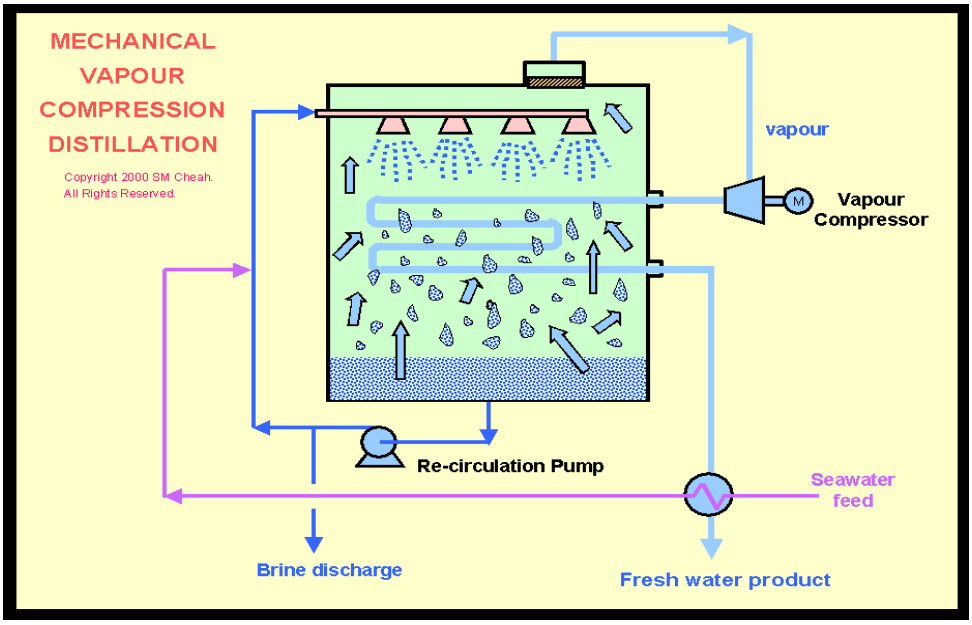

Figure 3.6: Schematic diagram of a conventional Vapor Compression (VC) system (www.separationprocesses.com)

Advantage:

a. It is a smaller unit compared with MSF and MED

b. It has high ability to withstand harsh conditions

c. It does not require special concentrate treatment

d. Pre -treatment is less rigorous compared with membrane treatment

Disadvantage:

a. Typically, low product water recovery is usually around 40%

b. It is not flexible for varying water flow rates

c. Scaling and corrosion can be a problem

d. High level of skills is required to operate system

Comparison between different Membrane Filtration Technology given at Appendix Section: Appendix-B

3.3 **Biological Aerated Filters**

Biological aerated filter (BAF) is a class of biological technologies which consists of permeable media that uses aerobic conditions to facilitate biochemical oxidation and removal of organic

constituents in polluted water. Media is not more than 4 in in diameter to prevent clogging of pore spaces when sloughing occur [Dores R. et al.2012; Igunnu E.T. et al.2014, U.S. Bureau of Reclamation,2003]. BAF can remove oil, ammonia, suspended solids, nitrogen, chemical oxygen demand (COD), biological oxygen demand (BOD), heavy metals, iron, soluble organics, trace organics and hydrogen sulphide from produced water Pars HM, Meijer DT.1998; Palmer L., Beyer A. and Stock J. 1981]. It is most effective for produced water with chloride levels below 6600 mg/l. This process requires upstream and downstream sedimentation to allow the full bed of the filter to be used. Removal efficiencies of up to 70% nitrogen, 80% oil, 60% COD, 95% BOD and 85% suspended solids have been achieved with BAF treatment [Bradley,B.W. 1990; Colorado School of Mines , 2009]

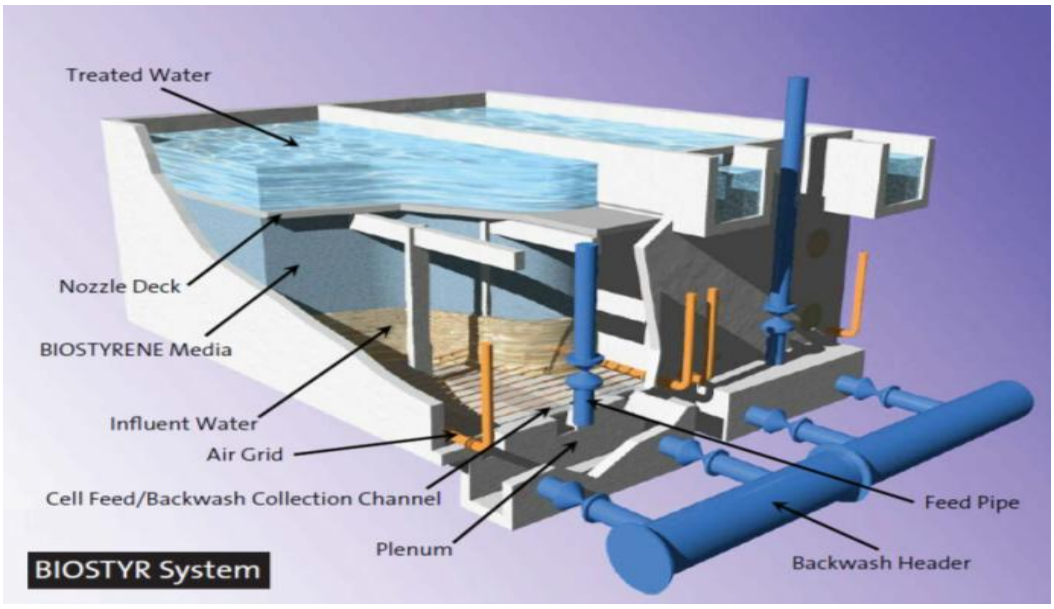

Figure 3.7: Schematic of BAF Using Polystyrene Media (www.AECOM.com)

Advantage:

a. Water recovery is almost 100%

b. Easy to adapt to wide range of water quality and quantity

c. Little need for maintenance.

d. Does not require post-treatment

e. Some BAF does not require any equipment

Disadvantage:

Solid disposal required for sludge that accumulates in the sedimentation basin can cost up to 40% of the overall cost

3.4 Hydrocyclones

Hydrocyclones use physical method to separate solids from liquids based on the density of the solids to be separated. They are made from metals, plastics or ceramic, and usually have a cylindrical top and a conical base with no moving parts (Figure 3.8). The performance of the hydrocyclone is determined by the angle of its conical section [Colorado School of Mines ,2009]. Total residence time of the liquid in the hydrocyclone is only 2-3 seconds [Bradley, B.W. 1990; Igunnu E.T et al. 2014].

Hydrocyclones can remove particles in the range of 5–15 µm and have been widely used for the treatment of produced water . Nearly 8 million barrels per day of produced water can be treated with hydrocyclones . They are used in combination with other technologies as a pre-treatment process. They have a long lifespan and do not require chemical use or pre-treatment of feed water. A major disadvantage of this technology is the generation of large slurry of concentrated solid waste.

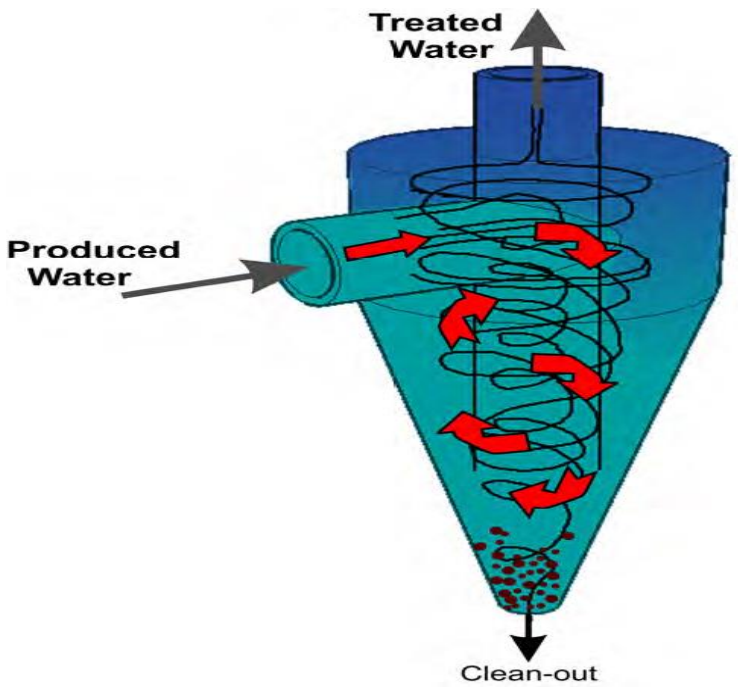

Figure 3.8: Hydrocyclone flow Scheme and mode of Operation [Science and Technology Research Report, 2014]

Advantage:

a. Does not require the use of chemicals and energy

b. High product water recovery

c. Can reduce oil and grease concentrations to 10 ppm

d. Can be used for treating any kind of produced water

e. Does not require pre-treatment

Disadvantage:

a. Solids can block inlet and scales formation can lead to extra cost in cleaning

b. Disposal is required for secondary waste generated

3.5 Flotation Separation

Gas flotation units work by introducing small gas bubbles into the wastewater being treated. The gas bubbles acquire a small electronic charge, opposite that of the oil droplets. As the gas bubbles rise through the oily wastewater, oil attaches to the bubbles [Arnold, K.E. Stewart, M.

2008]. Flotation units use two distinct methods for producing small gas/air bubbles needed to contact with water: pressurized gas/air injection and induced gas/air [Cline,J.T. 2000].

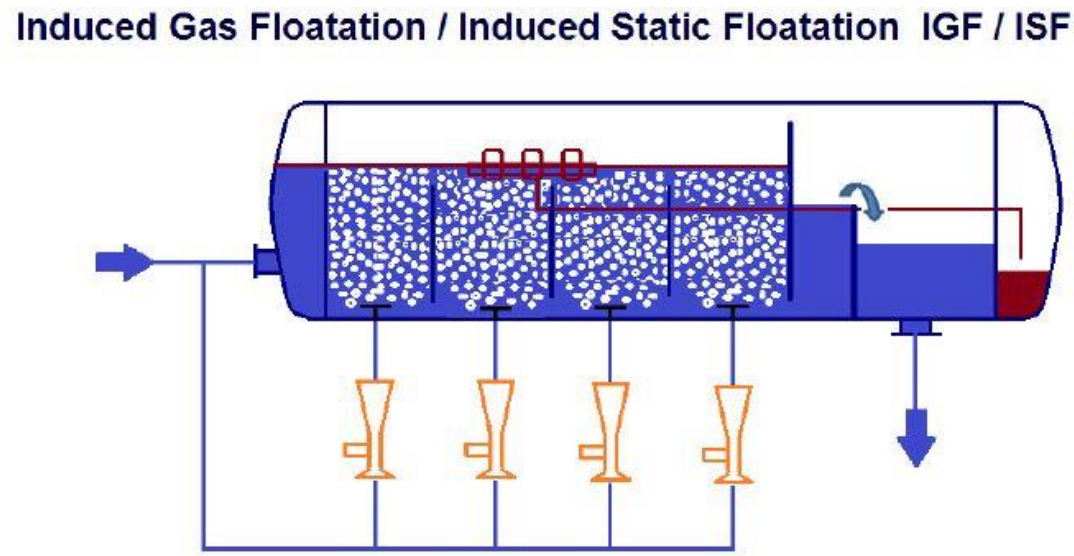

Figure 3.9: Flotation Separation Flow Scheme and mode of Operation [Arnold, K.E. et al. 2008]

Advantage:

a. Product water recovery is almost 100%

b. No post-treatment required

Disadvantage:

a. Not ideal for high-temperature feed water

b. Solid disposal is required for sludge generated

3.6 Evaporation Pond

Evaporation pond is an artificial pond that requires a relatively large space of land designed to efficiently evaporate water by solar energy [Velmurugan V., Srithar K. 2008]. They are designed either to prevent subsurface infiltration of water or the downward migration of water depending on produced water quality [ALL Consulting , 2003]. It is a favorable technology for warm and dry climates because of the potential for high evaporation rates. Evaporation ponds are typically economical and have been employed for the treatment of produced water onsite

and offsite. Ponds are usually covered with nettings to prevent potential problems to migratory waterfowl caused by contaminants in produced water [AWWA 1998; Velmurugan V. et al. 2008]. All water is lost to the environment when using this technology which is a major setback when water recovery is an objective for water treatment.

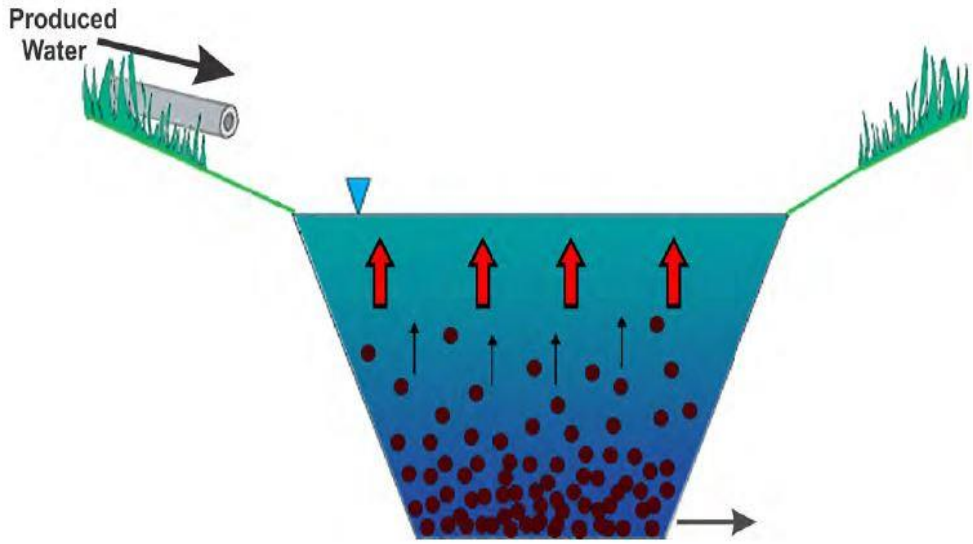

Figure 3.10: Schematic of Evaporation Pond [Science and Technology Research Report ,2014]

Advantage:

a. It is very cheap

b. Does not require the use of chemicals and energy

Disadvantage:

a. Water volume may be lost due to evaporation

b. Waste disposal is required for materials that settle out of feed water

3.7 Adsorption

Adsorption is commonly used for the treatment of produced water, as it can remove more than 80 percent of heavy metals and results in nearly 100 percent product water recovery. A variety of materials are used for adsorption, including zeolites, organoclays, activated alumina, and activated carbon, which can remove iron, manganese, TOC, and other contaminants [Igunnu

E.T et al. 2014]. Chemical use is minimal. However, the adsorbent can be easily overloaded with large concentrations of organics, so this process is not always ideal for primary treatment. The media also eventually become consumed with contaminants and must be disposed or regenerated using chemicals. Regeneration creates a liquid waste product that must be disposed. Media may require frequent replacement or regeneration depending on type and feedwater quality [ALL Consulting 2003]

Advantage:

a. 80% removal of heavy metals
b. Can achieve nearly 100% water recovery

Disadvantage:

Waste disposal system required for spent media or waste produced during media regeneration

Comparison between BAF, Hydrocyclone, Gas flotation, Evaporation pond, Adsorption given at appendix section: Appendix-C

3.8 Ion Exchange Technology

The process of ion exchange is a reversible chemical reaction which involves exchange of ion from a solution to similarly charged ion attached to an immobile solid. The technique is known for its role in water softening during treatment of potable water but to a lesser extent has been used for treatment of produced water. The process effectively removes arsenic, nitrates, radium, heavy metals, uranium, and salts from produced water [Daniel A. J. et al,2005]. Resins used for the process could be naturally occurring e.g. zeolites or artificially produced. It also requires the use of chemicals for resin regeneration and disinfection. The operating cost accounts for more than 70% of the overall cost of this technology [Colorado School of Mines,2009; Daniel A. J. et al,2005].

Advantage:

a. It requires minimal supervisory oversight

b. May operate continuously for 10–20 h

c. Energy requirements are minimal

Disadvantage:

a. High operating and chemical costs

b. High sensitive to fouling

3.9 Media Filtration

Filtration technology is extensively used for the removal of oil and grease and TOC from produced water [Colorado School of Mines ,2009]. Filtration can be accomplished by the use of various types of media such as sand, gravel, anthracite, walnut shell and others. Walnut shell filters are commonly used for produced water treatment. This process is not affected by water salinity and may be applied to any type of produced water. Media filtration technology is highly efficient for the removal of oil and grease, and efficiency of more than 90% has been reported [Dores R et al. 2012; Igunnu E.T; et al 2014]. Efficiency can be further enhanced if coagulants are added to the feed water prior to filtration. Media regeneration and solid waste disposal are setbacks to this process**.**

Figure 3.11: Cross section of a Media Filter [http://www.bluewaterbio.com/filterclear/]

Advantage:

a. 90% oil and grease removal efficiency

b. Can achieve nearly 100% water recovery

Disadvantage:

Waste disposal system required for spent media or waste produced during media regeneration

3.10 Chemical Oxidation

Chemical oxidation is an established and reliable technology for the removal of colour, odour, COD, BOD, organics and some inorganic compounds from produced water [Igunnu E.T; et al 2014; Veil J.,Pudor M., Elcock D.,Redweik R. ,2004]. Chemical oxidation treatment depends on oxidation/reduction reactions occurring together in produced water because free electrons cannot exist in solution. Oxidants commonly used include ozone, peroxide, permanganate, oxygen and chlorine. The oxidant mixes with contaminants and causes them to break down. The oxidation rate of this technology depends on chemical dose, type of the oxidant used, raw water quality and contact time between oxidants and water. Chemical cost during this process may be high [AWWA (1998),].Energy consumption accounts for 18% of the total cost of operations and maintenance [Colorado School of Mines ,2009]. It requires minimal equipment and has a life expectancy of 10 years or greater and solid separation post-treatment may be employed to remove oxidized particles

Advantage:

a. It requires minimal equipment

b. No waste is generated from this process

c. It does not require pre- and post-treatment

d. It has 100% water recovery rate

Disadvantage:

a. Chemical cost may be high

b. Periodic calibration and maintenance of chemical pump is required

c. Chemical metering equipment is critical for this process

3.11 Electrodialysis (ED)/Electrodialysis Reversal (EDR)

ED and EDR, both electrochemical-charge-driven separation processes, have been tested for produced water treatment at the laboratory-scale and are already being used for seawater and brackish water desalination and wastewater reclamation [Sirivedhin T, McCue J, Dallbauman L.2004]. The technologies utilize "dissolved ions which are separated from water through ion permeable membranes under the influence of an electrical potential gradient," according to the CSM report. ED/EDR membranes are not as susceptible to degradation by chlorine and can treat surface and wastewaters that have high concentrations of organic materials and microorganisms without significant fouling [Igunnu E.T et al. , 2014]. The technologies can withstand harsh conditions and are fairly flexible to varying water quality. However, ED/EDR have limited ability to remove non-charged constituents, including organics molecules, silica, and boron. A high level of skilled labor is also required to operate ED/EDR systems [Godshall N.A.2006]

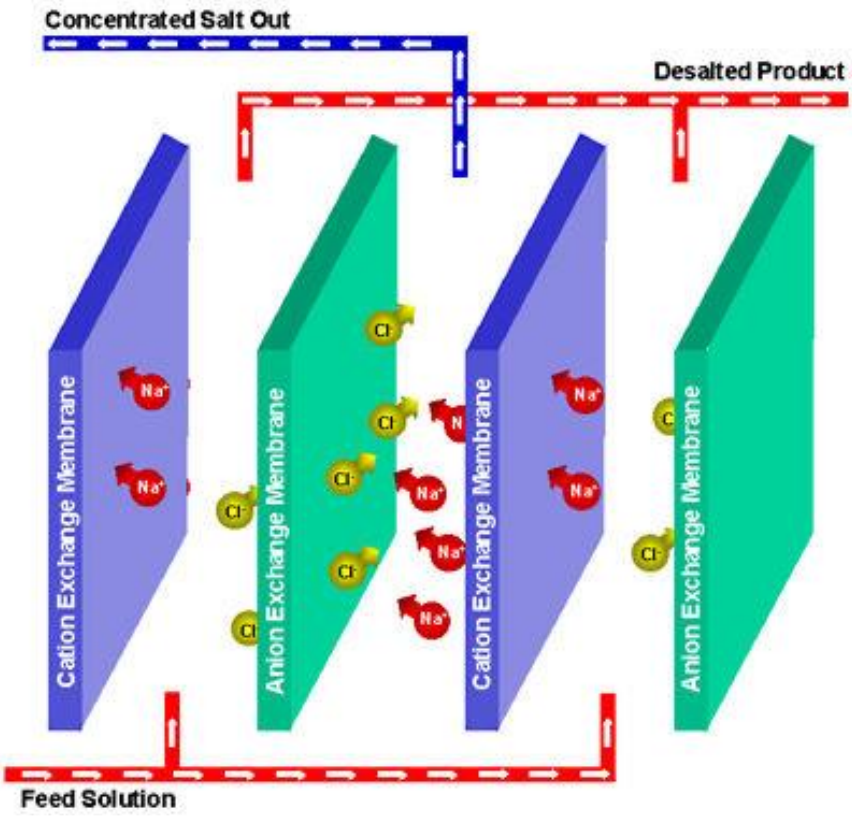

Figure 3.12: An ED unit in operation (Source: Electrosynthesis Company Inc) [Igunnu E.T et al, 2014]

Advantage:

a. It does not require special infrastructure

b. Modest to withstand harsh conditions

c. Excellent for produced water application

Disadvantage:

a. This technology has only been tested on a laboratory scale for produced water treatment

b. Fairly flexible to varying water quality

c. Operation requires highly skilled labour

d. Process requires periodic maintenance and chemical cleaning

e. Concentrate disposal is required

Comparison between Media filtration, Ion exchange technology, Chemical oxidation, ED/EDR given at appendix section -Appendix-D

3.12. Freeze-Thaw/Evaporation (FTE®)

BC Technologies and Crystal Solutions utilizes the FTE® process to treat produced water for full scale facilities. In this process, when the outdoor air temperature is less than 32 °F, the water to be treated is sprayed or dripped onto a freezing pad, forming a large pile of ice [Boysen J., 2007; Pars H.M, Meijer D.T., 1998] This process exploits the fact that saline water has a lower freezing point than fresh water; therefore, at temperatures cooler than 32 °F, the runoff from the ice pile will be salty brine. When the temperature is such that melting occurs, the runoff will be fresh water [Boysen J. 2007]. This process has been used successfully to treat produced water and is considered an established process for produced water treatment (**Figure 3.13**). It is easy to operate and monitor, and has a life expectancy of 20 years [Colorado School of Mines , 2009]. However, it can only work in a climate that has substantial number of days with temperatures below freezing and usually requires a significant amount of land. Waste disposal is essential when using FTE technology because it generates a significant amount of concentrated brine and oil.

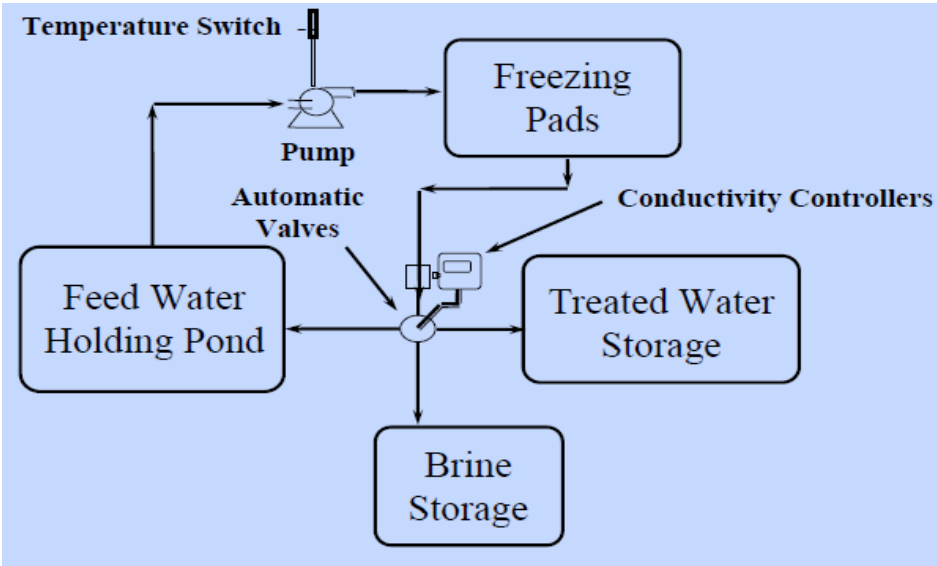

Figure 3.13. Schematic of Freeze/Thaw Evaporation (FTE®) [Boysen J.,2007]).

3.13 Dewvaporation: Altelarain^{sm} Process

Dewvaporation is a process that involves humidification-dehumidification desalination. It reduces the energy costs by using counter-current heat exchange technology [Godshall NA. ,2006]. Feedwater is evaporated by heated air, which condenses as fresh water on the opposite side of a heat transfer wall. The energy needed for evaporation is partially supplied by the energy released during condensation [Igunnu E.T et al. , 2014]. Heat sources can be combustible fuel, solar, or low-grade heat from various resources. The tower unit is built of thin plastic films to avoid corrosion and to minimize equipment costs. Towers are relatively inexpensive because they operate at atmospheric pressure [Science and Technology Research Report ,2014].

Altela, Inc. has designed, manufactured, and tested several AltelaRainSM prototype systems based on the dewvaporation process. Three full-scale AltelaRainSM ARS-4000 systems have been deployed at natural gas wells in the San Juan Basin near Farmington, NM [Energy & Environment Research Center. Free-Thaw. , 2010]. The ARS-4000 system can process approximately 4,000 gallons per day (100 bbl/day) of produced water with salt concentrations more than 60,000 mg/LTDS [Energy & Environment Research Center. Free-Thaw. ,2010; Godshall NA.,2006]

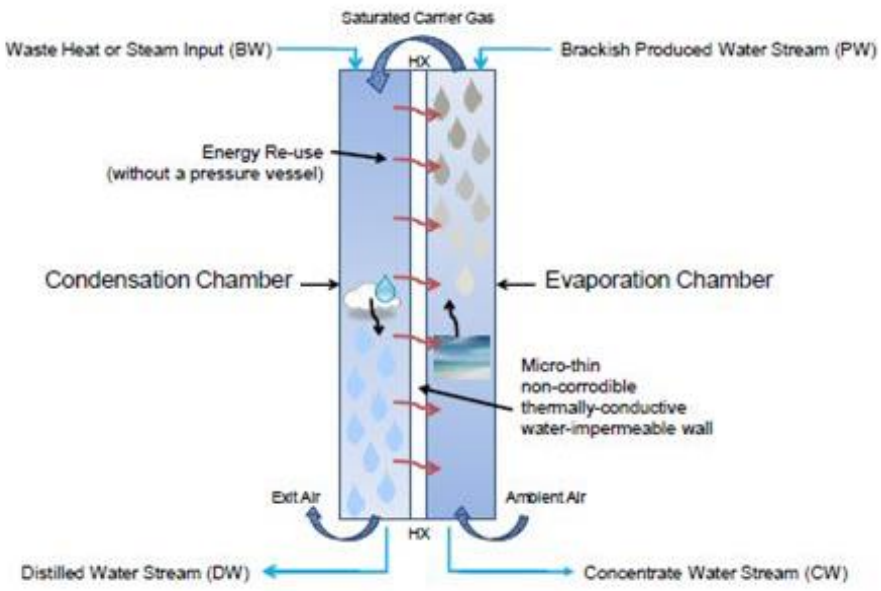

Figure 3.14: Schematic of Dewvaporation: Altelarain^{sm} Process (www.Altelainc.com)

Advantage:

a. Low capital operating and maintenance cost requirements

b. Precise control of economics

c. Low maintenance

d. Infinitely scalable

e. Reduced facility requirement

f. Extremely high quality of treated water

3.14 Macro-Porous Polymer Extraction Technology

The Macro Porous Polymer Extraction (MPPE) Technology is a higly effective, fully automated, remote controlled and guaranteed method for removing dissolved and dispersed hydrocarbons from water with efficiencies of 99.9999% down to below ppb level by means of extraction in an MPP bed [Akzo Nobel MPP Systems, 2004]

With over 80 years accumulated worldwide experiences the MPPE Technology is tested and proven with references by many respected companies [Igunnu E.T et al. 2014; Mondal S. 2008]. The Macro Porous Polymer (MPP) act as carrier for nontoxic and biodegradable

extraction medium that absorbs and extracts hydrocarbons from water. The miniscule plastic spheres can reduce contaminant concentrations in water by a factor of more than 1 million, which means that concentrations of thousands ppm (parts per million) can be lowered to below 1 ppb (parts per billion) [Pars H.M et al. ,1998] .This is done in only one cycle. Aside from clean water for recycling or discharging, the water purification unit also yields almost 100% pure hydrocarbons suitable for reuse [Akzo Nobel MPP Systems 2004;Pars H.M et al. ,1998]

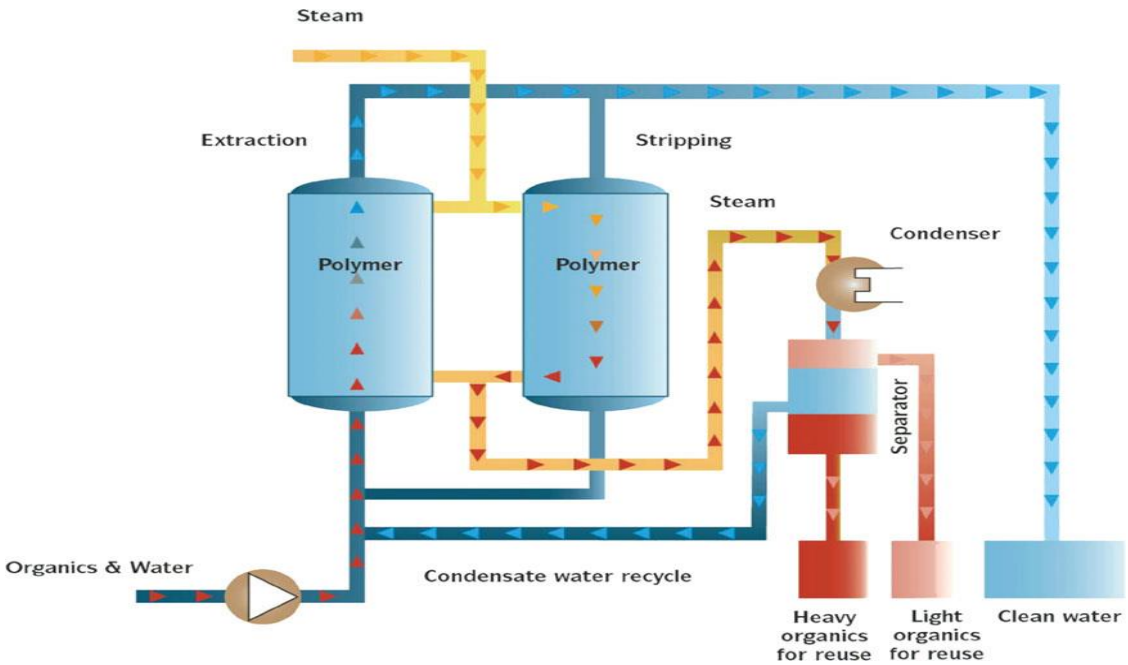

Figure 3.15. Schematic Diagram of MPPE process [Igunnu E.T. et al. 2014].

CHAPTER-4

METHODS SELECTION FOR BANGLADESH

All mentioned treatment methods have their own advantages and disadvantages. High initial capital costs and sensitivity to the feed stream quality are the most important disadvantages of physical methods; whereas hazardous sludge generation, high operating costs and sensitivity to the initial concentration of effluents in feed stream are disadvantages of chemical methods. On the other hand, fouling⁄scaling issues and high module price are the disadvantages of membrane-based treatment methods [Ahmadun, F. R et al. 2009; Bradley,B.W. 1990;, Colorado School of Mines ,2009]

Furthermore, in offshore production plants, space limitations encourage the engineers to use compact treatment processes, whereas in onshore production units, where enough space is available, a wider variety of treatment methods can be used.

Technology options for high-TDS waters for non-industrial uses require a multi-stage process. Conceptual process design requires further analytical work to develop priority technology combinations. Furthermore, in offshore production plants, space limitations encourage the engineers to use compact treatment processes, whereas in onshore production units, where enough space is available, a wider variety of treatment methods can be used.

It can be seen from the table that oil droplet size plays a critical role in determining whether such an oil droplet can be separated by a particular mechanical method. Most of the mechanical methods are now well established. Technologies such as hydrocyclones and gas flotation units with and without the use of chemicals are well applied offshore and onshore for produced water treatment to meet typical produced water discharge standards [Ettouney H.M. et al. 2002]

Table 4.1 Represents a general overview of treatment technologies which apply nowadays for PW treatment

Table 4.1*:* Represents a general overview of treatment technologies which apply nowadays for PW treatment.

Technology	Free oil	Other oil	Particles	Fe & Mn	Ca & Mg	TDS, NaCl	Heavy Metals	Silica	Soluble organics	H_2S
MF, UF		●	●	●			●			
RO-NF			●	●	●	●	●	●	●	●
Thermal technologies	●	●	●	●	●	●	●	●	●	●
Biological aerated filters	●	●	●	●	●	●	●	●	●	●
Hydrocyclones	●		●	●	●		●	●	●	
Gas Flotation	●		●	●			●	●	●	
Adsorption(Foam)	●	●	●	●			●	●	●	●
Ion Exchange				●	●	●	●	●		
Chemical oxidation				●			●		●	●
Electro-dialysis (ED)/Electro-dialysis reversal (EDR)				●	●	●	●			
Freeze thaw evaporation(FTE®)					●	●	●		●	●
Dewvaporation: AltelaRain℠						●	●		●	
Macro-porous polymer extraction (MPPE)	●	●				●	●		●	

- *(*sign*)* means applicable to remove the particles

For the removal of dissolved oil in produced water, non-mechanical based methods are often required. Absorption / adsorption / extraction are the current state of the art while oxidation and biological based methods are emerging, in particular for an example, the use of constructed wetlands / reed beds for the treatment of produced water [ALL Consulting(2003); Colorado School of Mines (2009); Igunnu E.T et al. 2014].

In order for produced water to be re-used for agriculture, irrigation use purpose, in addition to the removal of oil (dispersed and dissolved), salt content of the produced water needs to be reduced. There are several methods with which salt content or dissolved solids can be removed. These may include: thermal Evaporation (MSF, MED, VCD, membrane technology (NF,RO, UF, MF) , electrodialysis, ion exchange.

Thermal evaporators entered the PW treatment market by looking at niche opportunities, particularly in remote locations where other forms of traditional PW management tended to be more expensive, allowing the energy intensive thermal processes an opportunity to be cost-effective. Thermal technology is applicable to remove all partials like free oil, other oil, Fe, Mn, TDS but major disadvantage of the thermal technologies is its costly and required more energy than other methods [Ahmadun, F. R et al 2009;Darwish M.A. et al. 2003; Science and Technology Research Report , 2014]

Membrane technology such as MF, UF,RO, NF are the most applicable methods for desalination of water. RO membrane technology is now considered a mature technology and it is currently responsible for 60% of worldwide seawater desalination installed capacity (**Figure 4.1**)[Dores R.et al. 2012 ; Science and Technology Research Report , 2014]. Moreover, the operating costs of RO systems continue to decrease, with seawater desalination plants operating at a cost of 3 kWh/m^3 [Dores R.et al. 2012] . In 2010, 67.5 MIGD of RO capacities were contracted in Ras Azzour, Saudi Arabia. The San Ardo PW treatment facility in California is considered the first large scale application of RO to treat PW production capacity 50,000 bbd. Electro-dialysis (ED)/Electro-dialysis reversal (EDR) is a relatively cheap green technology. It does not generate secondary waste nor involve the use of additional chemicals, and offers improved beneficial uses of produced water. It can generate and store energy, remove organics, produce clean water and recover valuable materials from produced water with little or no negative impact on the environment. ED and EDR are established electrochemical treatment technologies of produced water and are mainly useful when removing salts from produced water for irrigation use [Colorado School of Mines (2009; Igunnu E.T et al 2014, Dores R. et al. 2012].

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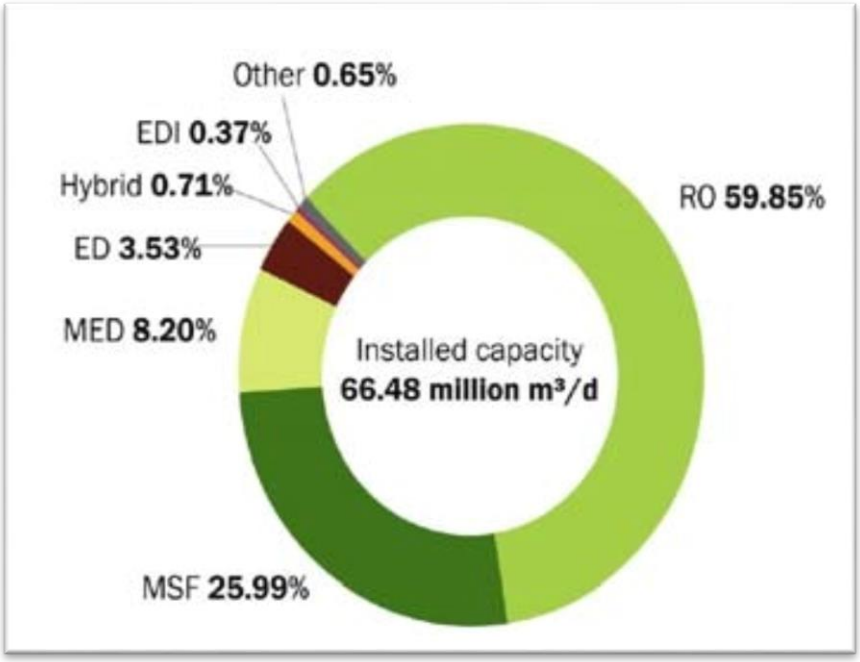

Figure 4.1: Installed capacity for sea water desalination worldwide , [Dores R. et al. 2012].

Depending on feedwater chemistry, water recovery in ED and EDR can be between 70 and 90%. ED membranes are not as susceptible to degradation by chlorine; therefore, dosing a small amount of chlorine to the feed water can control biological growth in the system. These features enable ED and EDR to treat surface and wastewaters having high concentrations of organic materials and microorganisms without significant fouling. EDR system is able to operate with maximum silt density index (SDI) of 15 compared to 5 for RO [Colorado School of Mines (2009); Igunnu E.T et al 2014]. A disadvantage of ED and EDR is its limited removal of non-charged constituents, including organics molecules, silica, boron, and microorganisms. Adsorbents are capable of removing iron, manganese, total organic carbon, BTEX compounds, heavy metals, and oil from produced water. Adsorption is generally utilized as a unit process in a treatment train rather than as a stand-alone process. The adsorbent can be easily overloaded with large retreatment process . Adsorption is capable of removing over 80% of heavy metals [Igunnu E.T et al. 2014] and can accomplish nearly 100% product water recovery.

Ion exchange processes are reversible chemical reactions to remove dissolved ions from solution, replacing them with less troublesome ions of the same charge.it can remove Fluoride,

nitrate, arsenate, selenate, chromate, or anionic uranium complexes but main limitations are High chemical demand for regeneration and limited TDS concentrations

Hydrocyclones use centripetal force to separate and remove suspended solids. Water is pumped into the inlet tangential to the wall. The water's spiral flow path causes particles to impact the walls of the separator. Heavier particles fall to the bottom; lighter particles may form a cake layer on the entrance wall and fall to the bottom in clumps. If oil is present, it is carried to the overflow exit. Water and sand or other heavy particles exit through the underflow. If the system is just for solids, then they are washed out through the underflow while treated water exits through the overflow. Depending on the design, both particulates and oil particles may be removed due to differing density from the main water stream.

Altela RainSM (Dewvaporation) process utilizes a humidification-dehumidification cycle to produce distilled water. Feed water is evaporated by hot air on one side of a heat transfer wall, and fresh water is condensed on the other side [AltelaRainTM System ARS-4000 ,2007]. The condensate or dew collects on the other side of the wall represents the purified water stream. This process has been utilized for produced water treatment and has undergone several pilot tests. It can remove TDS and heavy metal from water but free oil and other oils remain in water.

Considering the concentration of produced water in Bangladesh media filtration along with reverse osmosis are suitable methods for beneficiary use of produced water. As sample design for produced water treatment given at figure 4.2

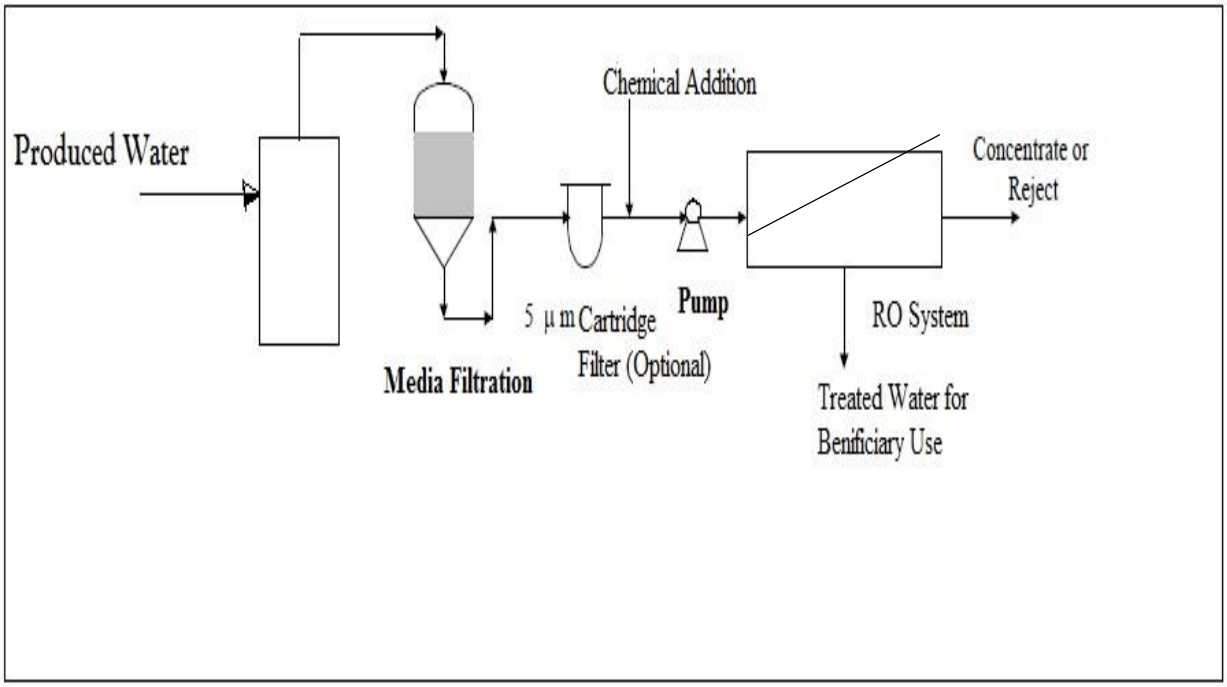

Figure 4.2: Schematic of a proposed produced water treatment for Bangladesh

CHAPTER 05

DESIGN GUIDELINES FOR A PRODUCED WATER TREATMENT PLANT

5.1 Plant Design

Produced water is a big issue at present in the world after the shortage of drinking water. Like other countries, we should think about the produced water management and how to convert produced water as beneficial use (agriculture, drinking, house hold and other).

Considering the chemical composition of Bangladeshi gas field water, the proposed produced water treatment plant consists the following parts

a. 3 stages separator
b. Media filtration
c. Reverse osmosis (RO)

1. **3 Stage Separator Design:**

   It's a normal designed separator based on capacity. For this field the separation capacity of the separator is 600 bbl/d

2. **Media Filtration Design**:

   Filtration technology is extensively used for the removal of oil and grease and TOC from produced water. It removes nearly 90% oil and grease from the water. It designed based on required capacity.

3. **Design Guidelines for a Reverse Osmosis plant**:

RO plant design is the main part to design a produced water treatment plant.

RO system includes:

Feed water pump

Pretreatment filter (according to your water analysis report choose the multi-media filter, activated carbon filter, soften system)

P^H dosing system

Cartridge filter

CIP clean System

High pressure pump

RO membrane

The following steps are guidelines to design a reverse osmosis plant are:

Step 1: Determine the product volume requirement

Step 2: Determine the characteristics of the feed water.

Step 3: Calculate the number of membranes required

Step 4: Calculate the feed pressure requirement

Step 5: Calculate pre-treatment supply requirements

Step 6: Estimate the energy requirements of the RO plant

Step 7: Consider discharge of brine water

Step 1: Determine the Product volume requirement:

First, a good evaluation should be carried out to determine the volume of produced water need to be treatment or manage. The considered gas field produced 600 bbl water equals 95400 letters water per day

Step 2: Determine the characteristics of the feed water:

We tested the Produced water sample collected from a Gas field in Bangladesh in BASF Bangladesh Ltd. construction chemical Lab. The lab test result showing that the dissolved oil, EC, TDS, Na+, Cl-, HCO3- , COD, Ca+ ,and other parameters of produced water are much higher than the acceptable limit define by Environment and Forest Ministry of Bangladesh.

Considering the chemical composition (Chapter 2), we consider the recovery ratio (RR) 75% for the plant.

Steps 3: Calculate the Number of Membranes Required:

Today, there are several excellent RO specialists around the world which can supply advice and service on any RO products. On request they can provide detailed information and the designer can use the data for a preliminary design. Some companies have developed their own design software programs that can help the designer to simulate an RO plant by using different types of membranes. These programs can simulate complicated RO designs that need iterations to solve RO equations.

By using the flux rate of a membrane the total membrane area can be calculated with Equation 5.1 [Hoffman A. M (2008)]

$$Area_{Total} \approx \left(\frac{1000.Q_{Total}}{\varphi_1}\right) + Z.\left(\frac{1000.Q_{Total}}{\varphi_2}\right) \qquad \text{..... 5.1}$$

$Area_{Total}$ - Total membrane area required [m^2]

Q_{Total} - Total amount of product water (m^3/d) = 93.5

φ_1 - First pass membrane flux [L/m^2·d] = 20 (assume Maximum limit 70 [L/ hr. m^2])

φ_2 -Second pass membrane flux [L/m^2·d]= 30 (assume , Maximum limit 70 [L/m^2·hr])

Z - Number of passes (Z 0 if one passes and Z = 1 if 2 passes)

Depending on the application, various ratios (5:2, 3: 1, etc.) can be used between the membrane arrays. In this case a multi array flow configuration was chosen with a ratio of 2: 1 between Array 1 and Array 2 (Figure 5.1)

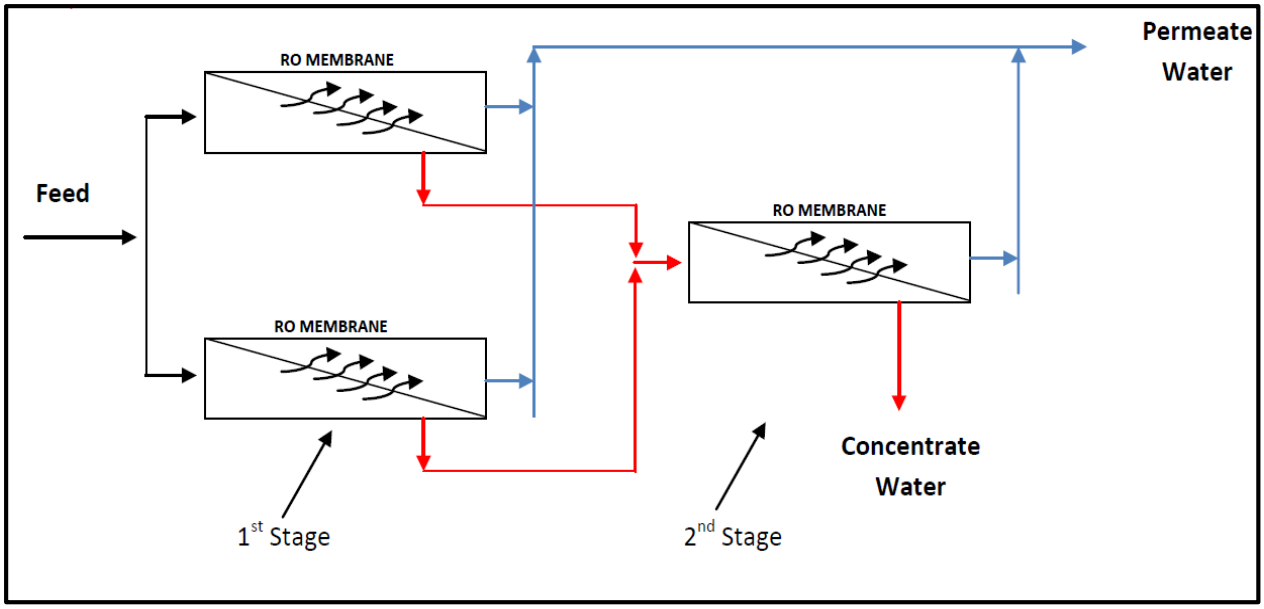

Figure: 5.1: 2 :1 Arrays RO membrane arrangement design.

Two different membrane types are chosen for the two arrays. For the first pass seawater membranes are used and for the second pass a brackish type membrane.

Putting this value in equation 5.1, the require total membrane area is **7791 m^2**

To calculate the number of membrane elements required, the applicable membrane area has to be known. Solving Equation 5.2 and rounding up to the highest integer will give an estimated amount of membranes required [Hoffman A. M (2008)].

$$Number_{Elements} = Area_{Total} / Area_{Membrane} \quad \text{.....5.2}$$

$Number_{Elements}$ - Total membrane elements required

$Area_{Total}$ -Total membrane area required $[m^2]$ = 7791 m^2 (From equation 5.1)

$Area_{Membrane}$-*Membrane* area of an element [m^2] =120 m^2 (Assume)

Number of membranes required for the RO plant is 66 (Seawater membranes 44 and for the second pass a brackish type membrane 22).

Step 4: Calculate the feed pressure requirement

Overpressure can damage membranes permanently and therefore the general feed pressure is limited at approximately 80 bar. For further protection, some manufacturers decrease this limit to 70 bar.

Step 5: Calculate pre-treatment supply requirements

A pre-treatment system requires additional water for maintenance purposes such as backwash, CIP, etc. Therefore, the feed pumps must supply an additional volume of water for the pretreatment system and not only for the RO membranes. P^H control, antifoaming, antiscalants /Scale Inhibitors, Water Softening chemical are added to protect the RO membrane and for performance increasing. Dozing depends on water quality.

Step 6: Estimate the energy requirements of the RO plant

In Step 4 it was mentioned that seawater RO membranes require pressures up to 70 bars. High pressure pumps are used to achieve this high feed pressure. However, this results in high energy demands for the RO process. Equation 5.3 gives an estimation of the desalination energy consumption.[Hoffman A. M (2008)]

$$E_{Desal} \approx \left[\frac{Q_{Total} \cdot P_{f(T)}}{36 \cdot RR \cdot \eta_{Pump}} \right] - S \cdot \left[\frac{Q_{Total} \cdot (P_{f(T)} - 5) \cdot (1 - RR)}{36 \cdot RR \cdot \eta_{Recovery}} \right] \quad \text{.....5.3}$$

E_{Desal} - Estimated desalination energy requirement [k W]

Q_{Total}- Total amount of product water obtained [m3/d]

P *f(T)* - Feed pressure

RR - Maximum recovery ratio allowed,

η_{Pump} - Pump efficiency

S - 0 if no pressure recovery is installed and 1 if a pressure recovery is installed

$\eta_{Reccrvery}$ - Pressure recovery efficiency (New positive exchangers can reach 96% efficiency)

Putting the all value in equation 5.3 the total energy require for RO plant is 388 KW (375 first pass ,13 kw second pass)

Step 7: Consider discharge of brine water

5 m^3/d high saline brine water discharged from the RO pant. Experts need to address this important issue and assess the discharge method. There are mainly two options for the discharging method, namely to use an evaporation pond or to discharge the brine back into the feed water source . Evaporation ponds can only be used in small RO applications, but will have an extra cost. In the case where the brine water is returned to the feed water source, currents, marine life, inflow of large rivers, etc. must be considered during the design.

The flowchart of the designed plant for produced water treatment in Bangladesh given at figure 5.2 and technical feature of the designed plant given at table 5.1.

The designed plant for a gas field in Bangladesh given at figure 5.3

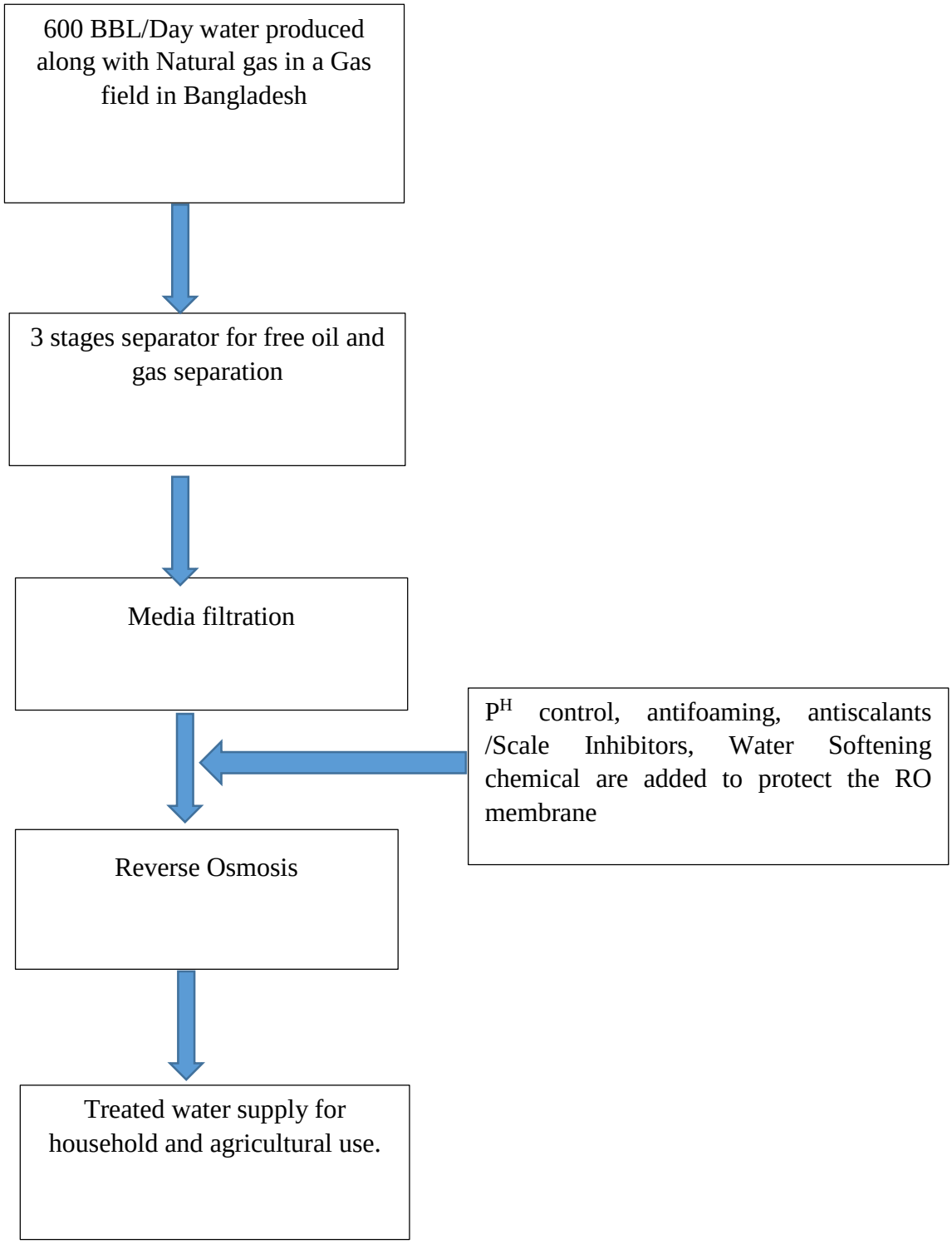

Figure 5.2: Flowchart of the designed water treatment plant

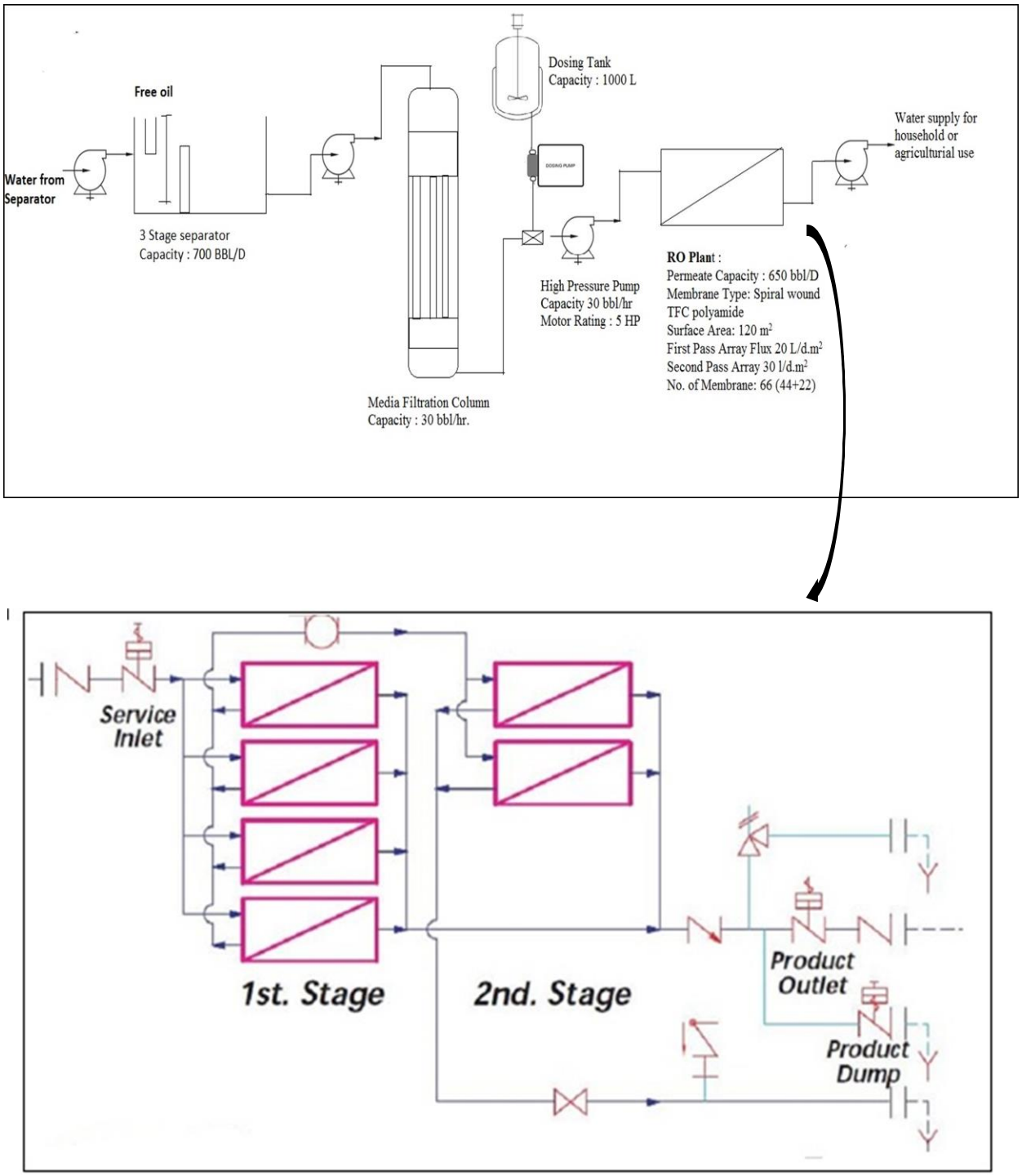

Figure 5.3: The designed plant for a gas field in Bangladesh

Figure 5.4: RO filter arrangement (https://www.wigen.com/portfolio/index.php)

Table 5.1: Technical features of the designed plant

SL.No	Description		Specifications
	Raw Water Collect Pump	Centrifugal pump	Minimum Flow rate 30 bbl/hr. Motor Rating minimum 2 HP
1	3 Stage Separator		Design Based on requirement. Minimum capacity 700 BBL/D
2	Raw Water Feed Pump	Centrifugal pump	Minimum Flow rate 30 bbl/hr. Motor Rating minimum 2 HP
3	Media Filter		Minimum capacity 30 bbl/hr.
4	Pretreatment Dosing System	Electromagnetic Pump	Minimum Flow rate 10L/hr.
5	Dosing Tank		Capacity 1000 L
6	RO Feed Pump Fist Pass Array	High Pressure Pump	Vertical Multistage Centrifugal Capacity 30 bbl/hr Motor Rating 5 HP
7	Reverse Osmosis Membrane		Permeate capacity :650 bbl/D Membrane Type: Spiral wound TFC polyamide Surface Area (each membrane): 120 m^2 First Pass Array Flux 20 L/d.m2 Second Pass Array 30 l/d.m2 No. of Membrane: 66 (44+22)
8	RO Feed Pump Second Pass	High Pressure Pump	Vertical Multistage Centrifugal Capacity 15 bbl/hr Mortor Rating 5 HP
9	Supply Water Pump	Centrifugal pump	Minimum Flow rate 30 bbl/hr. Motor Rating minimum 2 HP
10	Control Panel	Electrical panel	Complete Starters, Overload relays, and single-phase preventer for Pump, Incomers, Auto Switches etc
11	Installation	Instrumentations	Flow Meter, Pressure Switch, Rota Meter, Digital TDS meter, Pressure Gauges etc.

5.2 Cost analysis for per liter of treated water

The cost of RO system and Media Filtration & Annual Maintenance Charges collected from some published reports and manufacturers are as under

For 4000 LPH supply system: (All cost unit in BDT)

I.	Supply & Installation Cost	: 5,000,000
II.	AMC (Labor) charges per year	: 720,000
III.	Consumables (per year)	
	• Membrane	: 30,000 X 66= 1,980,000
	• Anti-scalant and antifoaming Chemical	: 20,000
	• Others Chemicals	: 20,000
	• Electricity (8.0 BDT per unit)	: 388 X 8.0 X 365 = 1132,960
IV.	Installation Cost of media filtration	: 1,600,000
V.	Service cost of media filtration (per year)	: 600,000

Assuming life of RO system as 5 Years, annual cost of one unit =5,000,000/5 = 1,000,000

Assuming life of media filtration system as 6 Years, annual cost of one unit =1,600,000/6 = 266,666

Total cost involved for a year =

1,000,000+720,000+1,980,000+20,000+20,000+1132960+266,666+600,000 = 5739,626

Cost of per liter treated water = 5,739,626/(96000X 365) = 0.16 BDT/L

CHAPTER-06

CONCLUSIONS

5. 1 Conclusions

A new approach to manage excessive amounts of produced water is discussed which can convert produced water as a source of fresh water or irrigation water in Bangladesh.

Following conclusions can be drawn from this study,

1. The volume of produced water produced from all gas fields in Bangladesh is not small.
2. Dissolved oil (oily odor), EC (11230 µs/cm), TS (13214 ppm), TDS (12543 ppm), Na^+ (3525.43 ppm), Cl^- (3423 ppm), $HCO3^-$ (3356.83 ppm), Turbidity (70 NTU), COD (730 mg/l), Ca+ (20.71 ppm) and other parameters of produced water are much higher than the acceptable limit define by Environment and Forest Ministry of Bangladesh.
3. More than 150 methods are available for produced water management and new technologies are coming everyday
4. Thermal treatment technologies of water are employed in regions where the cost of energy is relatively cheap because it's an energy consuming technology
5. BAF, Hydrocyclones, Gas Flotation, Adsorption methods are generally used for reduce free oil and other oil.
6. Other technologies such as MPPE, FTE®, ED or EDR are applicable in special case.
7. Membrane technology such as MF, UF, RO, NF are the most applicable methods for desalination of water

The following recommendations can be made based on the results and conclusions.

1. In produced water treatment, no single technology can meet suitable effluent characteristics, thus two or more treatment systems might be used in series operation. Choice of the best technology is based on produced water chemistry, cost effectiveness, space availability, reuse and discharge plans, durable operation, and byproducts
2. Considering the chemistry of produced water, location of gas fields, water volume media filtration as the oil removing technique and Reverse Osmosis (RO) as the dissolved solids removing technique along with three stage separator being the best for Bangladesh.
3. Media filtration remove more than 90% of the oil and grease and water recovery nearly 100%. The RO units remove more than 95% of total dissolved solids from the produced water and it is the most used technology in the world (> 60% of worldwide seawater desalination installed capacity)

NOMENCLATURE

PW: Produced Water

SGFL: Sylhet Gas Field Ltd.

BGFCL: Bangladesh Gas Field Company Ltd.

MMSCFD: Million Standard Cubic Feet Per Day

BBL: An Oil Barrel

IOC: International Oil Company

TS: Total solids

TDS: The Total Dissolved Solids

API: American Petroleum Institute

WOR: Water Oil Ratio

IEA: International Energy Agency

NORM: Naturally Occurring Radioactive Materials

MF: Microfiltration

UF: Ultrafiltration

RO: Reverse Osmosis

NF: Nanofiltration

MSF: Multistage flash

VCD: Vapor Compression Distillation

MED: Multieffect Distillation

TDS: Total Dissolve Solid

BAF: Biological Aerated Filter

COD: Chemical Oxygen Demand

BOD: Biological Oxygen Demand

TOC: Total Organic Contain

ED: Electro-dialysis

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APPENDIXES

Appendix-A: Comparison of Produced Water Membrane Treatment Technologies.

Technology	Ceramic MF/UF membrane	Polymeric MF/UF membrane	NF	RO
Feasibility	Ceramic membranes have been used to treat oilfield produced water and extensively used in other industrial water treatments. They are applicable to all types of produced water irrespective of their TDS and salt concentrations, but produced water with high concentrations may be problematic	Applicable to water with high TDS and salt concentrations and has the potential to treat produced water however it is extensively used in the municipal water treatment.	This technology is used for water softening and removal of metals from wastewater. It is specifically efficient for feed water containing TDS ranging from 500 to 25 000 mg/l. NF is a poor technology for produced water treatment and is inappropriate as a standalone technology	This is a robust technology for seawater desalination and has been employed in produced water treatment. For this technology to be effective in produced water treatment, extensive pre-treatment of feed water is necessary. Several pilot studies failed due to poor pre-treatment and insufficient system integration
Energy Consumption	Not available	Not available	It uses electrical energy and its energy requirement is less than what is required in RO systems. Approximately NF system requires 0.08 Kwh/bbl to power its high-pressure pumps	RO use electrical energy for its operation. SWRO requires 0.46–0.67 KWh/bbl if energy recovery device is integrated . BWRO require less energy than equivalent SWRO system. BWRO requires _0.02–0.13 KWh/bbl of energy to power the system's pumps
Overall cost	Not available	Capital costs depend on feed water quality and size of the polymeric membrane system. Approximate capital cost is $0.02–$0.05/bpd. Approximate Operation and Maintenance costs $0.02–$0.05/bpd	Capital cost range from $35 to $170/bpd. Operating cost is _$0.03/bbl.	Capital costs of BWRO vary from $35 to $170/bpd and operating costs are _$0.03/bbl. Capital costs of SWRO vary from $125 to $295/bpd and operating costs are _$0.08/bbl
Life cycle	>10 years	7 years or more	3–7 years	3–7 years
Advantages	1) Product water is totally free of suspended solids (2) It can be operated in cross-flow or dead-end filtration mode (3) Product water recovery range from 90% to 100% (4) Ceramic membranes have a longer lifespan than polymeric membranes	(1) Product water is free of suspended solids (2) Product water recovery range from 85% to 100%	1) It has high pH tolerance (2) System can be operated automatically leading to less demand of skilled workers (3) Energy costs can be reduced by implementing energy recovery subsystems (4) It does not require solid waste disposal (5) Water recovery between 75% and 90%	(1) It has high pH tolerance (2) System can be operated automatically leading to less demand of skilled workers (3) Energy costs can be reduced by implementing energy recovery subsystems (4) It performs excellently for produced water treatment with appropriate pre-treatment (5) It does not require concentrate treatment as brine generated is usually disposed into sea
Disadvantages	(1) Irreversible membrane fouling can occur with significant amount of iron concentration in feed water (2) Membrane requires periodic cleaning (3) Waste generated during backwash and cleaning processes require disposal/ recycling or further treatment	(1) Membrane requires periodic cleaning (2) Waste generated during backwash and cleaning processes require disposal/ recycling or further treatment	(1) It is highly sensitive to organic and inorganic constituents in the feed water (2) Membranes cannot withstand feed temperatures more than $45^{O}C$ (3) It requires several backwashing cycles	(1) It is highly sensitive to organic and inorganic constituents in the feed water (2) Membranes cannot withstand feed temperatures in excess of $45^{0}C$

Appendix-B: Comparison of Produced Water Thermal Treatment Technologies

Technology	MSF	MED	VCD technology	MED–vapour compression hybrid
Feasibility	This is a mature and robust desalination technology that can be employed for produced water treatment. MSF is applicable to all types of water with high TDS range up to 40 000 mg/l	This is a mature and robust desalination technology that can be employed for produced water treatment. MED is applicable to all types of water and a wide range of TDS	This is a mature and robust seawater desalination technology. It is applicable to all types of waste water with TDS level greater than 40 000 mg/l. Various enhanced VCD have been applied in produced water treatment	A mature desalination technology that has been employed in produced water treatment. It is usually employed for treating water with high TDS. In future product, water quality may be increased. For example, product water recovery of _75% was achieved by GE using brine concentrator and analyser.
Energy Consumption	Electrical energy required ranges from 0.45 kWh/bbl to 0.9 kWh/ bbl. Thermal energy required is estimated at 3.35 kWh/bbl. Overall energy required for MSF ranges from 3.35 to 4.70 kWh/bbl.	MED requires both thermal and electrical energy types. Electrical energy consumed is approximately 0.48 kWh/h/bbl and power consumption is 1.3–1.9 kWh/bbl	VCD requires both thermal and electrical energy. For desalination, power energy consumption is _1.3 kWh/bbl. Electricity consumption is 1.1 kWh/bbl for mechanical vapour compression (MVC) and to achieve zero-liquid discharge energy demand is _4.2– 10.5 kWh/bbl.	It uses both thermal and electrical energy. Power consumption for desalination is _0.32 kWh/bbl. To achieve zero-liquid discharge energy consumption is around 4.2–10.5 kWh/bbl .
Overall cost	Not available	Capital costs depend on feed water quality and size of the polymeric membrane system. Approximate capital cost is $0.02–$0.05/bpd. Approximate Operation and Maintenance costs $0.02–$0.05/bpd	Capital cost range from $35 to $170/bpd. Operating cost is _$0.03/bbl.	Capital costs of BWRO vary from $35 to $170/bpd and operating costs are _$0.03/bbl. Capital costs of SWRO vary from $125 to $295/bpd and operating costs are _$0.08/bbl
Life cycle	Typically 20 years but most plants operate for more than 30 years	Typically 20 years	Typically 20 years but may operate for more years	Typically 20 years but may be longer if made of materials with high corrosion resistance
Advantages	(1) It has a significantly long lifespan. (2) MSF system can withstand harsh conditions (3) It can easily be adapted to highly varying water quality (4) Cost of labour is cheaper than using membrane technology (5) Good for high TDS produced water treatment (6) Product water quality is high with TDS levels between 2 mg/l and 10 mg/l	(1) It has a long lifespan. (2) Energy requirement is cheaper than using MSF. (3) It can easily be adapted to highly varying water quality (4) Cost of labour is cheaper than using MSF or membrane technology (5) Good for high TDS produced water treatment (6) Product water quality is high	1) It is a smaller unit compared with MS F and MED (2) It has high ability to withstand harsh conditions (3) It does not require special concentrate treatment (4) Pre -treatment is less rigorous compared with membrane treatment	(1) It has high product water quality (2) Excellent treatment technology for produced water with high TDS and zero liquid discharge (3) System can withstand harsh condition
Disadvantages	1) Low product water recovery usually between 10 and 20% (2) It is not flexible for varying water flow rates (3) Scaling and corrosion can be a problem	1) Typically low product water recovery usually between 20% and 35% (2) It is not flexible for varying water flow rates (3) Scaling and corrosion can be a problem (4) High level of skilled labour Required	(1) Typically low product water recovery is usually around 40% (2) It is not flexible for varying water flow rates (3) Scaling and corrosion can be a problem (4) High level of skills are required to operate system	1) Not applicable to produced water wells point source (2) Being a hybrid design, it requires very highly skilled labour

Appendix-C. Comparison of produced water treatment technologies (BAF, Gas Flotation, Evaporation Pond, Adsorption, Hydrocyclone)

Technology	BAF	Gas flotation	Evaporation pond	Adsorption	Hydrocyclone
Feasibility	This is a well-established technology that has been used for produced water treatment. It is mostly effective for feed water with chloride levels below 6600 mg/l	This technology is widely used in the petroleum industry, primarily used for conventional oil and gas produced water treatment . It is applicable for produced water with high TO and particulate ,7% solids	This technology is often employed for produced water at full scale. It is applicable to any kind of produced water and its efficiency depends on system design	This technology is commonly used for produced water treatment. Applicable to all types of produced water irrespective of TDS and salt concentrations. It can significantly reduce heavy metals, TOC, BTEX and oil concentrations. It is best used as a polishing step rather than a major treatment process to avoid rapid consumption of adsorbent material	It is applicable for the treatment to all types of produced water irrespective of TDS, organic and salt concentrations. It can reduce oil and grease concentration to 10 ppm
Energy Consumption	1–4 KWh	Energy required to dissolve gas in the feed stream	None, except pumping is required to get water to/from the pond	Minimal	Does not require energy except to pump water to/from the hydrocyclone
Overall cost	Not available but capital accounts for majority of overall cost.	No information available	Not available	Not available	Not available
Life cycle	Long lifetime expected	No information available	Long lifespan	It depends on media type	Long lifespan
Advantages	(1) Water recovery is almost 100% (2) Easy to adapt to wide range of water quality and quantity (3) Little need for maintenance. (4) Does not require post-treatment (5) Some BAF does not require any equipment	(1) Product water recovery is almost 100% (2) No post-treatment required	(1) It is very cheap (2) Does not require the use of chemicals and energy	(1) 80% removal of heavy metals (2) Can achieve nearly 100% water recovery	(1) Does not require the use of chemicals and energy (2) High product water recovery (3) Can reduce oil and grease concentrations to 10 ppm (4) Can be used for treating any kind of produced water (5) Does not require pre-treatment
Disadvantages	Solid disposal required for sludge that accumulates in the sedimentation basin can cost up to 40% of the overall cost	(1) Not ideal for high-temperature feed water (2) Solid disposal is required for sludge generated	(1) Water volume may be lost due to evaporation (2) Waste disposal is required for materials that settle out of feed water	Waste disposal system required for spent media or waste produced during media regeneration	(1) Solids can block inlet and scales formation can lead to extra cost in cleaning (2) Disposal is required for secondary waste generated

Appendix-D: Comparison of Produced Water Treatment Technologies **(**MF, Ion exchange technology, Chemical oxidation, ED/EDR**)**

Technology	Media filtration	Ion exchange technology	Chemical oxidation	ED/EDR
Feasibility	This technology has been extensively used for produced water treatment. It is applicable for all TDS and independent of salt concentration	This is a large industrial operation applicable to produced water treatment. It is applicable to produced water with TDS range of 500–7000 mg/l. Efficiency of this technology depends on the quality of feed water and IX resin	This is a well-established and reliable technology for the removal of COD, BOD, organic and some inorganic compounds present in produced water. It is applicable to all types of produced water irrespective of TDS and salt concentration	This technology is robust for seawater desalination and waste water reclamation. Although it is excellent for produced water application it has only been tested for produced water treatment on laboratory scale
Energy Consumption	Minimal energy required. Energy is required for backwashing filters	Uses electrical energy. Energy requirements only include pumping costs. Typically 0.07 KWh/bbl assuming a 200 gpm flow rate, 5 m pumping head.	Energy consumption accounts for 18% of the total operation and maintenance of the oxidation process	Energy type: electricity. 0.14– 0.20 KWh/lb NaCl equivalent removed.
Overall cost	Not available	Cost for IX resin varies between $0.08 and $0.11/bbl at 5bbl per minute and $0.04–$0.07/bbl at 21bbl per minute. Operating costs account for _70% of the total cost at lower flow rate. At 21 bbl per minute, operating costs increase to 80%	Capital cost is about $0.01/gpd. Operation and maintenance cost is about $0.01/bbl.	Total costs depend on feed water TDS and site location. 8000 bbl/day treatment train of CBM produced water is estimated to cost 15 cents per barrel.
Life cycle	It depends on media type	Average lifecycle of anion resins is 4–8 years. Average lifecycle of cation resins is 10–15 years	Expected life of chemical metering is 10 years	ED membrane lifetime is estimated to be 4–5 years .
Advantages	(1) 90% oil and grease removal efficiency (2) Can achieve nearly 100% water recovery	1) It requires minimal supervisory oversight (2) May operate continuously for 10–20 h (3) Energy requirements are minimal	(1) It requires minimal equipment (2) No waste is generated from this process (3) It does not require pre- and post-treatment (4) It has 100% water recovery rate	(1) It does not require special infrastructure (2) Modest to withstand harsh conditions (3) Excellent for produced water application
Disadvantages	Waste disposal system required for spent media or waste produced during media regeneration	(1) High operating and chemical costs (2) High sensitive to fouling	(1) Chemical cost may be high (2) Periodic calibration and maintenance of chemical pump is required (3) Chemical metering equipment is critical for this process	(1) This technology has only been tested on a laboratory scale for produced water treatment (2) Fairly flexible to varying water quality (3) Operation requires highly skilled labour (4) Process requires periodic maintenance and chemical cleaning (5) Concentrate disposal is required