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Managing, Controlling And Improving The Treatment Of Produced Water Using The Six Sigma Methodology For The Iraqi Oil Fields

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MANAGING, CONTROLLING AND IMPROVING THE TREATMENT of PRODUCED WATER USING THE SIX SIGMA METHODOLOGY for THE IRAQI OIL FIELDS

by

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ABSTRACT

Produced Water (PW) is the largest volume of waste that is normally generated during oil and gas production. It has large amounts of contaminants that can cause negative environmental and economic impacts. The management method for PW relies highly on types and concentrations of these contaminants, which are field dependent and can vary from one oil field to another. Produced water can be converted to fresh water if these contaminants are removed or reduced to the acceptable drinking water quality level. In addition, increasing oil production rate and reducing amounts of discharged harmful contaminants can be achieved by removing dissolved hydrocarbons from PW. In order to identify the types of these contaminants, effective tools and methods should be used. Six Sigma, which uses the DMAIC (Define- Measure- Analyze- Improve- Control) problem-solving approach is one of the most effective tools to identify the root causes of having high percentages of contaminants in produced water. The methodology also helped develop a new policy change for implementing a way by which this treated water may be used. Six Sigma has not been widely implemented in oil and gas industries. This research adopted the Six Sigma methodology through a case study, related to the southern Iraqi oil fields, to investigate different ways by which produced water can be treated. Research results showed that the enormous amount of contaminated PW could be treated by using membrane filtration technology. In addition, a Multi Criteria Decision Making (MCDM) framework is developed and that could be used as an effective tool for decision makers. The developed framework could be used within manufacturing industries, services, educational systems, governmental organizations, and others.

This work is dedicated to my scholarship providers and supporters within the Iraqi Prime Minister's Office and the Higher Committee for Education Development in Iraq (HCED), who have selected me as international scholar and supported me throughout my MS program. Also, this work is dedicated to my wife Huda, and my children Rawan and Mahdi, who have provided continual life support and encouragement. I will never forget to dedicate all my research and work to my parents, Talib and Qasima Alshamkhani and my sister and her husband Faten and Mortatha, who instilled in me the value of education and a lifelong love of learning.

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LIST OF ABBREVIATIONS

ABB	Asea Brown Boveri
AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
API	American Petroleum Institute
BFN	Business Function Number
BOPD	Barrel Oil Per Day
BP	British Petroleum
BPD	Barrel Per Day
BPN	British Petroleum in Norwegian
BTEX	Benzene, Toluene, Ethylbenzene and Xylene
BWPD	Barrel Water Per Day
BWW	Back-Wash Water
CBM	Coal Bed Methane
CDS	Central Degassing Stations
CEA	Cause and Effect Analysis
CEO	Chief Executive Officer
CFU	Compact Flotation Unit
CGSS	Central Gas Separation Stations
CI	Consistency Index
CR	Consistency Ratio
CTQs	Critical To Quality Characteristics

DG	Dissolved Gases
DMAIC	Define, Measure, Analyze, Improve, Control
DO	Dissolved Oxygen
DPMO	Defects Per Million Opportunities
DS	Degassing Stations
DU	Distillation Units
EPA	Environmental Protection Agency
ESP	Electrical Submersible Pump
FMEA	Failure Mode and Effect Analysis
FMEA	Failure Mode and Effect Analysis
GE	General Electric
HOQ	House Of Quality
IC	Iron Content
IT	Information Technology
KOC	Kuwait Oil Company
KPIV	Key Process Input Variables
KPOV	Key Process Output Variables
LSS	Lean Six Sigma
MCDM	Multicriteria Decision Making
MMSCF	Million Standard Cubic Feet
MMSTB	Million Stock Tank Barrels
NEP	Natural Evaporating Pond

NFD	Non Fluid Detected
NORM	Naturally Occurring Radioactive Material
OGC	Oil and Grease Content
OWC	Oil in Water Content
PAHs	Polycyclic Aromatic Hydrocarbons
PCM	Pairwise Comparison Matrix
PDO	Petroleum Development in Oman
PW	Produced Water
PWRI	Produced Water Re-Injection
QFD	Quality Function Deployment
RCA	Root Cause Analysis
SAM	Stakeholders Analysis Matrix
SAR	Sodium Adsorption Ratio
SDWF	Safe Drinking Water Foundation
SIPOC	Suppliers, Inputs, Process, Outputs, Customers
SOC	South Oil Company
SPC	Statistical Process Control
SRB	Sulphate Reducing Bacteria
STA	System Thinking Approach
TDS	Total Dissolved Solids
TIR	Technical Importance Rating
TOC	Total Organic Carbon

TSS	Total Suspended Solids
VOC	Voice of Customer
VOCM	Voice of Customer Matrix
VSEP	Vibratory Shear Enhanced Process
WID	Water Injection Department

CHAPTER 1: INTRODUCTION

With increasing oil demand and consumption, the frequency of petroleum-related ecologic incidents is increasing. Petroleum related pollution events have the potential to cause extensive ecologic damage. More knowledge is required regarding occasional large oil spills and waste disposal management methods during oil and gas production activities.

Produced Water (PW) is the most common petroleum-related contaminant frequently discharged into the surrounding offshore and onshore ecosystems. One of the major environmental contaminants found in PW is petroleum hydrocarbons. The percentage of hydrocarbons could vary from one oil field to another because the geological features are different in all oil and gas fields. Although much effort has been spent to improve current methods for isolating these hydrocarbons prior to disposal, the initial steps still rely on the ability to identify and characterize the types of hydrocarbons in the PW stream. Identifying the types of hydrocarbons and measuring their amounts enables comparative evaluation of potential effects from PW discharges on the surrounding areas for both onshore and offshore oil fields. However, distinct factors can impact these hydrocarbons and are generally related to types and concentrations of chemicals usage, efficiency of extraction and production of oil equipment, and types of management methods for de-oiling, production, and waste disposal systems. The concentration and composition of contaminants in PW vary considerably in different geological formations; therefore region specific studies should be carried out to determine the environmental and economic risks from discharging that water from individual oil and gas production platforms.

Reducing the environmental and economic impacts of PW requires efficient tools to identify and characterize the types of contaminants in the PW stream. Then, the selection of proper methods to effectively manage that water will be possible. If PW is effectively managed, reusing it as clean water for human and oil field facilities will be also possible. Quality management concepts and methods have been widely implemented in different industries and organizations in order to achieve high-quality outputs with minimum effort and cost. Designing a new product or system with high quality and performance can be carried out through quality design and control principles. These principles can also be used to maintain the sustainability of the new systems for the long term period.

In this study, Six Sigma methodology, one of these quality practices and principles, is selected and used to develop an effective framework that can be implemented to achieve a proper and ecofriendly method of effectively managing the PW for the onshore Iraqi oil fields. This methodology has five phases, of which each phase has its own tools and procedures that can be used and followed to evaluate and analyze the main contaminants and their sources in the PW stream. These phases are Define phase, Measure phase, Analyze phase, Improve phase, and Control phase. Quality management and control tools can help to manage projects effectively and reduce waste and time, such as rework and redesign during a project life-cycle. These quality tools are used in this research to evaluate the contaminated PW that is being produced from the southern Iraqi oil fields by identifying contaminates in the PW stream, measuring their amounts, and analyzing the root causes of any increase in these amounts. Then, improve the current state of the southern Iraqi oil fields by selecting the best management method for PW from current existing methods by using the Multi Criteria Decision Making method. This new management method will help to convert PW from unusable water to clean water, reducing the negative impacts of PW in these fields.

In order to differentiate PW from other fluids and explain the reasons behind selecting these two methods for the selected case study, the following literature review is provided.

CHAPTER 2: LITERATURE REVIEW

2.1 The Origin of Produced Water

Produced Water is generally the largest volume of waste generated from offshore and onshore platforms during oil and gas production (Stephenson, 1992). Because PW has a higher density than oil, it is located below the hydrocarbon layer. PW is also discharged after separating formation water from oil during the oil extraction and production processes [(Reed & Johnsen, 1996) & (McCormack, Jones, Hetheridge, & Rowland, 2001)].

In addition, PW is normally generated once the production of oil and gas occurs in the field and it will reach the wells to form a PW layer. It can constitute as much as 80% of the waste produced from oilfield operations (McCormack et al., 2001). The amount of PW generated depends on the characteristics of the particular oil field and has a tendency to increase during the life of each well.

In 2010, the worldwide discharge volume of the PW was 1.5 times the volume of hydrocarbon production (International Association of & Gas, 2010). Generally, PW consists of water that has accumulated or is trapped within the petroleum in geologic formations over millions of years (Collins, 1975).

This ancient water is called formation water and is as old as the fossil fuel in the reservoir. With increasing oil production, a large amount of seawater is injected into the formation to replace the oil that has been extracted, thus maintaining the well pressure. This injected seawater is mixed with the formation water during the oil recovery process and is generally referred to as PW (Jerry M. Neff, 2002).

2.2 The Produced Water Composition

No two samples of PW composition are alike. The physical and chemical properties of PW can vary greatly depending on the geochemistry of the petroleum formation, the amount of injected seawater or underground water, and the type of process chemicals used. PW consists of complex dissolved and dispersed mixtures of various organic and inorganic chemicals specific to the type of petroleum formation and the production system. There are more than 17,000 distinct compounds in petroleum, making it one of the most complex natural chemical mixtures (Rodgers, Klein, Wu, & Marshall, 2003). As a result, PW is expected to have a variety of complex compounds and contaminants.

Although much of the volume of PW is simply from injecting surrounding seawater or underground water, the injected water is often heated within the formation and released at high temperature (up to 130°C), so PW can dissolve a wide variety of contaminants. The chemical composition of PW has been described and listed by several scientists and researchers. It contains organic compounds as well as heavy metals, radionuclides, inorganic nutrients (ammonia, sulphate, nitrate, etc.), organic acids, phenols, unidentified polar compounds, petroleum hydrocarbons, and chemical amendments that are used in various phases of production (i.e. emulsifiers, corrosion inhibitors, and biocides) [(Johnsen, Utvik, Garland, Vals, & Campbell, 2004); (Jerry M. Neff, 2002); (Somerville et al., 1987)].

Generally, petroleum hydrocarbons are the chemicals of greatest environmental concern in PW, thus it is usually treated to remove dispersed oil prior to disposal, depending on local environmental regulations and available technologies. Other than the evaluated chemical concentrations, most PW is discharged at high temperature and has high salinity [(Gordon, Robert, Robert, & Joseph) & (Collins, 1975)].

2.3 The Produced Water Constituents Classification

There are different types of PW, and each type has its own constituents. Particularly, PW can be associated with production processes for oil and gas. The constituents of PW have been classified according to the type of production process associated with PW. Mostly, constituents of PW are dispersed oil, dissolved or soluble organic compounds, chemicals, solids, bacteria, metals, sulphates, and Naturally Occurring Radioactive Material (NORM). Salinity and sodicity are considered the main constituents for PW from Coal Bed Methane (CBM) production (Veil, Puder, Elcock, & Redweik, 2004).

PW composition has been classified according to its toxicity and negative impacts on the environment after discharging it to the surface. Determination of types and concentrations of these constituents would help to reduce the negative impacts by finding the best way to treat or control these constituents. Handling, transporting, or disposing PW requires a better understanding of the physical and chemical properties for each of these constituents. Data that has been provided from operators from the North Sea and the Gulf of Mexico showed that PW composition consisted of inorganic components, organic components, Total Dissolved Solids (TDS), dispersed oil, and chemicals (Johnsen et al., 2004).

Benko and Drewes, Glude et al., and Veil et al., have mentioned that the geographical location is one of the most important factors that can affect the physical and chemical properties of PW. Therefore, PW contains a wide variety of organic, inorganic, metallic, and chemical compounds (Horner, Castle, & Rodgers, 2011). In their 2011 book "Produced Water Treatment Field Manual", Stewart and Arnold classified the composition of PW according to the types of PW treatment methods into the following:

- Total Dissolved Solids (TDS)
- Precipitated Solids (Scales)
- Dissolved Gases (DG)
- Oil in Water Content (OWC)
- Sands and Other Suspended Solids
- Chemicals

Having these compounds in PW means having thousands of compounds in that water stream. Each of these constituents may contain a variety of minor compounds that can be generated during exploration, extraction, and production processes within specific conditions. After discharging PW, these compounds will be subjected to a difference in pressure at the surface and new complicated compounds will form scale precipitates and deposits (Allen & Robinson, 1993).

2.4 The Produced Water Constituents Variation

The continuous production of oil and gas causes the continuous increase in the production of PW. The amount and the composition of PW are greatly variable from field to field. In 1984, researchers Tissot and Welte mentioned that in some crude oil samples up to 10,000 compounds have been detected, and any one of these compounds could be classified by the minor constituents, which leads to compositional variation in different oil fields (Allen & Robinson, 1993).

The volume of PW also varies from field to field. In their work, both Somerville and Stromgren indicated that the amount of PW that is drawn from a new oil field is very low when compared with the amount of oil that is produced from that field [(Somerville et al., 1987) & (Stromgren et al., 1995)]. However, the volume of PW will be several times the volume of oil that is produced from the same field if this field has aged enough (Henderson, Grigson, Johnson, & Roddie, 1999). Generally, the volume ratio of PW to oil will increase as the well age increases (Veil et al., 2004).PW can gain geological properties due to immediate contact with the formation for millions of years. Furthermore, additional compounds, such as chemical additives, are widely used to enhance some processes during the short and long term of oil and gas production life cycle. Most oil industries have been using these additives, which include demulsifiers, corrosion inhibitors, and antifoaming agents (Johnsen et al., 2004). These chemicals are sometimes discharged with the PW.

In his work, Breit mentioned that determining the amount of the constituents in PW could help to increase the production of oil and gas, and decrease the environmental hazards that could result from discharging the PW to the environment (Veil et al., 2004).

The amount of PW is approximately 1.3 times the amount of oil or gas that is produced in an oil or gas field. Some correlation was found between the “availability of freshwater” and the location of oil and gas reservoirs. PW could be used as a fresh water resource, specifically in onshore platforms that have some oil and gas reservoirs. Before reusing PW as a fresh water resource, treatment of PW must be performed by using primary, secondary, and tertiary technologies in order to remove the contaminants from that water. Selecting treatment technologies depends on the concentration and type of contaminants in PW. Also, the final usage of PW after treatment is considered as a determinant for the treatment selecting strategy (Nijhawan & Myers, 2006).

PW has been considered a major source of pollution associated with oil and gas production. The amounts and types of these contaminants must be determined to select the best treatment technology that can remove or decrease these amounts. Furthermore, the required quality of PW after treatment is the main factor that can affect the selection of treatment technology (Soltani, Mowla, Vossoughi, & Hesampour, 2010).

2.5 Environmental Impacts of Produced Water

The environmental impact of PW on the natural environment has usually been determined in terms of the chemical composition (Tibbetts, Buchanan, Gawel, & Large, 1993) ; (Jacobs et al., 1992), or by ecotoxicological assessment (Brendehaug et al., 1992); (J. M. Neff & Sauer, 1995). In 2001, Georgie et al showed that the impact of PW discharge is related to the concentrations and types of harmful chemicals in that water (Veil et al., 2004).

Monitoring by chemical composition usually entails a direct measurement of the chemicals, unique to the PW, in the surrounding environment. On the other hand, ecotoxicological assessments are conducted by measuring the acute toxicity, chronic toxicity, bioaccumulation, and sometimes by monitoring biomarkers. Acute toxicity is expressed as the concentration of a toxin that causes harmful effects through short-term exposure. Chronic toxicity is expressed as the concentration that produces harmful effects through long-term or repeated/continuous exposure. Other than toxicity from PW, organisms near the PW discharge might accumulate toxic metals and hydrocarbons from the ambient environment or from their food sources. This bioaccumulation could induce changes in the organisms at the physiological or biochemical levels that have no immediate harmful effects to the organisms, but these changes could be used as biomarkers to monitor the longer-term exposure effects of PW discharge and as an early warning of possible risk to the exposed organisms (Forbes, Palmqvist, & Bach, 2006).

Considering the dilution factor in the environment, monitoring for components of PW, such as metals, indicated that they were diluted to background concentrations in seawater within a few meters of the discharge point, so it was believed that it did not contribute to ecological risk (Jerry M. Neff, 2002).

In terms of ecotoxicological measurements, a number of studies in the North Sea deployed fish [(Abrahamson, Brandt, Brunström, Sundt, & Jørgensen, 2008);(Børseth & Tollefsen, 2004); (Hylland et al., 2008)] and shellfish [(Durell, Røe Utvik, Johnsen, Frost, & Neff, 2006);(Hylland et al., 2008);(Jerry M. Neff, Johnsen, Frost, Røe Utvik, & Durell, 2006); (Roe Utvik, Durell, & Johnsen, 1999)] to monitor the long term exposure of PW in the surrounding environment. The studies indicated that exposure levels were generally low.

The exposure level and the bioaccumulation concentrations were generally found to decrease with distance down-current from the discharges, suggesting that PW caused minor environmental impact after discharge [(Børseth & Tollefsen, 2004); (Jerry M. Neff & Burns, 1996)]. In contrast, marine environmental studies proved that discharging PW to the environment can cause toxicity because it contains toxic constituents such as heavy metals, toxic chemicals, and soluble hydrocarbons (Azetsu-Scott et al., 2007).

Rapid dilution of PW with ambient seawater is often believed to be sufficient to mitigate any influence from PW on the marine environment. A modeling study by Somerville found that even at a 10,000 m^3/day discharge rate, estimated a 100-fold dilution at 50 m from the platform, and a 2,800-fold dilution at 1,000 m from the platform (Somerville et al., 1987).

At a low discharge rate (2,000 m^3/day), Furuholt estimated a 1,000-fold dilution would be found at 50 m downstream from the discharge point (Furuholt, 1995). However, the dilution rate was expected to decrease at greater distances from the discharge point [(Terrens & Tait, 1996); (Stromgren et al., 1995); (Brandsma & Smith, 1995); (Smith, Brandsma, & Nedwed, 2004)].

Generally, the dilution rate is dependent on the discharge rate, ambient current speed, water turbulence, water depth, water column stratification, and differences in density and chemical composition between PW and the surrounding seawater. In terms of petroleum hydrocarbons, Terrens found that at an 11,000 m^3/day discharge rate, just 20 m downstream from the discharge most BTEX (Benzene, Toluene, Ethylbenzene and Xylene) and PAHs (Polycyclic Aromatic Hydrocarbons) were diluted by 2,000 to 14,900-fold (Terrens & Tait, 1996). These findings suggested that the discharge would dilute the contaminant concentration to non-acute toxic levels within a very short distance from the discharge point. These hydrocarbons have the potential to accumulate in marine organisms. The organisms will discharge these components to a varying degree. The variability in their discharge is based on the whether they are removing or treating the water column or not. The composition of PW also depends on the concentration of production chemicals in the discharge water. The concentration depends on both the amount used and the phases of oil and gas production.

2.5.1 Impacts of Discharging Produced Water with High Salinity

The Environmental Protection Agency (EPA) defined the Total Dissolved Solids (TDS) as consisting of dissolved, suspended, and settleable solids in the PW. The EPA considers that a high concentration of the TDS would make drinking water unpalatable. It focused on measuring the level of TDS in areas that discharged the industrial water. In addition, it considered that the high concentration of TDS would help to transfer toxicity between the aqueous solutions. As a result, high concentration of TDS in water will affect the life of aquatic organisms in that water ("United States Environmental Protection Agency," 2012).

Salinity, which is one TDS property, can be defined as the presence of soluble salts in water. It is considered one of the most important constituents in PW because of its negative impacts on the environment and human resources. Salinity also means the presence of different chemical compounds in waters such as sodium chloride, magnesium, calcium sulphates, and bicarbonates. The negative impacts of salinity are widely noticed in different areas of the world. The Department of Natural Resources and Mines in Australia has published many articles about the negative impacts of salinity that have been occurring in Queensland and other states, particularly Victoria, South Australia and Western Australia. High salinity can cause an increase in the probability of damage to buildings, roads, fences, and railways. It will cause a reduction in the productive capacity because the high concentration of soluble salts (Lubczenko, 2004).

Fucik indicated that salinity can kill crops, pollute the freshwater resources, and cause toxicity in some PW streams (Allen & Robinson, 1993). Also, TDS were considered the main constituents of concern in onshore oil and gas operations (Veil et al., 2004).High salinity in PW means a high concentration of TDS that will provide toxic materials such as metals and organic compounds, or it may provide benefits such as nutrients (Weber-Scannell, Duffy, Weber-Scannell, & Duffy, 2007).

In 2005, in their work, Dallbauman and Sirivedhin formulated an equation that can be used to find the Sodium Adsorption Ratio (SAR). SAR value equals the ratio of the sodium concentration to the square root of the average for both calcium and magnesium concentrations respectively as in the following:

$$SAR = \frac{[Na^{+2}]}{\sqrt{\frac{([Ca^{+2}]+[Mg^{+2}])}{2}}} \tag{1}$$

By using this equation, they determined whether the PW will have a future negative impact if it used in an irrigation process or not. In 2006, the American Petroleum Institute (API) found a decrease in soil permeability and increase in susceptibility to erosion associated with irrigation water which has an SAR value > 6 (Horner et al., 2011). High TDS in PW can be caused by the existence of dissolved solids which can vary from less than 100 mg/l to more than 300,000 mg/l. Discharging PW with high TDS will increase the amount of scales. These scales can form deposits during drilling and production processes. Large amounts of scales can be found in the tubing, vessels, and even the treatment equipment. Additional cost is required to remove these scales by adding chemical additives or using different treatment plants. Adding chemical additives or constructing new treatment plants requires specific conditions (Stewart & Arnold, 2011).

The Safe Drinking Water Foundation (SDWF) has reported that cleaning or removing these deposits needs extra effort and cost to make the production process continue and meet the environmental regulations. If these deposits are not treated, damage to the treatment equipment will occur. The SDWF also considered that the high TDS level is an indicator for the existence of harmful contaminants, such as iron, manganese, sulphate, bromide, and arsenic in the water ("TDS AND pH-Safe Drinking Water Foundation," 2012) . From its negative impacts on the environment and human resources to the additional cost and effort that may be required to remove these dissolved solids, high TDS in PW is considered one of the main concerns in oil and gas industries.

2.5.2 Impacts of Discharging Produced Water with High Organic Carbon Content

Oil in Water Content (OWC) can be defined as the amount of dispersed oil, soluble hydrocarbons, and soluble organic compounds in water. Most of the soluble hydrocarbons in PW are presented as simple aliphatic, aromatic hydrocarbons, fatty acids, and naphthenic acids. If these soluble components are exposed to the atmosphere, chemical reactions could occur, and new components may form. There are different technologies which can be used to separate these compounds from the PW as a part of the PW treatment process in oil and gas fields. Selection of the best technology to separate dissolved oil from PW depend on the diameter of the oil droplets. In addition, chemical compounds may be required to form coalesced droplets during the oil-water separation processes and that will help to remove hydrocarbons particles from PW (Bansal & Caudle, 1998).

Some of these dissolved hydrocarbons are required during oil and gas production processes. Particularly, BTEX (Benzene, Toluene, Ethylbenzene, and Xylene) have been used in the polishing stage of "granular activated carbon" (Doyle & Brown, 2000). Toxic effects from discharging PW that has high OWC can be noticed near the waste discharge points for both onshore and offshore oil fields (Veil et al., 2004).

In his work, Stephenson mentioned that discharging PW with high oil content can cause sheening (Stephenson, 1992). Also, the biological oxygen demand will increase near the discharging area (Veil et al., 2004).The average of oil presented in the PW discharge in 1994 was 23.5 mg/l from the total discharge that was 790 tons of oil (Reed & Johnsen, 1996). The size of oil droplets can vary from 0.5 to 200 microns in diameter (Stewart & Arnold, 2011). The existence of soluble hydrocarbons in high concentration could help to increase the productivity of oil if PW is recycled again to the oil-PW separator which results in the amount of soluble hydrocarbons in the PW decreasing and the oil production increasing. Decreasing the amount of soluble hydrocarbons helps to decrease the toxicity in the discharged PW.

2.5.3 Impacts of Discharging Produced Water with High Chemicals

A variety of chemicals in PW can cause chemical pollution for rivers and aquifers if it is discharged without treatment. Whenever chemical pollution occurs, freshwater resources will decrease. Therefore, freshwater resources for daily human use, such as for drinking and irrigation, will decrease. A variety of chemicals in PW such as biocides are toxic and harmful to most organisms (Allen & Robinson, 1993). Different chemical compounds have been used during operation and production processes, such as biocides, reverse emulsion breakers, and corrosion inhibitors are widely used during extraction, operation, and production processes (Veil et al., 2004).

2.5.4 Impacts of Discharging Produced Water with Heavy Metals

In 1999, Bansal and Claude agreed that metals in PW could cause operational problems during production of oil and gas. Also, after-production environmental problems would occur if these metals discharged to the surface without treatment or with the use of an improper discharge method. Because iron-oxygen reactions will produce solids and corrosive materials, these solids are commonly noticed when PW containing metals is discharged to the surface without treatment. In addition, for the onshore operations, discharging of iron will cause staining or deposits (Veil et al., 2004).

In his work, Utivek indicated that there is no correlation existing between the concentration of metals in crude oil and the water that is produced with it (Veil et al., 2004). Types and concentrations of heavy metals in PW are field dependent. In most PW, metals are represented by existing “zinc, lead, manganese, iron, and barium” (Veil et al., 2004).

In 2007, Duruibe, Ogwuegbu, and Egwurugwu, in their research paper “Heavy Metal Pollution and Human Biotoxic Effects” classified heavy metals according to toxicity depending on previous studies. Their conclusions from these studies can be summarized as in the following (Duruibe, Ogwuegbu, & Egwurugwu, 2007):

- In 2001, Ferner mentioned that lead is the most dangerous and toxic compound that could be absorbed by food and water, as well as inhalation.
- Permanent brain damage can occur because of existing high concentration of lead in a human brain.
- In 2005, Ogwuebgu and Muhanga discussed the toxicity of lead on humans. They mentioned that lead can cause inhibition of the synthesis of hemoglobin, dysfunctions in the kidneys, joints and reproductive systems.
- Furthermore, chronic damage in the central nervous systems can occur because of high concentration of lead in the human body.
- In 1991, McCluggage verified that the existence of zinc in body can cause the same illness for humans that is caused by lead poisoning.

- In their work, Kantor et.al mentioned that nerve inflammation could be caused by zinc poisoning, resulting in muscle weakness (Kantor, 2006; NINDS, 2007).

2.6 Economic Impacts of Produced Water Management

It is known that discharging PW without treatment will cause negative environmental and economic impacts. Also, in order to manage PW effectively, the constituents of PW should be determined. Compositions and types of these constituents should be identified prior to discharging or the reusing stage. PW treatment is the only way that helps to protect the environment and humans from that water. The cost of treatment depends on the quality of water needed and the purpose of treatment, such as reusing it as a drinking water, reusing it for irrigation, or reinjecting it to increase oil production by maintaining the well pressure [(Igunnu & Chen, 2012); (Doran, Carini, Fruth, Drago, & Leong, 1997); & (Essam Abdul-Jalil Saeed, 2010)].

The lowest cost to treat PW is to simply dispose of it directly without treatment. For this purpose, usually methods like deep well injection, ocean discharge and/or hauling are used. For the maintenance of well injectability and minimization of the cost of well maintenance, some pretreatment is required in particular before deep well injection. Mostly the cost of PW disposal ranges from \$0.63 to \$3.15/m^3 (Tomson, 1992).

The cost increases if there is a need for more extensive treatment for the water before disposal. The cost also increases if the PW is treated for reuse and operating costs of unit processes apply. The cost to treat PW includes the capital and operating costs of unit processes.

In addition, it also varies over time as prices change for the products that are required to be used for PW treatment. To improve the oil treatment system, hard decisions might face decision makers to select effective treatment facilities that could be different from field to field (Mofarrah, Husain, Hawboldt, & Veitch, 2011). In 2003, Khatib and Verbeek reported “Shell’s cost distribution” which is summarized as follows:

- 27.5 % of the total cost for the pumping processes
- 21% of the total cost for de-oiling (separation of oil) processes
- 17% for the lifting products processes
- 15% for the separation processes
- 14% for the filtration processes
- 5% for injecting processes

All of the above costs would be lower if the volume of PW was lower than actual volume. If the volume of PW increases in an oil and/or gas field, the operation cost will increase at that field. PW needs to be separated, treated, and managed effectively before disposal or reinjection to the oil wells. In short, the main components of the total cost are site separation, electricity needed, treatment technologies required, storage equipment, chemical additives, operating staff, controlling equipment and staff reporting (Veil et al., 2004).

2.7 Produced Water Management Method in Different Oil and Gas Industries

Studies have discussed different programs and methods for managing and controlling PW in different oil fields around the world. In this section, the summary provided for each selected study shows how PW could be treated, managed, and controlled effectively, as well as proving the beneficial use of PW after treatment.

In 1995, BP Norge Ltd, the first operator of the ULA oil field, located in the block 7/12 in the Norwegian sector of the North Sea, realized that the best way to reduce the PW discharge was designing the Full Scale PW Reinjection System for the ULA field. In the first quarter of 1995, BPN (British Petroleum in Norge) established the first trial of PW Re-Injection (PWRI) with a full scale instead of using individual well scale. Losses in the injectivity and accelerations in the reservoir resulted from injecting the PW in many oilfields. Therefore, BPN implemented the full-scale method in ULA field to avoid these problems. As a result, the reduction in injectivity has been observed after using the full-scale method. Also, no increases in bacteria, H_2S, decreases in the corrosion rates, and no Sulphate Reducing Bacteria (SRB) activity were observed. Finally, the negative impact of PW discharges, hydrocarbons, aromatics, organic acids, phenol, injection or production chemicals, and heavy metals discharges were also decreased.

Converting unusable PW into clean drinking water resources was the main goal of the team who created the PW treatment project in the Placerita field, which was located in California. In 1997, this team completed their project and conducted analysis tests for that oilfield to verify and validate their tasks which were followed by different techniques from previous projects. They found that the best technologies to remove the salinity from PW were thermal distillation and membrane processes. Also, they presented two technologies to remove the organic compounds which were fixed-film biological oxidation and granular activated carbon respectively. The gas flotation unit was considered an efficient technology to reduce oil and grease content. Also, silica in the warm softening process has been used to remove the hardness. The team computed the annual operating cost during the year 1996 and found that the operating cost was approximately 6.1 to 7.7 million per year. Then, they determined the treatment cost per barrel to be approximately 39 to 49 cents per barrel (Doran et al., 1997).

Since 1997, the Erawan field was reinjecting the PW as the means of water disposal. The reinjection of PW increased from 80% to 92% in 2002. Unocal Thailand which was the largest producer of natural gas in Thailand and the operator of Erawan field at that time, improved the facility design and overall operating efficiency in order to increase the reinjectivity of PW. At that time, Erawan produced 20,000 BWPD in 30 wells that were located on the 12 platforms. The amount of PW decreased due to using advanced water shutoff techniques such as tubing-patches, plugs, and straddle packers. The mini-fracturing test program was used to identify the fracture pressure and potential injection rate on the target wells. The results from this mini-test showed that the injection rate should be greater than 5 BPM to keep the fracture open. Also, the range of the fracture gradient should be 0.3-0.7 psi/ft., which could be based on the sand strength properties of the individual well (Sirilumpen & Meyer, 2002).

In 2002, the Indonesian government initiated the design of a PW reinjection program in the Bekapai field to decrease the amount of disposal PW. They designed an operational window for injecting PW into reservoir 14-0 by using the BA-6 well of the Bekapai field as an initial reservoir pressure. By using this operational program, they estimated the pressure build-up to water injection which was 7.82 psi/MMbbl. Also, they found the maximum capacity of the matched reservoir and aquifer was limited by reservoir fracture pressure of 161.76 MMbbl. In addition, they found that BA-6 was capable of accommodating an injection rate of up to 19,000 BWPD in the case of the worst injectivity index and 24,600 BWPD in the case of the best injectivity index. The surface discharge pressure required was in the range of 700 psi to 1,600 psi and in the range from 1,140 psi to 1,600 psi, which were in the best and worst case of injectivity index respectively (Singh, 2002).

Having deserts in many countries with lack of rain and fresh water resources has encouraged many oil and gas industries to re-use the PW in the desert environments instead of reinjecting it into deep aquifers. Since 1999, the Petroleum Development in Oman (PDO) has been examining the Reed Plant's method of treatment of PW in the Nimr field to reduce the high salinity and the high percentage of boron which was considered unsuitable for re-use. Nimr field, which is located in south Oman, generated more than 200,000 m^3 of PW at that time. PDO used the Reed Beds for Water technique in order to reduce the Oil in Water Content (OWC) and some suspended and dissolved particles. In 2003, chemical analysis over a 6 month period in Nimr field showed that the probability of OWC exiting from the reed bed with concentration less than 5ppm was 0.71 which corresponded to 240 ppm of oil per water. Constant flow rate of PW assumption was made and the volume of 60 liters of oil was treated in one day on the 3,500 m^2 Reed bed area. By using this assumption of flow, the average residence time was found equal to 5.6 days (Sluijterman et al., 2004).

As an initiative toward reducing the cost of disposing of PW and avoiding the difficulty in meeting requirements that were imposed by environmental regulations, the management of Petrobras oilfields in Brazil has been using the Re-injection of PW method to treat PW and reinject it into its oilfields. In its onshore oilfields in Brazil, 70 % of the PW was re-injected by Petrobras, and the remaining was disposed to the sea within a limit of the disposal area which was at least 20 km away from the coast. Although the environmental regulations in Brazil reported that Oil in Water Content (OWC) was lower than 20 mg/l, Petrobras created a pilot plant to treat PW, use it to clean the utilities, and generate steam from that water to reuse it in other processes. In 2003, Petrobras discharged all PW from its offshore oilfields. Then, the Pargo and Carapeba fields were reinjected with only PW with significant success. The PW was treated effectively by using Remediation or Prevention procedures. These procedures were selected based on the field exploitation characteristics (Furtado, Siqueira, Souza, Correa, & Mendes, 2005).

In 2007, Petroperu, which is a state-owned company, found that the large amount of PW can be reinjected to both Block 8 and 1-AB oil fields by developing an integral water management program. Block 8 and 1-AB are located in the northern part of foreland Maranon Basin in Peru. Pluspetrol was operating Block 8 and 1-AB oil fields. Two main actions were taken in that program for these two fields to achieve two important objectives. The first objective of using this program was reducing the water production. The second objective was converting some abandoned wells into water disposal wells to determine the best surface facilities which could be used to reinject the PW. Pluspetrol performed a series of injection tests in shallow formations within depths between 300 to 700 m and depths between 2,300 to 4,000 m. The initial injection rate in a water disposal well in this project varied between 800 and 1,800 Barrel Water per Day (BWPD) per well with a wellhead pressure close to 2,000 psi. All injection tests were achieved by using pressure and temperature sensors. The fracture was created at 8 BPM with lower pressure than the normal gradient fracture after using pressure with lower temperature (150 F-170 F rather than 190 F-130 F). As a result, injection rates increased to 30,000-40,000 BWPD with a wellhead pressure less than 2,000 psi. Horizontal electro centrifugal pumps were used to ensure that the required injection volumes from 20,000 to 40,000 BWPD with a discharge pressure of 2,000 psi were achieved. At the end of this project, the reinjecting volume was 275,000 BWPD by using 10 water disposal wells and wellhead pressure less than 2,000 psi (Navarro, 2007).

Surace, Broccia, Salemi, & Iovane (2010) optimized and installed a new PW system on Raml field that is located approximately 500 km from Cairo in Egypt's western desert. The PW flow rate in Raml field was about 960 m^3/d, with an oil concentration of 140 ppm and solid content 76 ppm. They specifically tested the Epcon CFU technology and found it effective in removing oil from water with a discharge value below 10 ppm. The suspended oil decreased by using a bulk/fine de-oiling system that can be selected based on water flow rate, available utilities, inlet oil concentration, and oil droplet size. The suspended solid content was treated by using a bulk/fine de-sanding unit that was presented by the Merpro FilTore separation technology. This technology was chosen to reduce solid content to less than or equal to 15 ppm and maximum diameter equal to 3 microns. The results from a battery of tests proved that the Epcon CFU was very satisfied. This technology was installed to reduce the negative impact of disposing PW into the environment, to improve the water quality of PW reinjection, and to recover oil from PW by injecting it back into the separation system (Surace, Broccia, Salemi, & Iovane, 2010).

2.8 Quality Management Concepts

Quality has become an important and vital component for any organization that has initiatives toward continuous improvement for its products, services, and goods. High quality requires good management that can realize the best approach to meet or exceed customers' expectations. Sometimes, the expectations of two customers for the same particular service or product are different. As a result, extra efforts might be taken to reduce the gap between customers' expectations and specifications of products or services that have been already delivered to customers. The best measurement for the performance of any organization is its outputs. Thus, managing for good quality means spending the best efforts with good strategic plan and using the best quality tools to meet or exceed customers' expectations [(Stamatis, 2003) & (J. R. Evans & Lindsay, 2011)]. Because innumerable processes within different organizations and industries provide these products and services, variation in these processes can occur during short and long term of the production life cycle. Reducing this variation will help to reduce wastes that can be associated with processes, such as reducing the number of defective products, reducing waiting time of customers in the line, reducing the amount of pollutants that are discharged from industries…etc. (J. R. Evans & Lindsay, 2011).

Recently, two approaches have been widely used in different organizations for that purpose. Both of them are considered the best approaches to manage organizations for good quality and to reduce waste, increase the efficiency of processes, increase the customer satisfaction, and improve current and future financial status for organizations. These two approaches are known as Six Sigma and Lean Six Sigma. Each of them has its tools and methodologies to implement according to the situation of the selected organization [(Creveling, 2007); (Taghizadegan, 2006); (J. Evans & Lindsay, 2005); & (Kwak & Anbari, 2006)].

2.9 Six Sigma Methodology

Six Sigma can be defined as a business process improvement methodology that can be implemented to find and eliminate the root causes of variations in processes within organizations and industries (J. R. Evans & Lindsay, 2011). The existence of variations in processes may lead to defects, errors, and undesirable results. Because this methodology has its own problem solving approach known as the DMAIC (which stands for Define Phase, Measure Phase, Analyze Phase, Improve Phase, and Control Phase), it will help to identify, reduce, and eliminate variations, as well as improve the control of processes over time. Six Sigma is all about helping to identify what is unknown about the process behavior as well as focusing on what should be done regarding the existing variation, and making decisions to reduce that variation. Furthermore, it helps to reduce rework that costs time, money, effort, and opportunities for improvement. Six Sigma converts that knowledge into chances for business growth. Many organizations believe that working with errors is a portion of the cost of doing business (Stamatis, 2003). However, Six Sigma declines this logic. With the Six Sigma approach, most errors and variations in processes can be eliminated, costs to perform required processes can be reduced, and better customer satisfaction is achieved [(Eckes, 2003) & (J. R. Evans & Lindsay, 2011)].

In addition, Six Sigma has specific tools to help define what the targets should be in any process. Clearly, the real world application of Six Sigma is to make a product that satisfies the customer and reduces the cost of production by reducing variation in operation and control processes. Six Sigma differs from other quality initiatives because it emphasizes that the quality programs have been economically viable (Harry & Schroeder, 2000). The Six Sigma approach is more than a Greek letter that is associated with standard deviation (6 σ). Many questions need to be answered in order to understand this approach and to obtain a clear idea about it. For example, why use Six Sigma? What are the differences between Six Sigma and other improvement approaches? Apparently, achieving Six Sigma means processes are delivering only 3.4 Defects Per Million Opportunities (DPMO) (J. R. Evans & Lindsay, 2011). In other words, processes are working in higher efficiency with little to no variation. Six Sigma helps to reduce cycle time and cost of operations, improve productivity, and improve the ability to meet specific customer needs. The main point of the Six Sigma approach is that if the defects in any process can be measured, the best ways to eliminate them can be determined, reach a quality level of zero defects, and better satisfy customers" (J. Evans & Lindsay, 2005).

2.9.1 The Birthplace of Six Sigma

The birthplace of Six Sigma took place in one of the largest companies in 1979, which was Motorola. This company changed the scale of defective measurements from defects per thousand parts to defects per million parts in order to improve the quality of these parts. Using this scale would give an accurate sense to the people because of a low defect-per-thousand quality score. The next step for this company was constructing the main road map of using Six

Sigma to solve problems, and they focused on making the projects show a positive effect on the base line, which is normally called the bottom line (Harry & Schroeder, 2000).Mikel Harry studied the variations in the various processes of Motorola. He had begun to see where the higher variation is and which process is involved in order to reduce this variation to meet or exceed the requirements of customers. Unlike the classical quality efforts that concentrated on the measurement, Harry applied a package of tools to reduce and control the variation that could be the source of the poor quality in the products. Not only Harry, but also many people in Motorola focused on what process produced the most variation. They used a complete package of statistical tools to find, measure, and reduce the variation in the poorly performing processes. Harry and those people did their best efforts and they were greatly successful. In addition to their success, they engaged their Chief Executive Officer, Bob Galvin, in their work. Galvin started to control these variations among the processes in Motorola. Eventually, he considered Six Sigma the main management philosophy in all his works (Eckes, 2003). Briefly, before applying Six Sigma in Motorola, the company was spending 5 to 10 percent of annual revenues, and in some cases, more than 20 percent, to correct the poor quality issues. Therefore, the company was spending from $800 million to $900 million to perform processes with high quality. After implementing Six Sigma in Motorola, the company saved $2.2 billion within four years and the performance of processes increased (Harry & Schroeder, 2000).

2.9.2 Growth of Six Sigma in General Electric (GE)

The Six Sigma approach had grown soon after, and many companies had begun to learn how they could implement the tools that are used in Motorola. By the end of 1995, GE was one of these companies that decided to make Six Sigma a "Corporate- Wide Initiative." As a result, GE averaged 5.7 of sigma when it introduced the program of implementing Six Sigma methodology in its industrial sectors (Eckes, 2003).In 1998, GE had an impossible operating margin of 16.7 percent. This margin reduced to 13.6 percent in 1995 when the company implemented Six Sigma. If we count the magnitude of the variation in dollar amounts, Six Sigma provided more than $300 million to GE's 1997 operating income. In 1998, the financial benefits of implementing Six Sigma were more than doubled. Over $600 million was returned as revenue to the bottom line of the company. By then, the company had trained thousands of employees from different departments and staff functions in Six Sigma in order to increase the productivity 6 percent each year in its industrial sectors. However, this methodology allowed operating margins to increase from 12 percent in 1998 to 14.1 in the first quarter of 1999.

Implementing Six Sigma results had measured accurately by measuring the cumulative impact that has savings in excess of $2 billion in direct costs (Harry & Schroeder, 2000).

2.9.3 Implementation of Six Sigma in Manufacturing

Daniel P. Burnham, who was Raytheon's Chief Executive Officer (CEO) in 1998, made Six Sigma the main approach of the company’s strategic plan. The tools of Six Sigma applied in Raytheon and the cost of doing business had improved by more than $1 billion annually by 2001 (Harry & Schroeder, 2000).

In 1999, Ford Company implemented Six Sigma methodology. In just three years, more than 6,000 projects were successfully accomplished. As a result, the company saved more than $1 billion since its beginning (J. Evans & Lindsay, 2005).

In the book "Six Sigma", Harry and Schroeder mentioned that Asea Brown Boveri (ABB) has successfully implemented Six Sigma methodology to its power transformer facility in Muncie and Indiana (Harry & Schroeder, 2000). After implementing this methodology, the results were as following:

- The measurement equipment error reduced by 83%
- The loss of no-load reduced by 2%
- Improving material handling process helped to save an annual cost that was $775,000 for each single process within a single plan

The management of the Duri oil field, located in Indonesia, used a specific method to measure the volume of oil and PW. Before applying Six Sigma, each well had been tested approximately twice a month. Whenever the Non Fluid Detected (NFD) occurred during the test, the well should be checked again to see what requires maintenance. Since the Duri oilfield had 3,000 wells, the cycle time for testing wells and putting the well back into production was dependent on many conditions, such as response time to NFD, number of NFD found, type of maintenance and repair required, and the availability of resources required to perform the maintenance. Based on the historical data of one of the Duri oilfield areas, Area- 4 selected from the total nine areas , the Six Sigma methodology was implemented by the selected team which consisted of the area 4 tester, maintenance, IT engineer, and production analyst. The results obtained from implementing this methodology were as following (Sihombing, Purnomo, & Brahmantyo, 2001):

- The average response time was reduced from 405 days to 160 days per month

- The average number of NFD was reduced from 70 to 25
- An opportunity to gain 1.0 MM US $ per year resulted from increasing the annual oil production of the Duri oil field.

In 2004, Eckhouse mentioned that one of the largest engineering and construction companies, Bechtel Corporation, had reported a savings of $200 million with an annual investment around $30 million since implementing Six Sigma methodology in its projects. Implementation of this methodology was represented by identifying and preventing reworks and defects during various projects life cycles (Kwak & Anbari, 2006).

In central Arabia oil fields of Saudi Arabia, Six Sigma was used to diagnose, measure, improve, and control the root causes of Electrical Submersible Pump (ESP) failures. In these fields, there were 241 ESPs, and the failure rate was gradually increasing. Replacing new ESPs had a negative impact on the field performance and economic resources that would be utilized in Saudi Arabia fields.

After implementing Six Sigma statistical tools on 23 ESP failures occurring in 2005, the teams obtained the following results (Al-Hamdan, 2007):

- 22% of total failures were caused by sand accumulation inside the pump stages.
- 51% of total failures were caused by scales, downthrust, and seal problems, at a rate of 17% for each type of failure
- 18% of total failures were caused by poor installation practices and inaccurate water cut forecast, at a rate of 9% for each of these causes.

- 8% of total failures were caused by upthrust and cable problem, with failure rate of 4% for each cause.

Six Sigma was applied in a naphtha reforming plant in order to improve energy efficiency. Because distillation units account for more than 25% of the total energy in gas and oil refineries, energy improvement is required to reduce the consumption of energy in refineries. The team who was working on this project identified 14 key input factors to understand and to reduce process variation.

As a result of implementing this methodology with its statistical tools to reduce variations of processes in Distillation Units (DU), multivariate models of the energy performance were obtained. These models reproduced the past energy performance of the DU. Also, operating modes that could optimize the energy efficiency of the DU have been proposed with an annual expected savings around €150,000. (Falcón, Alonso, Fernández, & Pérez-Lombard, 2012).

In their work, Adwani et al indicated that Kuwait Oil Company (KOC) implemented Six Sigma methodology within its initiatives toward reducing the operating costs for both the BS-140 and BS-150 facilities (Adwani, Al-Zuwayer, & Kapavarapu, 2011).

As a part of COSTAIN improvement, these two facilities were designed in 1999 to dehydrate wet gas to 20.9 lb./MMSCF and 21.9 lb./MMSCF respectively. High consumption rates of Glycol in these facilities caused high operating costs for this company. The BS-140 facilities were selected for optimizing the Gas Dehydration unit performance during the summer period to monitor the consumption of Glycol by implementing the Six Sigma process plan.

After implementing the DMAIC approach, the team obtained the following results:

- The Glycol consumption was reduced by 33%.
- The revenue gained from that reduction was approximately equal to $565,049.

2.10 The DMAIC Approach

The DMAIC approach which stands for Define phase, Measure phase, Analyze phase, Improve phase, and Control phase is widely used in different organizations and is considered the improvement approach or the principal problem solving model (J. R. Evans & Lindsay, 2011). A better understanding of these phases is required to implement Six Sigma methodology in an organization.

Each phase of the DMAIC is demonstrated in order to provide an overview of the DMAIC approach as in the following sections:

2.10.1 Define Phase

This is the first phase of a Six Sigma project. After selecting the problem, a full understanding of the problem should be achieved by the selected teams. Also, teams should clarify the problem according to needs of customers and based on provided or collected data. The goals and constraints of the problem will be identified. At the end of this phase, the problem statement should be delivered. The problem statement must be clear and have an understandable identification for customers' requirements, which are commonly called Voice of Customer (VOC). Also, it must define the CTQ (Critical to Quality) factors, which may have impacts on the performance of services, goods, and products (J. Evans & Lindsay, 2005). Different statistical tools can be used within the define phase analysis, such as histograms and Pareto chart, that would be helpful to identify the most important causes of problems of the selected project.

This phase creates a clear vision of what success will be at the end of the project. Furthermore, high-level mapping is very important and strongly recommended in this phase. The purpose of this mapping is to catalog the processes that are affected by or will support the entire process to achieve the project goals. Also, it is used to clarify the processes that would be involved in the project. These processes should be mapped out at a high level in order to build the foundation to accomplish a measurement system (Cavanagh, Neuman, & Pande, 2005). Furthermore, the flow chart is one of these useful tools that can be used in the define phase. The outputs of this phase are used as inputs to the second phase, which is the measure phase.

2.10.2 Measure Phase

In this phase, the internal processes that may have an impact on CTQs and VOC will be measured. After defining the boundaries and goals of a project in the previous phase, gathering data to establish an understanding of the current state of the selected problem can be performed. However, in some circumstances, there is a difficulty to gather or collect current reliable data. Generally, different kinds of questions that teams should ask before collecting data include where the important data may be found, who can provide reliable data, and how the data can be collected with minimal effort. Brainstorming techniques can be used to encourage creativity of team members. In addition, process-mapping tools are important to document and verify how processes work within specific conditions. The Key Process Input Variables (KPIV) and Key Process Output Variables (KPOV) for processes of the selected project and those that have high impacts on CTQs and VOC respectively will be measured in this phase as well. In addition, there are different useful tools that can be also used in this phase such as check sheets, descriptive statistics, process capability analysis, measurement system evaluation, and benchmarking (J. R. Evans & Lindsay, 2011).

2.10.3 Analyze Phase

In this phase of a Six Sigma project, analyzing the data that is already collected and converted to an effective statistics interpretation can be performed. Also, System-Thinking Approach (STA) is very important in this phase because it will help to analyze the causes between performance of processes and systems of the selected project and the outputs, which are measured in the previous phase. Cause and effect diagrams which are also commonly called Ishikawa diagrams or fishbone diagrams are widely used in this phase, and are appreciable to perform in order to analyze the root causes of problems. Identifying the current problems and their causes can help to identify the reason behind an increase in the variations of the whole system. Furthermore, statistical inference is important in this phase because it can help to translate the results obtained from the measure phase to understandable problem statements. The addressed problems can be prepared in different ways and can be distributed among team members in order to find the best solutions for these problems [(Cavanagh et al., 2005) & (J. R. Evans & Lindsay, 2011)].

2.10.4 Improve Phase

The pure objective of Six Sigma is to increase the improvement factors that will help to achieve a perfect level of performance. Focusing on characteristics that are very critical to customers and identifying, reducing, or eliminating causes of errors that may have an effect on the performance of processes or quality of products is the main purpose of this phase. After analyzing the root causes of problem from the previous phase, teams will work on finding the best solution for these problems. How to eliminate the root causes of problems is a common question in the improve phase, which is the main objective of team members. In some cases, redesigning organization culture or reengineering technical systems may be required in order to eliminate these causes. Because organizations do not have the same infrastructures, the development and improvement of processes can be varied from one organization to another in order to achieve high improvement levels. List of design alternatives will be provided at the end of this phase. Different disciplines are required to make alternatives work and give useful comments about the performance of proposed solutions. These comments will help to identify the best alternative ideas. These ideas can be classified into failure resistances, predicted capabilities, and impacts on the CTQs. Different quality and statistical tools can be used in this phase, such as design for experiments, mistake proofing, lean production, Deming cycle, and seven management and planning tools [(J. R. Evans & Lindsay, 2011) & (Stamatis, 2003)].

2.10.5 Control Phase

Maintaining and keeping the improvements for the selected solutions are the main goals of this phase of. After proposing the best solution, done based on the results obtained from the previous phases, the team will be responsible for finding the best control tools that will help to ensure the key variables in the obtained maximum acceptable ranges (J. Evans & Lindsay, 2005). In addition, in some organizations, training is required for employees to increase their skills to manage and avoid mistakes that can cause errors and variation in the improved processes. In addition, this training can help to improve the knowledge of workforces regarding the selected solutions or new culture for such organization. Within this phase, it is important to ensure that problems that are already solved will not return, and focus on keeping them in good statistical control (controllable processes) (Creveling, 2007). Several statistical and quality tools are most commonly used in this phase, such as Statistical Process Control (SPC) and standard operating procedures. Some of them are simple and easy to use, such as using a checklist to ensure that provided procedures are correctly followed. However, some of these tools require people who have statistical knowledge and skills, such as using control charts to ensure that processes are in control.

CHAPTER 3: FRAMEWORK METHODOLOGY

3.1 Framework Development

Six Sigma methodology has been widely implemented in different organizations such as service, safety, business, manufacturing, and government as a part of its initiatives toward continuous improvement programs. Six Sigma tools and techniques are generally used to reduce or eliminate waste, which are possibly generated during planning, operation, production, and packaging and delivering processes by reducing service time, the number of defective products, or eliminating the root causes of problems from different processes and systems. However, from a review of literature, Six Sigma is not widely implemented in oil and gas industries. Some literature showed that Six Sigma and quality improvement tools have been successfully implemented in manufacturing, services, and governmental sectors. In addition, other literatures confirmed that using Six Sigma methodology and its tools helped different organizations to reach their goals with lower effort, cost, and waste with high performance and quality.

This work introduces Six Sigma as a principle that can be used to solve problems associated with oil and gas operations. Reducing the time of making proper decisions and minimizing the cost of rework and re-identifying the root causes of problems can be achieved by implementing the developed framework.

Some literature and published papers will be used in this work to analyze the root causes of several problems that are related to the selected case study. Also, System Thinking Approach (STA) will be used to visualize the root causes of the identified problems and show the effects of these causes on the current state of the selected case study and will be provided as casual loops diagrams. Following that, the problem-solving approach will be conducted to solve the identified problems which are related to one of the largest oilfields in the world. Finally, Analytical Hierarchy Process (AHP) approach will be selected from Multi Criteria Decision Making Methods (MCDM) and will be used to choose the best solution for these problems from different alternatives.

3.2 Application of Six Sigma Methodology in the Southern Iraqi Oil Fields

After reviewing the current state of the Zubair oil field, one of the largest oilfields in the world, the author found that the main concern within that field is the large volume of PW that is normally associated with oil and gas production operations.

The current PW management method in the Zubair field is disposing it into Natural Evaporating Ponds (NEPs) near the Zubair field without treatment. With a lack of rain in the last few years, almost 420,000 barrels of PW per year is being disposed into NEPs and through injection into Zubair formation. Cleaning drilling equipment needs fresh water in that field. Fresh water is also required to complete some processes during oil production such as Back Wash Water (BWW) for the desalting processes. Environmental pollution for Dammam aquifers, geological damage of the soil of the surrounding stations, and negative impacts on the human resources in that area could result from discharging PW without treatment to the NEPs. Discharging PW directly to the surrounding area can cause clogging to that formation. According to various literature reviews, discharging PW without treatment can cause acute toxicity because of a high concentration of chemical compounds, metals, and soluble hydrocarbons existing in the water.

Determining the environmental and economic impacts of discharging PW in that field by using quality tools such as continuous improvement tools will help to improve oil production and manage PW in the Zubair field effectively. It is known that Six Sigma tools can help to identify the root causes of producing waste from industries, it will be demonstrated how the selected tools in this study can be used to reduce waste and improve oil and gas production by selecting an effective treatment technology to manage the enormous amount of contaminated PW in the Zubair field. The DMAIC approach will be used in this framework to evaluate the PW stream that is being discharged from onshore southern Iraqi oil fields. Finally, recommendations will be provided in order to manage this excessive amount of PW successfully based on the current technologies in the market that already have high efficiency to reduce and remove these contaminants from PW. The methodology flow chart in Figure 3.1 explains the steps of creating this framework.

3.3 Significance of the Study

Identifying most contaminants in PW, measuring their amounts, and analyzing the root causes of increase in these amounts will be performed by using the developed framework. A new management method of the PW problem in the Zubair field will be provided in this study, and that can be used to improve the current and future state of southern Iraqi oil fields. The AHP model will be developed to select the best treatment technology for PW among different alternatives. The validation of this framework can be achieved through application of a case study in the Zubair field, and it could be used for other worldwide onshore oilfields.

3.4 Objective of the Study

The main objective of the study is developing a framework by using the Six Sigma methodology to recommend policy changes for PW management method in the Zubair field. This framework can help to analyze PW contaminants associated with oil and gas production in that field. The sources of these contaminants in the discharged PW can be identified by using quality design and control tools. As a result, procedures and control steps can be developed and put in place to reduce the negative environmental and economic impacts from discharging PW.

3.5 Limitation of the Study

Some data of this study is adopted from literature, published papers, and reports that have discussed the current state of Iraqi oil fields, specifically, the Zubair oil field. According to the literature, the main contaminants of PW are oil and salt content that should be removed prior to discharge or reuse as a clean water resource (Soltani et al., 2010). As a result, this study is limited to identify the sources of oil, salt, NORM, and corrosive materials in PW, analyzing the amount of TDS, TSS, and Oil and Grease Content (OGC), measuring their amounts, and controlling them during and after oil and gas production by using quality principles and practices. In addition, analyzing the root causes of corrosion was performed in this study, and the results helped to understand how other contaminants could increase the corrosion rate and amount of scales, deposits, and corrosive compounds in pipes and equipment of the Zubair field.

The sources of problems that could impact the concentrations of various contaminants in PW were analyzed in detail in order to develop a high level control plan for the new selected technology.

3.6 Assumptions of the Study

The author of this study has made many assumptions that are demonstrated as follows:

1. Six Sigma methodology and its tools used in this study can be applied to solve problems and improve systems in different oil and gas industries.
2. Because of the data limitation, some literature and published papers are considered the sources of data.
3. STA is used in this study as a part of the brainstorming and the study development stages.

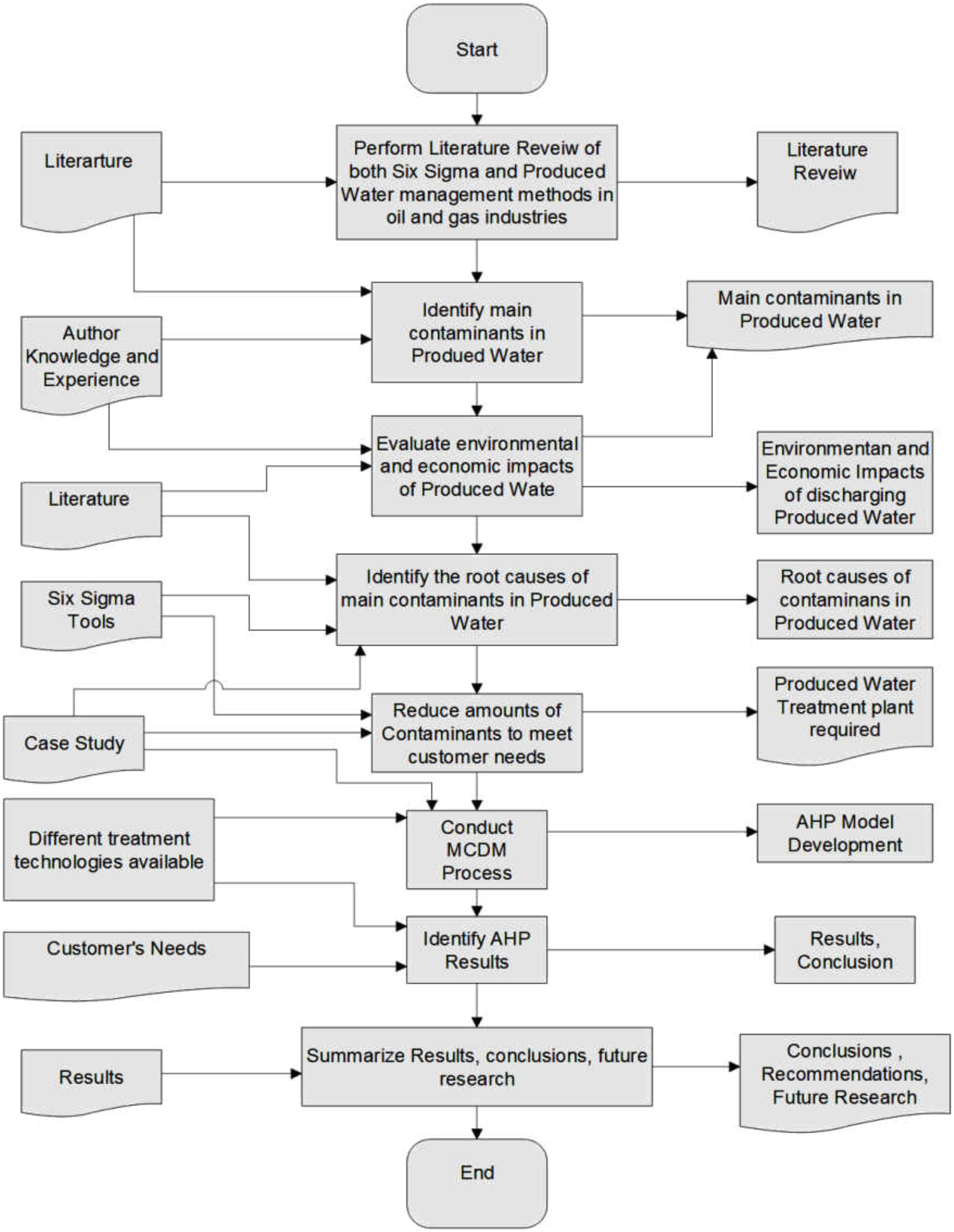


Figure 3. 1: Methodology Flow Chart

CHAPTER 4: CASE STUDY

4.1 Current Produced Water Management Method in the Zuabair Oil Field

Approximately 35,000 barrels of PW have been produced along oil and gas production in the south of Iraq (SOC, 2012). Currently, there is no treatment plant for PW in the Zubair field, thus water has been disposed into NEPs with large amounts of various contaminants such as heavy metals, toxic chemicals, and solids. Negative environmental and economic impacts can result from using the current management method for PW. This excessive amount of PW can be a source of fresh water if it is properly treated and managed. In addition, this water, after treatment, can prove beneficial to humans who are living close to the Zubair field or for the oil field itself. Furthermore, if this amount is effectively treated and properly managed, the reinjection of PW process into oil wells can be achieved. Then, the productivity of oil and fresh water resources will increase, and the negative environmental and economic impacts will decrease. For both purposes, reinjection of PW into the Zubair oil wells and reusing it as a fresh water resource, there is a need to find an effective treatment and management method for the water in that field.

4.2 The Zubair Oil Field Profile

In 1949, the Basrah Petroleum Company discovered the Zubair field, which is located in south of Iraq to the west of Basrah, see Figure 4.1, as modified from “U.S.Energy Information Administration” shows the geographical location of the Zubair oil field ("U.S.Energy Information Administration," 2010). It is considered one of the largest oilfields in the world. Currently, it is holding around 4.1 billion barrels of crude oil. In 2009, the Eni Company won the service contract for that field, and an expansion program is taking place in order to develop the infrastructure of the Zubair field. As a result of this program, the production of oil is expected to increase from 195,000 to 1,125,000 BPD (Barrel Per Day) by 2017 (SOC, 2012). In addition, more than 200 wells will be drilled in this program ("Iraqi Oil Reporting A guide for reporters," 2010). Furthermore, the treatment facilities, required collection network, and the reconstructing of the existing plant will be accomplished by the end of this program. Since the volume of PW has increased from 4,000 BPD in 2008 to 35,000 BPD in 2012, this volume is expected to increase to more than 1,169,000 BPD in the near future (SOC, 2012).

Figure 4. 1: Geographical Location of Zubair Oil Fields

4.3 Problem Statement

The South Oil Company (SOC) has been using Degassing Stations (DS) to separate oil from gas. These stations have dehydrator and desalter units, which have been used to accomplish the separation process of oil, gas, and formation water. An excessive amount of PW has been produced with oil and gas production activities in that field. This water has been managed by injecting it into NEPs (SOC, 2012), see Figure 4.2.

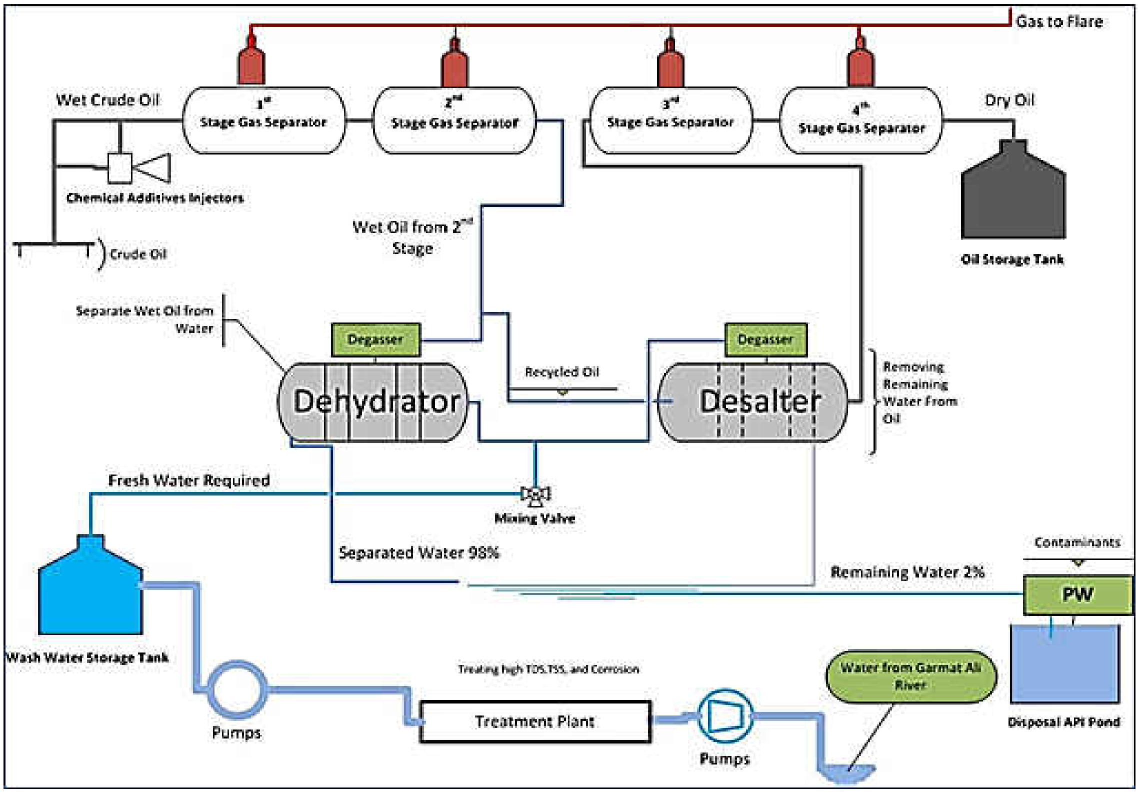


Figure 4. 2: A Schematic Diagram for the Zubair CDS

Because that water has contaminants such as heavy metals, sands, dissolved gases, bacteria, and dissolved hydrocarbons; the current method of managing this contaminated water has negative environmental and economic impacts on Dammam formation, aquifer, employees, and human resources in the areas surrounding the Zubair field. Since production of oil will increase because of different programs, the amount of PW is expected to increase by more than half of oil and gas amounts (SOC, 2012). Predictions have been made by the experts in the Zubair field to expect PW production rate from 2008 to 2025, and the results showed that this amount is rapidly increasing, see the bar chart in Figure 4.3(SOC, 2012). Therefore, decisions should be taken to determine the best methods to solve the problem of PW in the Zubair field.

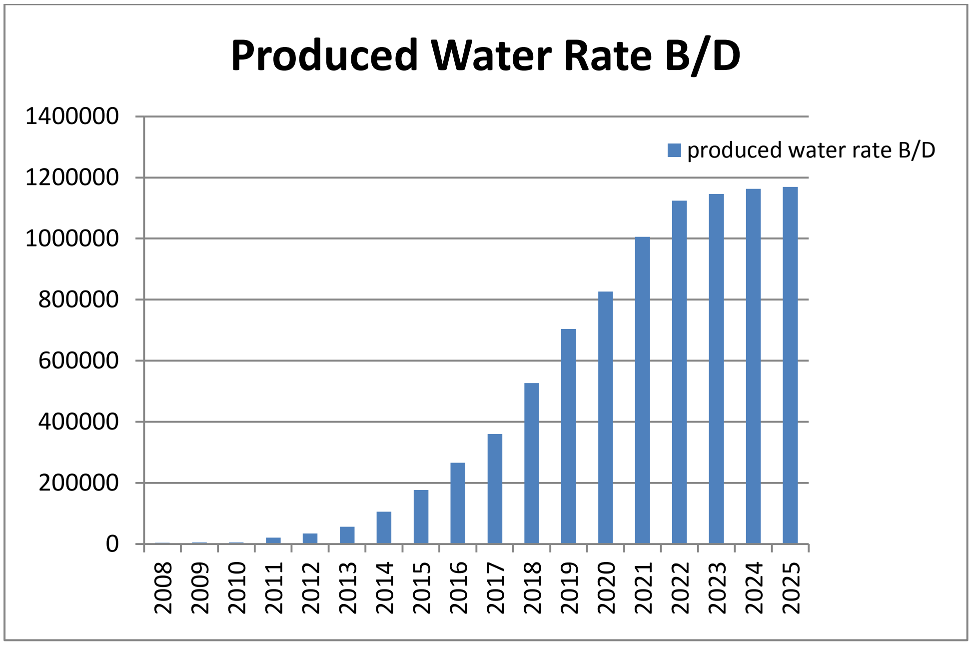


Figure 4. 3: Produced Water Production Rate from 2008-2025

4.4 DEFINE Phase

In this phase of the DMAIC approach, the limitations of the project and its current and future benefits were identified. The customer requirements, which are known as Voice of Customer (VOC), were determined in order to set the best tools and methods that could be used to meet or exceed the customers' expectations. Furthermore, important customers’ needs, known as Critical to Quality characteristics (CTQs), were identified which helped to set the target of the selected case study and to use proper tools in order to meet or exceed these expectations. It was important to monitor some local and foreign tenders that have been requested by SOC which are related to the development project of the Zubair field. Therefore, internet monitoring helped to identify the most important needs of the SOC and understand the reason behind requesting some parts, equipment, and materials for our areas of focus, such as Garmat Ali River, Degasing Stations (DS) of the Zubair field, and NEPs.

4.4.1 The Scope of the Study

In this phase, contaminants in PW that have high environmental and economic impacts will be identified. This study is limited to investigate the main sources of these contaminants in PW, to show how these contaminants could cause variation in operation and production conditions, increase concentrations of corrosive materials, and to investigate the reason behind the increase in the amount of contaminants in PW. Therefore, it is limited to identify the sources of contaminants that are related to each other in such a way and have contributed to increase the negative impacts of discharging PW. Briefly, the project scope is using Six Sigma methodology to evaluate the main contaminants in PW in order to find the best management method for that water to help improve the current and future state of the Zubair field. Also, an AHP model is developed that can help decision makers to select the best treatment technology for PW with its current physical and chemical properties with less effort and time. Finally, recommendations will be provided to the SOC for a proper management method and effective treatment technology for PW in the Zubair field.

4.4.2 Study Goals

The main goals of this study are as follows:

- Evaluate the main contaminants in the discharged PW
- Identify which containment have large amounts and high priority for treatment

- Identify the relationship between these containments and the production of oil, equipment failure rates, and the ecological risks
- Identify the root causes of corrosion that can be caused by PW contaminants
- Convert PW to fresh water
- Reduce the environmental impacts from discharging PW
- Reduce the equipment failure rates
- Reduce the required amount of fresh water in the Zubair field during extraction and production of oil operations
- Improve the policy to manage PW effectively in the Zubair oil field

4.4.3 Study Benefits

The study benefits were determined according to a comparison between the current state of the Zubair field and the expected results after completing the project that were clearly explained in the analyze and improve phases. Briefly, the benefits from this project were mentioned as in the following:

- Safety

1. The environmental hazards that could result from discharging PW can be decreased if it is effectively treated and properly managed.
2. Protect people who are working and living close to the Zuabir's DS from the radioactivity that can be increased by discharging NORM with PW.

- Financial

1. If the remaining oil and grease particles are removed from PW prior to discharge and recycled again to the de-oiling units, the production of oil will increase and that will help to increase sales of oil per day.
2. Reducing the cost of selling expensive chemical additives that should be injected prior and during oil production processes.
3. Identifying the root causes of corrosion will help to develop a new control method for chemicals used and other identified causes of corrosion. As a result, pipe, valve, and storage tank failure rate will decrease.

- Oil Field Management

Improving the current management methods of the oil fields that belongs to the SOC by reducing waste, hazards, and cost can be achieved by using the proposed solutions and implementing one of the quality principles and practices, which is the Six Sigma methodology. MCDM offers new opportunities and challenges to the decision makers in the SOC to make proper decisions with less effort, time, and errors. Training in Six Sigma and quality tools, such as problem solving approach, can improve skills of people who are working in SOC or other organizations that are related to the current development programs in some Iraqi oil and gas industries. Root Causes Analysis (RCA) and STA are helpful tools to investigate and break down any complicated problem that may require to be analyzed and then to be solved.

4.4.4 Stakeholder Analysis

In order to identify people who could influence the success of the selected project, the stakeholder analysis was performed to distinguish between Vital, Supportive, and Adversarial stakeholders. This analysis was performed in the early stages of the DMAIC approach because it was important to know who will be supportive for the initiatives toward problem-solving and quality improvement steps, see Table 4.1. Brainstorming was used to organize stakeholder categories. Thus, each stakeholder group was given a specific code to make it different from other groups. The values for Attitude, Activity, Power, and Interest columns were entered based on the specific scale as provided in following:

- Attitude: -10 (Strongly Against), 10 (Strongly for)
- Activity: 0 (Completely Passive), 10 (Strongly Active)
- Power: 0 (No Effective Power), 10 (Powerful Influence)
- Interest: 0 (No Interest), 10 (Very Interested)

Table 4.1: Stakeholder Analysis Matrix

Stakeholder Categories	**Relevant Stakeholders**	**Code**	**Attitude (-10)-(10)**	**Activity (0-10)**	**Attitude Rating**	**Power (0-10)**	**Interest (0-10)**	**Power Rating**
Environmental Protection Agency	EPA	EPA	8	9	72.00	5	9	45.00
South Oil Company	SOC	SOC	5	10	50.00	10	6	60.00
Coworkers	Engineers and Workers	HU	9	7	63.00	5	2	10.00
Current unit Plants	Operators	OP	-6	9	-54.00	8	10	80.00
Current Production Rate	Producers	PR	-10	9	-90.00	8	1	8.00
Wells Management	Managers	MA	-9	6	-54.00	8	7	56.00
Governors	Ministry of Oil	GOV	9	10	90.00	7	10	70.00
Contractors	International Oil companies	F.CO	9	8	72.00	8	10	80.00
Domestic Governors	Do.Gov	D.GOV	-6	8	-48.00	7	7	49.00

Note: Attitude Rating equals Attitude times Activity; and Power Rating equals Power times Interest.

After conducting Stakeholder Analysis Matrix (SAM), stakeholders were classified according to their attitudes, activities, powers, and interests for the selected project. Then, Interest / Power and Attitude /Activity plots were drawn by using MINITAB/Quality Companion software to emphasize and describe the SAM results as provided in the following figures:

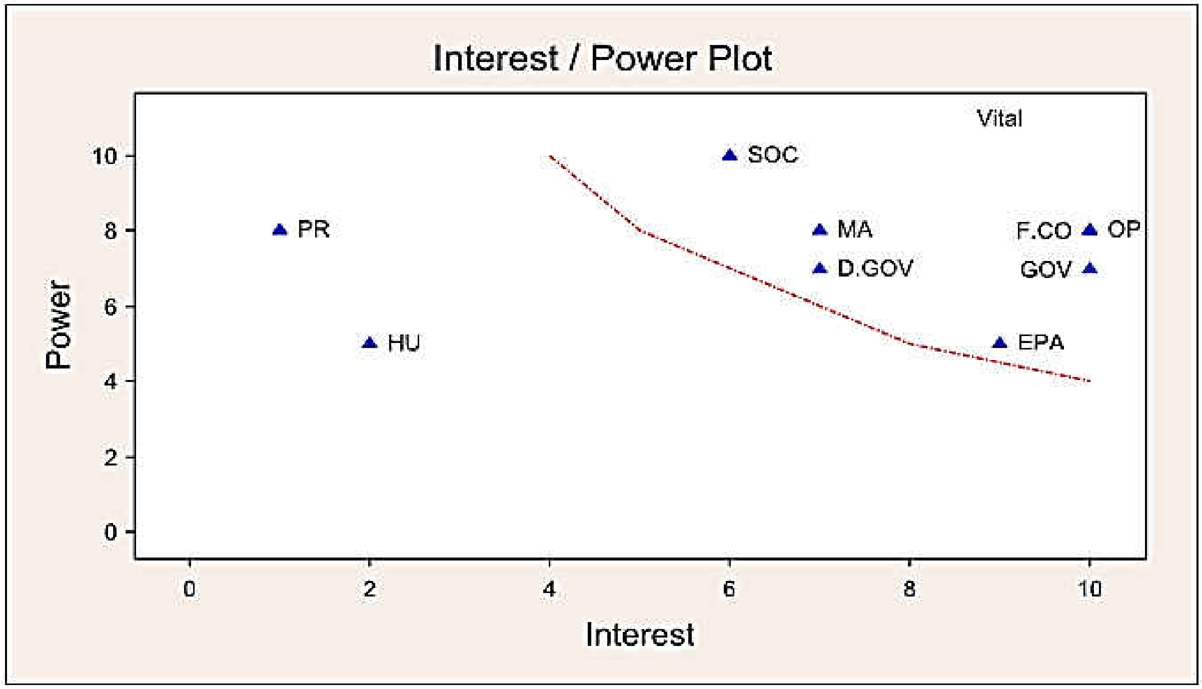


Figure 4. 4: Interest/ Power Plot

The reference line represented the ideal balance for a vital stakeholder. Points above the line represented stakeholders with potentially high influence on the success of the project; they could be either powerful supporters or powerful detractors. From the Power-Interest plot, the SOC was considered one of the most vital stakeholders because it manages all oilfields that are located in the south of Iraq, which includes Zubair oil field. Furthermore, it has the authority to develop new management methods for all oil fields in Basrah. Additionally, the SOC is the only company responsible for finding the best correction plan for its ineffective current management method for PW. On the other hand, the coworkers and the current production rate (Producers) were located below the reference line and were considered powerful detractors for the project because their activities cause an increase in PW production rate.

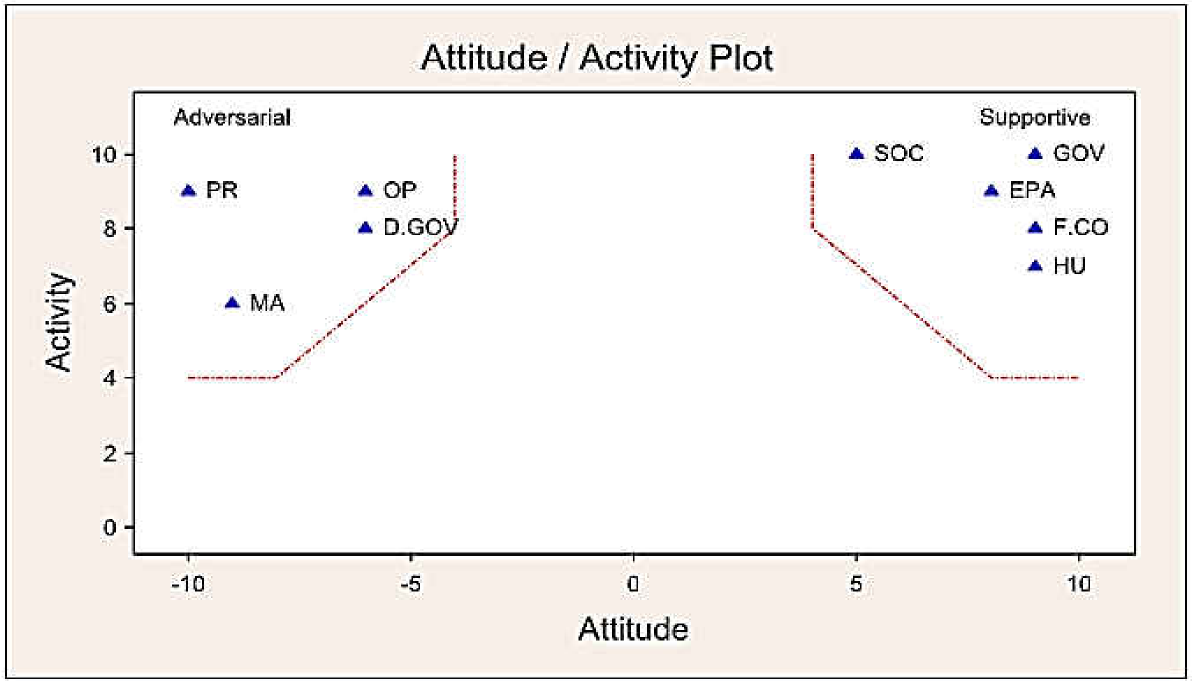


Figure 4. 5: Attitude/ Activity Plot

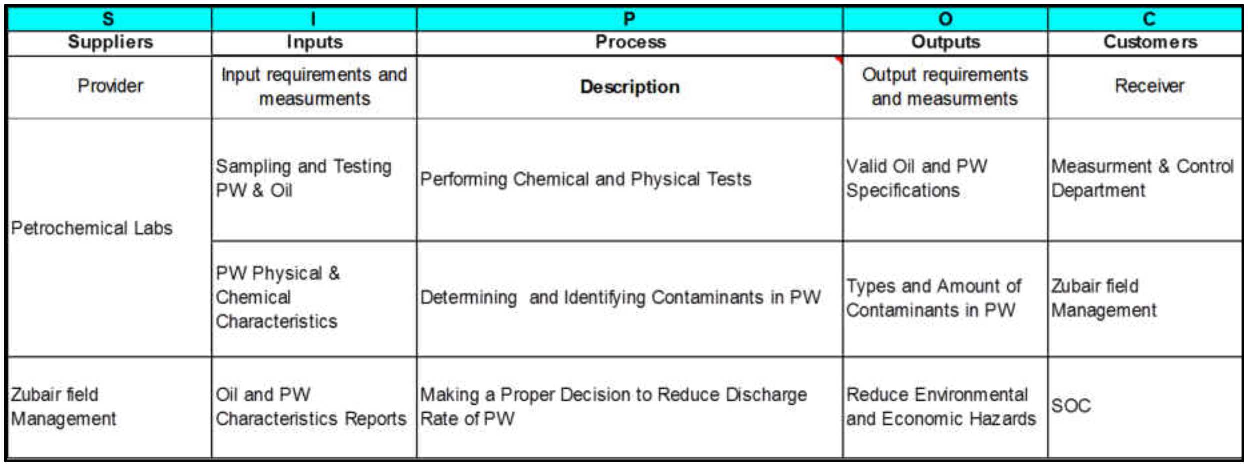
The reference line on the left marked the point at which stakeholders were considered potentially adversarial to the project. Points to the left of this line represented stakeholders that who could present roadblocks for improvement initiatives. The reference line on the right marked the point at which stakeholders were considered potentially supportive for the project. Points to the right of this line represented stakeholders that could provide assistance in overcoming the identified roadblocks.

From the figure above, it was important to notice that PR (Producers of oil) was located above the reference line of the adversarial section because their production activities increase the amount of contaminated PW. However, the HU, which is the code given for the coworkers moved to the supportive side because both workers and engineers might participate and work to find the best methods and techniques that could be used to manage PW properly in order to protect them and the environment. Furthermore, SOC, EPA, F.CO, and GOV were located above the reference line of the supportive section, which indicated that those stakeholders could work and contribute to support any initiative toward solving the PW problem in the Zubair oil field.

4.4.5 SIPOC

The SIPOC process, which stands for Suppliers, Inputs, Process, Outputs, and Customers, was used to explain what and who was involved in the study. Defining the customers and the sources of information that were used in the next phases was also demonstrated by using SIPOC. The start and the end point for each involved process were also defined in this section.

Table 4.2: SIPOC



S	I	P	O	C
Suppliers	**Inputs**	**Process**	**Outputs**	**Customers**
Provider	Input requirements and measurments	**Description**	Output requirements and measurments	Receiver
Petrochemical Labs	Sampling and Testing PW & Oil	Performing Chemical and Physical Tests	Valid Oil and PW Specifications	Measurment & Control Department
	PW Physical & Chemical Characteristics	Determining and Identifying Contaminants in PW	Types and Amount of Contaminants in PW	Zubair field Management
Zubair field Management	Oil and PW Characteristics Reports	Making a Proper Decision to Reduce Discharge Rate of PW	Reduce Environmental and Economic Hazards	SOC

- Suppliers
    1. Chemists in petrochemical labs were performing physical and chemical tests for both oil and PW samples, which were taken in this study from the output stream of the dehydrator units at different locations. Also, they were reporting types and concentrations of contaminants in PW.
    2. The Zubair field management departments were responsible for reviewing the routine operation and production reports that could help to measure the effectiveness of oil-gas production operations and separation equipment.

Furthermore, these departments were responsible for supporting and providing all needs of production, maintenance, sales, and other departments, such as, buying required equipment and parts for operation, production, maintenance, and control processes.

- Inputs
    1. Samples from oil, sludge, formation, and PW were taken and tested by petrochemical labs in order to study physical and chemical properties of the main constituents in PW.
    2. The results obtained from the petrochemical labs were included in this study.
    3. Reports that discussed physical and chemical properties of discharged PW from the Zubair oil field were also included in this study.
- Process
    1. Performing chemical and physical tests for PW samples.
    2. Evaluating the main contaminants in the discharged PW and identifying its environmental and economic impacts.

3. Improving the current method for managing PW in the Zubair field.

- Outputs

The ultimate output was reducing the environmental and economic impacts that can result from discharging contaminated PW into areas surrounding Zubair field. This output could be achieved if PW properties were determined accurately, and that would help to select the best method for managing that water.

- Customers

The internal customers in this Project were SOC, measurement and control department, workforces, and the Zubair oil field management departments. From the perspective of safety, conducting chemical and physical tests could help to measure the harmful contaminants which must be eliminated or controlled to protect employees during handling of that water. Managing PW properly could help to protect the Dammam formation and Zubair aquifer, and that could help to protect the environment in the south of Iraq. Eliminating or at least reducing the amount of contaminants associated with PW to the accepted levels could increase the protection of humans who are living close to the Zuabair oil field areas and those are considered the external customers.

4.4.6 Flow Chart of Central Degassing Stations in the Zubair Oil Field

In order to understand the current basic processes that were involved in producing oil and contaminated PW in the DS of the Zubair field, the flow chart in Figure 4.6 was developed.

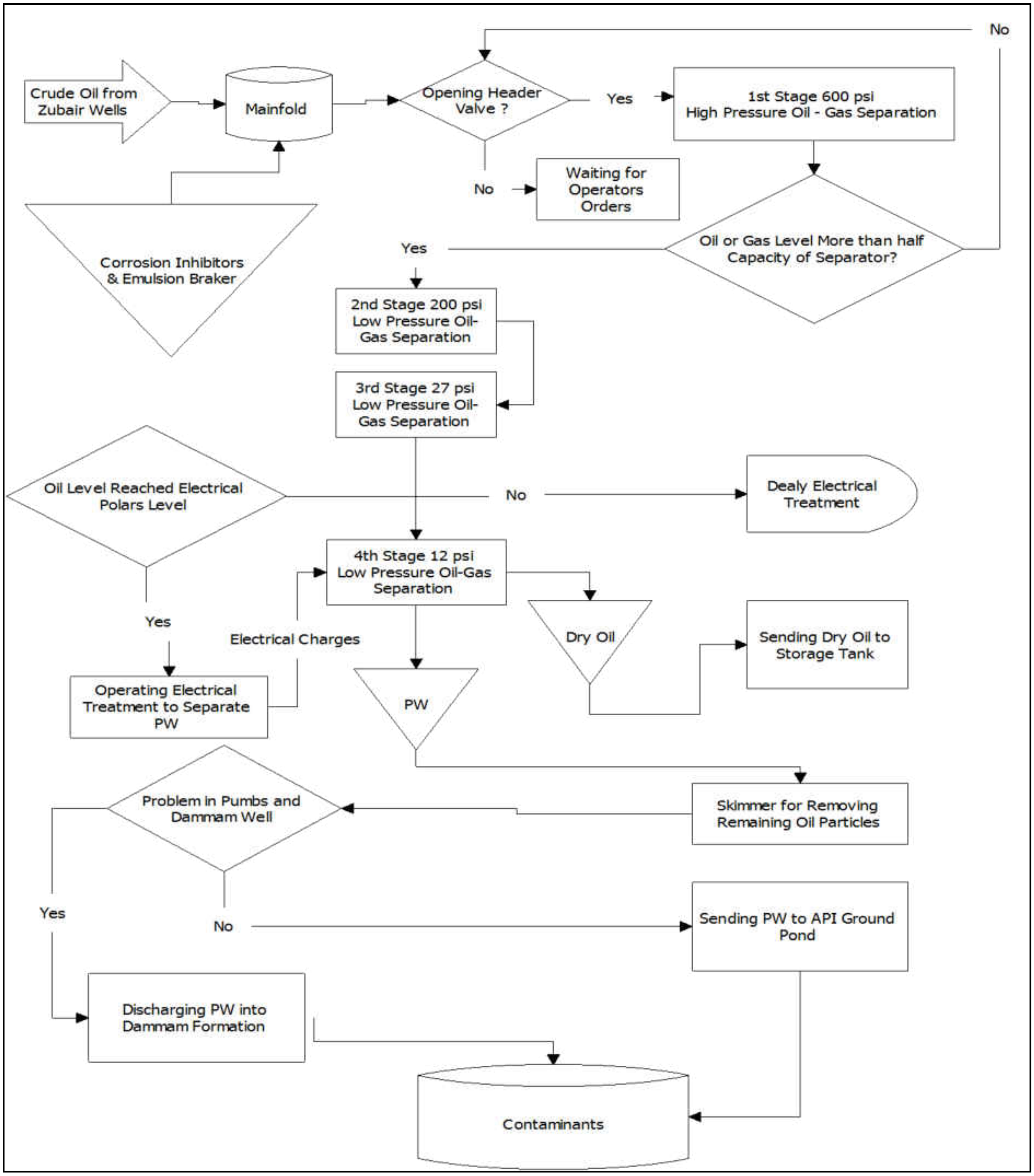


Figure 4. 6: Flow Chart of Central Degassing Station Processes

This flow chart illustrates how the current oil production in the DS was continuously increasing the amount of contaminated discharged PW by using the current management method. The provided oil field manual to the engineers in the southern oil fields indicated that in case of having problem in the injection systems of discharging PW to the NEPs, the PW should be discharged to the surrounding areas (SOC, 2012).

4.4.7 Voice of the Customer

Understanding the needs for both internal and external customers required assigning the best key approaches to gather information about those customers. This information could help to determine their requirements and expectations. Different key approaches could be used to gather this information in the define phase of the Six Sigma project. Direct customer contact, internet exploring, and field intelligence were used to gather information about SOC and its requirements that were related to main concerns about increase in the discharge rate of PW with high concentrations of harmful contaminants. According to the customers' requirements, see Table 4.3 (SOC, 2012), which are all about reducing the amount of specific contaminants to the required levels, the VOCM (Voice Of Customer Matrix) was used to assess the preliminary required business function in order to meet the customers' needs and the results obtained were provided in Table 4.4

Table 4.3: The Required Properties of PW

Requirement	Unit	Value
PH	None	6.5-7.5
TSS	Mg/liter	<2
Turbidity	NTU	<1
Particle Size	Micro-m	<4
TDS	Mg/liter	250,000
OGC	Mg/liter	<5
Total Iron	Mg/liter	<5
DO	Mg/liter	<0.02
Bacteria	None	Not detected

SOC required that PW contains the above properties by using an effective treatment technology. These properties helped the author to conduct specific research in order to see which technology has an ability to reduce the concentrations of the identified contaminants to the required levels. Also, it helped him to perform brainstorming in order to set the best business functions that could be used to meet the customers' requirements. Meeting these requirements will help to reuse PW as clean water and reduce the environmental and economic impact of PW.

Table 4.4: Voice of the Customer Matrix

● 5 Strong
○ 3 Medium
△ 1 Weak

	Voice of the Customer														
			Plan			Develop			Market		Deliver			Support		
	Business Functions / Customer Requirements	Importance (1-5)	PW Treatment Prior to Disposal	Perform Geo, Che, and Phy Tests	Reinjecting and Reusing PW	Produced Water Evaluation Approach	Best Methodology for Managing Produced Water	Candidate Solutions Matrix	Study Existing PW Managing Systems	Evaluate Current Treatment Plants	Select the Best Methods to Perform PW Analysis	Produced Water Treatment Plant	Produced Water Reinjection System	Provide Training for Operators, Managers,& Producers	Warranty for the Selected Technologies and Systems	Construct an Advanced Environmental Labs
Better	Oil and Gas Production Rate	5	5	4	4		4			4	3	5	5		4	
	Produced Water Management Method	5			5	4			5	3	4	5	4	4	3	5
	Processes Work right	5		3			5							5	4	
	Meet EPA Requirments	4	5	5			5					5				5
	Ease of Recycle	4	3	3	5		3				4	5	5	4		
	Fix it right the first time	5				3	2							5	4	
	Reinjection of Produced Water	4	5	4	5	3	3	2	3	4	4	5	5	4	2	1
	Quality of Produced Water	5	5	1	4		2		2	4	3	5		2		4
	Products meet Customers' Needs	5	5				5					5				
Reduce	Discharge Rate of Produced Water	5			5		5					5				
	Corrosion	5	4	3	2		5						2	4		3
	Environmental Pollution	5	5		5		4					5	5	2		5
	Amount of Fresh Water needed	4	5		5				2			5	5		3	
	Hazards	4					4							4		4
	Equipement Failure Rate	5			4		4				4		3	5		3
	Constraints of Oilfields Development	4	5		5		4						5	2		3
	Chemical Additives Amounts	3		4			4				4		4			5
Cheaper	Delivered Treatment Plant	5			5			5		4				5		
	Help to save money	5		2			5					4	5			2
	Help to save time	5	5				5						4	4	3	
	Reduce cost to own or use	4			5		2									
	Training	5	5	4	5	3	3			4		3	4			4
	Maintenance and Replaced Parts	4												4	5	
	Reinjection Proposal	5	5	4	4		4			3	5	4	5	3		3
	Total Weight		287	165	315	62	361	33	55	126	139	285	277	267	130	212

In order to make the results of VOCM understandable, the bar chart for the total weight for each requirement was developed regarding the suggested business functions. The bar chart showed that the most important requirements that have high priority to the customer with respect to other requirements. For the purpose of constructing the bar chart, each business function was given a specific number which was the Business Function Number (BFN) as demonstrated in the following table:

Table 4.5: Business Function Number of VOCM

VOC .NO.	Business Functions	BFN
1	PW Treatment Prior to Disposal	BFN-1
2	Perform Geo, Che, and Phy Tests	BFN-2
3	Reinjecting and Reusing PW	BFN-3
4	Produced Water Evaluation Approach	BFN-4
5	Best Methodology for Managing Produced Water	BFN-5
6	Candidate Solutions Matrix	BFN-6
7	Study Existing PW Managing Systems	BFN-7
8	Evaluate Current Treatment Plants	BFN-8
9	Select the Best Methods to Perform PW Analysis	BFN-9
10	Produced Water Treatment Plant	BFN-10
11	Produced Water Reinjection System	BFN-11
12	Provide Training for Operators, Managers,& Producers	BFN-12
13	Warranty for the Selected Technologies and Systems	BFN-13
14	Construct an Advanced Environmental Labs	BFN-14

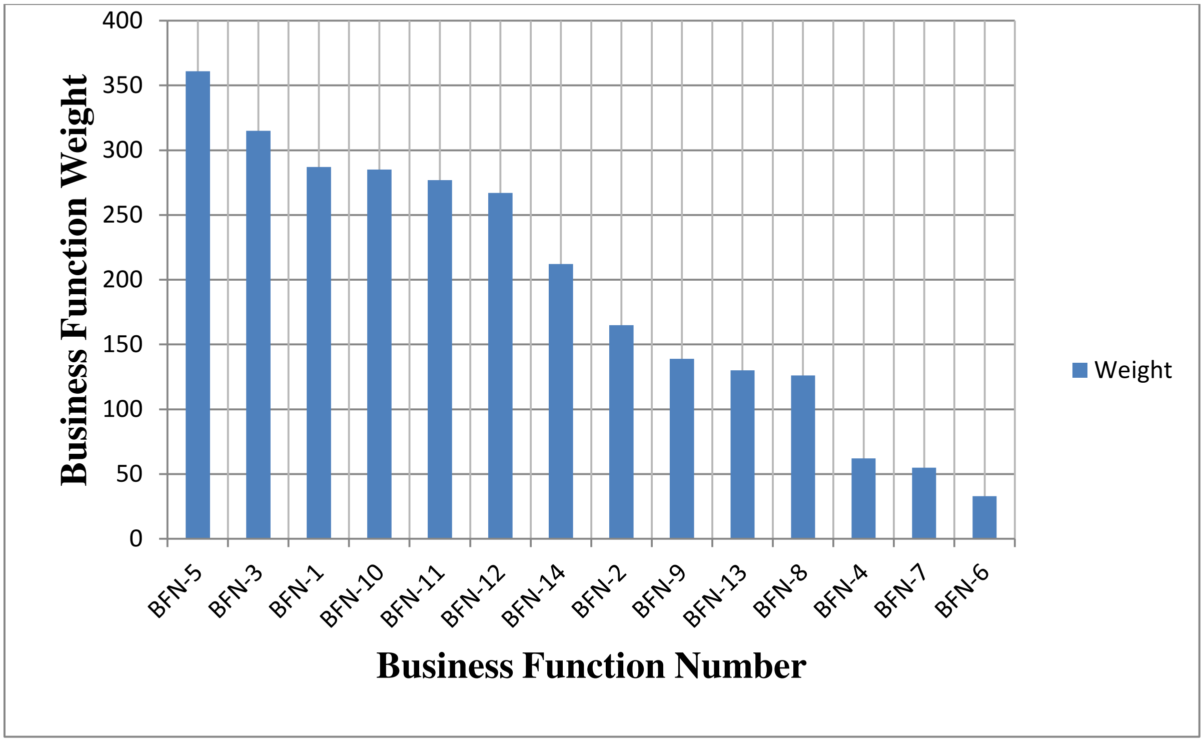


Figure 4. 7: Histogram for Total Weight of VOCM

From the above figure, it was clear to notice that the highest voice of the customer was providing the best method for managing PW. The second important voice of the customer was reinjecting and reusing PW instead of disposing it. Offering PW treatment prior to disposal, designing a PW treatment plant, and constructing a PW reinjection system were also given high priority. Other functions were very important and showed some weight of business functions.

4.4.8 Key Process Input Variables and Key Process Output Variables

For this study, it was important to determine the Key Process Output Variable (KPOV) because all factors that could influence the amounts of contaminants in PW were required to be identified. Therefore, the results obtained from VOCM were analyzed and helped the author to identify all causes behind the increase in the concentrations of contaminants in PW, which was considered the KPIVs. The KPOV and its causes (KPIVs) were identified and listed as in follows:

KPOV:

- Increase in the amount of Contaminants in PW

KPIVs:

- PW Management Method
- PW Analysis Methods
- Operation and Production Methods
- Operation and Production Plants
- Field Observation and Control Methods
- Maintenance Methods
- IT Method
- The Nature Causes

4.5 MEASURE Phase

In this phase of the DMAIC approach, the internal processes and activities that could impact CTQs were measured. The KPIVs and KPOV were discussed in details in order to measure the relationship between them and CTQs. Chemical and physical tests results of PW were used and prepared for the analyze phase. Identifying types and measuring amounts of different contaminants in PW were helpful to identify the root causes of corrosion, equipment failure rate, and the high concentration of NORM and toxic materials in the discharged PW.

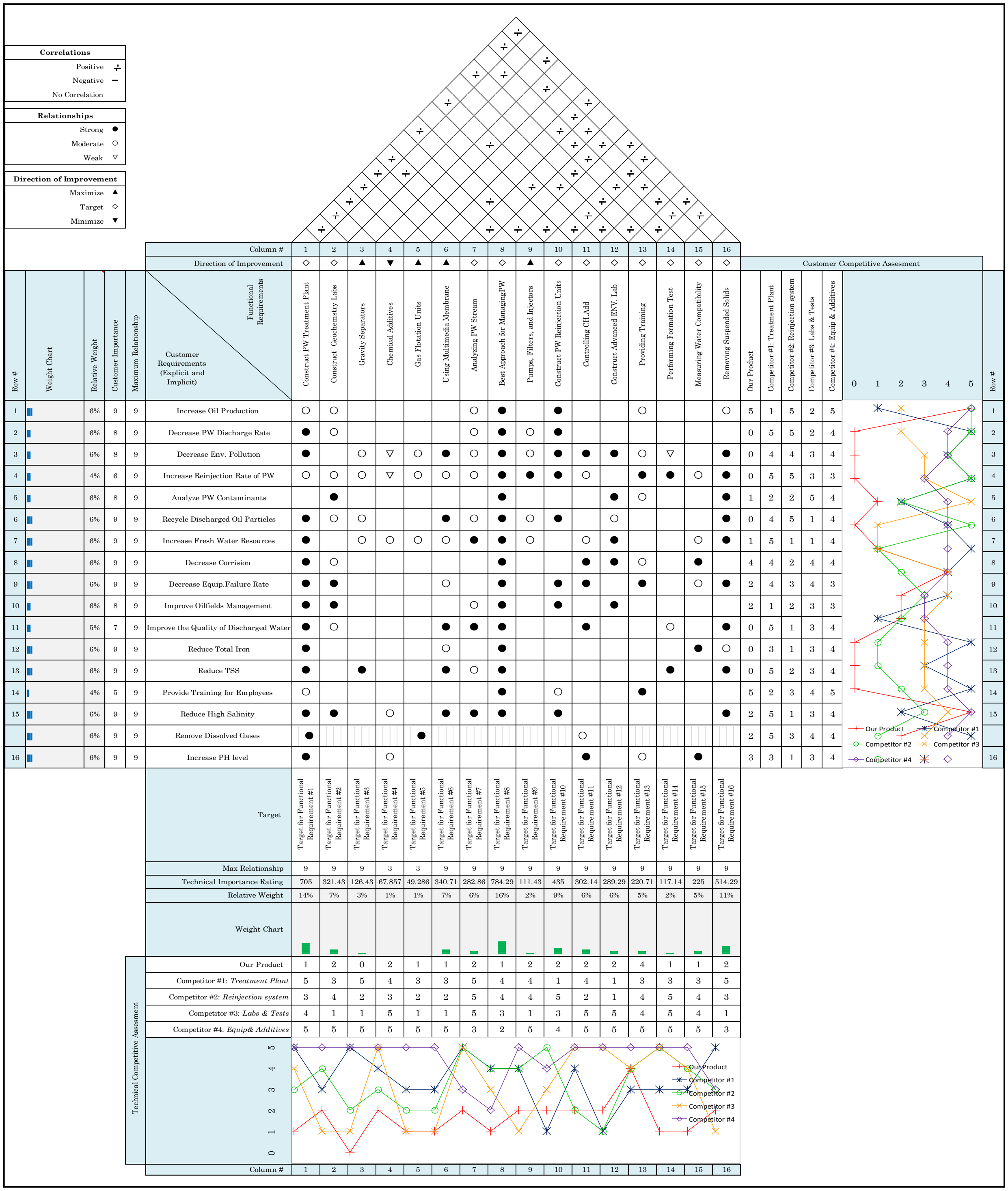
4.5.1 Critical to Quality Characteristics

In order to capture the VOC and CTQs in a more detailed mode, the QFD (Quality Function Deployment) approach was used to determine the relationship between the customers' and technical requirements that were needed to meet or exceed the customers' expectations. The House OF Quality (HOQ), which is a matrix diagram that can be used to present data and information that are related to the technical requirements, customer requirements, and competitors evaluation, was used in this study (J. R. Evans & Lindsay, 2011).

The principle focus of QFD is identifying the customer needs properly in the early stages, and that would help to reduce waste, such as rework, redesign, and rethink to find the quick solution that will be another problem in the near future.

The HOQ was used in order to compare between VOC and technical requirments, process control plans, required equipment, and manufacturing operations as shown in Figure 4.8.

The Technical Importance Rating (TIR) was determined to identify which requirements have high weight and need to set high targets that could help to meet critical needs of customers (J. R. Evans & Lindsay, 2011). Also, it was considered the source of a competitive advantage. Internet monitoring for all local and foreign tenders that have been requested by Iraqi Ministry of Oil and the SOC helped to gather more details about CTQs; that also helped to construct HOQ and to identify the most important technical factors that could impact the CTQs [("Republic of Iraq-Ministry of Oil," 2012) & ("South Oil Company," 2012)].



Correlations	
Positive	✛
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

					Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
					Direction of Improvement	◇	◇	▲	▼	▲	▲	◇	◇	▲	◇	◇	◇	◇	◇	◇	◇	Customer Competitive Assesment					
Row #	Weight Chart	Relative Weight	Customer Importance	Maximum Relationship	Functional Requirements Customer Requirements (Explicit and Implicit)	Construct PW Treatment Plant	Construct Geochemstry Labs	Gravity Separators	Chemical Additives	Gas Flotation Units	Using Multimedia Membrane	Analyzing PW Stream	Best Approach for ManagingPW	Pumps, Filters, and Injectors	Construct PW Reinjection Units	Controlling CH.Add	Construct Advanced ENV. Lab	Providing Training	Performing Formation Test	Measuring Water Compatibility	Removing Suspended Solids	Our Product	Competitor #1: Treatment Plant	Competitor #2: Reinjection system	Competitor #3: Labs & Tests	Competitor #4: Equip & Additives	Row #
1		6%	9	9	Increase Oil Production	○	○					○	●		●			○			○	5	1	5	2	5	1
2		6%	8	9	Decrease PW Discharge Rate	●	○					○	●	○	●							0	5	5	2	4	2
3		6%	8	9	Decrease Env. Pollution	●		○	▽	○	●	○	●	○	●	●	●	○	▽		●	0	4	4	3	4	3
4		4%	6	9	Increase Reinjection Rate of PW	○	○	○	▽	○	○	○	●	●	●	○		●	●	○	●	0	5	5	3	3	4
5		6%	8	9	Analyze PW Contaminants		●						●				●	○			●	1	2	2	5	4	5
6		6%	9	9	Recycle Discharged Oil Particles	●	○	○			●	○	●	○	●		○				●	0	4	5	1	4	6
7		6%	9	9	Increase Fresh Water Resources	●		○	○	○	○	●	●	○		○	●			○	●	1	5	1	1	4	7
8		6%	9	9	Decrease Corrision	●	○						●			●	●	○		●		4	4	2	4	4	8
9		6%	9	9	Decrease Equip.Failure Rate	●	●				○		●		●	●		●		○	●	2	4	3	4	3	9
10		6%	8	9	Improve Oilfields Management	●	●					○	●		●		●					2	1	2	3	3	10
11		5%	7	9	Improve the Quality of Discharged Water	●	○				●	●	●			●			○		●	0	5	1	3	4	11
12		6%	9	9	Reduce Total Iron	●					○		●							●	○	0	3	1	3	4	12
13		6%	9	9	Reduce TSS	●		●			●	○	●						●		●	0	5	2	3	4	13
14		4%	5	9	Provide Training for Employees	○							●		○			●				5	2	3	4	5	14
15		6%	9	9	Reduce High Salinity	●	●		○		●	●	●		●						●	2	5	1	3	4	15
		6%	9	9	Remove Dissolved Gases	●				●						○						2	5	3	4	4	
16		6%	9	9	Increase PH level	●			○							●		○		●		3	3	1	3	4	16

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Target	Target for Functional Requirement #1	Target for Functional Requirement #2	Target for Functional Requirement #3	Target for Functional Requirement #4	Target for Functional Requirement #5	Target for Functional Requirement #6	Target for Functional Requirement #7	Target for Functional Requirement #8	Target for Functional Requirement #9	Target for Functional Requirement #10	Target for Functional Requirement #11	Target for Functional Requirement #12	Target for Functional Requirement #13	Target for Functional Requirement #14	Target for Functional Requirement #15	Target for Functional Requirement #16
Max Relationship	9	9	9	3	3	9	9	9	9	9	9	9	9	9	9	9
Technical Importance Rating	705	321.43	126.43	67.857	49.286	340.71	282.86	784.29	111.43	435	302.14	289.29	220.71	117.14	225	514.29
Relative Weight	14%	7%	3%	1%	1%	7%	6%	16%	2%	9%	6%	6%	5%	2%	5%	11%
Weight Chart																
Our Product	1	2	0	2	1	1	2	1	2	2	2	2	4	1	1	2
Competitor #1: *Treatment Plant*	5	3	5	4	3	3	5	4	4	1	4	1	3	3	3	5
Competitor #2: *Reinjection system*	3	4	2	3	2	2	5	4	4	5	2	1	4	5	4	3
Competitor #3: *Labs & Tests*	4	1	1	5	1	1	5	3	1	3	5	5	4	5	4	1
Competitor #4: *Equip& Additives*	5	5	5	5	5	5	3	2	5	4	5	5	5	5	5	3

Figure 4. 8: HOQ Matrix for the Customers' needs in the Zuabir oilfields

In order to understand the relationship between the functional requirements and customer requirements, each target of the functional requirements has been given a specific number, see Table 4.6. The bar chart for these targets and respective importance rating was constructed as provided in Figure 4.9.

Table 4.6: Technical Importance Rating

Target	Target	Technical Importance Rating
Target for Functional Requirement #1	TFR-1	705
Target for Functional Requirement #2	TFR-2	321.4285714
Target for Functional Requirement #3	TFR-3	126.4285714
Target for Functional Requirement #4	TFR-4	67.85714286
Target for Functional Requirement #5	TFR-5	334.2857143
Target for Functional Requirement #6	TFR-6	340.7142857
Target for Functional Requirement #7	TFR-7	282.8571429
Target for Functional Requirement #8	TFR-8	784.2857143
Target for Functional Requirement #9	TFR-9	111.4285714
Target for Functional Requirement #10	TFR-10	435
Target for Functional Requirement #11	TFR-11	302.1428571
Target for Functional Requirement #12	TFR-12	289.2857143
Target for Functional Requirement #13	TFR-13	220.7142857
Target for Functional Requirement #14	TFR-14	117.1428571
Target for Functional Requirement #15	TFR-15	225
Target for Functional Requirement #16	TFR-16	514.2857143

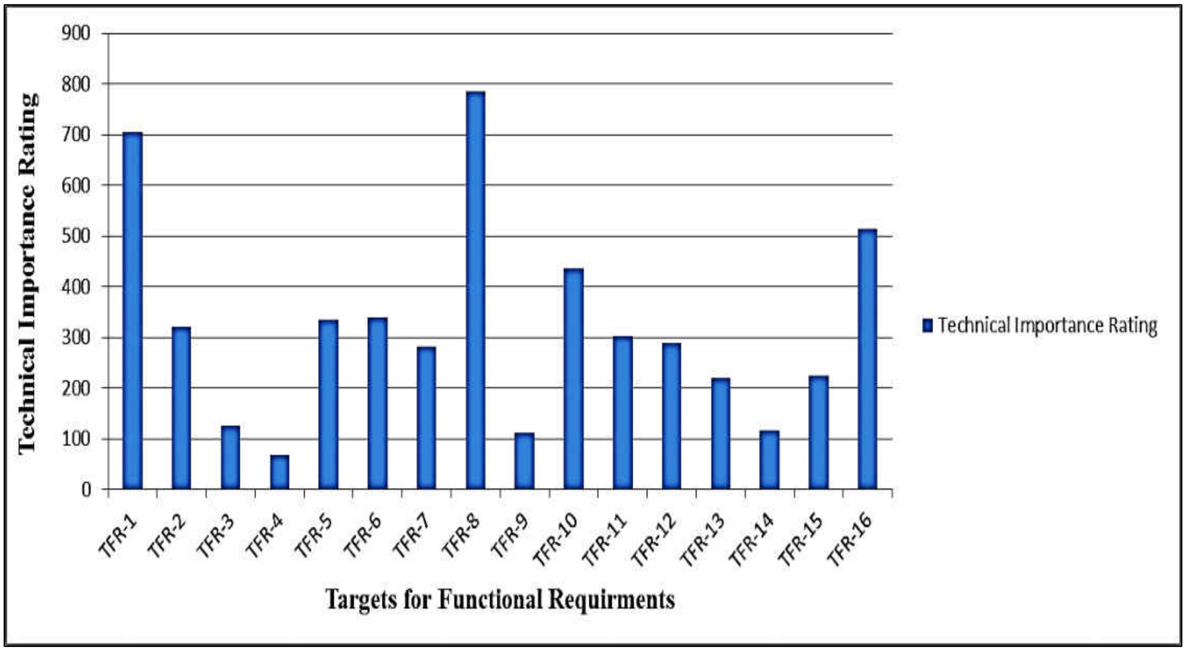


Figure 4. 9: Histogram of Technical Importance Rating

The technical importance rating was very high for each of the following requirements:

1. Best Approach for Managing PW
2. Construct PW Treatment Plant
3. Removing Suspended Solids
4. Construct PW Reinjection Units
5. Using Multimedia Membrane
6. Construct Geochemistry Labs

The results obtained from both VOCM and HOQ indicated that the main requirements were related to Manage, Treat, Reuse, and Reinject PW. The benefit from meeting these requirements was reducing environmental and economic impacts that could result from discharging PW. As a result, the CTQs were identified and represented the important needs of customers as follows:

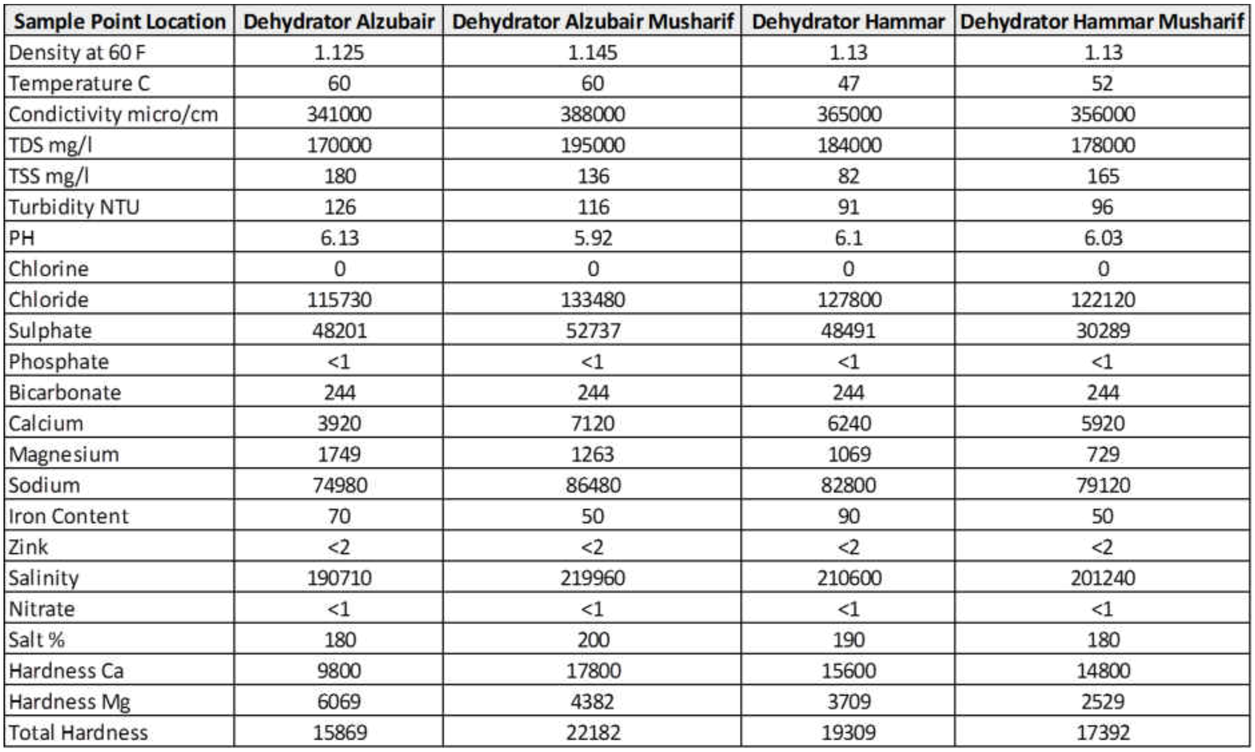
- Finding the best method for Managing PW
- Converting PW to usable water

It was important to notice that there was a strong relationship between these two requirements. Converting PW to usable or clean water was the most important requirement because the management method of PW is highly based on the quality of that water. As a result, further measurements were required to measure and analyze PW properties at different locations of DS of the Zubair oil field. Initiatives toward meeting these two requirements started with measuring the KPOV, the amount of contaminants in PW. Reducing this amount required identifying and measuring physical and chemical characteristics of theses contaminants in PW and identifying the root causes of increasing the amounts of TDS, TSS, Iron content, OGC, and other important constituents.

4.5.2 Key Process Output Variable Measurement

Increase in the amounts of contaminants in PW was identified as the KPOV for this study. In the define phase, the increase in the discharge rate of PW was illustrated, but types and amounts of contaminants in that water were not measured. Therefore, in this section, types and characteristics of these contaminants were measured and explained by testing PW samples that were taken from the output stream of four dehydrator units, which were located at different locations in the Zubair oil field. These samples were tested in January 2012 and the physical and chemical properties of PW were summarized in Table 4.7 (SOC, 2012).

Table 4.7: Produced Water Properties before Treatment



Sample Point Location	Dehydrator Alzubair	Dehydrator Alzubair Musharif	Dehydrator Hammar	Dehydrator Hammar Musharif
Density at 60 F	1.125	1.145	1.13	1.13
Temperature C	60	60	47	52
Condictivity micro/cm	341000	388000	365000	356000
TDS mg/l	170000	195000	184000	178000
TSS mg/l	180	136	82	165
Turbidity NTU	126	116	91	96
PH	6.13	5.92	6.1	6.03
Chlorine	0	0	0	0
Chloride	115730	133480	127800	122120
Sulphate	48201	52737	48491	30289
Phosphate	<1	<1	<1	<1
Bicarbonate	244	244	244	244
Calcium	3920	7120	6240	5920
Magnesium	1749	1263	1069	729
Sodium	74980	86480	82800	79120
Iron Content	70	50	90	50
Zink	<2	<2	<2	<2
Salinity	190710	219960	210600	201240
Nitrate	<1	<1	<1	<1
Salt %	180	200	190	180
Hardness Ca	9800	17800	15600	14800
Hardness Mg	6069	4382	3709	2529
Total Hardness	15869	22182	19309	17392

- Additional tests were performed in order to determine OGC (Oil and Grease Content). The results showed that the average of OGC in these locations was equal to 1,000 mg/l, which was extremely high (SOC, 2012)
- In addition, the particle size of the TDS and TSS was measured and the average particle size was equal to 60 micrometers.
- Biochemistry tests were also conducted to identify types of Bacteria at the same locations. The results showed existence of all types of bacteria that are listed as follows:
    - Aerobes

- Anaerobes
- Facultative Anaerobes
- Planktonic
- Sessile

The average of data obtained of PW properties before treatment and important factors that could affect the characteristics and concentrations of contaminants in PW were presented in Table 4.8. (SOC, 2012):

Table 4.8: The Average of Produced Water Important properties before Treatment

Component	Unit	Value
PH	None	5
TSS	Mg/l	300
Turbidity	NTU	700
Particle Size	Micron-m	60
TDS	Mg/l	250,000
Oil and Grease	Mg/l	1,000
Total Iron	Mg/l	300
Dissolved Gases	Mg/l	>2
Bacteria	None	All Types
CO2	Mg/l	470

Furthermore, sludge and formation samples were taken from different locations at the southern oil fields and were tested for radon concentration. The results showed that PW contained radium isotopes, which were mainly "Alpha and Gamma emitter" (Subber, Ali, & Salman, 2011). Radon gas (^{222} Rn), which was reflected in the presence of NORM in the sludge that could be accumulated by discharging oily sediment and PW during oil production operations, was found in high concentrations in these locations, see Appendix A. The Pareto chart was used to show the average of radon concentrations at different locations, see Figure 4.10

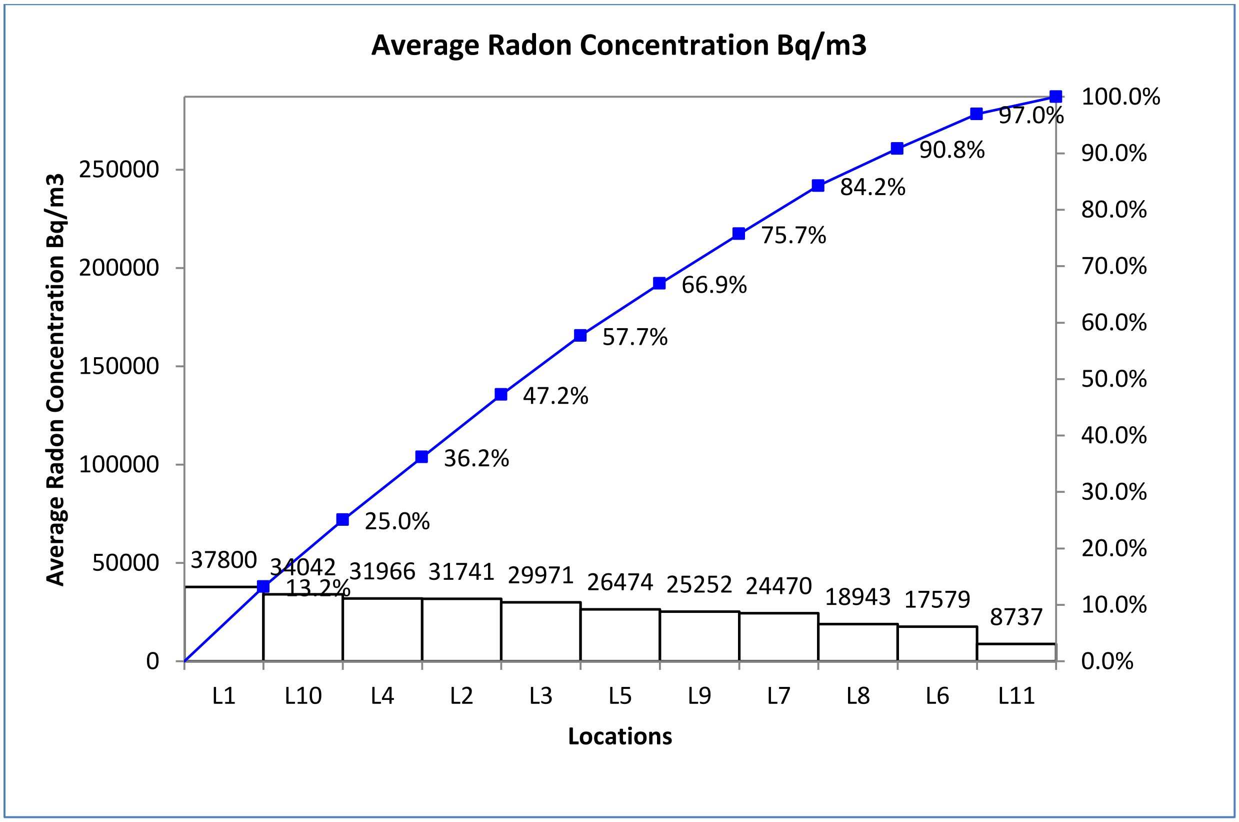


Figure 4. 10: Pareto Chart of Average of Radon Concentration

Where L1 was the location of sludge samples that had been tested for radon gas concentration and that had been taken from the DS of the southern Rumaila oil field. From the Pareto chart analysis, it was important to notice that the highest concentration of the radon gas (^{222}Rn) existed in the Central Gas Separation Stations (CGSS) of the southern Rumaila oil fields. Furthermore, the mathematic mean for all tested sludge samples was 26,089 Bq/ m^3 which was 60 µ Sv h^{-1}. That exceeded the recommended limits of worker exposure and increased the likelihood of getting lung and stomach cancer (Subber et al., 2011).

Pareto chart indicated that the sludge and formation samples that were taken from CGSS of the southern Rumaila oil field have high average radon concentration and that was 37,800Bq/m^3. In general, the probability of getting cancer for someone who is subjected to radon radiation is 0.0016 Bq/m^3 for each 37 Bq/m^3 (Cross, 1992), thus from the obtained average, the probability increases to 705 multiple (Subber et al., 2011). In addition to the (^{222}Rn), PW also contained radium isotopes ^{226}Ra from ^{238}Uranium decay series. Figure 4.11 showed the most ^{238}U decay series that could be associated with oil and gas production activities and products, as adopted from Jamal (Jamal, 2010).

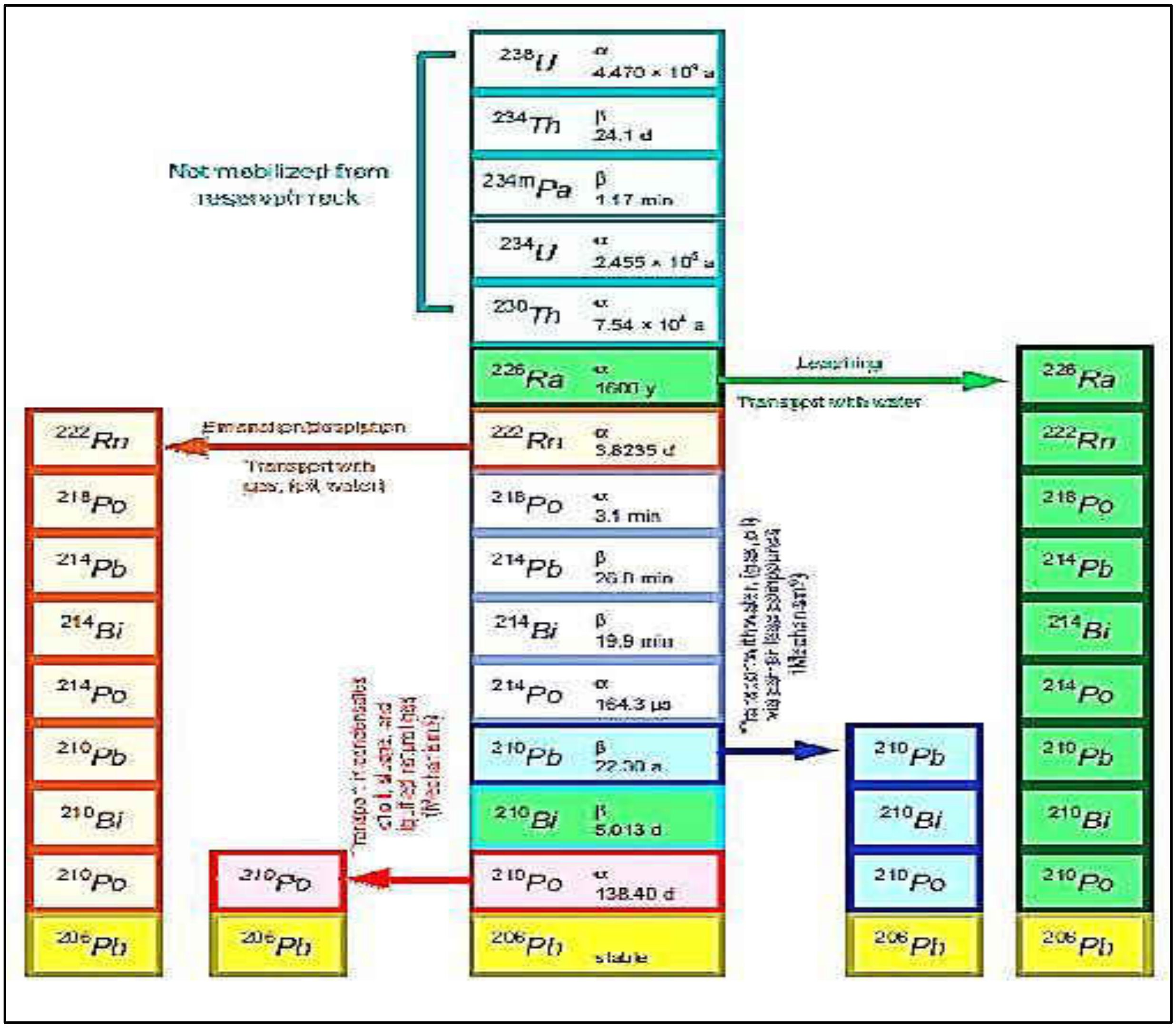


Figure 4. 11: ^{238} U Decay Series in Oily Sludge and Produced Water

In conclusion, all three main radium isotopes could generally appear in the PW. Drop in pressure and temperature could increase the solubility of PW constituents, such as sulphates and carbonates that existed in high concentrations. This solubility was considered the main source of the ^{228} Th and that was detected in aged sludge and scales and likely appeared as a decay of the mobilized ^{228} Ra (Jamal, 2010).

Based on PW properties that were provided in Table 4.7, the SAR calculations were also performed to determine the value of SAR in the discharged PW. All required steps to do these calculations at the selected locations were explained as in following:

By using equation (1), the SAR values were calculated

Knowing that:

The molecule weight of Magnesium=24

The molecule weight of Calcium =40

The molecule weight of Sodium =23,

In order to calculate the Equivalent Weight for each component, the Valence of each of them should be known:

The valence of Sodium= 1

The valence of Magnesium= 2

The valence of Calcium= 2

Then, the Equivalent weight for each compound can be calculated by using the following equation:

$$Eq.Wt = \frac{MolecularWt}{Valence} \qquad (2)$$

Eq.Wt of Sodium = $\frac{23}{1} = 23$

Eq.Wt of Calcium = $\frac{40}{2} = 20$

Eq.Wt of Magnesium = $\frac{24}{2} = 12$

Before substituting in the SAR equation, milliequivalent weight for each compound was required, as a result, the following formula was used to calculate Milli-Equivalent weight:

$$M.Eq.Wt = \frac{concentration(ppm)}{Eq.Wt} \tag{3}$$

Milliequivalent Weight Calculations at Dehydrator Alzubair:

Milliequivalent Weight of Sodium at Dehydrator Alzubair = $\frac{74980}{23} = 3260$

Milliequivalent Weight of Calcium at Dehydrator Alzubair = $\frac{3920}{20} = 196$

Milliequivalent Weight of Magnesium at Dehydrator Alzubair = $\frac{1749}{12} = 145.75$

SAR at Dehydrator Alzubair = $\frac{3260}{\sqrt{\frac{196+145.75}{2}}} = 249.39$

By using equation (2), milliequivalent weights for all three compounds were obtained at the Dehydrator of Alzubair Musharif as in the following:

Milliequivalent Weight Calculations at Dehydrator Alzubair Musharif:

Milliequivalent Weight of Sodium at Dehydrator Alzubair Musharif = $\frac{86480}{23} = 3760$

Milliequivalent Weight of Calcium at Dehydrator Alzubair Musharif = $\frac{7120}{20} = 356$

Milliequivalent Weight of Magnesium at Dehydrator Alzubair Musharif = $\frac{1263}{12} = 105.25$

The SAR value at the Dehydrator of Alzubair Musharif was calculated by using equation (1):

$$\text{SAR at Dehydrator Alzubair Musharif} = \frac{3760}{\sqrt{\frac{356 + 105.25}{2}}} = 247.6$$

Milliequivalent Weight Calculations at Dehydrator Hammar:

Milliequivalent Weight of Sodium at Dehydrator Hammar = $\frac{82800}{23} = 3600$

Milliequivalent Weight of Calcium at Dehydrator Hammar = $\frac{6240}{20} = 312$

Milliequivalent Weight of Magnesium at Dehydrator Hammar = $\frac{1069}{12} = 89.08$

$$\text{SAR at Dehydrator Hammar} = \frac{3600}{\sqrt{\frac{312 + 89.08}{2}}} = 254.215$$

Milliequivalent Weight Calculations at Dehydrator Hammar Musharif:

Milliequivalent Weight of Sodium at Dehydrator Hammar Musharif = $\frac{79120}{23} = 3440$

Milliequivalent Weight of Calcium at Dehydrator Hammar Musharif = $\frac{5920}{20} = 296$

Milliequivalent Weight of Magnesium at Dehydrator Hammar Musharif = $\frac{729}{12} = 60.75$

$$\text{SAR at Dehydrator Hammar Musharif} = \frac{3440}{\sqrt{\frac{296+60.75}{2}}} = 257.56$$

From the results obtained from the calculations of SAR at the selected dehydrator units, it was reasonable to conclude that the SAR values were very high and it exceeded the normal expected value.

4.5.3 Key Process Input Variables Measurement

In order to measure the internal activities, processes, and variables that could affect KPOV, the KPIVs were identified and measured. Measuring KPIVs was based on the literature that discussed the root causes of producing and increasing the concentrations of various contaminants in PW, such as scales, deposits, chemicals, NORM, and others. In addition, the author used his knowledge and background to formalize in detail all activities that could influence the KPOV as demonstrated in the following sections.

4.5.3.1 Current Management Method of Produced Water

Since the management method of PW in the Southern Iraqi oil fields is discharging it into API ponds, this method is ineffective and helps to increase the amount of contaminants in the areas surrounding CDS of the Zubair field. The reasons behind that were listed and discussed in the following:

- Most of the PW volume can be evaporated by the solar energy. Therefore, if the objective is reusing or recycling it by reinjecting it again into oil wells, this method is inefficient and the remaining volume will not be enough for the reinjection process (Igunnu & Chen, 2012). Evaporation of PW can cause gas emissions and that causes air pollution.
- Waste disposal is generally required for materials that settle out of feed water (Igunnu & Chen, 2012).
- Due to the fact that PW contains toxic hydrocarbon material, the disposal and the concentration of these materials should be reduced to meet environmental regulations. Currently, the PW is being disposed without treatment (SOC, 2012). As a result, injecting it into NEPs presents a real hazard to the environment and that attributes to the effects of different hazardous contaminants in that water (Keiter, Ruple, & Tanana, 2011). Therefore, if these contaminants are not managed properly, the amount of accumulated hazardous materials, such as heavy metals will increase and the NEPs will not occupy the increased PW.
- The current expansion program for the southern Iraqi oil fields was also considered a root cause of increase in the amount of contaminated PW. Increasing oil production rate causes increases in the amount of PW. Furthermore, the volume of PW increases whenever the age of oil wells gets older [(Somerville et al., 1987); (Stromgren et al., 1995); & (Veil et al., 2004)].
- Sometimes, existence of precipitated materials (scales) in the transportation pipe systems may cause failure in the injection processes of PW into NEPs. According to SOC, if that

case happened the quick fix for the problem is discharging it into the Dammam formation (SOC, 2012). As a result the ecological risks would be very high.

4.5.3.2 The Root Causes in Transferring Pipe Systems, Oil Field Equipment and Natural Causes

High salinity and large amounts of TDS, TSS, IC, and other constituents can cause an increase in the amounts of scales, moving particles, and corrosive materials. Normally these materials could be found in the transferring pipe systems, casing, tubing, and field equipment. Some references were used to investigate and identify the root causes of contaminants and accumulated deposits and waste that could exist in pipes and field equipment as discussed in the following:

- With different operation and production conditions, ions can react to form precipitated solids (scales), and deposits that are generally formed and accumulated in tubing, flow lines, vessels, and PW treatment equipment (Stewart & Arnold, 2011).
- By the direct contact with a metal surface, the corrosion of iron in an aqueous environment can be increased uniformly. Thus, the amount of corrosive materials increases over time to form continuous layers of corrosion scales (P. Sarin, Snoeyink, Lytle, & Kriven, 2004); (Fang, Brown, & Nesi, 2010).
- NORM concentration in the sludge waste that has been produced from an oil field is very high [(Subber et al., 2011) & ("United States Environmental Protection Agency," 2012)]. The oily sludge consists of sand that pumps up during oil production, extraction of heavy hydrocarbons, such as paraffin, and scales and duct surfaces. These sands normally exist

in the storage tanks, valves and pumps (Subber et al., 2011). Since this NORM is naturally produced along oil and gas production activities and associated with the PW, it is considered the main source of scales and radioactive materials that can affect equipment and workforces negatively.

From the above, it was important to notice that the amounts of scales, precipitated and corrosive materials, and NORM could be found in pipes, valves, pumps, storage tanks, and other field facilities. Therefore, ineffective monitoring, cleaning, and maintenance plan could help to increase these amounts. Then the PW, oily sludge, and other disposals could have high concentrations of these risky contaminants and that causes a need for reevaluation of a management method that could be used to handle, transport, and dispose them safely. The root causes of high amounts of various contaminants in PW were classified into two categories. First root causes category was the current management method of discharging PW. The second category was the root causes that were attributed to existence of various contaminants in the oil fields equipment, pipes, and all activities that could help to increase the amount of these contaminants, such as an ineffective maintenance plan and type of chemicals used during oil and gas production operations. The affinity diagram in Figure 4.12 was created to list these two categories for the root causes and their sub-root causes.

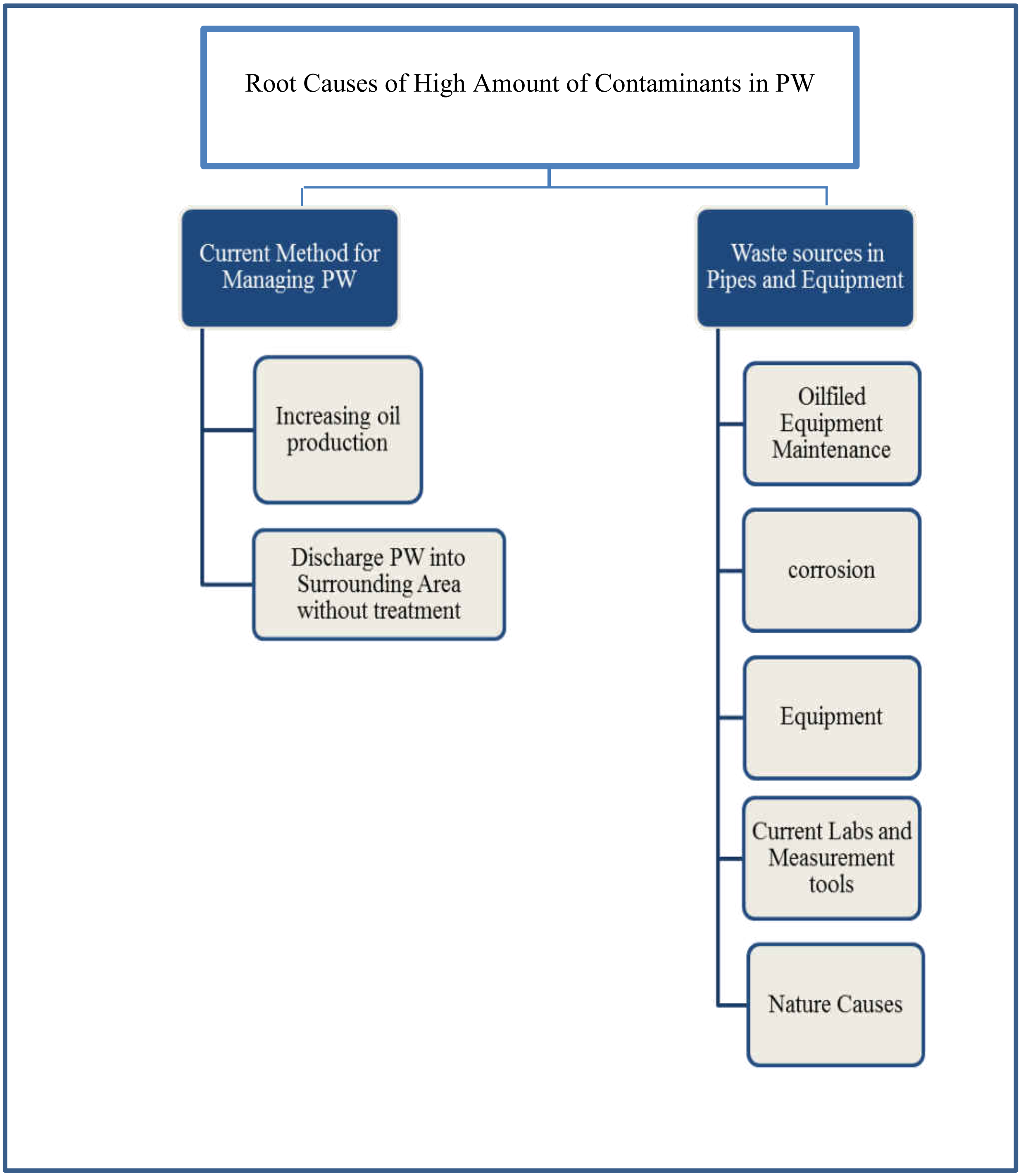


Figure 4. 12: Affinity Diagram for Root Causes of Contaminants in Produced Water

All root causes that were listed in the above affinity diagram are investigated and identified in details in the analyze phase. Identifying these causes could help to develop a failure prevention plan, effective maintenance plan, or at least develop recommendations to protect humans who are working in or living close to Southern Iraqi oil fields

4.6 ANALYZE Phase

In this phase of the Six Sigma project, conducting a problem solving approach was performed to determine why there was such a large amount of contaminants in PW, and how the current management method for that water in the Zubair oil field was helping to increase these amounts.

According to the outputs of the measure phase, the KPIVs were determined. Therefore, the main focus of this phase was analyzing the following:

- The main sources of contaminants in the DS of the Zubair oil field.
- The current method for managing PW in the Zubair oil field.

4.6.1 The Main Sources of Wastes in Pipes and Field Equipment

In this section, the main sources of waste that could influence the amount of contaminants in PW were identified. Identifying these sources helped to develop the control plan, and to select the best technology from different alternatives at the MCDM stage. In other words, it was very important to know how these sources produce contaminants that might have interrelationship between each other and how they could affect the performance of the selected technology in the future. Since most of contaminants are heavy metals, hydrocarbons, and chemicals, this section helped to uncover the hidden sources of these contaminants.

4.6.1.1 KPIV- Corrosion

Having high iron content (IC) in any pipe system, equipment, or plant causes a high rate of corrosion that could cause an increase in the equipment failure rate (Grigg, Water Research, & United States. Environmental Protection, 2010). Corrosion can increase scale formation, deposits, and sludge wastes. From the main specifications of PW that were obtained from the Measure phase, the average of high IC was more than 300 mg/l, which was very high. The reason behind that were the multiple corrosions during oil operation and production processes and types of corrosion inhibitors used.

Different factors could influence the IC, such as the high amount of TDS and existing high concentration of various types of Dissolved Gases (DG) during extracting, operation, and production processes. Therefore, dissolved materials, such as, TDS and DG were measured and existed in high concentrations as listed below:

- TDS = 250,000 mg/l
- DO > 2 mg/l
- CO2 = 470 mg/l

It was important to identify the root causes of existing high corrosion rate in the DS of the Zubair field. Therefore, the Cause and Effect Analysis (CEA) was performed in order to analyze these roots and their effects on the corrosion rate at the selected locations. The fishbone diagram was used to investigate the factors behind the increase of the corrosion rate as follows:

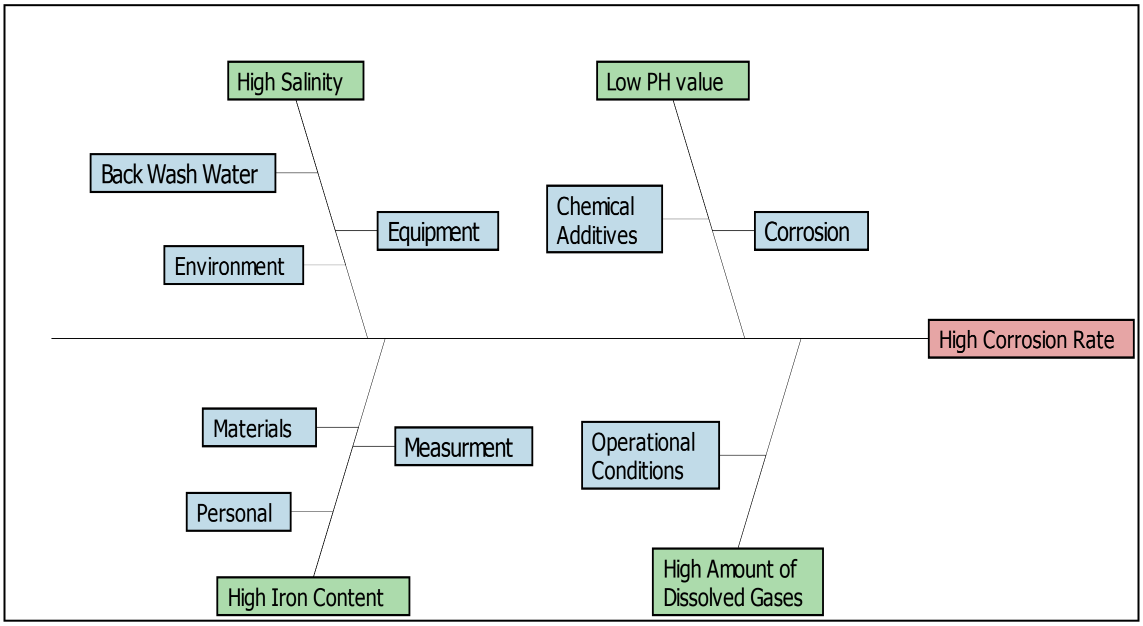


Figure 4. 13: Fishbone Diagram for Corrosion Rate

The main and sub-causes were investigated in detail and demonstrated in the following sections:

The high corrosion rate that was categorized as existence of high salinity in PW stream was caused by the following:

1. BWW (Back-Wash Water)
    - Since clean water was required to complete removal of water-oil-salt mixture during desalination process, that water was supplied from the Garmat Ali River. Water samples from that river were taken and tested. The results showed that the salinity in the Garmat Ali River exceeded 200,000 ppm. In addition, the corrosion rate was equal to 12 milli-inches/year.

- Although BWW has been treated before pumping it into the mixing valves between the output stream of the dehydrators and the input stream of the desalter, the existing pipes that were transporting that water from the Garmat Ali treatment plant to these mixing valves were considered as the main source of having high scales, deposits, and high salinity in the BWW after treatment.

2. Equipment
    - Type of filters and their efficiency
    - Inefficient methods for reducing TDS and TSS existed
    - The average particle size that was obtained from the output stream of the four selected dehydrator units was equal to 60 micron, which was very large. This average was considered the main indicator of having inefficient filtration units to separate different suspended solids, such as NaCl and oil and grease particles.
3. Environment

The nature of the Zubair formation is permeable sandstones and interbedded shale. This nature of formation can produce sand particles, and cause an increase in TSS during petroleum exploration, extraction, and production processes (Al-Ameri, Pitman, Naser, Zumberge, & Al-Haydari, 2011).

The low PH values, which could increase the corrosion rate in different locations, resulted from the following factors:

1. Corrosion
    - Presence of high concentration of dissolved gases that contain oxygen particles, such as CO_2 at the formation surface were the root cause of having high corrosion rate and corrosive materials in the PW stream. Clearly, once the oxidation reaction occurred between the organic compounds and the atmosphere during production processes, the CO_2 could be formed. Presence of CO_2 in PW could help to provide oxygen that could interact with iron and then an increase in the corrosion rate could occur.
    - Corrosion that was attributed to the presence of multiple corrosions in transportation systems, separation vessels, storage tanks, and production tubing and casing was identified. These corrosions could increase the concentration of iron and decrease the pH level because the concentration of DG and the probability of presence of moving corrosive particles could increase.
2. Using different kinds of chemical additives in order to control scales, break emulsion, pH, and remove hardness. These additives could cause an increase in the concentrations of dissolved gases, such as CO_2, H_2S, and DO whenever direct contact with the atmosphere occurred.

The high corrosion rate that came under having a high amount of total iron was related to the following causes:

1. Personnel
    - Focusing on quick fixing of problems at the moment of their occurrences rather than performing failure prevention plan or at least scheduling equipment cleaning plan, see Figure 4.14. For example, leaks help to increase the amount of DG in pipes and production systems.
    - Failure detection plan such as, leaks detection plan did not exist.
    - Lack of data sharing between internal and external customers to increase recommendations about how corrosive materials could be properly handled and how the problem solving and RCA could help to reduce corrosion.
    - Unfixed leaks have been noticed in some systems and subsystems that might cause an increase in the amount of DG, and variation in the operational and control conditions.
    - Leaving some replaced old pipes, fittings, and old metallic materials that failed because of the corrosion problems closer to the new replaced materials. By the direct contact by moisture and existence of atmosphere with these older disposed corrosive materials, the reoccurring of corrosion problem could occur.
2. Materials
    - Old tubing, casing, and transferring pipe systems, see Figure 4.15
    - Some manual control valves were not working properly because they contained accumulated scales and deposits, see Figure 4.16.
    - Unpainted and unprotected pipes, pumps, and systems that were in direct contact with the corrosive formation and acid rain, see Figure 4.17
    - Unprotected power stations were noticed in some DS, see Figure 4.18

3. Measurement

- The oil sludge samples, PW samples, and formation samples analyses were sometimes performed based on prediction and historical data.
- Some of the control meters were not working properly and needed to be checked.
- Using old hydrollic meters that have high probability of failure and inaccurate readings.
- Some of the plate tags that should contain descriptions about specific measurement meters were not present and some of them were not clear enough to read because of scratches and the effects of corrosion.

The high corrosion rate that resulted by operational condition issues and that were effecting the amounts of DG are explained as follows:

- Existing ineffective manual control valves that were used to control gas and oil flow rates, so the operational conditions might be varied over operation and production time.
- The selection of chemical additives was based on types of pumps, filters and injectors rather than selecting these additives with regards to how they could participate in increasing the corrosion rate.
- Some air was supplied into oil wells during oil and PW production.

Figure 4. 14: Ineffective Maintenance Plan

Figure 4. 15: Old Transportation Pipe Systems

Figure 4. 16 : Valves Contain Scales and Accumulated Deposits

Figure 4. 17: Unprotected Transportation Pipe System

Figure 4. 18: Unprotected Power Stations

After identifying the root causes of having a high corrosion rate in the DS, the STA was used to relate between these main causes in order to complete an analysis of all the data obtained from the previous phase. In addition, using this approach also helped to demonstrate the relationship between these causes, see Figure 4.19.

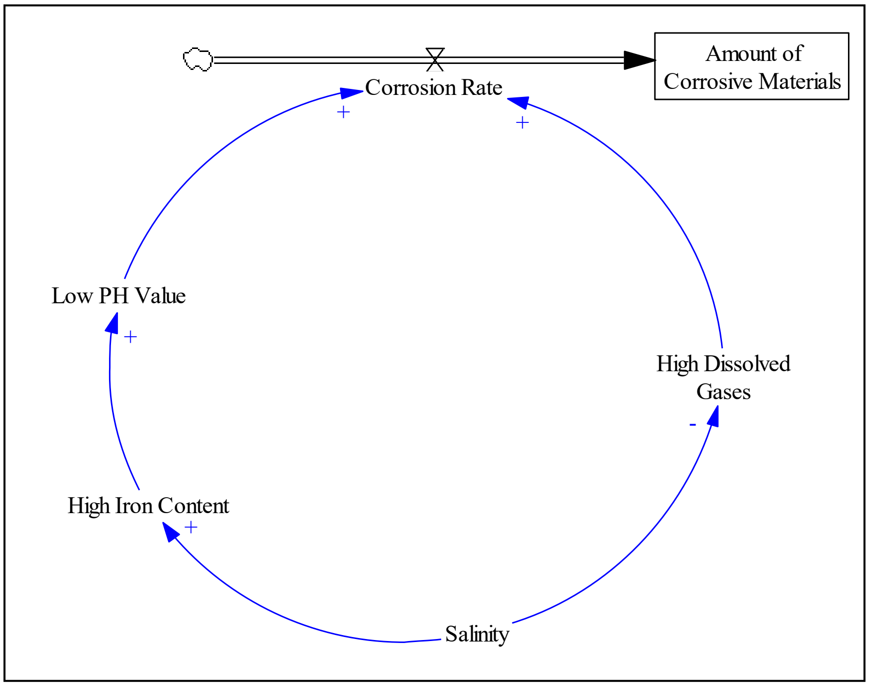


Figure 4. 19: Casual Loop for the Corrosion

From Figure 4.19, it was important to explain the following facts:

- Increase in the salinity can cause decrease in the amount of DG, in this case, DO and Dissolved CO_2. However, having high concentration of DG can increase the corrosion rate (Fang et al., 2010).
- High salinity can increase IC, which is generally causing reduction in the pH value (Al Zubaidy, Mohammad, & Bassioni, 2011).

- The lower PH value can cause an increase in the corrosion rate with the presence of a reaction between dissolved oxygen and absorbed atomic hydrogen and vice versa, see Figure 4.20 as adopted from (DOE, 1993).
- Both high values of chloride and sulphate can increase the release of iron that can cause an increase in the corrosion rate (P. Sarin et al., 2004).

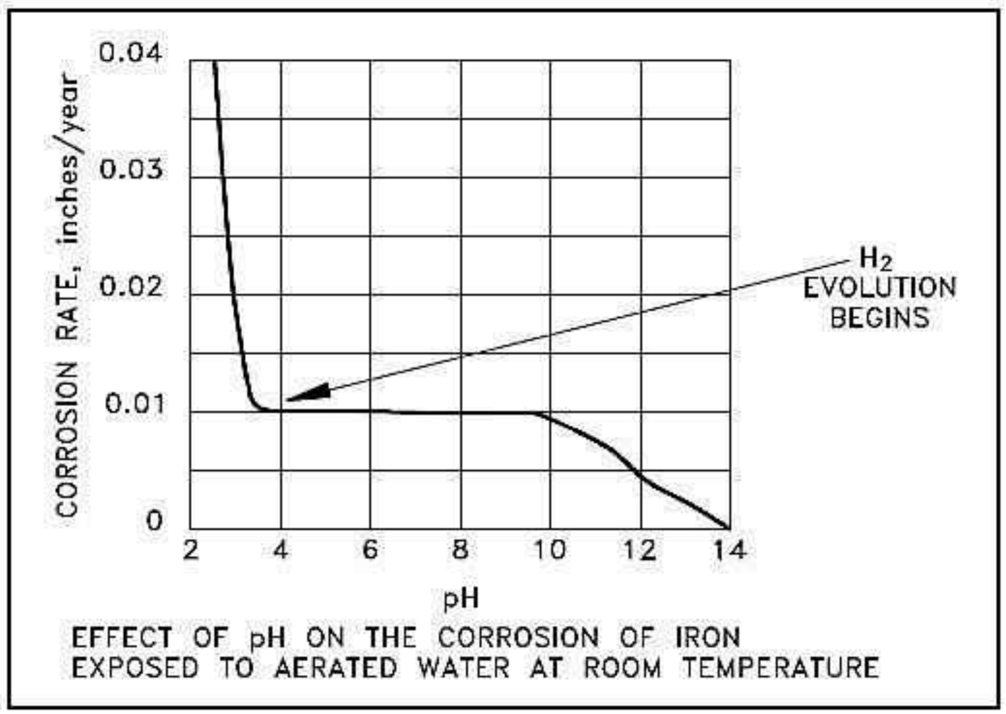


Figure 4. 20: The Relationship between Corrosion Rate and PH

These facts were used to analyze the data obtained and to identify which dehydrator has the highest corrosion rate among the all selected dehydrators and which dehydrator can be selected to test the performance of the proposed technology. Also, the descriptive statistics were used in order to visualize this data. Therefore, histograms were constructed and explained in details as provided in the following figures:

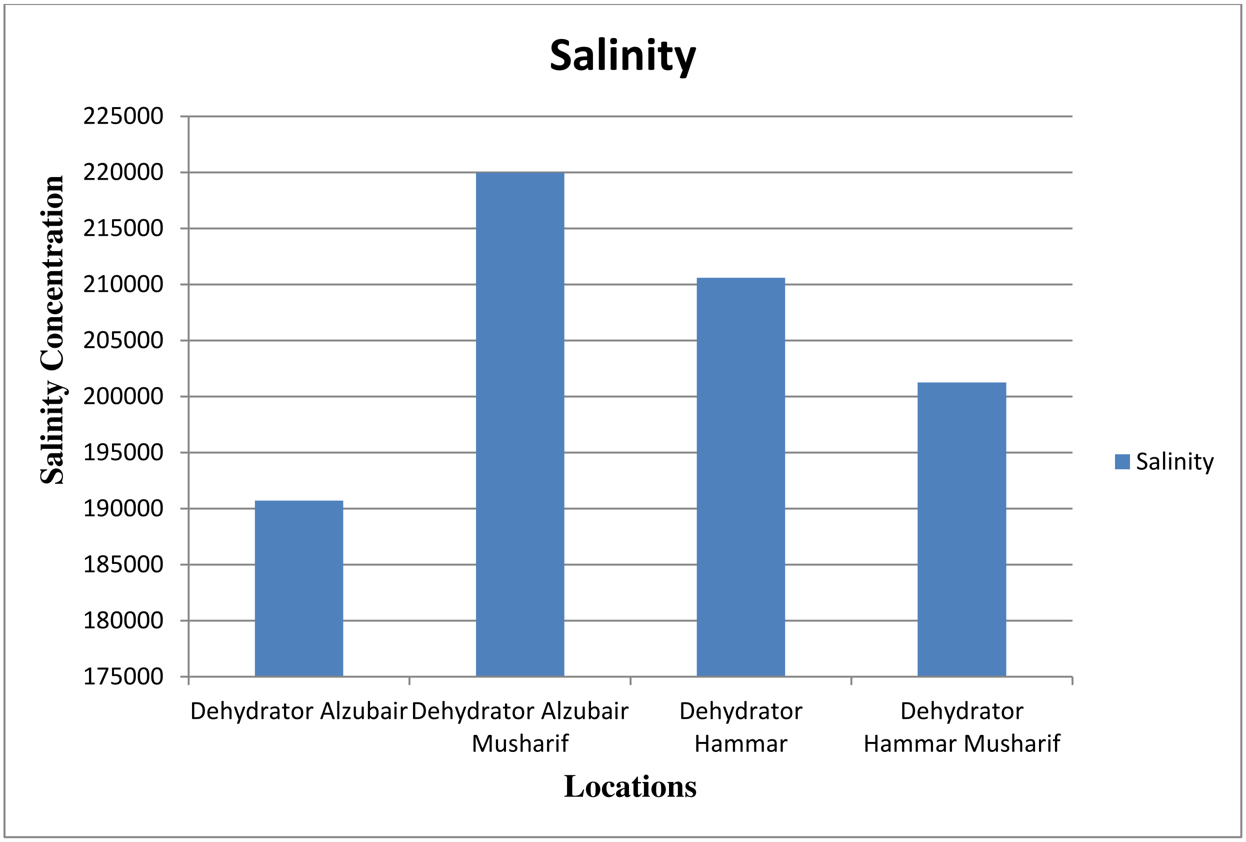


Figure 4. 21: Histogram of Salinity Concentration at the Selected Dehydrators

From Figure 4.21, the dehydrator of the Alzubair Musharif station has been discharging PW with the highest amount of salinity, see the salinity scale in below:

Alzubair Musharif > Hammar > Hammar Musharif > Alzubair

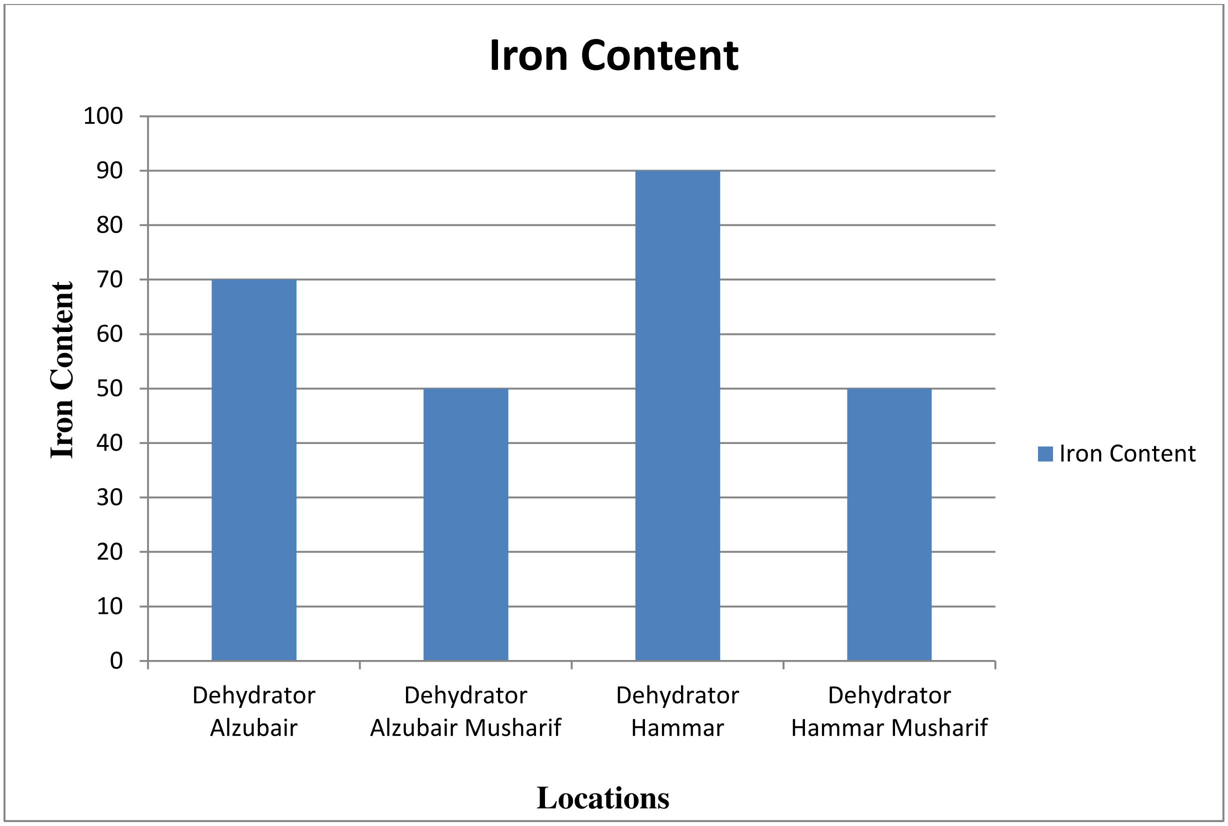


Figure 4. 22: Histogram of Iron Content at the Selected Dehydrators

Figure 4.22 showed that the dehydrator of Hammar station has been discharging PW with the highest IC; see the IC scale in below:

Hammar > Alzubair > Alzubair Musharif = Hammar Musharif

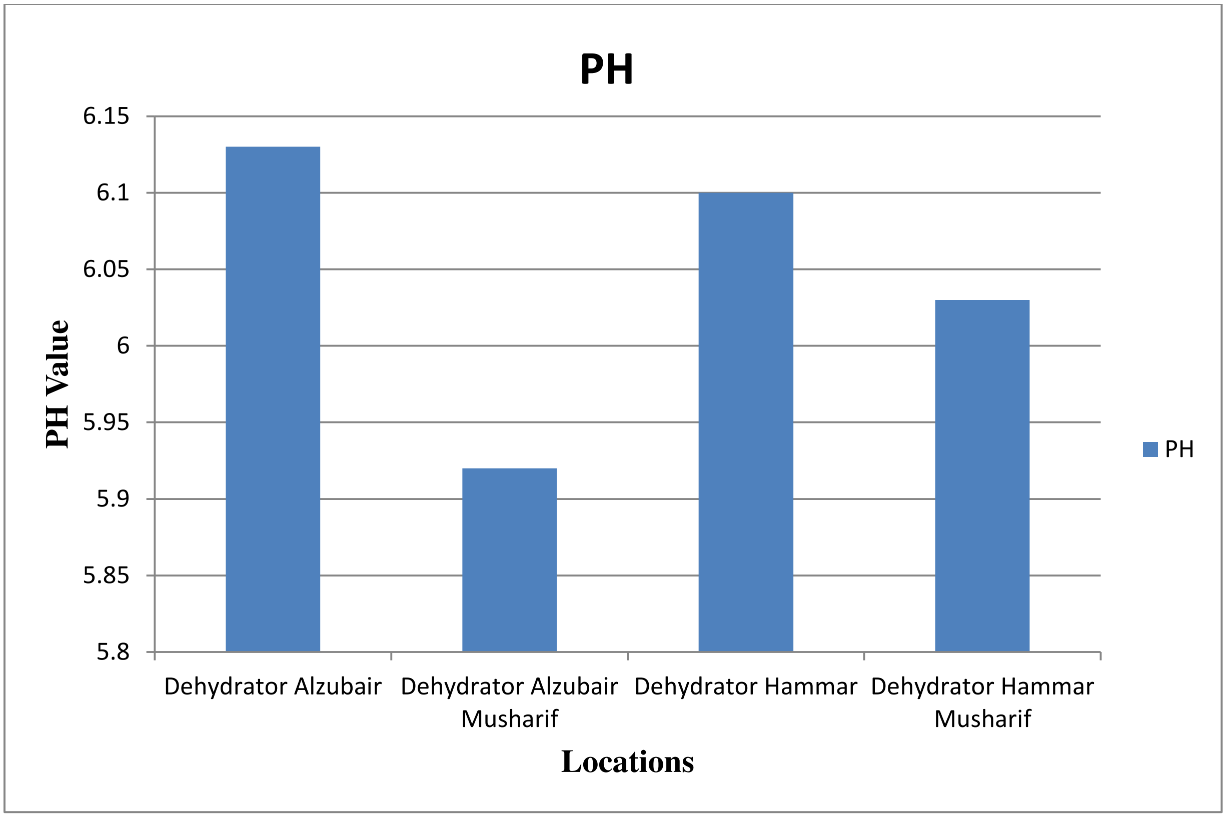


Figure 4. 23: Histogram of the pH Values at the Selected Dehydrators

The histogram in Figure 4.23 showed that the dehydrator of Alzubair station has the highest pH value, while the dehydrator of Alzubair Musharif station has the lowest pH value, see the pH value scale in below:

Alzubair > Hammar > Hammar Musharif > Alzubair Musharif

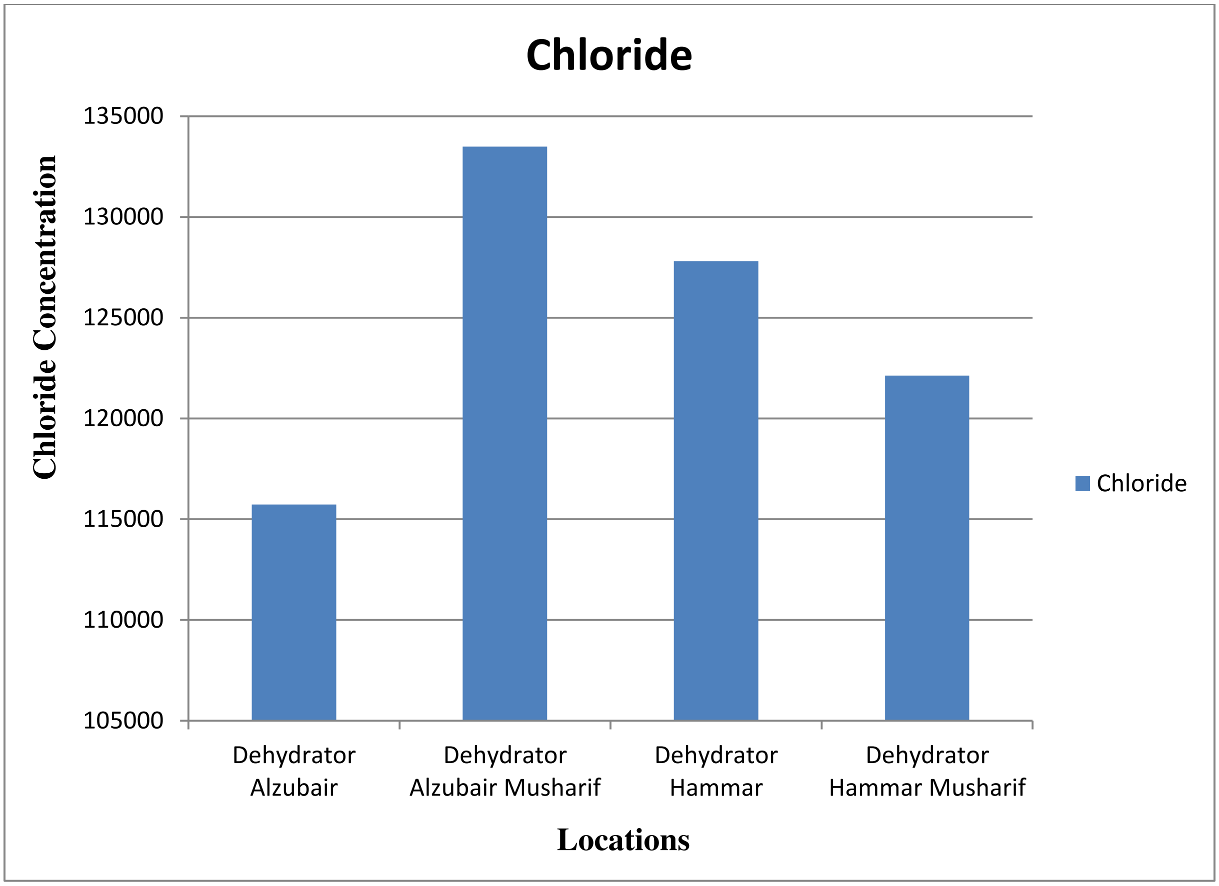


Figure 4. 24: Histogram of Chloride Concentration at the Selected Dehydrators

Figure 4.24 indicated that the output stream of the dehydrator of Alzubair Musharif has been discharging PW with the highest amount of chloride; see the chloride scale in below:

Alzubair Musharif > Hammar > Hammar Musharif > Alzubair

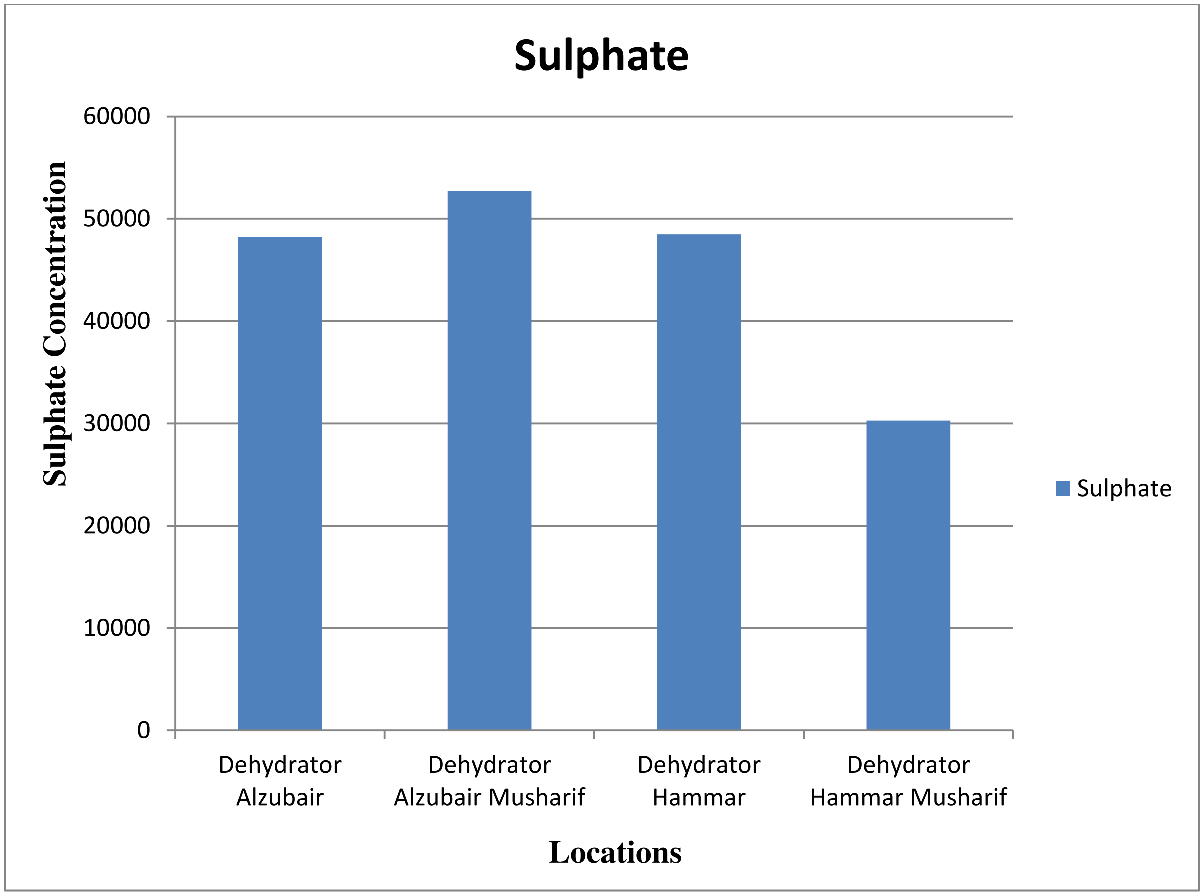


Figure 4. 25: Histogram of Sulphate Concentration at the Selected Dehydrators

The histogram in figure 4.25 showed that the dehydrator of Alzubair Musharif station has been discharging PW with the highest amount of sulphate; see the sulphate scale in below:

Alzubair Musharif > Hammar > Alzubair > Hammar Musharif

From all the analyzed results that were obtained from the above histograms, it was important to conclude that the dehydrator of Alzubair Musharif has produced a high amount of salinity, chloride, and sulphate if it is compared with the other selected dehydrators. On the other hand, the same dehydrator produced dry oil-PW mixture with low PH value, which was less than 6. From these results, the highest corrosion rate was expected to exist at the dehydrator of Alzubair Musharif.

4.6.1.2 KPIV- Field Equipment

- Old wet crude oil separator
- Power supply and power cables failures
- Control valves failure
- Old pipe systems that contain accumulated deposit and precipitated solids (scales)

4.6.1.3 KPIV- Field Equipment Maintenance

- Lack of communication between internal and external customers.
- Information Technology (IT) was limited between oil well management departments.
- Lack of information about Iraqi oil fields.
- Ineffective maintenance plan and some equipment and storage tanks that were replaced recently was the main indicator of ineffective cleaning plan.
- Lack of training in PW management.
- Unsafe maintenance and observation areas surrounding the southern oil fields, see Figure 4.26.

Figure 4. 26: Unsafe Maintenance and Observation Areas

4.6.1.4 KPIV- Labs and Measurement Tools

- Chemists and geologists in the geochemistry and petrochemical labs need to have precise and efficient oil and PW analyzers. These analyzers could help to analyze PW-oil mixture and offer safe tests procedures for them with samples containing radioactive materials and other hazardous contaminants.

- Lack of data sharing between researchers, students, and academic organizations with these labs because of the restricted policy of the SOC and Iraqi Ministry of Oil.

4.6.1.5 KPIV- Nature Causes

- Producing high concentrations of NORM during oil production
- High amounts of heavy metals in underground geological formation
- High salinity of formation water
- Different kinds of bacteria in formation water
- Formation produces sands with large particle sizes

4.6.2 The Current Management Method of Produced Water in the Southern Iraqi Oil Fields

In this section, the current management method of PW was analyzed by using STA. This approach helped to show how this method has helped to in increase the amount of contaminants in PW.

Based on the problem statement, the Fixes That Backfire Archetype was selected as an initial template in order to develop the casual loops for the identified problem. Dynamic hypothesis of the environmental and economic issues from discharging PW was represented in these loops. Since the amount of PW has increased enormously with increased oil production, SOC has been injecting PW into NEPs and disposing it into Dammam formation in the case of having problem in the injection systems in order to keep normal production of oil. Discharging a large volume of PW into NEPs is considered the classic treatment method or quick fix for PW problem and that was represented by evaporating PW by the solar energy. This kind of treatment does not need to use chemicals and energy, but waste disposal is required for the accumulated materials (Igunnu & Chen, 2012).

Since the production of oil is expected to increase, the number of NEPs is also required to increase. Different aspects about this current management method of PW in Iraqi oil fields were deeply analyzed by using STA.

The selected theme "Fixes That Backfire Archetype" fits exactly with the story of the current management method (Systems, 2012). Therefore, the author considered the main problem in casual loop model to be discharging a large volume of PW. Also, the possible factors of the two main loops in this archetype, which were balance loop and reinforcing loop, were demonstrated.

The generic feedback loop diagram of the selected archetype was as in the following diagram:

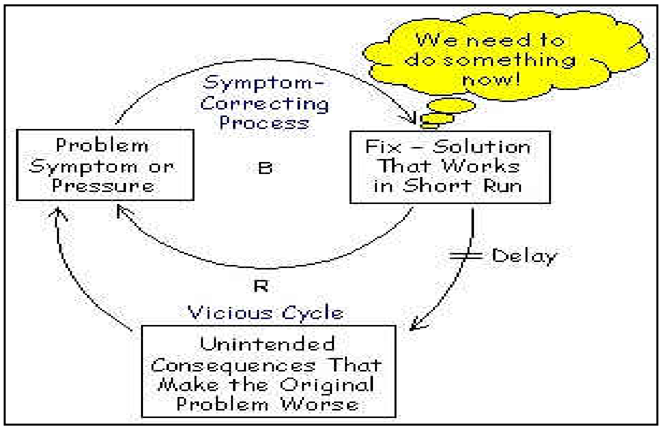


Figure 4. 27: Fixes that Backfire Archetype

This archetype means that the quick fixes of today's problems will be tomorrow's problems. In other words, injecting PW to the NEPs or discharging it into surrounding areas is not a good solution for the long term. Also, consequences and negative side effects are expected to happen whenever this method is not changed or improved. Some hidden aspects could be analyzed that are affecting the development stage of the Southern Iraqi oil fields. Thus, the STA helped to uncover these aspects and study them carefully to see how the new method could be delivered to achieve the desired goals. To do so, the casual loops concepts were used to connect between these aspects and to see their effects on the current and future states of the Iraqi oil fields. Not only that, but also STA helped to understand the reasons behind selecting this case study and to introduce new concepts that could be applied in other oil industries.

4.6.2.1 Developing the Casual Loops

The causal loops were created one loop at a time and presented as in the following.

4.6.2.1.1 Balancing Loop- Oil Production and Produced Water Volume (B1)

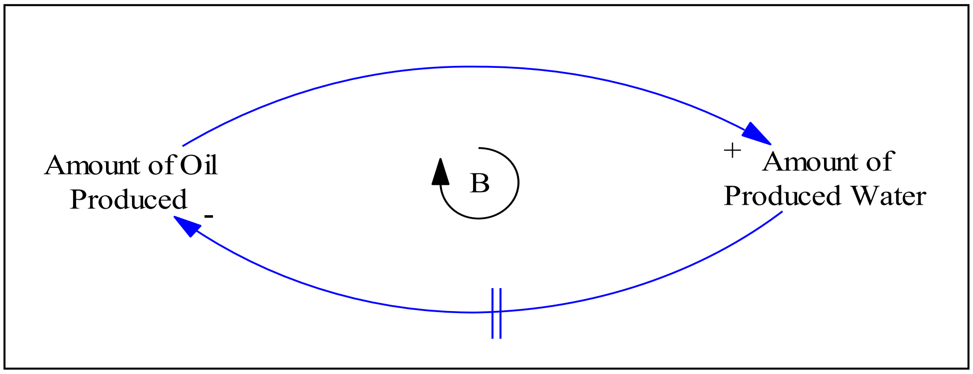


Figure 4. 28: Balance Loop- B1

The amount of oil that has been produced and will be produced was considered here as a problem symptom of the main casual loop. Heads of this oil field manage this problem by discharging PW into NEPs and surrounding areas. Particularly, increasing oil production causes an increase in PW volume. In fact, discharging that water without treatment requires large and safe discharging area to ensure that contaminated water will not pollute or affect the environment and humans. If PW is discharged into surrounding areas without treatment, formation plugging for that area could occur, so the permeability of that formation will decrease. Large disposal area and formation plugging can be considered main constraints that can cause delay in oilfield development projects.

4.6.2.1.2 Reinforcing Loop - Impacts of Discharging Produced Water in the Zubair Oil Field (R1)

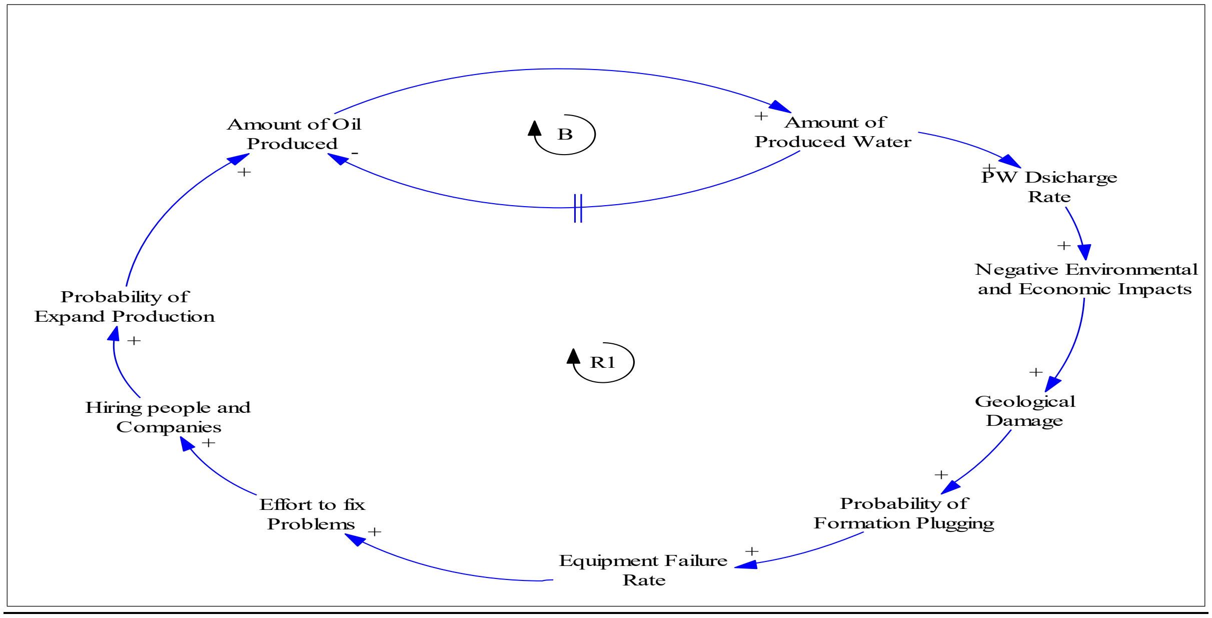


Figure 4. 29: Reinforcing Loop- R1

The best regulatory practice that has emerged in the Zubair field is discharging rate of PW will be increased whenever oil production increased. From the literature in the previous chapters, there was some evidence that discharging PW could cause environmental and economic hazards, such as formation plugging and reducing permeability of that formation which can be called a geological damage or formation damage. Also, discharging PW with high concentrations of chemicals could cause corrosion and acute toxicity. Furthermore, high corrosion rates can increase equipment failure rates. Therefore, more efforts are required to fix problems that have been associated with oil production and resulted from discharging contaminated PW. These efforts can be represented by hiring experts or large oil companies, which have good experience in managing PW. That was exactly what SOC did in order to improve oil production and the current state of the Zubair oil field.

4.6.2.1.3 Reinforcing Loop - Continuous Development of the Zubair Field (R2)

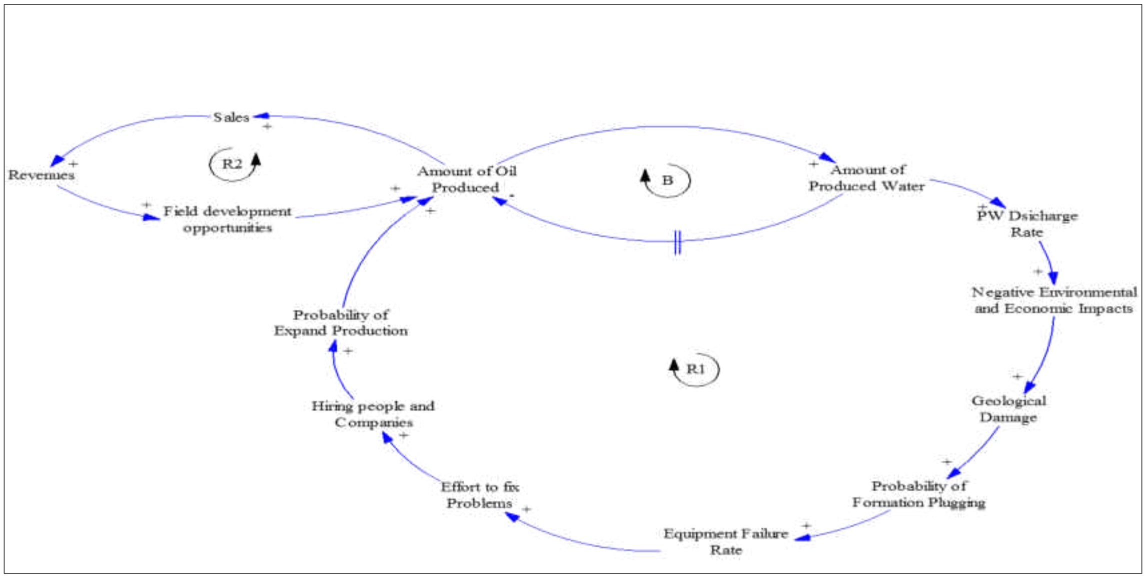


Figure 4. 30: Reinforcing loop- R2

Increase oil production for an oil field helps increase the revenues of that field. Because the number of oil wells will increase to more than 250 wells in the Zubair field, the production of oil will increase and sales of oil per day are expected to increase. As a result, the revenues will also increase. Therefore, increase the revenues encourages the government to search for the best opportunities that can increase oil production. In contrast, the amount of waste that can be associated with oil production will increase. Thus, reducing or eliminating the root causes of increasing these amounts needs more effort and sometimes needs to develop a new strategic plan or change the current management method.

4.6.2.1.4 Reinforcing Loop-Produced Water Discharge Rate and Oil Production: (R3)

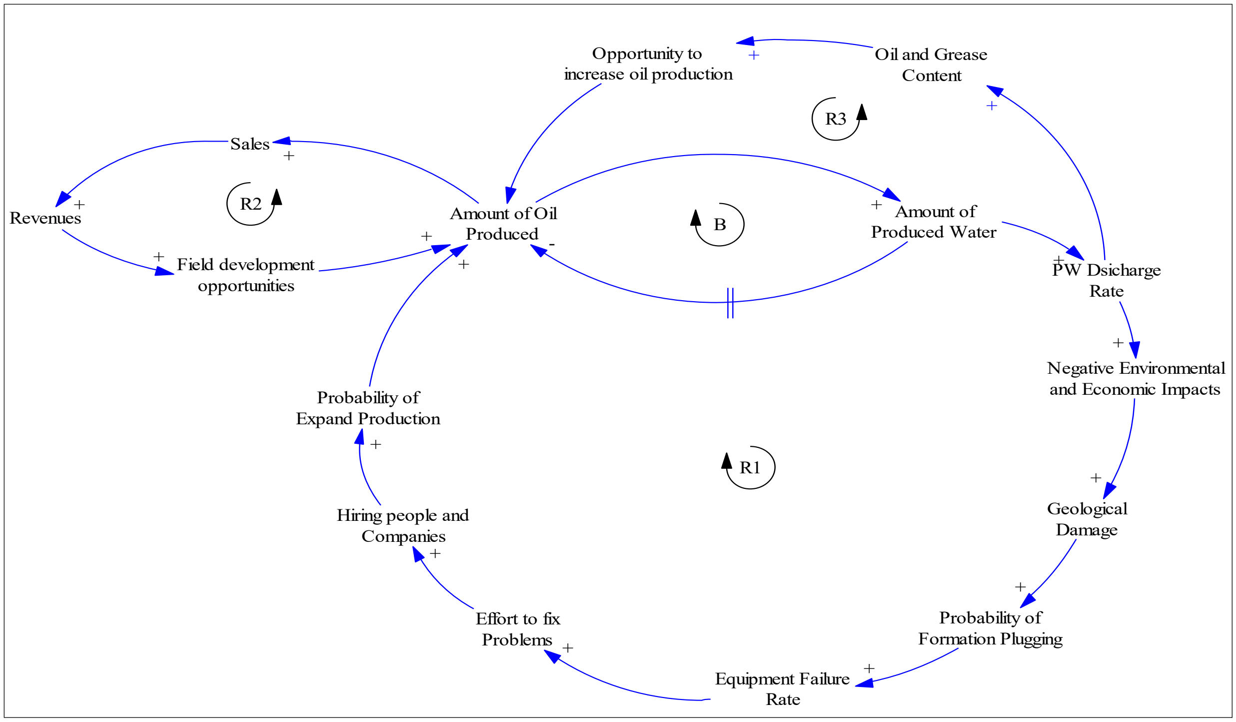


Figure 4. 31: Reinforcing Loop- R3

Because PW has two beneficial constituents, which are oil and grease particles, the amount of these particles can be added to the current amount of oil that has been produced if it separated from PW. As a result, the opportunities of increasing oil production in Zubair field will increase.

4.6.2.1.5 Balancing Loop-High Discharge Rate of Produced Water Increases the Amount of Pollutants (B2):

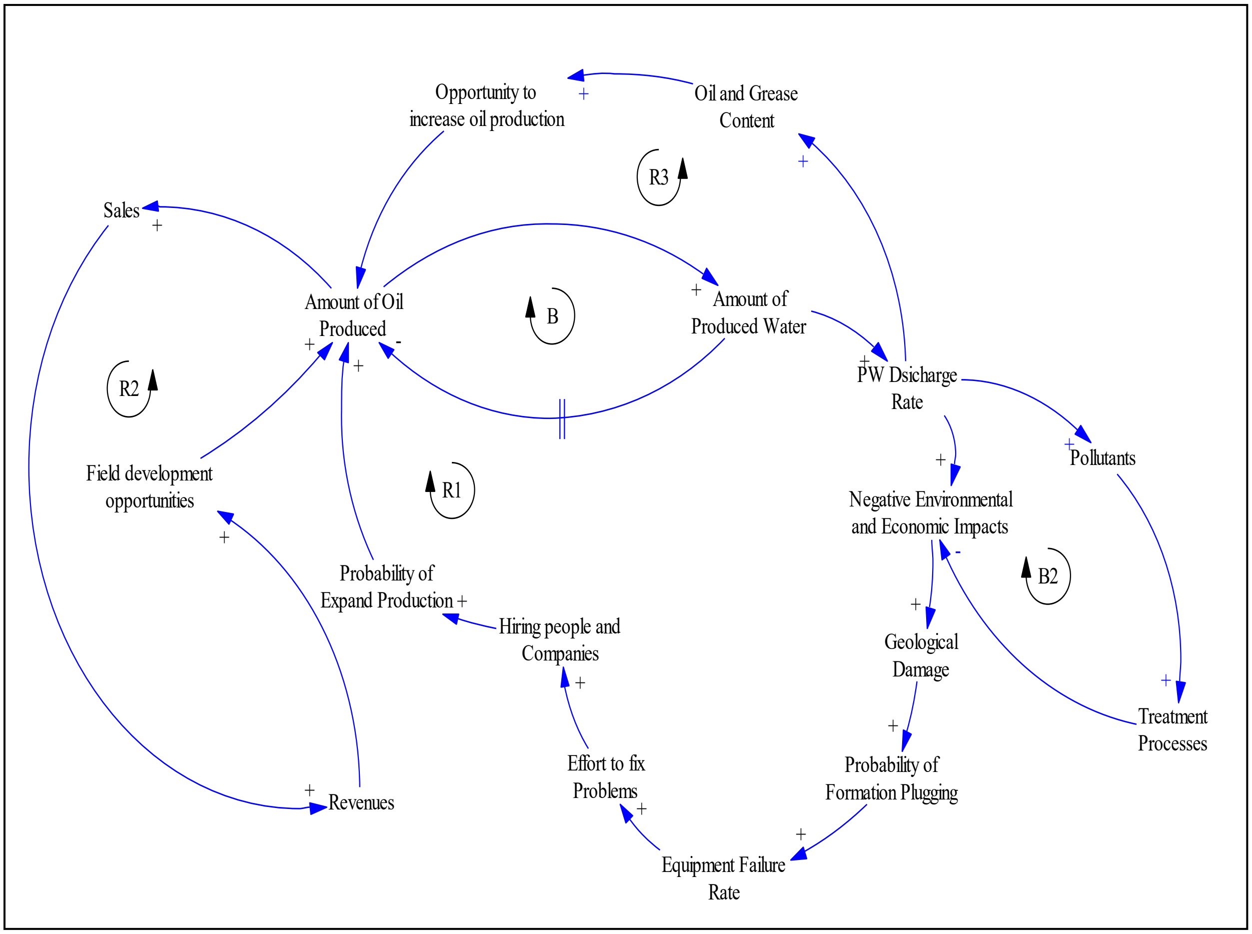


Figure 4. 32: Balance Loop- B2

The higher discharge rate of PW without treatment causes an increase in the amount of pollutants and various contaminants in that water. To reduce these amounts, different treatment processes are required, such as filtration, ultrafiltration, distillation, and adsorption. Reducing these amounts can help to reduce the negative environmental and economic impacts that could result from discharging contaminated PW.

4.6.2.1.6 Balancing Loop- Treatment Costs and Revenues: (B3):

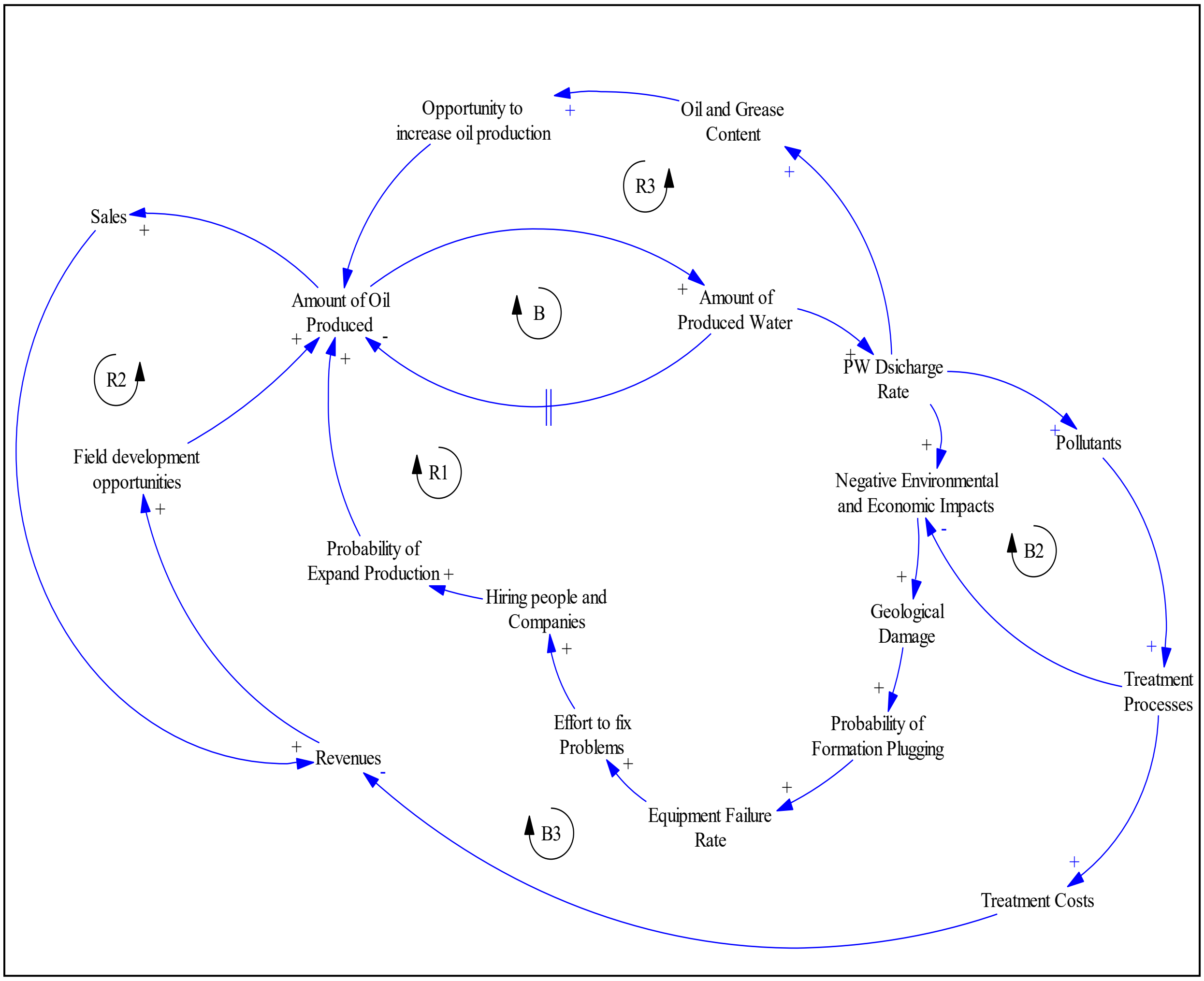


Figure 4. 33: Balance Loop- B3

The treatment of PW depends on the types and concentrations of contaminants in that water and the quality of water needed. For example, high OGC with small particle sizes needs advanced technology that can remove or reduce that content. In addition, selection of treatment technology is field dependent and based on the regular practices during production operations.

Usually, treatment may be needed to reduce the concentration of chemicals, which are mostly used to reduce the corrosion, bacteria, and DG during oil production.

4.6.2.1.7 Reinforcing loop-Reducing the Required Amount of Fresh Water (R4):

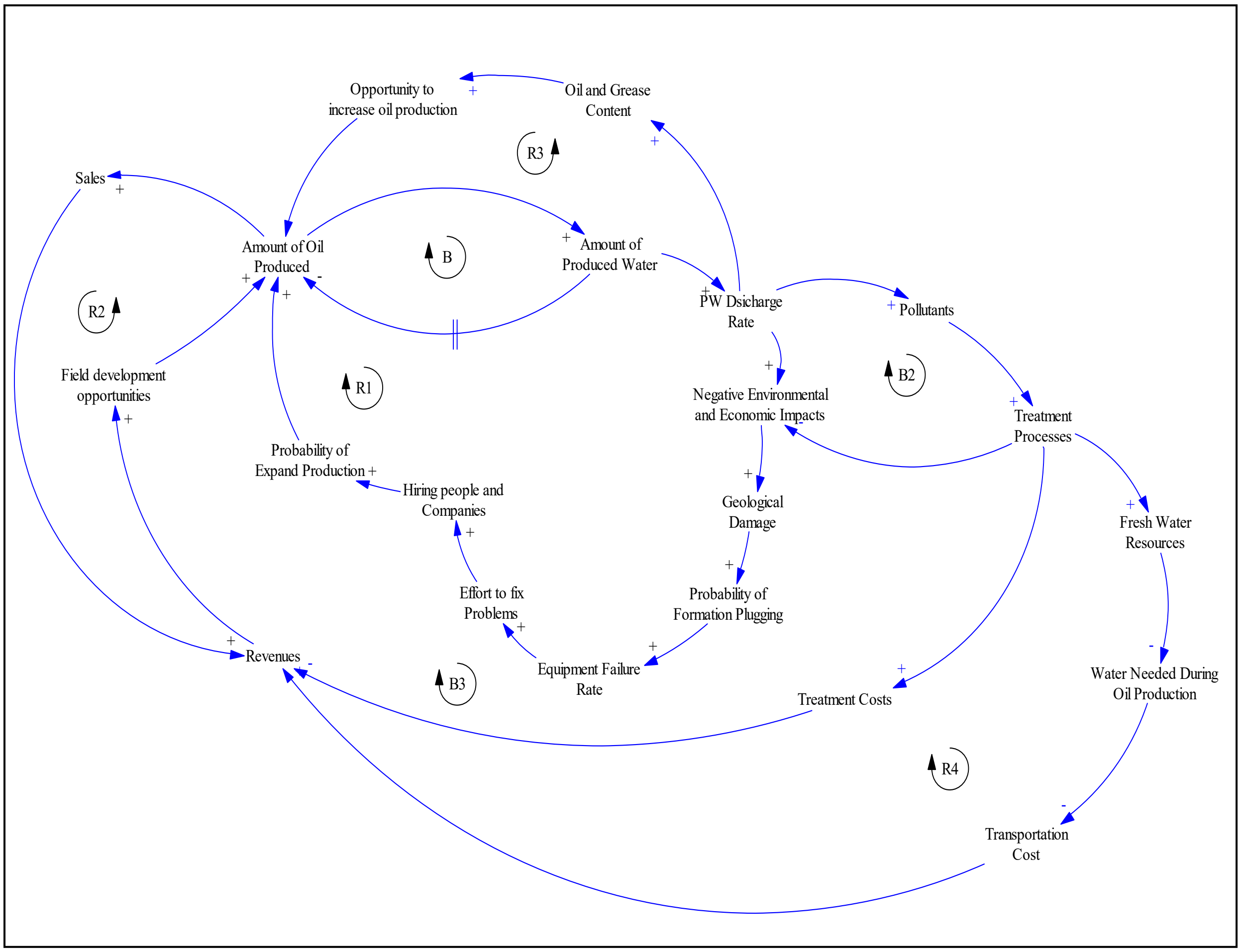


Figure 4. 34: Reinforcing Loop- R4

If PW is effectively treated, the fresh water resources will increase. Usually, cleaning drilling equipment requires fresh water (clean water free from salt and metals). In the Zubair field, fresh water is required for both cleaning field equipment and removing the remaining amount of water and salt in the Desalter.

In fact, this amount of fresh water was provided from Garmat Ali River after reducing amounts of TDS and TSS. Furthermore, anti-corrosion additives were normally used to reduce the corrosion impacts on drilling equipment, operation units, and production plants. Because of the high salinity in BWW (Back Wash Water), the treatment was expected to be very expensive. In loop R4 the transportation cost was added to explain that providing BWW for the Zubair field is not an easy task, see Figure 4.34.

Transferring water from Garmat Ali River to the Zubair field required long distance pumping units, long pipe systems that will reach to more than 10 miles away from the DS. These systems and plants require operational, control, and maintenance cost. Converting PW to fresh water could help to reduce the required amount of supplied water from Garmat Ali River. Furthermore, the fresh water could be injected again into the oil wells to maintain the oil well pressure, and then increase oil productivity of these wells.

4.6.2.1.8 Balancing Loop- Meeting the Environmental Regulations (B4):

Meeting the environmental regulation needs from industries requires extra efforts and costs. One of these efforts is searching for a good solution with lower cost and high efficiency to reduce waste and pollutants to the required concentrations.

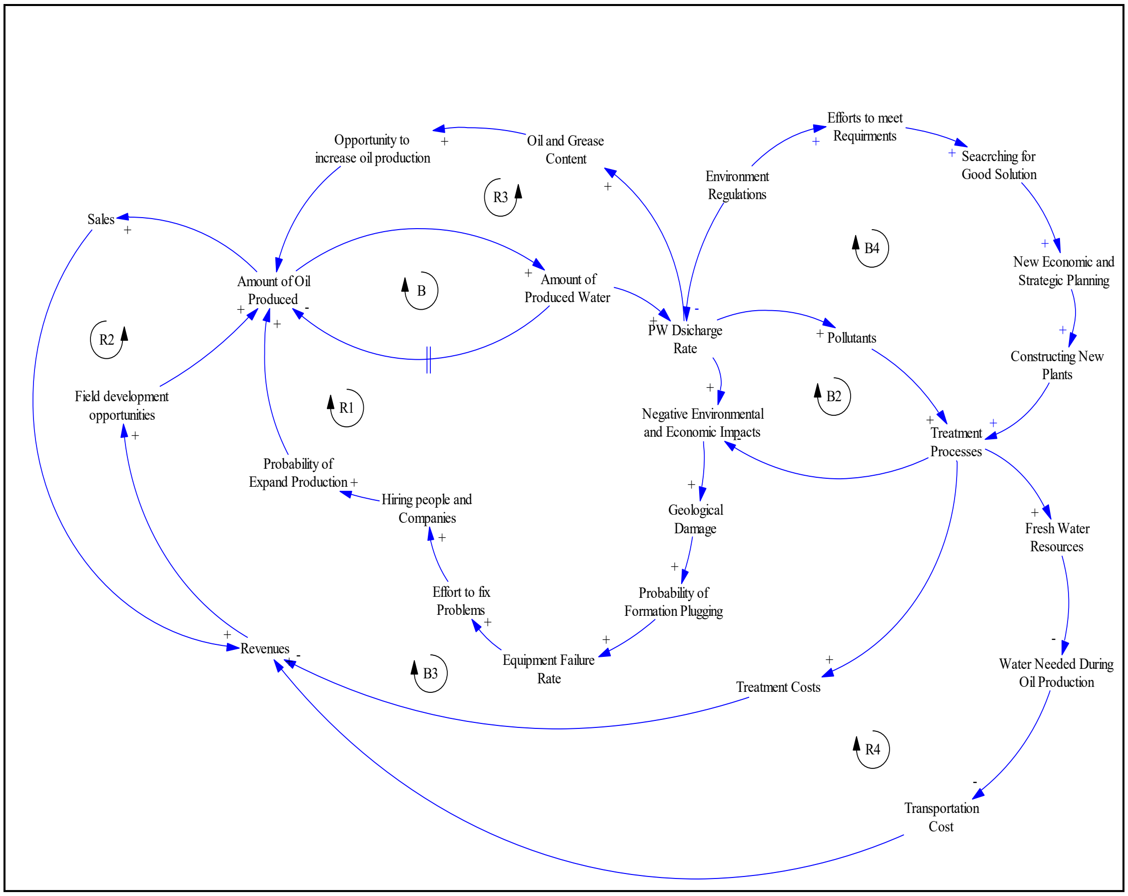


Figure 4. 35: Balance Loop- B4

In fact, a new strategic plan will be required to construct a PW treatment plant in the Zubair field to remove or reduce the concentrations of contaminants in PW. Meeting the requirements of the EPA can help to save and protect organisms and, the environment and decrease the ecological risks.

4.6.2.1.9 Reinforcing Loop- High Discharge Rate of Produced Water Increases Total Dissolved Solids: (R5)

The R5 loop is a reinforcing loop, which showed that the higher discharge rate of PW leads to an increase in TDS amount, but the amount of TDS is field dependent. The large amount of TDS can cause formation damage if it is discharged directly with PW without treatment.

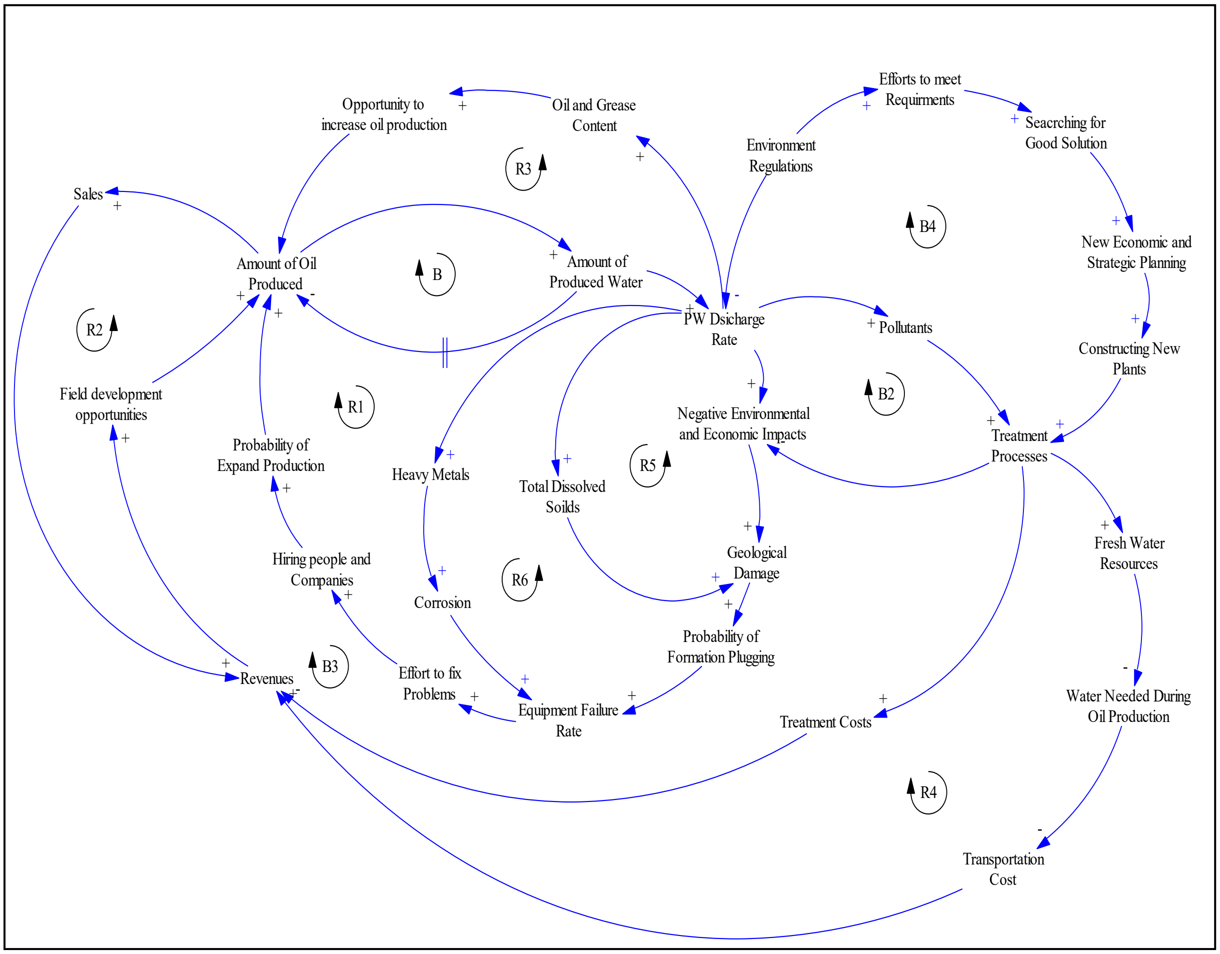


Figure 4. 36: Reinforcing Loop- R5

4.6.2.1.10 Reinforcing Loop- Produced Water Discharge Rate Increase the Amount of Heavy Metals: (R6)

The R6 loop is a reinforcing loop between the PW discharge rate and the amount of heavy metals that could be discharged with that water. Virtually, the large amount of heavy metals, such as iron, can cause corrosion once it contacts the surface. This corrosion increases the failure rate of the equipment during oil and gas operations see Figure 4.36.

4.7 IMPROVE Phase

In this phase, reducing the amount of contaminants that has been discharged with PW was the main objective. The results obtained from both measure and analyze phases were used to develop an effective framework that could be used to manage PW in the Zubair oilfield effectively. These results also showed that there was a strong relationship between the quality for that water and type of management and treatment methods. Since the current method was considered ineffective, continuous improvement initiatives toward finding the best method and effective technology to treat that water, to decrease the amount of contaminants, and to convert PW to usable water were started by proposing stationary PW treatment plant.

4.7.1 Stationary Produced Water Treatment Plant

First of all, from the analyze phase, the main causes of high salinity and corrosion problems were related to use of BWW that has been treated and supplied from Garmat Ali River through old pipe systems that contain scales and deposits. A treatment plant for that water closer than that river existed and it has been used to reduce TSS from more than 200 ppm to 3 ppm with particle size equals 10- micron (SOC, 2012). Furthermore, anti-corrosion additives have also been used as a part of this treatment with pesticides to kill different kinds of bacteria. However, once that water pumped through the transportation pipe system, an intermediate contact with deposits, corrosive materials, and scales could occur. As a result, these cumulative contaminants could be carried with BWW into DS. Therefore, the amount of these contaminants can be added to those that were coming with formation water during oil extraction operations. Thus, the amount of contaminants that could be associated with the PW, which was being discharged from the dehydrator and desalter units, was increased.

In order to understand the reason behind proposing a stationary PW treatment plant, see the schematic diagram in Figure 4.37.

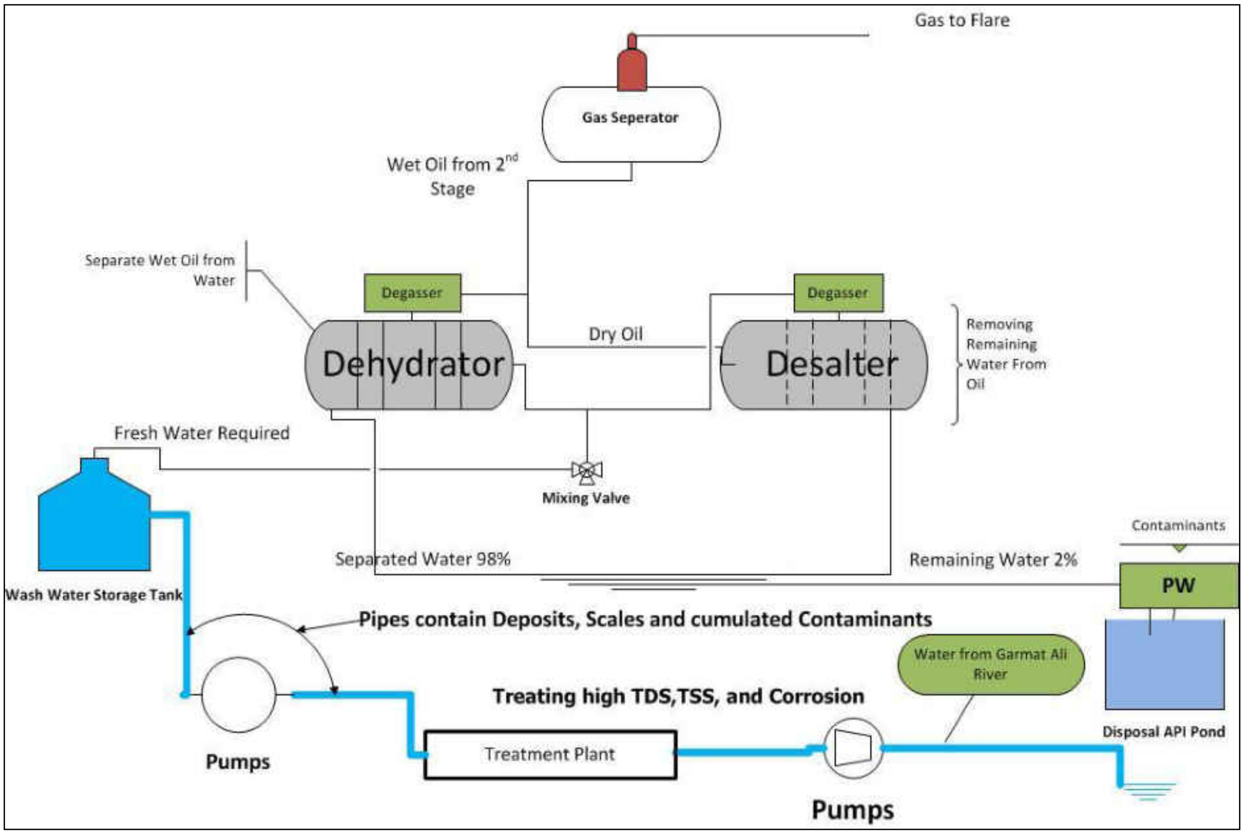


Figure 4. 37: Schematic Diagram for BWW Source

Secondly, the existence of a PW treatment plant at the DS has some benefits. Firstly, treating PW closer to DS will help to reduce the demand on obtaining water from Garmat Ali River. As a result, the amount of moving suspended scales and deposits in pipe systems from the river to the DS will decrease. Thirdly, converting PW to usable water will help to use it not only for production operation purposes, but also, it could be used for cleaning field facilities, such as, cleaning drilling equipment or can be used as a cooler fluid for some cooling systems.

Furthermore, if PW is effectively treated, the reinjection process into oil wells will be possible. The latest method will increase oil production and maintain oil well pressure. Finally, the disposal rate of PW will be decreased and that will result in decreasing the environmental and economic impacts. Due to the fact that there are different existing technologies for the purpose of PW treatment, it was necessary to search for the best methodology that can help to select an effective treatment technology for that water with less efforts and time. Meeting customers' requirements requires studying different treatment technologies taking into account some important criteria. In addition, treatment technologies for onshore oil fields require technologies that are different than those technologies for offshore oilfields. In the analyze phase, STA helped to analyze the results obtained from the measure phase, specially, these related to corrosion sources and all activities that can affect the KPOV and result from the current management method of PW. In this phase, Multi Criteria Decision Making (MCDM) methodology was used to select an ecofriendly technology to treat PW for onshore Iraqi oilfields with respect to all measured and analyzed variables (KPIVs and KPOV).

4.7.2 Selection of Produced Water Treatment Plant

According to VOC and CTQs results that have been measured and analyzed in the previous phases and based on the customers' requirements, AHP was used to select an effective management method for PW. Since current specifications of PW were measured and analyzed, further research was conducted in order to meet the required properties for that water (customers' needs) after treatment. Meeting these requirements could help to convert PW to clean water and that was one of the most important needs of SOC.

According to the VOC, the PW treatment plant was required to convert PW to usable water. Therefore, PW properties before treatment helped to identify the current root causes of high amounts of contaminants in the discharged PW. It also helped to identify the relationship between these causes and how the new approach should be developed in order to avoid selecting a method that might fail to meet these requirements. Then, required specifications of PW after treatment helped to identify the goals of this study and to select the best PW management method. Meeting these requirements helped to improve the current state of Iraqi oilfields by reducing negative environmental and economic impacts of PW.

In fact, different technologies for managing that water are available in current markets. However, selecting the best technology with the respect to the main important factors, such as cost, environmental, technical requirements, and health and safety were performed by using MCDM.

In their work, Mofarrah et al. used MCDM to develop the basic structure that can be used to select the best PW management technology for offshore oilfields (Mofarrah et al., 2011). They based their research on the offshore discharged standards to select this technology and they considered these standards as customer's requirements. In this study, the outputs of VOCM and CTQs, and the required properties of PW were used to select the best management technology for that water. Converting PW to usable water was required to meet the customers' needs.

Therefore, selecting alternatives for these technologies was started by setting a target equal to meeting PW properties after treatment, see Table 4.9 (SOC, 2012).

Table 4.9: Requirement of Produced Water Specifications after Treatment

Factor	Unit	Value
PH	None	6.5-7.5
TSS	Mg/liter	<2
Particle Size	Micro-m	<4
TDS	Mg/liter	250,000
OGC	Mg/liter	<5
Total Iron	Mg/liter	<5
DO	Mg/liter	<0.02
Bacteria	None	Not detected

Selecting alternatives was performed with respect to the main important principle criteria that were very important to the customer (SOC). Therefore, four principle criteria categories were selected to be the same as those used in Mofarrah.A et.al's work. These categories were technical feasibility, cost, environment, and health and safety.

The main difference was between the sub-criteria and the main criteria of technical feasibility. Because the amounts and types of these contaminants are field dependent, the sub-criteria categories of the technical feasibility for offshore oilfields are different from the sub-criteria categories for onshore oilfields. Size and weight of treatment facilities are very important for offshore oilfields and they are mostly the two main constraints for selecting field facilities. In this project, weight and size were not considered important for onshore oilfields.

As a result, the types of alternative technologies were different from that used for offshore oilfields.

4.7.2.1 Analytical Hierarchy Process

Making hard decisions provides either conscious or unconscious results (T. L. Saaty, 2008). Sometimes, useful information to make a proper decision may by not available. Then, making a decision with a lack of quantitative data can lead to fatal results, but decision makers can use a pairwise comparison technique in order to make proper comparison between different criteria [(De Ridder, 2005) & (Mofarrah et al., 2011)]. Thomas L. Saaty developed the Analytical Network Process (ANP) which "provides the way to input judgments and measurements to derive ratio scale priorities for the distribution of influence among the factors and groups of factors in the decision" (R. W. Saaty, 2003). The well-known decision theory, the Analytical Hierarchy Process (AHP) is a special case of the ANP. Both of them derive ratio scale priorities by performing paired comparisons of elements on a common property or criterion (T. L. Saaty, 2008).

AHP is an emerging solution to complex decision making processes and it is widely used as the best method for making decisions in developing an effective strategic plan for organizations and selecting new manufacturing technologies (Yang & Shi, 2002).

In 1982, Saaty and Gholmnezhad used AHP to evaluate different strategies to select the safe disposal for high level nuclear waste, as cited in Qureshi & Harrison (Qureshi & Harrison, 2003). Also AHP was used in China to select an appropriate solid waste landfill site in Beijing. Because of the complexity of the waste management system in the selected region, they used AHP method to select the best site from different candidate criteria (Wang, Qin, Li, & Chen, 2009). Furthermore, AHP was used in Mahshahr, Iran to prioritize the affected ecosystems by the impacts of petrochemical industries on the existing habitats (Malmasi, Jozi, Monavari, & Jafarian, 2010).

The SuperDesisions Software that was developed by William J. Adams of Embry Riddle Aeronautical University was used in this phase to build a hierarchical decision model to select the best PW management technology for the Iraqi oil fields. This model helped to evaluate different technologies to select the most ecofriendly method for PW management. In this model, the weighting calculations and ranking of alternatives, score calculations, and making decision process were performed. The following sections describe the steps used to develop this model:

4.7.2.1.1 Main Objective Identification

Recalling the outputs of the DEFINE phase, the main goal of this study was developing an effective framework to manage PW in the Zubair field effectively. Since the KPOV was increasing in the amount of contaminants in PW, different alternatives were selected regarding to KPIVs that were affecting the KPOV. These alternatives were identified with the respect to four basic criteria as follows:

1. Technical Feasibility
2. Cost
3. Environment
4. Health and Safety

For each criterion, sub-criteria were identified as well. Then, four technologies were selected as the main alternatives for the main objective. These technologies were selected and studied carefully with the respect to the customer requirements and the results obtained from the Six Sigma previous phases. Technical reports and published papers were used to investigate how each technology could be used to achieve these requirements. As a result, the main model that was used to select one of the technologies as an optimum solution for PW problem was developed by using SuperDesisions software.

This software was widely used to select the best alternative from different candidates. It was used to study selecting aircraft to purchase for Turkish Airlines (Yavuz, Huseyin, & Merve, 2011) and used in Kotarpur, India to compare the performance of existing water treatment plants within a model to assess the efficiency analysis between them (Borad, 2012). In this study, this software connected the main goal to the selected criteria. Then each criterion connected to its sub-criteria. Furthermore, each sub criterion was connected to the four selected alternative technologies. Finally the main goal was connected to these alternatives through these sub-criterions. These connections were important to perform pairwise comparisons between them with the respect to the main goal. By this way, the analytical hierarchy model that was created to achieve the main goal of this study was provided in Figure 4.38.

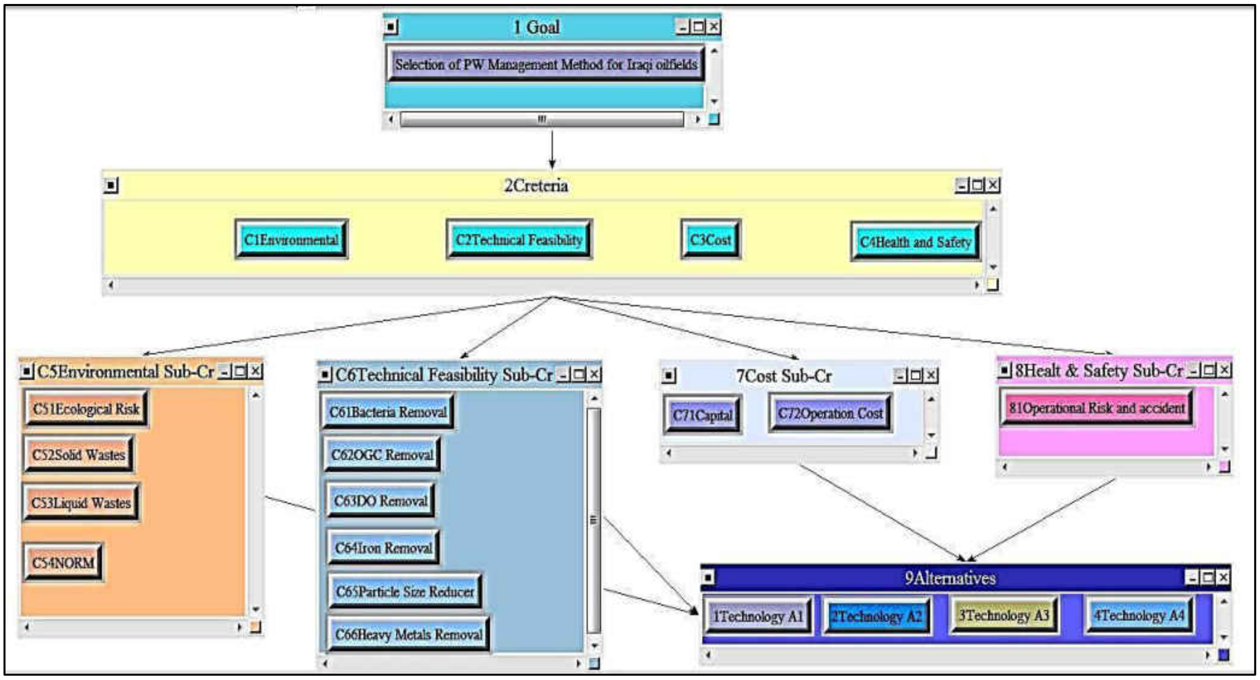


Figure 4. 38: Analytical Hierarchy Model

4.7.2.1.2 Treatment Technologies -Selection of Alternatives:

Four alternative technologies were selected for the purpose of meeting the required PW properties. These technologies are listed and discussed in the following sections.

4.7.2.1.2.1 Hydrocyclones - Technology -A1

Hydrocyclones, or sand separators, have been used since the early 1980s (Stewart & Arnold, 2011). The principle of the separation process in this technology is based on the density of solids within liquid-solid phase (Igunnu & Chen, 2012). Strong centrifugal forces and controlling pressure can force both heavier and lighter phases toward underflow (bottom exit) and overflow (top exit/ product exit) of Hydrocyclones respectively (Ditria & Hoyack, 1994). There are two types of Hydrocyclones in the current markets which are static Hydrocyclones and dynamic Hydrocyclones (Stewart & Arnold, 2011). Hydrocyclones can be made from metals, plastics, or ceramics (Igunnu & Chen, 2012). It usually has two main parts which are called a cylindrical top and a conical base and can be used for any kind of PW (Igunnu & Chen, 2012). In order to understand the mechanism of PW treatment by this technology, see Figure 4.39 as adopted from Igunnu & Chen (Igunnu & Chen, 2012).

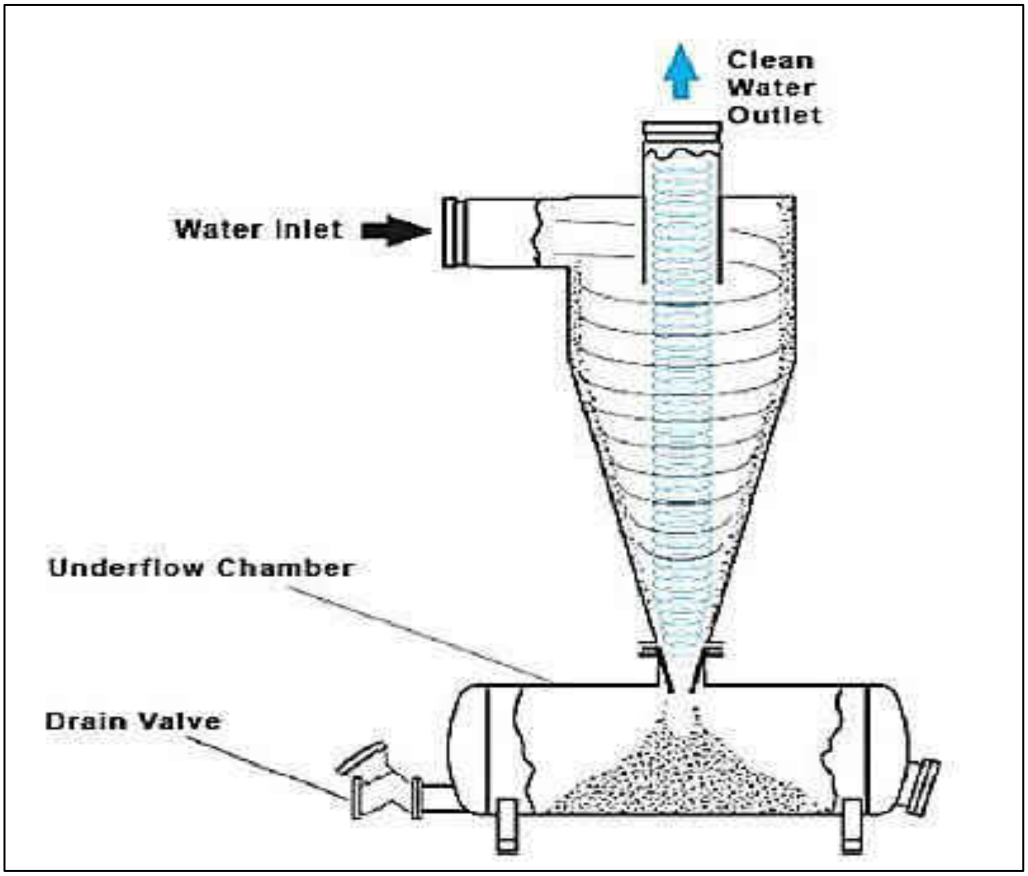


Figure 4. 39: A schematic Diagram for Hydrocyclones Technology.

The performance of Hydrocyclones separation is measured by the angle of the conical section. It can remove particles in the range 5-15milimicron and reduce OGC to 10 ppm without primary treatment (CSM, 2009). In 1992, Svarovsky mentioned that approximately 8 million barrels per day of the PW can be treated by using this technology (Igunnu & Chen, 2012).

4.7.2.1.2.2 Media Filtration- Technology -A2

This technology is widely used for PW treatment that has high salinity because it is not effected by the amount of salinity during the treatment process. There are different types of media that can be used in this technology, such as walnut shell, sand, and anthracite. However, the most common media used for removing OGC and TOC is the walnut shell (CSM, 2009). This technology can remove OGC of up to 90% and can achieve nearly 100% PW recovery without a pretreatment stage [(Igunnu & Chen, 2012) & (CSM, 2009)]. Dual media membrane filtration can be used to remove heavy metals with a specific bacterial strain (Toral, 2011).

4.7.2.1.2.3 Membranes Filtration- Technology -A3

The EPA defined this technology as follows: “Membrane filtration is defined as the rule as a pressure- or vacuum-driven separation process in which particulate matter larger than 1 mm is rejected by an engineered barrier, primarily through a size exclusion mechanism, and which has a measurable removal efficiency of a target organism that can be verified through the application of a direct integrity test” ("United States Environmental Protection Agency," 2012).

This technology can be classified into four membrane filtration processes, which are: Micro Filtration (MF), Ultra Filtration (UF), Reverse Osmosis (RO), and Nano Filtration (Igunnu & Chen, 2012). Each of these technologies has advantages and disadvantages, but in general, it is considered one of the most effective technologies to treat PW. RO membrane has been tested, and the results showed that this technology could remove TOC to less than 5ppm and TDS to less than 250ppm (Patel, 2005). Puntener and Venerus mentioned that UF technology was an efficient method that would help to reduce the amount of sulphate and other various impurities, and that could help to reduce the amount of salinity in the polluted water (Scholz & Lucas, 2003). Membrane filtration could also remove Benzene, Toluene, Ethylbenzene, and Xylene (BTEX) from PW. In their work, Sullivan et.al tested one of the membrane systems, which was called VSEP, and the results obtained were a comparison between RO filtration system and NF system (Essam Abdul-Jalil Saeed, 2010). These results are listed in Table 4.10

Table 4.10: Results of Using VSEP Membrane Filtration System

Typical VSEP Results	**Untreated**	**NF Filtrate**	**RO Filtrate**
Total Organic Carbon (TOC)	810 mg/l	120 mg/l	20 mg/l
Total Suspended Solids (TSS)	9000 mg/l	ND	ND
Chemical Oxygen Demand (COD)	2600 mg/l	270 mg/l	71 mg/l
Oil and Grease	580 mg/l	16 mg/l	ND
Chlorides (Cl)	4700 mg/l	2900 mg/l	15 mg/l
Sulphates (SO2)	210 MG/L	ND	ND
Calcium (Ca)	400 mg/l	8 mg/l	ND
Magnesium (Mg)	50 MG/L	ND	ND
Zinc (Zn)	100 mg/l	5	ND
ND= Not defined			

The results above showed that the RO system has a removal efficiency higher than the NF system.

In his thesis, Beech tested three commercial ultrafiltration membranes which were JW, 5K, and BN to test their efficiency to reduce turbidity, removing oil particles, and identify factors that could affect the overall efficiency of the selected technologies(Beech, 2006). The results showed that the turbidity removal ranges were almost 99.8% and oil removal ranges for JW, 5K, and BN were 59.52% to 90.43%, 47.32% to 87.27%, and 78.2% to 94.31%, respectively. Beech concluded that the best membrane available for the treatment of PW to meet feed specifications was the BN membrane.

4.7.2.1.2.4 Evaporation Pond- Technology -A4

This is an Eco - method that can be used to remove water from different contaminants by using solar power under the evaporation process principles (Velmurugan & Srithar, 2008). Large space is required to use this technology and it is more effective in dry climates (Igunnu & Chen, 2012). This technology is not effective to improve the quality of PW. Also, all water will be evaporated to the environment whenever the PW is treated by this technology (Igunnu & Chen, 2012). It does not need pretreatment or any operational cost, but the only energy requirement is pumping PW to these ponds (CSM, 2009).

4.7.2.1.3 Pairwise Comparison

The Pairwise Comparison Matrix (PCM) was provided by the software for all selected criteria and was used to perform comparisons between important selected criteria. Quantitative and qualitative data regarding the performance of the selected technology were used to compare between them and selected criteria, alternatives, and the main goal of this study. The required data to perform this comparison was collected from different sources, including (Igunnu & Chen, 2012), (Velmurugan & Srithar, 2008), (Ditria & Hoyack, 1994), ("United States Environmental Protection Agency," 2012), and other published data that discussed the geological and operational conditions of Sothern Iraqi oilfields. Table 4.11 was used to select the fundamental scale for making a judgment as adopted from Saaty (R. W. Saaty, 2003). For the performance of the technologies, the higher values referred to the high performance of the selected technology and vice versa. For the cost, the lower values were preferred. Making judgments between clusters was not performed because all clusters in this model were equally important (R. W. Saaty, 2003).

Table 4.11: The Fundamental Scale for Making Judgments

Scale	Description
1	Equal
2	Between Equal and Moderate
3	Moderate
4	Between Moderate and Strong
5	Strong
6	Between Strong and Very Strong
7	Very Strong
8	Between Very Strong and Extreme
9	Extreme
Notes	Decimal judgments, such as 3.5, are allowed for fine tuning, and judgment greater than 9 may be entered, though it is suggested that they be avoided

Checking the inconsistency was a very important step and it was performed at each comparison matrix. If the Consistency Ratio (CR) found was less than 0.1, the judgment within selected PCM could be considered consistent (R. W. Saaty, 2003). The SuperDesisions software can measure CR during judgment making for each comparison matrix. But, in order to explain the calculations behind measuring this ratio by the program, the estimation of inconsistency of 2Criteria cluster was provided and explained as in the following:

1. Pairwise comparison for criteria was performed first based on the scale for making judgment between nodes. The following table showed how each node compared with others. To perform the comparison with a less inconsistent method, it is better to say node A is 3 times more important than node B (R. W. Saaty, 2003). Therefore, the following Table 4.12 for 2Criteria cluster was created based on that method. Each node in the Criteria cluster compared by scaling how much is more important than other nodes as in following:

Table 4.12: PCM for Criteria Cluster

Nodes	C1 Env	C2 Tech Feas	C3 Cost	C4 H & S
C1 Env	1	3	2	1
C2 Tech Feas	1/3	1	2/3	1/3
C3 Cost	1/2	3/2	1	½
C4 H & S	1	3	2	1

This table demonstrated the degree of comparison between C1, C2, C3, and C4 nodes for Criteria Cluster. This table was considered a PCM for the 2Criteria cluster, and the same matrix with different comparisons values between nodes were performed by using SuperDesisions software for the other clusters.

The next step was synthesizing the judgments for the above matrix. This step was performed by the program and it was illustrated manually as in the following:

- Finding summation of values in each column of PCM:

Table 4.13: Step 1- Synthesizing Judgments

Nodes	C1 Env	C2 Tech Feas	C3 Cost	C4 H & S
C1 Env	1	3	2	1
C2 Tech Feas	1/3	1	2/3	1/3
C3 Cost	1/2	3/2	1	½
C4 H & S	1	3	2	1
Sum	2.833333333	8.5	5.666666666	2.833333333

- Calculating the normalized PCM values by dividing each value in the column over its corresponding summation value at the same column:

Table 4.14: Normalized PCM

Nodes	C1 Env	C2 Tech Feas	C3 Cost	C4 H & S
C1 Env	0.352945	0.352941176	0.352941591	0.352941591
C2 Tech Feas	0.117647	0.117647058	0.117647197	0.117647197
C3 Cost	0.176470	0.176470588	0.176470795	0.176470795
C4 H & S	0.352941	0.352941176	0.352941591	0.352941591
Sum	1	1	1	1

- Calculating the relative priorities by calculating the average of normalized values for each raw PCM :

Table 4.15:Relative Priorities of PCM

Nodes	C1 Env	C2 Tech Feas	C3 Cost	C4 H & S	Relative Priorities
C1 Env	0.352945	0.352941176	0.352941591	0.352941591	0.352942
C2TechFeas	0.117647	0.117647058	0.117647197	0.117647197	0.117647
C3 Cost	0.176470	0.176470588	0.176470795	0.176470795	0.176470
C4 H & S	0.352941	0.352941176	0.352941591	0.352941591	0.352941

The relative priorities values with the respect to the 2Criteria cluster refers that Environmental and Health and Safety were preferred first with the percentage of preference equal to 35% for each. Then, cost was preferred with 18%. Finally, technical feasibility was preferred with 12%.Synthesizing all nodes could be performed manually by using the above steps for each cluster with their nodes.

- Checking consistency for the above PCM was performed mathematically by using two main equations. Saaty, 1980 and Modarres, 2006 introduced two equations that could be used to check the consistency of the PCM for each cluster, and these equations were provided in following (Mofarrah et al., 2011).

$$CI = \frac{\lambda \max - n}{n-1} \tag{4}$$

$$CR = \frac{CR}{RI} \tag{5}$$

Where: $\lambda \max$: maximum eigenvalue ; n= number of selected parameter in PCM ; CI: Consistency Index ; CR: Consistency Rate ; RI: Random Index.

$\lambda \max$ was calculated first by using the following steps:

- Finding the weighted sum vectors by multiplying PCM by calculated relative priorities values:

$$0.352942\begin{vmatrix}1\\1/3\\1/2\\1\end{vmatrix}+0.117647\begin{vmatrix}3\\1\\3/2\\3\end{vmatrix}+0.176470\begin{vmatrix}2\\2/3\\1\\2\end{vmatrix}+0.352941\begin{vmatrix}1\\1/3\\1/2\\1\end{vmatrix}=\text{Weighted Sum Vector}$$

$$\begin{vmatrix}0.352942\\0.117647\\0.176471\\0.352942\end{vmatrix}+\begin{vmatrix}0.352941\\0.117647\\0.176470\\0.352941\end{vmatrix}+\begin{vmatrix}0.35294\\0.117646\\0.176470\\0.35294\end{vmatrix}+\begin{vmatrix}0.352941\\0.117647\\0.1764705\\0.352941\end{vmatrix}=\begin{vmatrix}1.411764\\0.470587\\0.7058815\\1.411764\end{vmatrix}=\text{Weighted Sum Vector}$$

- Then, dividing the values of weighted sum vectors by the associated relative priority values:

$$\frac{1.411764}{0.352942}=3.99999\cong 4$$

$$\frac{0.470587}{0.117647}\cong 4$$

$$\frac{0.7058815}{0.176470}\cong 4$$

$$\frac{1.411764}{0.352941} \cong 4$$

Then, λmax was calculated by dividing the summation of results from the previous step over n:

$$= \frac{4+4+4+4}{4} = 4$$

Substitute in equation (4)

$$= \frac{4-4}{3} = 0$$

$CR = \frac{CI}{RI}$, Consistency Index (CI) = 0

Consistency Ratio (CR) was obtained by using the Random Index table that was provided by Saaty,1980 (Mofarrah et al., 2011). This table provides RI with different values of n, see Table 4.16

Table 4.16: Random Index Values

n	1	2	3	4	5	6	7	8	9	10
RI	0.0	0.0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Since n= 4, the corresponding RI value = 0.9

Then, $CR = \frac{0}{0.9} = 0$

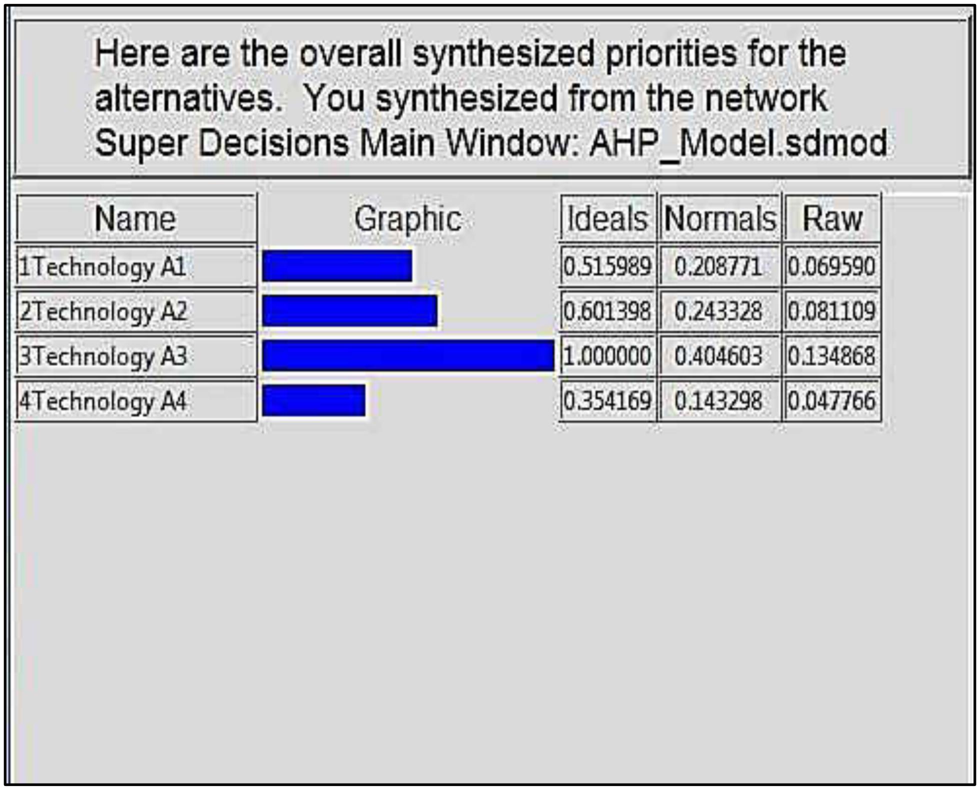
According to Saaty, if CR<0.1, the assumptions of PCM is consistent (R. W. Saaty, 2003). The overall normalized PCM values, relative priorities, and checking IR steps were performed by using SuperDesisions software. At each comparison matrix, inconsistencies were checked by the program that was providing an inconsistency expert checking model. By using this model, all inconsistent selected values could be reviewed. This model can help to check whether entered judgments need to be corrected or not. However, the decision maker is the only person who could realize the comparison values between different criteria.

4.7.2.1.4 The Super Matrix of The Model

The priorities derived from PCMs were entered in the unweighted Supermatrix. Then, the weighted Supermatrix included all priorities of pairwise comparisons. In this model, the unweighted Supermatrix and weighted Supermatrix were the same because the clusters were not weighted (R. W. Saaty, 2003). Pairwise comparisons were performed for all nodes within created clusters with the respect to the main goal of the model. The weighted Supermatrix was obtained by multiplying all elements of the unweighted Supermatrix by cluster weight. In addition the limit Supermatrix was obtained by multiplying it times itself. Appendix B includes the unweighted Supermatrix, weighted Supermatrix, and limited Supermatrix.

4.7.2.1.5 Synthesizing the Model

In this step, the optimum method that could be used to manage PW in Iraqi oilfield was identified. The best way that to report the result was synthesizing the whole model (T. L. Saaty, 2008). The results showed that the best method was using membrane filtration which is technology A3 with the normalized value equal to 0.404603. The second alternative technology that can be used for the same purpose was technology A2 (media filtration) with the normalized value equal to 0.243328. Technology A1 was considered an intermediate candidate between the above technologies with the normalized value equal to 0.208771. Finally, technology A4, which was the current method for managing PW in the Zubair oil field, which is considered the bad alternative that could not be used to achieve the goal of study with normalized weight 0.143298, see Figure 4.40.



Here are the overall synthesized priorities for the alternatives. You synthesized from the network Super Decisions Main Window: AHP_Model.sdmod

Name	Graphic	Ideals	Normals	Raw
1Technology A1		0.515989	0.208771	0.069590
2Technology A2		0.601398	0.243328	0.081109
3Technology A3		1.000000	0.404603	0.134868
4Technology A4		0.354169	0.143298	0.047766

Figure 4. 40: The Results of Synthesizing Whole Model

The Normals column represents the results in terms of priorities. The ideals column was obtained by dividing each value in Normals column by the largest value in the same column. The normalized values by cluster and limiting values were summarized in Table 4.17:

Table 4.17: Overall Normalized Weighting Factors of Criteria and Subcriteria

Name	Normalized By Cluster	Limiting
Selection of PW Management Method for Iraqi oilfields	0	0
C1Environmental	0.35294	0.117647
C2Technical Feasibility	0.11765	0.039216
C3Cost	0.17647	0.058824
C4Health and Safety	0.35294	0.117647
C71Capital	0.2	0.011765
C72Operation Cost	0.8	0.047059
81Operational Risk and accident	1	0.117647
1Technology A1	0.20877	0.06959
2Technology A2	0.24333	0.081109
3Technology A3	0.4046	0.134868
4Technology A4	0.1433	0.047766
C51Ecological Risk	0.21529	0.025328
C52Solid Wastes	0.08231	0.009683
C53Liquid Wastes	0.10239	0.012046
C54NORM	0.60001	0.070589
C61Bacteria Removal	0.05324	0.002088
C62OGC Removal	0.29915	0.011731
C63DO Removal	0.15772	0.006185
C64Iron Removal	0.13291	0.005212
C65Particle Size Reducer	0.19607	0.007689
C66Heavy Metals Removal	0.16091	0.00631

The normalized values were used to visualize the obtained results by using node analysis. Histogram and horizontal charts are provided in Figure 4.41 and Figure 4.42 to show priorities for each technology.

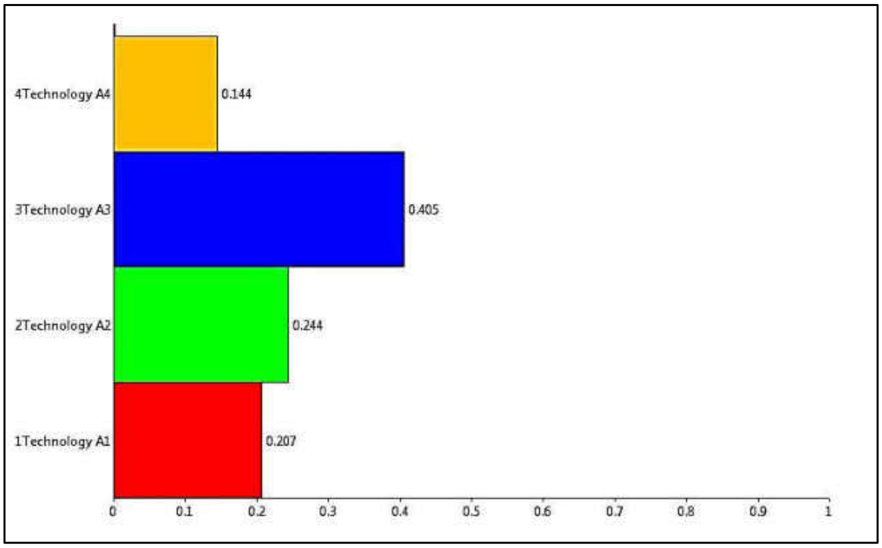


Figure 4. 41: Horizontal Histogram-Priorities between Technologies

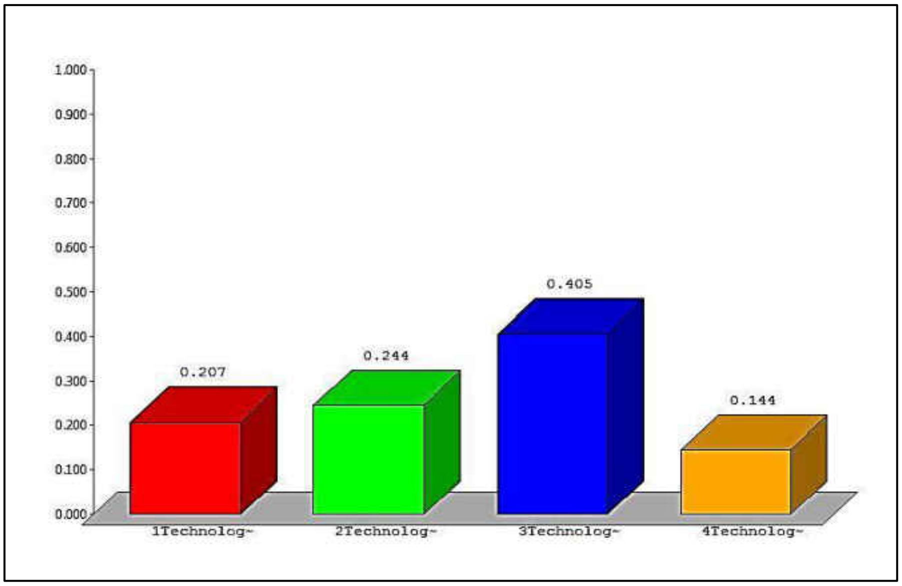


Figure 4. 42: Vertical Histogram-Priorities Sensitivity between Alternatives

4.7.2.1.6 Sensitivity Analysis

Sensitivity analysis technique is "a comprehensive result that takes into consideration all benefits, opportunities, costs, and risks that could be resulted from implementing the selected solution”(R. W. Saaty, 2003). Sensitivity analysis can measure the economic impact that can result from alternative values of uncertain variables that could affect the economics of the selected project. The great amount of factors that can affect the project can be taken into consideration by conducting sensitivity analysis (Khomenko & Poddubnaya, 2011). Therefore, sensitivity analysis was performed in this phase to measure risks, economic impacts and risks that could result from using the selected technology. Sensitivity analysis in this model was performed and the results obtained were based on the following assumptions:

- The higher weighted value for the technology with the respect to Environmental criterion means the lowest environmental negative impacts (Ecological risks, discharging NORM, disposing solid wastes, and disposing liquid wastes).
- The higher weighted value for the technology with respect to Technical Feasibility criterion assumed to be the technology has high efficiency to meet technical feasibility-sub criteria objectives.
- The higher weighted value for the technology with the respect to Health and safety assumed the technology is effective to improve health and safety policy, such as minimizing the probability of getting cancer for employees who are subjected to NORM.
- The higher weighted value for the technology with the respect to cost criterion means the selected technology needs high capital cost and lower operation cost.

Visual presentation was performed to illustrate these analyses as providing in Figure 4.43.

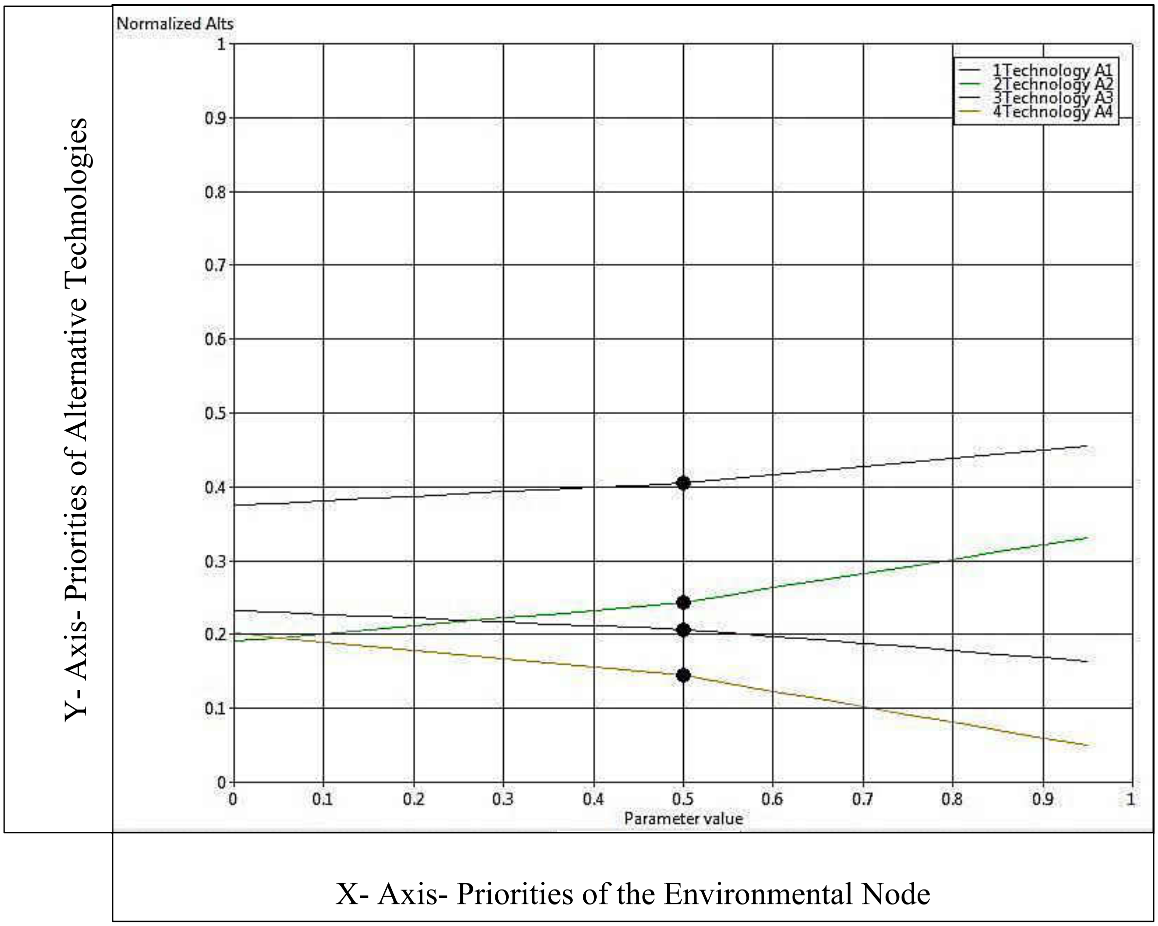


Figure 4. 43: Sensitivity Graph for Environmental Node

The sensitivity graph in Figure 4.43 was plotted when the priorities of Environmental node was located on the x axis and the priorities of the Alternatives were located on the y axis. The graph shows that at the environmental priority = 0.5, technology A1, which was Hydrocyclones, was about 0.2 (the intersection of red line\technology A1 with parameter value\ black line at 0.5 on y axis), Technology A2 about 0.25, Technology A3 about 0.41, and Technology A4 about 0.14. It was noticed from Figure 4.43 that if the priority of Environmental node was greater than about 0.4, Technology A3 became the preferred choice; and before 0.4, the Technology A2 was the best alternative technology.

The pie chart in Figure 4.44 is also provided to show the sensitivity analysis results between the alternatives at the parameter value = 0.5 with the respect to the Environmental node.

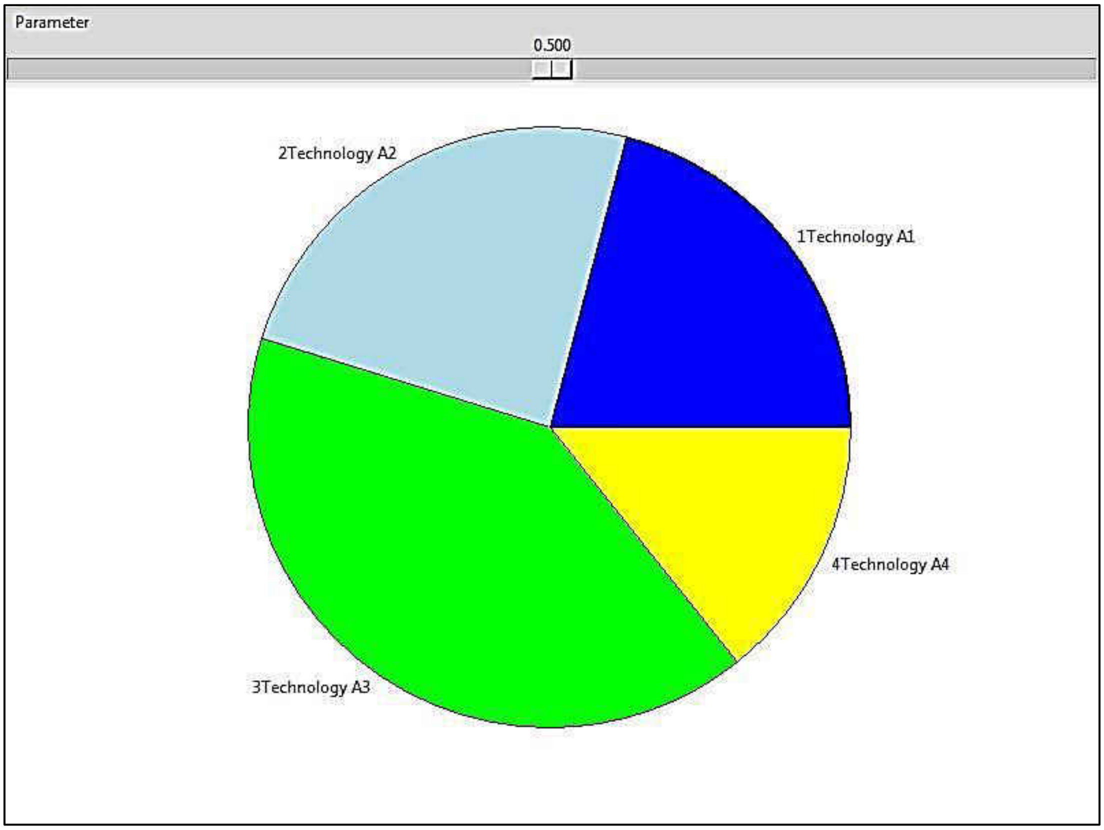


Figure 4. 44: Pie Chart for Alternatives Sensitivity Analysis

The results from sensitivity analysis showed that the best selected technology, which was technologyA3, is the best technology to meet the required specifications of PW, but it required high capital cost. Due to the fact that each technology has its specific efficiency and capability to remove contaminants from PW, variation between these technologies existed. Technology A4, which was the current method of pumping PW to the API evaporation ponds, was considered ineffective to protect the environment and humans, but it was the cheapest technology. Media filtration technology, which was technology A2, was also considered an effective technology to meet some of these requirements, such as removing heavy metals and reducing turbidity, with capital cost lower than Technology A3. Technology A1 was considered the best technology to remove OGC and treat any kind of PW, but the only problem was this technology requires high operation and maintenance cost because solids can block the inlet of Hydrocyclones (Igunnu & Chen, 2012). Extra cleaning efforts and costs may also be required for the latest technology. In addition, it generates wastes because of the accumulated wastes in its inlet, and then the disposal cost will increase. Technology A3 and technology A2 can be concluded as the best technologies that can be used to recycle 100% of PW and that was expected to decrease environmental and economic impacts of discharging PW. In order to achieve multiple goals of treatment, these technologies could be used together and designated in such way to meet these goals. Also, multiple stages of treatment might be required to reduce the amount of contaminants to the accepted levels.

4.7.3 Produced Water after Treatment

If PW is treated effectively and the amounts of TDS, TSS, NORM, and Dissolved hydrocarbons is reduced to the required level (PW specifications after treatment), reusing PW as new source of clean water could be possible for both human and oil field facilities. PW can be used as clean water for irrigation processes. Reducing the amount of salinity and other common contaminants that can impact plants and formations will offer new a source of clean water. Also, cleaning field facilities or use in a fire fighter station will be possible because there will not be any hazardous material existing that can affect humans or equipment.

Also, PW with the required specifications can be reinjected into oil wells to maintain well pressure and increase oil production by removing the amount of dissolved hydrocarbons in that water. In his work, Jreou has recommended to use Re-entry horizontal injection wells for PW in order to recover the amount of oil in that water. The results showed that the production from the productive sector in southern Iraq oil fields has increased by 22.629% with an ultimate recovery percentage of 78.16% (Al-Qurainate sector). Prediction within the time period from 2011 to 2020 has showed that the oil production with the proposed reinjection method will increase from 1,564.33 MMSTB to 1,698.5 MMSTB.

In addition, PW can be used to produce electrical power by using different technologies (Veil et al., 2004). If that happened, oilfields will not need to get power from the power stations that are producing electricity for cities and other factories. Then, the electrical power generation rate in the country will increase.

4.8 Control Phase

This is the last phase of the Six Sigma project in which the right actions, correct decisions, and failure prevention actions can be provided in the control plan. The control plan could help to list the most popular failures or procedures that could affect the sustainability and the performance of the selected technology. In our study, if the membrane filtration technology has been selected to treat the PW in the southern Iraqi oilfields some procedures and processes were required to maintain the high performance of that technology. Therefore, the high level control plan was conducted and introduced in this phase to propose some procedures and actions that could be taken to protect the sustainability of the selected technology and to ensure that most of the common causes of problems, such as corrosion problems, types of chemical used could be eliminated or at least reduced for the long term operation period, see Table 4.18 and Table 4.19.

Table 4.18: High Level Control Plan for the Membrane Filtration Technology

CONTROL PLAN								
PART/ PROCESS NUMBER	PROCESS NAME/ OPERATION DESCRIPTION			CTQ?	METHODS			REACTION PLAN
		PRODUCT	PROCESS		PRODUCT/PROCESS SPECIFICATION TOLERANCE	EVALUATION/ MEASUREMENT TECHNIQUE	CONTROL METHOD	
1	Backwashing		Remove contaminants accumulated on the membrane	y	During backwash the direction of flow reverses between 30 seconds to 3 minutes	Alarm will sound if the amount of contaminants need to be discharged	100% monitoring	Check the productivity level after each backwash
2	Chemical Cleaning		Remove organic and inorganic scaling, and befouling that are not removed by backwashing process	y	Chemical cleaning can be conducted for both MF/ UF and NF/ RO systems	Fouling, Scaling, and befouling flush detectors	Control Charts	Identify types and measure amounts of the remaining contaminants to identify the required chemicals for cleaning process
3	Waste Disposing		Dispose the concentrate stream by deep well injection or dilution and spray irrigation methods	y	from 5 to 10 percent of the treated water is discharged as waste	Follow the manufacturer guide	Measure Process Capability after each disposing process	Measure the amounts of chemicals in the disposal and meet the environmental regulations
4	Filters Protecting	Filters	prevent filters to contact with chemicals that used in chemical cleaning process	N	Isolate cleaning chemicals from treatment filters	Follow the manufacturer guide	100 % monitoring	Flush the membrane unit after chemical cleaning process
5	Corrosion inhibitors	chemicals	Select the proper inhibitor for corrosion	Y	Inhibitors must not react with other chemical used in the treatment and should be able to reduce IC to less than 5 mg/l	Design a pilot test for the selected technology	100 % monitoring	Measure the amount of Iron Content in the effluent and measure the performance of the technology during pilot plant testing
6	Early detecting of Leaks		Use the effective method to detect leaks before occurrences	Y	Leaks must be fixed once are detected to prevent instable turbidity that can cause bubbles and increase the amount of DG	Use effective method such as Ozone injection method to detect leaks	Pipes and Pumps leak test Scheduling	Schedule appropriate test plan to detect leaks, especially in the old pipes and pumps systems

Table 4.19: High Level Control Plan for the Membrane Filtration Technology -Continued

CONTROL PLAN

PART/ PROCESS NUMBER	PROCESS NAME/ OPERATION DESCRIPTION			CTQ?	METHODS			REACTION PLAN
		PRODUCT	PROCESS		PRODUCT/PROCESS SPECIFICATION TOLERANCE	EVALUATION/ MEASUREMENT TECHNIQUE	CONTROL METHOD	
7	Control Valves maintenance and replacement	Mechanical and Electrical Valves	Remove scales and deposits from the control valves and check for any defects or non-working control valves	Y	All control valves must be clean and easy to open and close if they are mechanical, and working properly if they are electrical	Increase data sharing, communication, and the feedback between the maintenance department and the operational and control department	Control Charts	Schedule weekly meetings between previous departments until developing an effective maintenance and cleaning plan. That will help to select proper control valves that will not affect by chemicals and other materials.
8	Power Supply	Electrical Power Stations	Ensure that the supplied power is stable and power generators are ready to supply enough power for the treatment units	Y	Power must be stable during PW treatment operations	Check with Electrical suppliers if there is any power-cut to prepare the generators	100 % monitoring	Report if any wrong will be going with either power station or generator to the head management Departments
9	Wells Head Control		Open and close the head of wells without allowing to air passing inside the well	N	Atmosphere must not pass through the head of wells during opening and closing them	Training can help wells operators and controllers to work effectively with this matter	Data sharing and Feedback	Provide training in wells controlling and increase recommendations about the problem that could be associated with ineffective wells head control

CHAPTER 5: RESULTS DISCUSSION/CONCLUSIONS

5.1 Results Discussion

PW that is being produced from southern Iraqi oilfields has high concentrations of contaminants that have high negative environmental impacts. These contaminants could be removed or at least reduced to the required levels if they are properly identified, measured, and treated. The most hazardous contaminants that existed in PW were heavy metals, iron, NORM, bacteria, and chemicals. In this study, by implementing the Six Sigma methodology, the proper and effective framework was developed in order to reduce the concentrations of these contaminants and to convert PW into usable water. The Six Sigma structural problem solving approach DMAIC and its powerful tools helped to obtain the following results:

- The Define phase helped to identify the stakeholders who might be involved in the PW treatment plant selection project. Also, it delivered a clear statement which was the core problem of the selected case study "Increase in the amount of contaminants in the discharged PW." This problem statement helped to focus on identifying and measuring the main contaminants in PW and find the relationship between them. Basically, the results obtained from the define phase were summarized and discussed as in following.
- According to SAM, the most vital stakeholders were SOC, MA, D.GOV, EPA, GOV, F.CO, and OP. Those stakeholders have high influence on the success of the project. Also, they might be either powerful supporters or powerful detractors. However, the PR and HU were considered powerful detractors because both of them were taking orders from the head managements which were represented by SOC, GOV, and D.GOV. As a

result, changing the policy management for PW was required, but extra time and effort might also require providing training for PR, and HU to increase their skills to manage that water effectively and to make them familiar with new policy.

- The flow chart for the current oil production processes that have taken place in one of the DS of southern Iraqi oil fields showed that either injecting PW into the NEPs or discharging it into Dammam formation was an ineffective management method.
- Based on the results obtained from VOCM, the highest voice of the customer was finding an ecofriendly management method for PW. Then, the second highest VOC was reusing PW as clean water. For both purposes, identifying the KPOV and the KPIVs were required.
- At the end of the define phase, the KPIVs were identified and they were represented by all factors that could impact the amount of contaminants in PW. These factors were related to the current management method of PW and all operation, maintenance, and control activities that might be highly influencing the KPOV.

The measure phase helped to measure the VOC and CTQs based on the results obtained from the define phase. Clearly, in this phase, evaluating PW constituents was performed and helped to identify the main sources of these contaminants and all factors that could influence the amounts and compositions of various hazardous materials in that water. Mainly, the results obtained from the measure phase helped to narrow the choices of selecting PW treatment technology. In order to capture more details about the VOC and CTQs, the QFD approach was used by implementing one of its effective tools which was the HOQ. In short, the results obtained from the Measure phase were listed and discussed in following:

- The QFD, specifically the HOQ, was used to connect between VOC and technical requirements, process control plan, required equipment, and manufacturing operations. The results obtained from HOQ indicated that the main customers' requirements were related to managing, treating, reusing, and reinjecting the PW. The technical importance rating was measured for each technical requirement and that helped to identify which requirement needed to set higher targets and that was considered the source of a competitive advantage.
- From PW specifications before treatment, the average of OGC at the selected locations was 1,000 mg/l and it was extremely high.
- The average particles size was 60 micrometer.
- Biochemistry tests showed existence of different kinds of bacteria, such as aerobes, anaerobes, facultative anaerobes, planktonic, and sessile.
- The average PH level at the selected locations was 5.
- Sludge and formation samples tests were performed to measure radon concentration. The results showed that these samples contained radium isotopes which were mainly alpha and gamma emitter and were normally associated with the discharged PW.
- The mathematic mean for radon concentration for the all sludge and formation samples was 26,089 Bq/m$^{3.}$
- Pareto chart indicated that the sludge and formation samples that were taken from CGSS of the southern Rumaila oil field had high average radon concentration and that was 37,800 Bq/m^3. In general, the probability of getting cancer for someone who is subjected

to radon radiation is 0.0016 Bq/m^3 for each 37 Bq/m^3, thus from the obtained average, the probability increases by a 705 multiple.

- The average of calculated SAR values at all selected dehydrators was 252.19 and it was extremely high.
- Dissolved oxygen concentration was 2 mg/l and the average of dissolved CO_2concentration was more than 2 mg/l
- TDS amount was 250,000 mg/l and TSS amount was 300 mg/l
- OGC was 1,000 mg/l
- Total IC was 300 mg/l and that attributes to the effects of different factors

The outputs from the Measure phase were analyzed in the third phase which was the Analyze phase. The Analyze phase helped to connect between main causes of contaminants, oil field problems, and their ecological effects. After identifying the main contaminants, measuring their amounts, and analyzing their root causes, the following results were obtained:

- The high IC was attributed to multi-corrosion processes that were mostly occurring during oil and gas production in casing, pipes, and storage tanks.
- Since the values of TDS, DO, and CO_2 were 250,000 mg/l, 2 mg/l, and 470 mg/l respectively, the corrosion rate was increased according to the interrelationships between them.
- The corrosion helped to increase amounts of contaminants in the discharged PW because corrosion caused an increase in the accumulated amounts of scales in pipes, valves, storage tanks, and other equipment with improper handling or management method.

- The dehydrator of Alzubair Musharif, because it contains high salinity, chloride, Sulphate, low pH, it is expected to have high corrosion rate.
- The most important factors and variables that were influencing the corrosion rate were the high concentration of scales and corrosive materials in casing, tubing, and pipes. Also, the maintenance and failure prevention plan were considered very important and highly influence these variables.
- Ineffective maintenance, protection plan, and safety plan were identified.
- The current management method for PW in Iraqi oilfields was considered one of the root causes of increasing amounts of contaminants in PW. By the current method, almost 90% of the PW could be evaporated, and then the remaining PW contained a high amount of heavy metals and sludge that contained dissolved hydrocarbons and NORM. As a result, it was necessary to have a treatment plant that could be used to remove these hazardous materials before disposing that water.
- The results obtained from STA showed that with increasing oil production and by using NEPs method to manage the excessive amount of PW, the current management method was risky.

The fourth phase was the Improve Phase. This phase was conducted in order to find an ecofriendly method to solve the problem of PW based on the measured and analyzed results from previous phases. Since there were different methods and technologies existing in markets that could be used to treat PW, each having advantages and disadvantages, the MCDM process was used to select the best method or technology from the identified alternatives that could be used to meet or exceed customer's expectations (SOC's requirements). Therefore, the AHP model was developed and used to rank between these alternatives with the respect to the PW properties before and after treatment. Based on the results obtained from that model, the best technology that could be used to treat PW effectively was the membrane filtration. This technology could remove most of the contaminants and could recycle almost 100% of the PW. Accordingly, it was considered as an optimum solution for the PW problem. The results obtained from the improve phase were discussed in the following:

- Changing the policy to effectively manage PW in the southern Iraqi oilfields was required.
- The MCDM method was used to select the best ecofriendly technology to treat PW and to meet SOC's required properties for that water.
- Four important criteria were selected to rank between the four selected alternatives. These criteria were very critical to the SOC and were highly dependent on the results obtained from the Analyze phase. These criteria were cost, environmental, technical feasibility, and health and safety.
- Each main criterion was connected to its sub-criteria that were represented by the VOC and CTQs and comparisons between them were conducted with the respect to the main goal, which was selecting the PW management method for Iraqi oilfields.
- The results were obtained by synthesizing the whole model and showed that the best method to effectively manage the PW was using membrane filtration technology to treat that water prior to disposal or reusing it as clean water.
- Ranking between alternatives, main criteria, and sub-criteria was performed by using comparison super-matrices.

- The unweighted Supermatrix included all priorities from the pairwise comparisons; see Tables B1 and B2 in Appendix B.
- The weighted Supermatrix for the developed model was the same as the unweighted Supermatrix because the clusters were not weighted; see Tables B3 and B4 in Appendix B.
- The final priorities for the four alternatives were provided in the final Supermatrix, which was called the limit Supermatrix. The latest Supermatrix in the model included the final answers in the column under the Goal; see Tables B5 and B6 in Appendix B.

The last phase was the control phase in which the high level control plan was developed to maintain the sustainability and the performance of the selected technology. If the proposed technology was implemented to treat PW, some important procedures were required to protect that technology for the short and long term period. Therefore, the control plan was developed to prevent reoccurring of current problems in the near future, such as corrosion, leak, operational conditions variation, ineffective waste management, and ineffective maintenance plan.

5.2 Conclusions

The application of Six Sigma in oil and gas industries using the DMAIC approach is a powerful method to successfully identify problems, measure and analyze their causes, remove these causes by using quality control tools, improve the current states of existing systems, and control those systems for the long term period. Implementing quality principles, practices, and tools in the selected case study are effective to identify the main contaminants in PW and uncover the main and sub-causes of an increase in the amount of these identified contaminants.

All of that could be done by using effective quality tools such as Pareto analysis, flow chart, histogram, and cause and effect analysis, stakeholder analysis, and statistical process control tools. Meeting customer's needs is very important, thus, the QFD method could be used to identify the required technical assessment to meet or exceed the required specifications of the PW prior to disposal. The STA could also help to perform brainstorming and to connect between main and sub-causes of current problems and to identify them accurately. The MCDM process could be conducted to find the best solution for PW problem with the respect to the customers' needs with less time and effort. The latest could be used once all root causes of problems are analyzed in details. This study introduces new quality concepts, principles, tools, and methods that can be used to solve problems, improve systems, and manage organizations effectively within oil industries. Therefore, Six Sigma is not only quality principle, but also a powerful guide that can be implemented successfully in oil and gas industries whenever an initiative toward quality improvement is conducted to improve processes and systems.

CHAPTER 6: RECOMMENDATIONS/ FUTURE RESEARCH

6.1 Recommendations

- Implementing Six Sigma in oil and gas industries can help to manage these industries and improve them effectively.
- Providing training in the quality tools for the control engineering and design departments will help them to identify problems, remove their causes, and reduce wastes.
- Quality management concepts are very important for the head management and engineers who are working in oil and gas industries. These concepts, such as Six Sigma will provide them efficient methods and tools whenever initiatives toward quality improvement processes are started within their organizations.
- Statistical process control tools and system analysis methods are effective to perform data measurement and analysis precisely.
- STA is more beneficial to use whenever root causes of problems and their effects were required to be identified.
- MCDM is an effective method to select the optimum solution from different alternatives with the respect to customers' needs and the main goal for the selected project with a lack of quantitative data.
- For the selected technology, a pilot treatment plant is highly recommended to construct prior to constructing the whole treatment system for PW in the southern Iraqi oil fields. Since the dehydrator of Alzubair Musharif is discharging high amount of contaminants in

PW stream, a pilot treatment plant should be constructed at the degasing station of the Alzubair Musharif.

- Pilot treatment performance monitoring should be performed by testing samples from filtrated stream to check for TDS, IC, TSS, OWC, existence of bacteria, and NORM.
- Regular and effective testing for sludge and PW samples can help to detect and then identify the reason behind an increase in the amounts of contaminants in the disposals.
- Using Quality control tools, such as using control charts for monitoring the performance of the selected technology and other processes over their operation and production time, is highly recommended.
- The RCA is very important to identify the hidden causes of problems and that will help to develop a problem prevention plan and control plan.
- Providing training in advanced quality design and control tools and explaining the importance of using the Six Sigma methodology is also recommended to improve processes and systems and reduce waste during operation and production activities.

6.2 Future Research

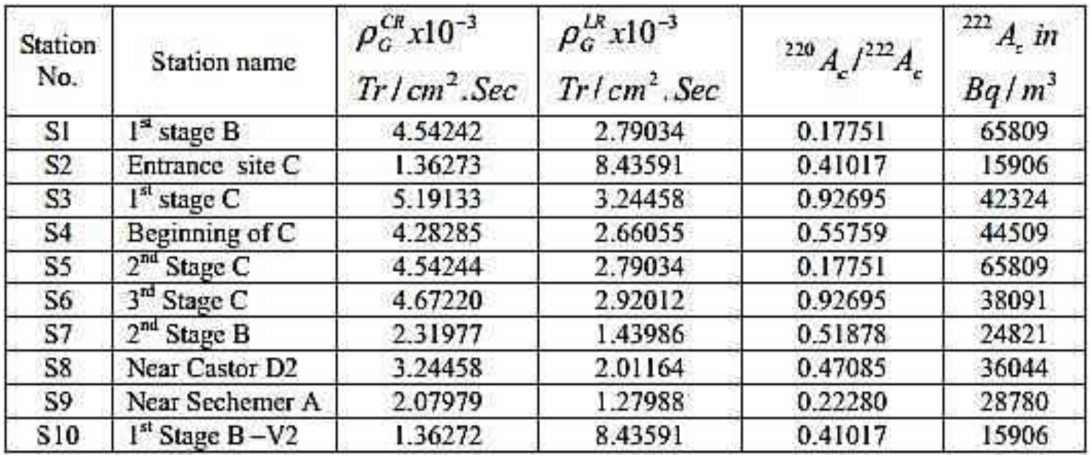
There are many areas of future work related to using the Six Sigma methodology. Implementing Six Sigma in oil and gas industries to improve processes and systems, reduce waste, and identify the most common causes of problems is new approach. The developed framework in this study could be adapted to other problems in petroleum manufacturing sectors. Industries that have not yet implemented Six Sigma could be real sources of future research opportunities. Different quality tools and practices can be selected to modify an existing framework or develop a new framework that will be properly related to quality improvement initiatives. After identifying the best treatment method for PW by using the Six Sigma methodology, it will be possible to select the best reinjection system for that water and that will help to increase oil production and maintain well pressure. More data and further analysis may require developing new framework for the purpose of selection the best reinjection system. However, using QFD, and specifically the HOQ, will help to connect between the critical success factors for the selected project and prioritize them with the respect to customers' needs.

Developing Iraqi infrastructure requires advanced quality methods and tools. Implementing quality tools at the beginning of projects will help to reduce the development time, cost of bad outcomes or reworking to fix problems, and increase the performance of processes, systems, and workforces. Therefore, implementing this methodology in different areas, such as education, government, services, and health care, will help to introduce this new method for quality improvement initiatives and performance excellence for Iraq.

APPENDIX A: RADON CONCENTRATION IN OILY SLUDGE PRODUCED FROM SOUTHERN IRAQI OIL FIELDS

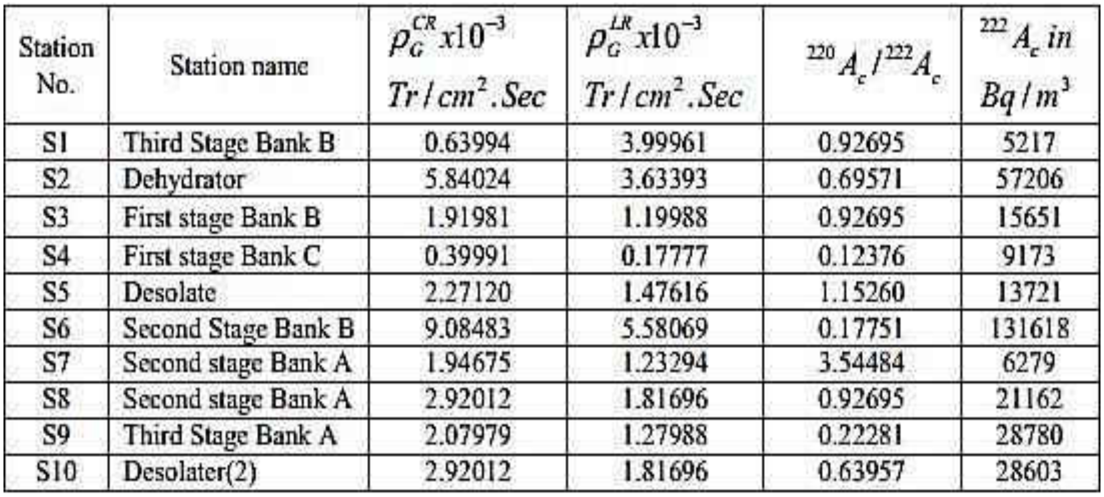
All tables in this Appendix were adopted from Subber (Subber et al., 2011).

Table A 1: Radon gas concentration in sludge samples from the Southern CDS



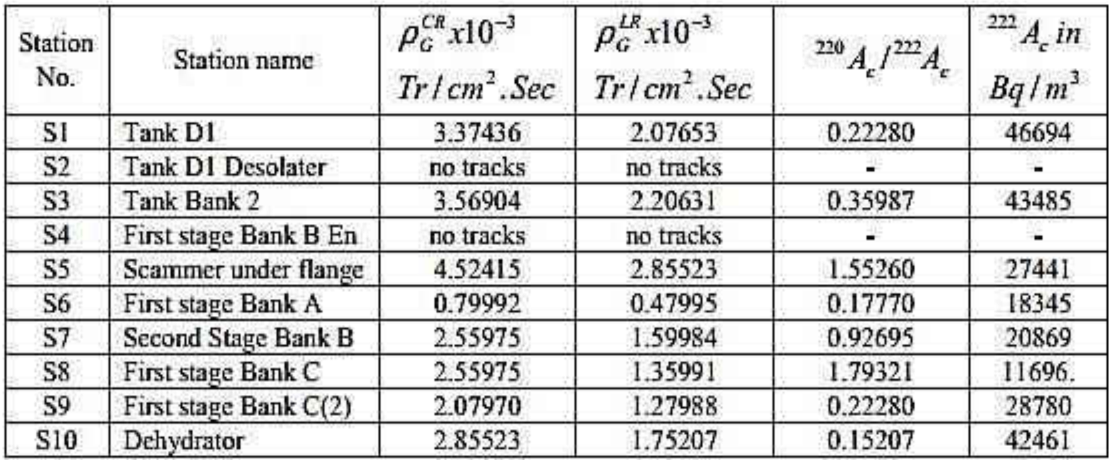
Station No.	Station name	$\rho_G^{CR} x10^{-3}$ $Tr/cm^2.Sec$	$\rho_G^{LR} x10^{-3}$ $Tr/cm^2.Sec$	$^{220}A_c/^{222}A_c$	$^{222}A_c$ in Bq/m^3
S1	1st stage B	4.54242	2.79034	0.17751	65809
S2	Entrance site C	1.36273	8.43591	0.41017	15906
S3	1st stage C	5.19133	3.24458	0.92695	42324
S4	Beginning of C	4.28285	2.66055	0.55759	44509
S5	2nd Stage C	4.54244	2.79034	0.17751	65809
S6	3rd Stage C	4.67220	2.92012	0.92695	38091
S7	2nd Stage B	2.31977	1.43986	0.51878	24821
S8	Near Castor D2	3.24458	2.01164	0.47085	36044
S9	Near Sechemer A	2.07979	1.27988	0.22280	28780
S10	1st Stage B –V2	1.36272	8.43591	0.41017	15906

Table A 2: Radon gas concentration in sludge samples from the Southern CDS



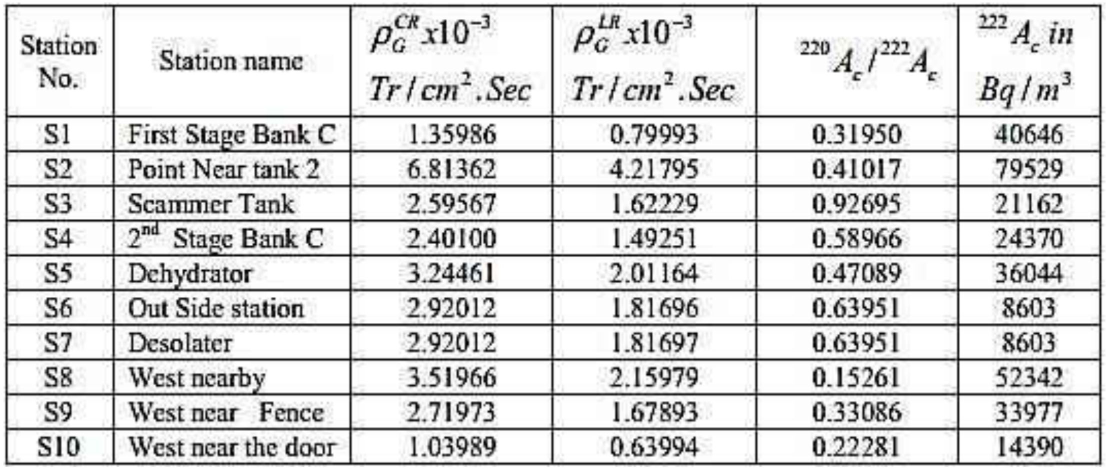
Station No.	Station name	$\rho_G^{CR} x10^{-3}$ $Tr/cm^2.Sec$	$\rho_G^{LR} x10^{-3}$ $Tr/cm^2.Sec$	$^{220}A_c/^{222}A_c$	$^{222}A_c$ in Bq/m^3
S1	Third Stage Bank B	0.63994	3.99961	0.92695	5217
S2	Dehydrator	5.84024	3.63393	0.69571	57206
S3	First stage Bank B	1.91981	1.19988	0.92695	15651
S4	First stage Bank C	0.39991	0.17777	0.12376	9173
S5	Desolate	2.27120	1.47616	1.15260	13721
S6	Second Stage Bank B	9.08483	5.58069	0.17751	131618
S7	Second stage Bank A	1.94675	1.23294	3.54484	6279
S8	Second stage Bank A	2.92012	1.81696	0.92695	21162
S9	Third Stage Bank A	2.07979	1.27988	0.22281	28780
S10	Desolater(2)	2.92012	1.81696	0.63957	28603

Table A 3: The radon gas concentration in the sludge samples from Qurenit CDS



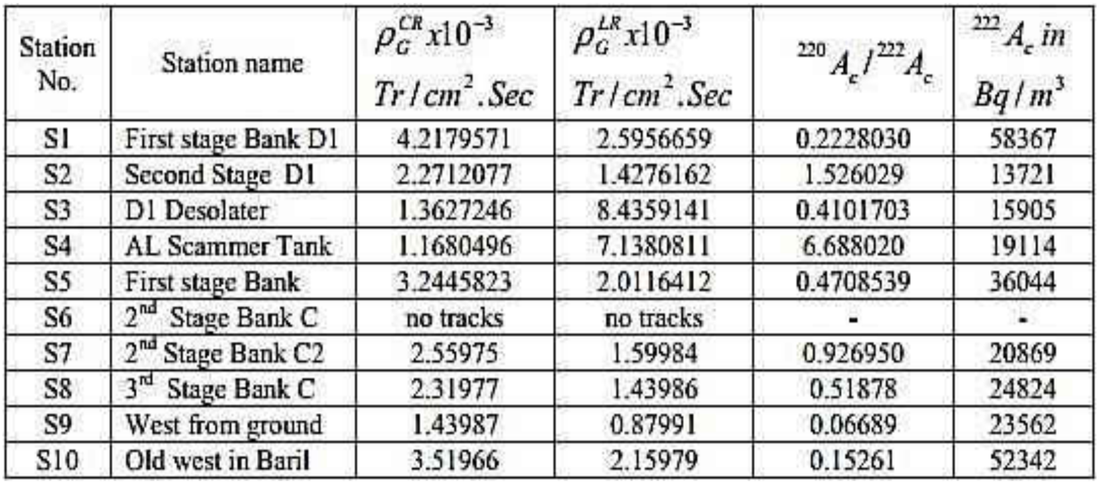
Station No.	Station name	$\rho_G^{CR} x10^{-3}$ $Tr/cm^2.Sec$	$\rho_G^{LR} x10^{-3}$ $Tr/cm^2.Sec$	$^{220}A_c/^{222}A_c$	$^{222}A_c$ in Bq/m^3
S1	Tank D1	3.37436	2.07653	0.22280	46694
S2	Tank D1 Desolater	no tracks	no tracks	-	-
S3	Tank Bank 2	3.56904	2.20631	0.35987	43485
S4	First stage Bank B En	no tracks	no tracks	-	-
S5	Scammer under flange	4.52415	2.85523	1.55260	27441
S6	First stage Bank A	0.79992	0.47995	0.17770	18345
S7	Second Stage Bank B	2.55975	1.59984	0.92695	20869
S8	First stage Bank C	2.55975	1.35991	1.79321	11696.
S9	First stage Bank C(2)	2.07970	1.27988	0.22280	28780
S10	Dehydrator	2.85523	1.75207	0.15207	42461

Table A 4: The radon gas concentration in the sludge samples from Shamei CDS



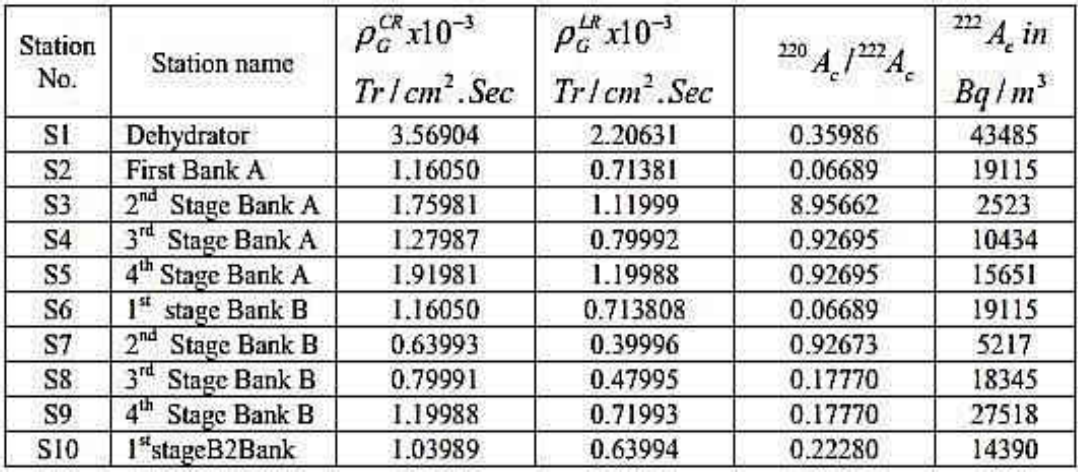
Station No.	Station name	$\rho_G^{CR} x10^{-3}$ $Tr/cm^2.Sec$	$\rho_G^{LR} x10^{-3}$ $Tr/cm^2.Sec$	$^{220}A_c/^{222}A_c$	$^{222}A_c$ in Bq/m^3
S1	First Stage Bank C	1.35986	0.79993	0.31950	40646
S2	Point Near tank 2	6.81362	4.21795	0.41017	79529
S3	Scammer Tank	2.59567	1.62229	0.92695	21162
S4	2nd Stage Bank C	2.40100	1.49251	0.58966	24370
S5	Dehydrator	3.24461	2.01164	0.47089	36044
S6	Out Side station	2.92012	1.81696	0.63951	8603
S7	Desolater	2.92012	1.81697	0.63951	8603
S8	West nearby	3.51966	2.15979	0.15261	52342
S9	West near Fence	2.71973	1.67893	0.33086	33977
S10	West near the door	1.03989	0.63994	0.22281	14390

Table A 5: The radon gas concentration in the Sludge samples from Ratka CDS



Station No.	Station name	$\rho_G^{CR} x10^{-3}$ $Tr/cm^2.Sec$	$\rho_G^{LR} x10^{-3}$ $Tr/cm^2.Sec$	$^{220}A_c/^{222}A_c$	$^{222}A_c$ in Bq/m^3
S1	First stage Bank D1	4.2179571	2.5956659	0.2228030	58367
S2	Second Stage D1	2.2712077	1.4276162	1.526029	13721
S3	D1 Desolater	1.3627246	8.4359141	0.4101703	15905
S4	AL Scammer Tank	1.1680496	7.1380811	6.688020	19114
S5	First stage Bank	3.2445823	2.0116412	0.4708539	36044
S6	2nd Stage Bank C	no tracks	no tracks	-	-
S7	2nd Stage Bank C2	2.55975	1.59984	0.926950	20869
S8	3rd Stage Bank C	2.31977	1.43986	0.51878	24824
S9	West from ground	1.43987	0.87991	0.06689	23562
S10	Old west in Baril	3.51966	2.15979	0.15261	52342

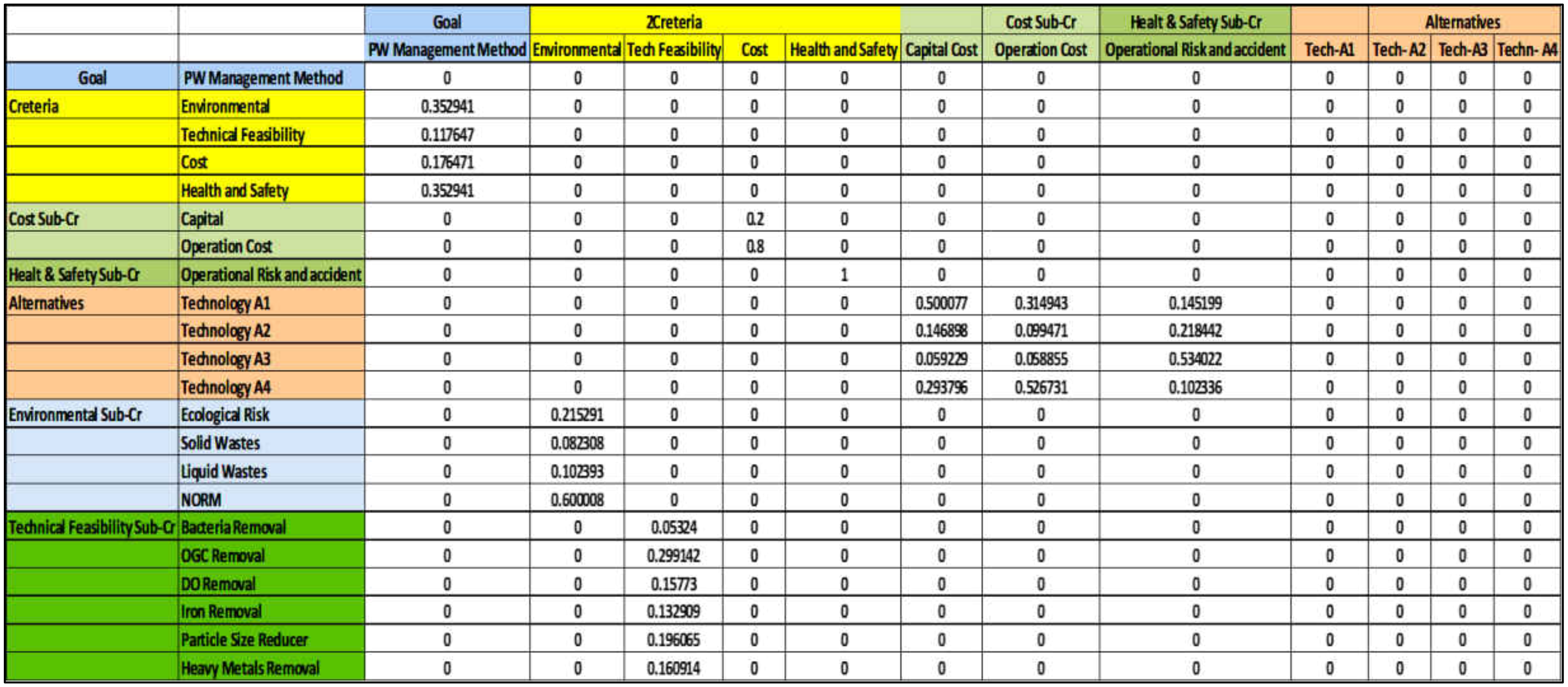
Table A 6: The radon gas concentration in the Sludge samples from Northern Rumaila CDS



Station No.	Station name	$\rho_G^{CR} x10^{-3}$ $Tr/cm^2.Sec$	$\rho_G^{LR} x10^{-3}$ $Tr/cm^2.Sec$	$^{220}A_c/^{222}A_c$	$^{222}A_c$ in Bq/m^3
S1	Dehydrator	3.56904	2.20631	0.35986	43485
S2	First Bank A	1.16050	0.71381	0.06689	19115
S3	2nd Stage Bank A	1.75981	1.11999	8.95662	2523
S4	3rd Stage Bank A	1.27987	0.79992	0.92695	10434
S5	4th Stage Bank A	1.91981	1.19988	0.92695	15651
S6	1st stage Bank B	1.16050	0.713808	0.06689	19115
S7	2nd Stage Bank B	0.63993	0.39996	0.92673	5217
S8	3rd Stage Bank B	0.79991	0.47995	0.17770	18345
S9	4th Stage Bank B	1.19988	0.71993	0.17770	27518
S10	1ststageB2Bank	1.03989	0.63994	0.22280	14390

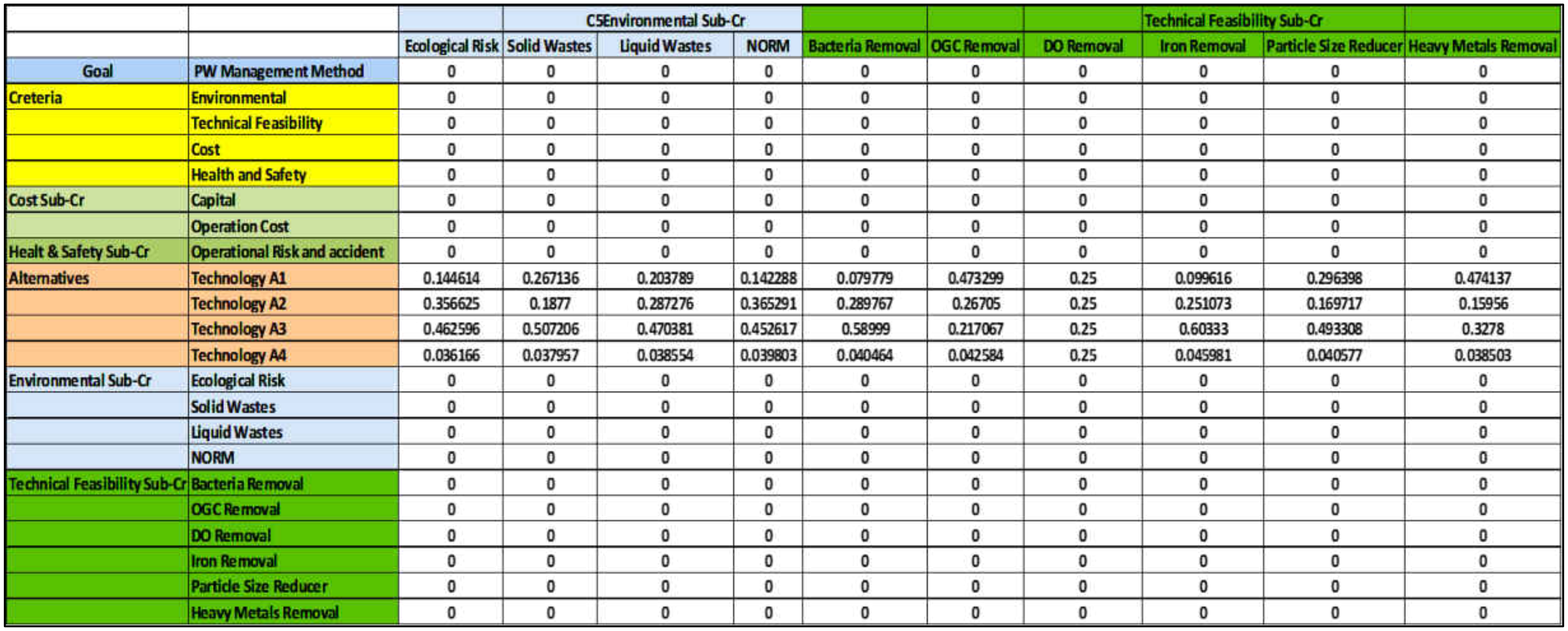
APPENDIX B: THE MODEL SUPER MATRICES

Table B 1: The Unweighted Supermatrix



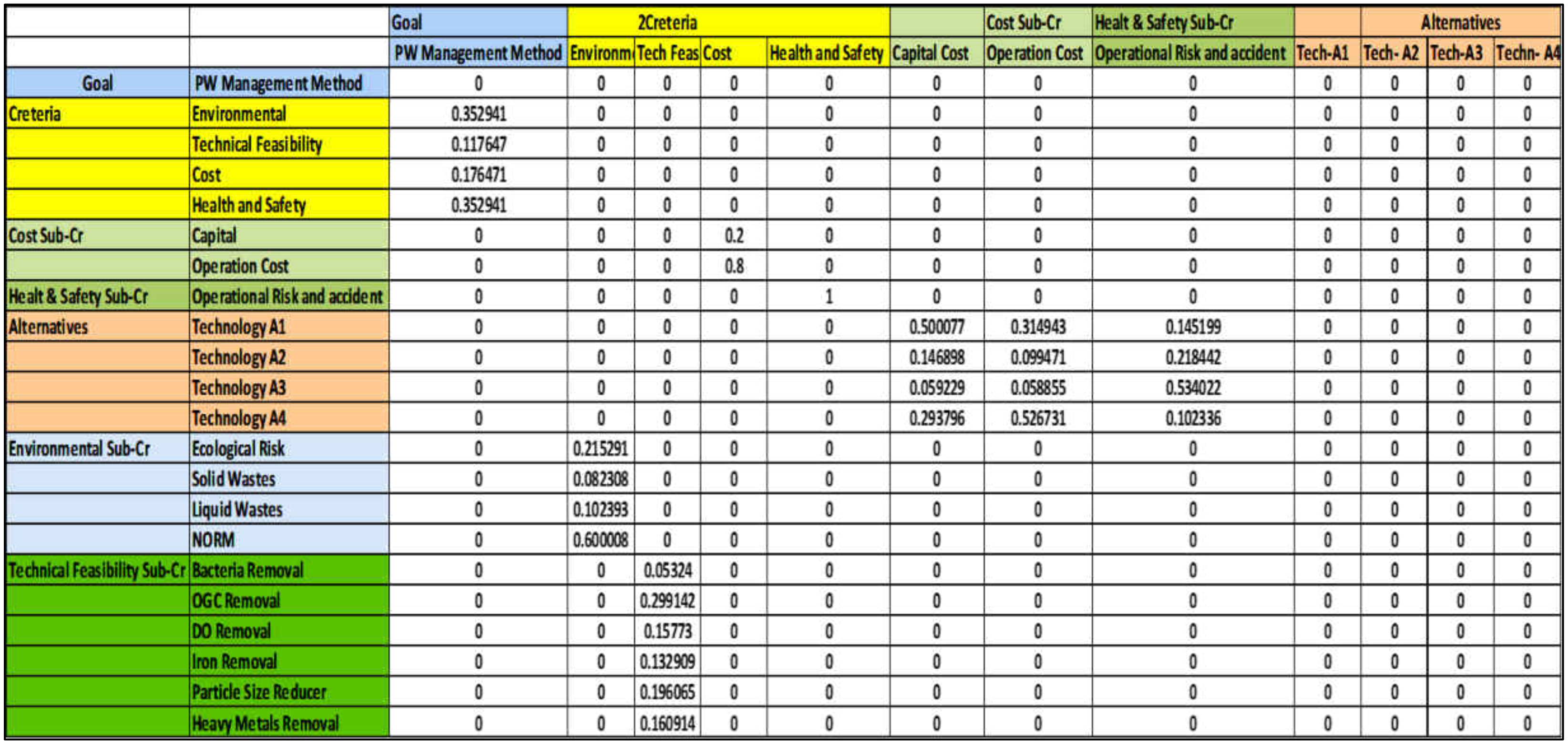
		Goal	2Creteria					Cost Sub-Cr	Healt & Safety Sub-Cr		Alternatives		
		PW Management Method	Environmental	Tech Feasibility	Cost	Health and Safety	Capital Cost	Operation Cost	Operational Risk and accident	Tech-A1	Tech- A2	Tech-A3	Techn- A4
Goal	PW Management Method	0	0	0	0	0	0	0	0	0	0	0	0
Creteria	Environmental	0.352941	0	0	0	0	0	0	0	0	0	0	0
	Technical Feasibility	0.117647	0	0	0	0	0	0	0	0	0	0	0
	Cost	0.176471	0	0	0	0	0	0	0	0	0	0	0
	Health and Safety	0.352941	0	0	0	0	0	0	0	0	0	0	0
Cost Sub-Cr	Capital	0	0	0	0.2	0	0	0	0	0	0	0	0
	Operation Cost	0	0	0	0.8	0	0	0	0	0	0	0	0
Healt & Safety Sub-Cr	Operational Risk and accident	0	0	0	0	1	0	0	0	0	0	0	0
Alternatives	Technology A1	0	0	0	0	0	0.500077	0.314943	0.145199	0	0	0	0
	Technology A2	0	0	0	0	0	0.146898	0.099471	0.218442	0	0	0	0
	Technology A3	0	0	0	0	0	0.059229	0.058855	0.534022	0	0	0	0
	Technology A4	0	0	0	0	0	0.293796	0.526731	0.102336	0	0	0	0
Environmental Sub-Cr	Ecological Risk	0	0.215291	0	0	0	0	0	0	0	0	0	0
	Solid Wastes	0	0.082308	0	0	0	0	0	0	0	0	0	0
	Liquid Wastes	0	0.102393	0	0	0	0	0	0	0	0	0	0
	NORM	0	0.600008	0	0	0	0	0	0	0	0	0	0
Technical Feasibility Sub-Cr	Bacteria Removal	0	0	0.05324	0	0	0	0	0	0	0	0	0
	OGC Removal	0	0	0.299142	0	0	0	0	0	0	0	0	0
	DO Removal	0	0	0.15773	0	0	0	0	0	0	0	0	0
	Iron Removal	0	0	0.132909	0	0	0	0	0	0	0	0	0
	Particle Size Reducer	0	0	0.196065	0	0	0	0	0	0	0	0	0
	Heavy Metals Removal	0	0	0.160914	0	0	0	0	0	0	0	0	0

Table B 2: The Unweighted Suprmatrix Continued



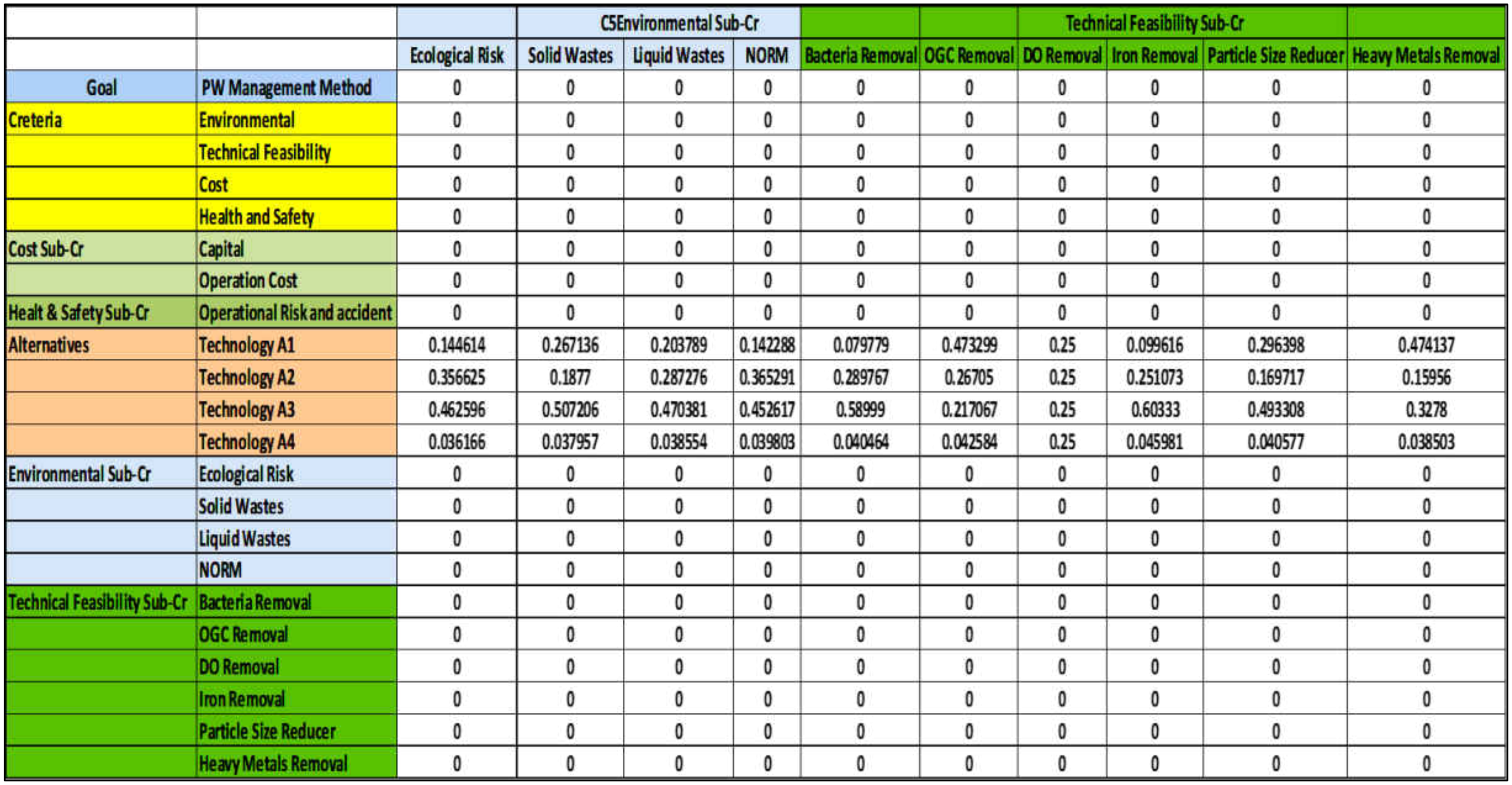
		C5Environmental Sub-Cr				Technical Feasibility Sub-Cr					
		Ecological Risk	Solid Wastes	Liquid Wastes	NORM	Bacteria Removal	OGC Removal	DO Removal	Iron Removal	Particle Size Reducer	Heavy Metals Removal
Goal	PW Management Method	0	0	0	0	0	0	0	0	0	0
Creteria	Environmental	0	0	0	0	0	0	0	0	0	0
	Technical Feasibility	0	0	0	0	0	0	0	0	0	0
	Cost	0	0	0	0	0	0	0	0	0	0
	Health and Safety	0	0	0	0	0	0	0	0	0	0
Cost Sub-Cr	Capital	0	0	0	0	0	0	0	0	0	0
	Operation Cost	0	0	0	0	0	0	0	0	0	0
Healt & Safety Sub-Cr	Operational Risk and accident	0	0	0	0	0	0	0	0	0	0
Alternatives	Technology A1	0.144614	0.267136	0.203789	0.142288	0.079779	0.473299	0.25	0.099616	0.296398	0.474137
	Technology A2	0.356625	0.1877	0.287276	0.365291	0.289767	0.26705	0.25	0.251073	0.169717	0.15956
	Technology A3	0.462596	0.507206	0.470381	0.452617	0.58999	0.217067	0.25	0.60333	0.493308	0.3278
	Technology A4	0.036166	0.037957	0.038554	0.039803	0.040464	0.042584	0.25	0.045981	0.040577	0.038503
Environmental Sub-Cr	Ecological Risk	0	0	0	0	0	0	0	0	0	0
	Solid Wastes	0	0	0	0	0	0	0	0	0	0
	Liquid Wastes	0	0	0	0	0	0	0	0	0	0
	NORM	0	0	0	0	0	0	0	0	0	0
Technical Feasibility Sub-Cr	Bacteria Removal	0	0	0	0	0	0	0	0	0	0
	OGC Removal	0	0	0	0	0	0	0	0	0	0
	DO Removal	0	0	0	0	0	0	0	0	0	0
	Iron Removal	0	0	0	0	0	0	0	0	0	0
	Particle Size Reducer	0	0	0	0	0	0	0	0	0	0
	Heavy Metals Removal	0	0	0	0	0	0	0	0	0	0

Table B 3: The Weighted Supermatrix



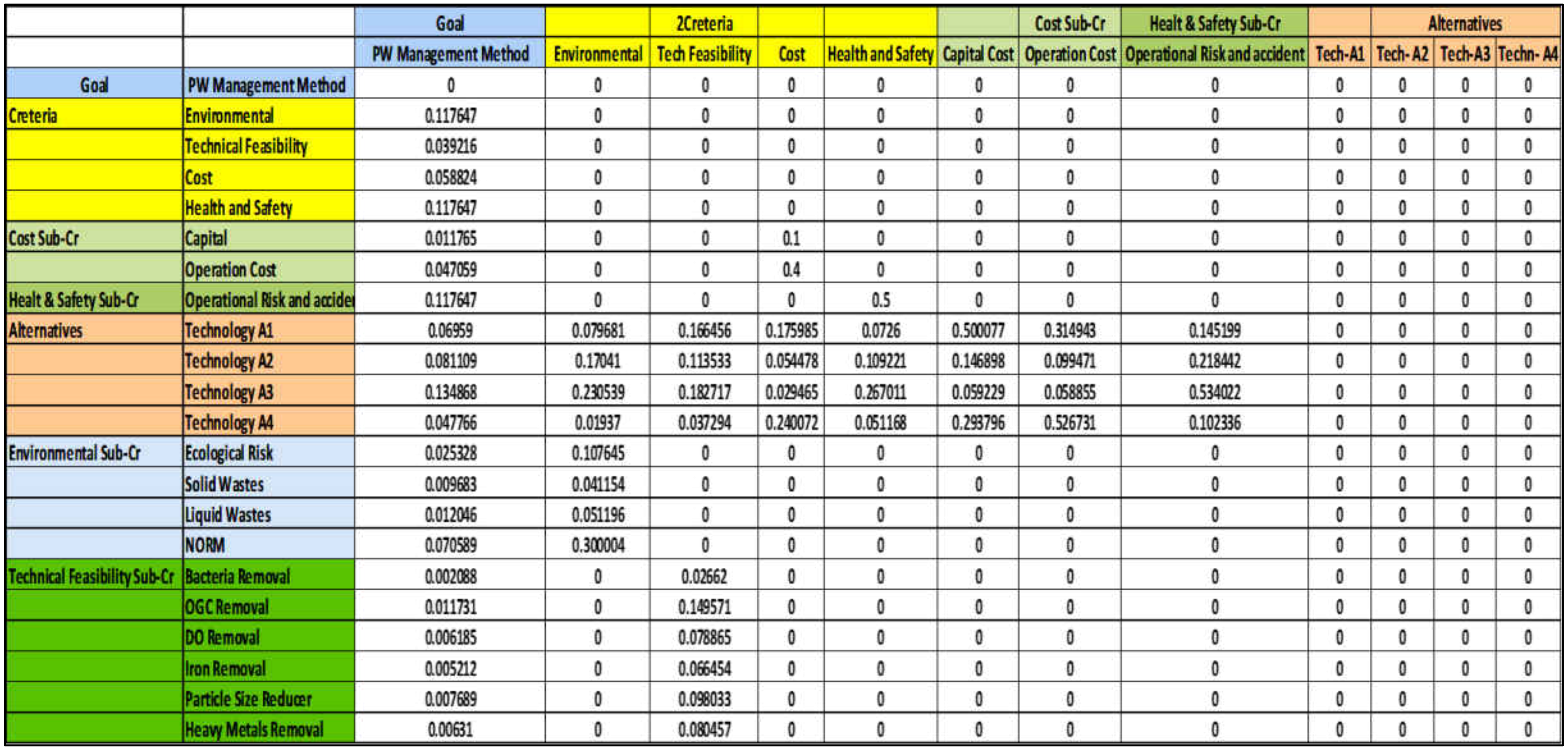
		Goal	2Creteria					Cost Sub-Cr	Healt & Safety Sub-Cr		Alternatives		
		PW Management Method	Environm	Tech Feas	Cost	Health and Safety	Capital Cost	Operation Cost	Operational Risk and accident	Tech-A1	Tech- A2	Tech-A3	Techn- A4
Goal	PW Management Method	0	0	0	0	0	0	0	0	0	0	0	0
Creteria	Environmental	0.352941	0	0	0	0	0	0	0	0	0	0	0
	Technical Feasibility	0.117647	0	0	0	0	0	0	0	0	0	0	0
	Cost	0.176471	0	0	0	0	0	0	0	0	0	0	0
	Health and Safety	0.352941	0	0	0	0	0	0	0	0	0	0	0
Cost Sub-Cr	Capital	0	0	0	0.2	0	0	0	0	0	0	0	0
	Operation Cost	0	0	0	0.8	0	0	0	0	0	0	0	0
Healt & Safety Sub-Cr	Operational Risk and accident	0	0	0	0	1	0	0	0	0	0	0	0
Alternatives	Technology A1	0	0	0	0	0	0.500077	0.314943	0.145199	0	0	0	0
	Technology A2	0	0	0	0	0	0.146898	0.099471	0.218442	0	0	0	0
	Technology A3	0	0	0	0	0	0.059229	0.058855	0.534022	0	0	0	0
	Technology A4	0	0	0	0	0	0.293796	0.526731	0.102336	0	0	0	0
Environmental Sub-Cr	Ecological Risk	0	0.215291	0	0	0	0	0	0	0	0	0	0
	Solid Wastes	0	0.082308	0	0	0	0	0	0	0	0	0	0
	Liquid Wastes	0	0.102393	0	0	0	0	0	0	0	0	0	0
	NORM	0	0.600008	0	0	0	0	0	0	0	0	0	0
Technical Feasibility Sub-Cr	Bacteria Removal	0	0	0.05324	0	0	0	0	0	0	0	0	0
	OGC Removal	0	0	0.299142	0	0	0	0	0	0	0	0	0
	DO Removal	0	0	0.15773	0	0	0	0	0	0	0	0	0
	Iron Removal	0	0	0.132909	0	0	0	0	0	0	0	0	0
	Particle Size Reducer	0	0	0.196065	0	0	0	0	0	0	0	0	0
	Heavy Metals Removal	0	0	0.160914	0	0	0	0	0	0	0	0	0

Table B 4: The Weighted Supermatrix Continued



			C5Environmental Sub-Cr					Technical Feasibility Sub-Cr			
		Ecological Risk	Solid Wastes	Liquid Wastes	NORM	Bacteria Removal	OGC Removal	DO Removal	Iron Removal	Particle Size Reducer	Heavy Metals Removal
Goal	PW Management Method	0	0	0	0	0	0	0	0	0	0
Creteria	Environmental	0	0	0	0	0	0	0	0	0	0
	Technical Feasibility	0	0	0	0	0	0	0	0	0	0
	Cost	0	0	0	0	0	0	0	0	0	0
	Health and Safety	0	0	0	0	0	0	0	0	0	0
Cost Sub-Cr	Capital	0	0	0	0	0	0	0	0	0	0
	Operation Cost	0	0	0	0	0	0	0	0	0	0
Healt & Safety Sub-Cr	Operational Risk and accident	0	0	0	0	0	0	0	0	0	0
Alternatives	Technology A1	0.144614	0.267136	0.203789	0.142288	0.079779	0.473299	0.25	0.099616	0.296398	0.474137
	Technology A2	0.356625	0.1877	0.287276	0.365291	0.289767	0.26705	0.25	0.251073	0.169717	0.15956
	Technology A3	0.462596	0.507206	0.470381	0.452617	0.58999	0.217067	0.25	0.60333	0.493308	0.3278
	Technology A4	0.036166	0.037957	0.038554	0.039803	0.040464	0.042584	0.25	0.045981	0.040577	0.038503
Environmental Sub-Cr	Ecological Risk	0	0	0	0	0	0	0	0	0	0
	Solid Wastes	0	0	0	0	0	0	0	0	0	0
	Liquid Wastes	0	0	0	0	0	0	0	0	0	0
	NORM	0	0	0	0	0	0	0	0	0	0
Technical Feasibility Sub-Cr	Bacteria Removal	0	0	0	0	0	0	0	0	0	0
	OGC Removal	0	0	0	0	0	0	0	0	0	0
	DO Removal	0	0	0	0	0	0	0	0	0	0
	Iron Removal	0	0	0	0	0	0	0	0	0	0
	Particle Size Reducer	0	0	0	0	0	0	0	0	0	0
	Heavy Metals Removal	0	0	0	0	0	0	0	0	0	0

Table B 5: The Limit Supermatrix



		Goal		2Creteria				Cost Sub-Cr	Healt & Safety Sub-Cr		Alternatives		
		PW Management Method	Environmental	Tech Feasibility	Cost	Health and Safety	Capital Cost	Operation Cost	Operational Risk and accident	Tech-A1	Tech- A2	Tech-A3	Techn- A4
Goal	PW Management Method	0	0	0	0	0	0	0	0	0	0	0	0
Creteria	Environmental	0.117647	0	0	0	0	0	0	0	0	0	0	0
	Technical Feasibility	0.039216	0	0	0	0	0	0	0	0	0	0	0
	Cost	0.058824	0	0	0	0	0	0	0	0	0	0	0
	Health and Safety	0.117647	0	0	0	0	0	0	0	0	0	0	0
Cost Sub-Cr	Capital	0.011765	0	0	0.1	0	0	0	0	0	0	0	0
	Operation Cost	0.047059	0	0	0.4	0	0	0	0	0	0	0	0
Healt & Safety Sub-Cr	Operational Risk and accider	0.117647	0	0	0	0.5	0	0	0	0	0	0	0
Alternatives	Technology A1	0.06959	0.079681	0.166456	0.175985	0.0726	0.500077	0.314943	0.145199	0	0	0	0
	Technology A2	0.081109	0.17041	0.113533	0.054478	0.109221	0.146898	0.099471	0.218442	0	0	0	0
	Technology A3	0.134868	0.230539	0.182717	0.029465	0.267011	0.059229	0.058855	0.534022	0	0	0	0
	Technology A4	0.047766	0.01937	0.037294	0.240072	0.051168	0.293796	0.526731	0.102336	0	0	0	0
Environmental Sub-Cr	Ecological Risk	0.025328	0.107645	0	0	0	0	0	0	0	0	0	0
	Solid Wastes	0.009683	0.041154	0	0	0	0	0	0	0	0	0	0
	Liquid Wastes	0.012046	0.051196	0	0	0	0	0	0	0	0	0	0
	NORM	0.070589	0.300004	0	0	0	0	0	0	0	0	0	0
Technical Feasibility Sub-Cr	Bacteria Removal	0.002088	0	0.02662	0	0	0	0	0	0	0	0	0
	OGC Removal	0.011731	0	0.149571	0	0	0	0	0	0	0	0	0
	DO Removal	0.006185	0	0.078865	0	0	0	0	0	0	0	0	0
	Iron Removal	0.005212	0	0.066454	0	0	0	0	0	0	0	0	0
	Particle Size Reducer	0.007689	0	0.098033	0	0	0	0	0	0	0	0	0
	Heavy Metals Removal	0.00631	0	0.080457	0	0	0	0	0	0	0	0	0

Table B 6: The Limit Supermatrix continued

			C5Environmental Sub-Cr						Technical Feasibility Sub-Cr		
		Ecological Risk	Solid Wastes	Liquid Wastes	NORM	Bacteria Removal	OGC Removal	DO Removal	Iron Removal	Particle Size Reducer	Heavy Metals Removal
Goal	PW Management Method	0	0	0	0	0	0	0	0	0	0
Creteria	Environmental	0	0	0	0	0	0	0	0	0	0
	Technical Feasibility	0	0	0	0	0	0	0	0	0	0
	Cost	0	0	0	0	0	0	0	0	0	0
	Health and Safety	0	0	0	0	0	0	0	0	0	0
Cost Sub-Cr	Capital	0	0	0	0	0	0	0	0	0	0
	Operation Cost	0	0	0	0	0	0	0	0	0	0
Healt & Safety Sub-Cr	Operational Risk and accident	0	0	0	0	0	0	0	0	0	0
Alternatives	Technology A1	0.144614	0.267136	0.203789	0.142288	0.079779	0.473299	0.25	0.099616	0.296398	0.474137
	Technology A2	0.356625	0.1877	0.287276	0.365291	0.289767	0.26705	0.25	0.251073	0.169717	0.15956
	Technology A3	0.462596	0.507206	0.470381	0.452617	0.58999	0.217067	0.25	0.60333	0.493308	0.3278
	Technology A4	0.036166	0.037957	0.038554	0.039803	0.040464	0.042584	0.25	0.045981	0.040577	0.038503
Environmental Sub-Cr	Ecological Risk	0	0	0	0	0	0	0	0	0	0
	Solid Wastes	0	0	0	0	0	0	0	0	0	0
	Liquid Wastes	0	0	0	0	0	0	0	0	0	0
	NORM	0	0	0	0	0	0	0	0	0	0
Technical Feasibility Sub-Cr	Bacteria Removal	0	0	0	0	0	0	0	0	0	0
	OGC Removal	0	0	0	0	0	0	0	0	0	0
	DO Removal	0	0	0	0	0	0	0	0	0	0
	Iron Removal	0	0	0	0	0	0	0	0	0	0
	Particle Size Reducer	0	0	0	0	0	0	0	0	0	0
	Heavy Metals Removal	0	0	0	0	0	0	0	0	0	0

REFERENCES

Abrahamson, Alexandra, Brandt, Ingvar, Brunström, Björn, Sundt, Rolf C., & Jørgensen, Even H. (2008). Monitoring contaminants from oil production at sea by measuring gill EROD activity in Atlantic cod (Gadus morhua). *Environmental Pollution, 153*(1), 169-175. doi: 10.1016/j.envpol.2007.07.025

Adwani, Adnan Eid Al, Al-Zuwayer, Hamad, & Kapavarapu, Venkata Madhusudana Rao. (2011). *Six Sigma Approach to meet Gas Dehydration unit Optimization*. Paper presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=SPE-147042-MS&societyCode=SPE

Al-Ameri, T.K., Pitman, J., Naser, M.E., Zumberge, J., & Al-Haydari, H.A. (2011). Programed oil generation of the Zubair Formation, Southern Iraq oil fields: results from Petromod software modeling and geochemical analysis. *Arabian Journal of Geosciences, 4*(7), 1239-1259.

Al-Hamdan, Mohammed Radhi. (2007). *Application of Six Sigma Statistical Methodology to Reduce ESP Failures in Central Arabia Fields*.

Al Zubaidy, E.A.H., Mohammad, F.S., & Bassioni, G. (2011). Effect of pH, Salinity and Temperature on Aluminum Cookware Leaching During Food Preparation. *Int. J. Electrochem. Sci, 6*, 6424-6441.

Allen, R.M., & Robinson, Keith. (1993). *Environmental Aspects of Produced Water Disposal*. Paper presented at the Middle East Oil Show, Bahrain. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=00025549&societyCode=SPE

Azetsu-Scott, Kumiko, Yeats, Phil, Wohlgeschaffen, Gary, Dalziel, John, Niven, Sherry, & Lee, Kenneth. (2007). Precipitation of heavy metals in produced water: Influence on contaminant transport and toxicity. *Marine Environmental Research, 63*(2), 146-167. doi: 10.1016/j.marenvres.2006.08.001

Bansal, K.M., & Caudle, D.D. (1998). *Interferences With Produced Water Treatment for Dispersed Oil Removal*. Paper presented at the SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, Caracas, Venezuela. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=00046576&societyCode=SPE

Beech, S.J. (2006). *Oil removal for produced water treatment and micellar cleaning of ultrafiltration membranes.* Texas A&M University.

Borad, Madhu M. Tomar and N.N. (2012). Use of AHP Method in Efficiency Analysis of Existing Water Treatment Plants. *International Journal of Engineering Research and Development, 1*(7), 42-51.

Børseth, J. F., & Tollefsen, K. E. (2004). Water Column Monitoring 2003RF - Summary Report *Water Column Monitoring 2003RF - Summary Report B2 - Water Column Monitoring 2003RF - Summary Report*. Stavanger, Norway: Rogaland Research.

Brandsma, M. G., & Smith, J. P. (1995). Dispersion Modeling Perspectives on the Environmental Fate of Produced Water Discharges. *Environmental Sience Research, 52*, 215-224.

Brendehaug, J., Johnsen, S., Bryne, K. H., Gjøse, A. L., Eide, T. H., & Aamot, E. (1992). Toxicity testing and chemical characterization of produced water - a preliminary study *Produced Water B2 - Produced Water* (pp. 245-256). New York: Plenum Press.

Cavanagh, Roland R., Neuman, Robert P., & Pande, Peter S. (2005). *What Is Design for Six Sigma?* : McGraw-Hill.

Collins, A. G. (1975). Geochemistry of oilfield waters-developments in petroleum science *Geochemistry of oilfield waters-developments in petroleum science B2 - Geochemistry of oilfield waters-developments in petroleum science*. New York: Elsevier.

Creveling, Clyde M. (2007). *Six sigma for technical processes : an overview for R&D executives, technical leaders, and engineering managers / Clyde M. Creveling*: Upper Saddle River, NJ : Prentice Hall, c2007.

Cross, Fredrick T. (1992). *Indoor radon and lung cancer, reality or myth? : Twenty-ninth Hanford Symposium on Health and the Environment, October 15-19, 1990 / edited by Fredrick T. Cross ; sponsored by the United States Department of Energy and Battelle, Pacific Northwest Laboratories*: Columbus : Battelle Press, 1992.

CSM. (2009). An Integrated Framework for Treatment and Management of Produced Water : Technical Assessment of Produced Water Treatment Technologies 1st Edition. Colorado School of Mines.

De Ridder, W. (2005). Sustainability A-Test: Inception Report. *Progress to date and future tasks. Report, 555000001*, 2005.

Ditria, J. C., & Hoyack, M. E. (1994). The separation of solids and liquids with hydrocyclone based technology for water treatment and crude processing *SPE Asia Pacific Oil and Gas Conference B2 - SPE Asia Pacific Oil and Gas Conference (November 10)*. Melboume, Australia.

DOE. (1993). *DOE Fundamentals Handbook Chemistry Module 2 Corrosion* Vol. 1 of 2. Retrieved from http://www.hss.doe.gov/nuclearsafety/techstds/docs/handbook/h1015v1.pdf

Doran, Glenn F., Carini, Frank H., Fruth, Darrell A., Drago, Joseph A., & Leong, Lawrence Y.C. (1997). *Evaluation of Technologies to Treat Oil Field Produced Water to Drinking Water or Reuse Quality*. Paper presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=00038830&societyCode=SPE

Doyle, D.H., & Brown, A.B. (2000). *Produced Water Treatment and Hydrocarbon Removal with Organoclay*. Paper presented at the SPE Annual Technical Conference and Exhibition, Dallas, Texas. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=00063100&societyCode=SPE

Durell, Gregory, Røe Utvik, Toril, Johnsen, Ståle, Frost, Tone, & Neff, Jerry. (2006). Oil well produced water discharges to the North Sea. Part I: Comparison of deployed mussels (Mytilus edulis), semi-permeable membrane devices, and the DREAM model predictions to estimate the dispersion of polycyclic aromatic hydrocarbons. *Marine Environmental Research, 62*(3), 194-223. doi: 10.1016/j.marenvres.2006.03.013

Duruibe, J. O., Ogwuegbu, M. O. C., & Egwurugwu, J. N. (2007). Heavy metal pollution and human biotoxic effects. *International Journal of Physical Science 2*(5), 112-118.

Eckes, George. (2003). *Six sigma for everyone / George Eckes*: Hoboken, N.J. : J. Wiley, c2003.

Essam Abdul-Jalil Saeed, Hamed, H. Abdulah, & Ayad, A. Al-Haleem (2010). Components and Treatments of Oilfield Produced Water *Al-Khawarizmi Engineering Journal 6*(1), 24-30.

Evans, J., & Lindsay, W. (2005). An introduction to Six Sigma and process improvement *An introduction to Six Sigma and process improvement B2 - An introduction to Six Sigma and process improvement*. Mason, OH: South-Western.

Evans, James R., & Lindsay, William M. (2011). Managing for Quality and Performance Excellence *Managing for Quality and Performance Excellence B2 - Managing for Quality and Performance Excellence*: Cengage Learning.

Falcón, R. González, Alonso, D. Velázquez, Fernández, L. M. Gallego, & Pérez-Lombard, Luis. (2012). Improving energy efficiency in a naphtha reforming plant using Six Sigma methodology. *Fuel Processing Technology, 103*(0), 110-116. doi: 10.1016/j.fuproc.2011.07.010

Fang, H., Brown, B., & Nesi, S. (2010). *10276 high salt concentration effects on CO2/ H2S corrosion*.

Forbes, V. E., Palmqvist, A., & Bach, L. (2006). The use and misuse of biomarkers in ecotoxicology. *Environmental Toxicology And Chemistry / SETAC, 25*(1), 272-280.

Furtado, Claudio Jose Alves, Siqueira, Alexandre, Souza, Antonio Luiz Serra de, Correa, Antonio Claudio, & Mendes, Roberta. (2005). *Produced Water Reinjection in Petrobras Fields: Challenges and Perspectives*. Paper presented at the SPE Latin American and Caribbean Petroleum Engineering Conference, Rio de Janeiro, Brazil. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=SPE-94705-MS&societyCode=SPE

Furuholt, E. (1995). Environmental Effects of Discharge and Reinjection of Produced Water. *Environmental Sience Research, 52*, 275-288.

Gordon, Rittenhouse, Robert, B. Fulton, III, Robert, J. Grabowski, & Joseph, L. Bernard. Minor elements in oil-field waters. *Chemical Geology, 4*, 189-209. doi: 10.1016/0009-2541(69)90045-X

Grigg, Neil S., Water Research, Foundation, & United States. Environmental Protection, Agency. (2010). *Secondary impacts of corrosion control on distribution system and treatment plant equipment*. Denver, Colo.: Water Research Foundation.

Harry, Mikel, & Schroeder, Richard. (2000). Six Sigma *Six Sigma B2 - Six Sigma*. New York: Doubleday.

Henderson, S. B., Grigson, S. J. W., Johnson, P., & Roddie, B. D. (1999). Potential impact of production chemicals on the toxicity of produced water discharges from North Sea oil platforms. *Marine Pollution Bulletin, 38*(12), 1141-1151.

Horner, J. E., Castle, J. W., & Rodgers, J. H., Jr. (2011). A risk assessment approach to identifying constituents in oilfield produced water for treatment prior to beneficial use. *Ecotoxicol Environ Saf, 74*(4), 989-999. doi: 10.1016/j.ecoenv.2011.01.012

Hylland, Ketil, Tollefsen, Knut-Erik, Ruus, Anders, Jonsson, Grete, Sundt, Rolf C., Sanni, Steinar, . . . Børseth, Jan Fredrik. (2008). Water column monitoring near oil installations in the North Sea 2001–2004. *Marine Pollution Bulletin, 56*(3), 414-429. doi: 10.1016/j.marpolbul.2007.11.004

Igunnu, Ebenezer T., & Chen, George Z. (2012). Produced water treatment technologies. *Int. J. Low-Carbon Tech.*, cts049. doi: 10.1093/ijlct/cts049

International Association of, Oil, & Gas, Producers. (2010). Environmental Performance in the E&P Industry 2009 Data, 442 *Environmental Performance in the E&P Industry 2009*

Data, 442 B2 - Environmental Performance in the E&P Industry 2009 Data, 442. London, UK: International Association of Oil & Gas Producers.

Iraqi Oil Reporting A guide for reporters. (2010). Retrieved 04-15, 2012, from http://openoil.net/wp/wp-content/uploads/2011/06/Iraq_Oil_Reporting_0.3_101205.pdf

Jacobs, R., P.W.M, Grant, E., Kwant, J., Marqueine, J. M., & Mentzer, E. (1992). The composition of produced water from shell operated oil and gas production in the north sea *Produced Water B2 - Produced Water*. New York: Plenum Press.

Jamal, A, Zaidan. (2010). Natural Occuring Radioctive Materials (NORM) in the oil and gas Industry. *Journal of Petroleum Researches and Studies, 1*(1), 4-21.

Johnsen, Ståle, Utvik, Toril Inga Røe, Garland, Emmanuel, Vals, Bruno de, & Campbell, John. (2004). *Environmental fate and effect of contaminants in produced water*. Paper presented at the SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, Calgary, Alberta, Canada. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=00086708&societyCode=SPE

Keiter, R., Ruple, J., & Tanana, H. (2011). Policy Analysis of Produced Water Issues Associated With IN-SITU Thermal Technologies: The University Of Utah.

Khomenko, YV, & Poddubnaya, OA. (2011). Senstivity Analysis As A Tool For Risk Managment *Economic Herald of the Donbas, 4*(26), 193-197.

Kwak, Young Hoon, & Anbari, Frank T. (2006). Benefits, obstacles, and future of six sigma approach. *Technovation, 26*(5–6), 708-715. doi: 10.1016/j.technovation.2004.10.003

Lubczenko. (2004). *The Saltwatch resource book - part a: what is salinity?* Retrieved from http://www.derm.qld.gov.au/education/teachers/land/resources/resource_book_a.pdf

Malmasi, S., Jozi, SA, Monavari, SM, & Jafarian, ME. (2010). Ecological Impact Analysis on Mahshahr Petrochemical Industries Using Analytic Hierarchy Process Method. *International Journal of Environmental Research, 4*(4), 725-734.

McCormack, P., Jones, P., Hetheridge, M. J., & Rowland, S. J. (2001). Analysis of oilfield produced waters and production chemicals by electrospray ionisation multi-stage mass spectrometry (ESI-MSn). *Water Research, 35*(15), 3567-3578. doi: 10.1016/S0043-1354(01)00070-7

Mofarrah, Abdullah, Husain, Tahir, Hawboldt, Kelly, & Veitch, Brian. (2011). Decision-Making Tool for Produced Water Management

Produced Water. In K. Lee & J. Neff (Eds.), (pp. 573-586): Springer New York.

Navarro, William. (2007). *Produced Water Reinjection in Mature Field With High Water Cut*. Paper presented at the Latin American & Caribbean Petroleum Engineering Conference, Buenos Aires, Argentina. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=SPE-108050-MS&societyCode=SPE

Neff, J. M., & Sauer, T. C., Jr. (1995). Aromatic hydrocarbons in produced water: bioaccumulation and trophic transfer in marine food webs *Produced Water 2 B2 - Produced Water 2* (pp. 163-176). New York: Plenum Press.

Neff, Jerry M. (2002). *Bioaccumulation in marine organisms : effect of contaminants from oil well produced water / Jerry M. Neff*: Amsterdam : London : Elsevier, 2002. 1st ed.

Neff, Jerry M., & Burns, William A. (1996). Estimation of polycyclic aromatic hydrocarbon concentrations in the water column based on tissue residues in mussels and salmon: An equilibrium partitioning approach. *Environmental Toxicology and Chemistry, 15*(12), 2240-2253.

Neff, Jerry M., Johnsen, Ståle, Frost, Tone K., Røe Utvik, Toril I., & Durell, Gregory S. (2006). Oil well produced water discharges to the North Sea. Part II: Comparison of deployed mussels (Mytilus edulis) and the DREAM model to predict ecological risk. *Marine Environmental Research, 62*(3), 224-246. doi: 10.1016/j.marenvres.2006.03.012

Nijhawan, Nishi, & Myers, James E. (2006). *Constructed Treatment Wetlands for the Treatment and Reuse of Produced Water in Dry Climates*. Paper presented at the SPE International Health, Safety & Environment Conference, Abu Dhabi, UAE. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=SPE-98567-MS&societyCode=SPE

P. Sarin, Frank K., Snoeyink, V. L., Lytle, D. A., & Kriven, W. M. (2004). Iron Corrosion Scales: Model for Scale Growth, Iron Release, and Colored Water Formation. *Journal of Environmental Engineering, 130*(4), 364-373. doi: 10.1061/(ASCE)0733-9372(2004)130:4(364)

Patel, C. (2005). Management of produced water in oil and gas operations: Texas A&M University 2005-02-17T21:04:53Z 2005-02-17T21:04:53Z 2004-12 2005-02-17T21:04:53Z.

Qureshi, M., & Harrison, S. (2003). Application of the analytic hierarchy process to riparian revegetation policy options. *Small-Scale Forestry, 2*(3), 441-458. doi: 10.1007/s11842-003-0030-6

Reed, M, & Johnsen, S. (1996). *Produced water 2 : environmental issues and mitigation technologies* New York : Plenum Press, c1996.

Republic of Iraq-Ministry of Oil. (2012). from http://www.oil.gov.iq/moo/tenders.php?lang=en&page_name=tenders

Rodgers, R.P., Klein, G.C., Wu, Z., & Marshall, A.G. (2003). Environmental applications of ESI FT-ICR mass spectrometry: The identification of polar N, S and O containing PAH species in crude oil and coal extracts. *Prepr. Pap.-Am. Chem. Soc., Div. Fuel Chem, 48*(2), 758.

Roe Utvik, Toril I., Durell, Gregory S., & Johnsen, Stale. (1999). Determining produced water originating polycyclic aromatic hydrocarbons in North Sea waters: Comparison of sampling techniques. *Marine Pollution Bulletin, 38*(11), 977-989.

Saaty, R. W. (2003). Decision-making in complex environment: the analytic hierarchy process (AHP) for decision making and the analytic network process (ANP) for decision making with dependence and feedback; a manual for the AHP and ANP software SuperDecisions *Decision-making in complex environment: the analytic hierarchy process (AHP) for decision making and the analytic network process (ANP) for decision making with dependence and feedback; a manual for the AHP and ANP software SuperDecisions B2 - Decision-making in complex environment: the analytic hierarchy process (AHP) for decision making and the analytic network process (ANP) for decision making with dependence and feedback; a manual for the AHP and ANP software SuperDecisions*. Pittsburgh, PA: Creative Decisions Foundation.

Saaty, Thomas L. (2008). Decision making with the analytic hierarchy process. *Int. J. Services Sciences, 1*(1), 83-98.

Scholz, W., & Lucas, M. (2003). Techno-economic evaluation of membrane filtration for the recovery and re-use of tanning chemicals. *Water research, 37*(8), 1859-1867.

Sihombing, Santun, Purnomo, Agus, & Brahmantyo, Akson. (2001). *Six Sigma Tools Applied in Automatic Well Testing-Reducing Response Time to 'No Fluid Detected Wells'*. Paper presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=00068750&societyCode=SPE

Singh, Kalwant. (2002). *Designing a Produced Water Re-Injection Program in Bekapai Field*.

Sirilumpen, Mala, & Meyer, John C. (2002). *Water Reinjection for Disposal in Erawan Field*. Paper presented at the SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Kuala Lumpur, Malaysia. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=00073857&societyCode=SPE

Sluijterman, A.C., Al-Lawati, Y., Al-Asmi, S., Verbeek, P.H.J., Schaapveld, M.A.S., & Cramwinckel, J. (2004). *Opportunities for Re-use of Produced Water around Desert Oil Fields*. Paper presented at the Abu Dhabi International Conference and Exhibition, Abu Dhabi, United Arab Emirates. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=00088667&societyCode=SPE

Smith, J. P., Brandsma, M. G., & Nedwed, T. J. (2004). Field verification of the Offshore Operators Committee (OOC) Mud and Produced Water Discharge Model. *Environmental Modelling & Software, 19*(7–8), 739-749. doi: 10.1016/j.envsoft.2003.08.007

SOC. (2012). *Produced Water Treatment for Zubair field in SOC*. South Oil Company. Basrah, Iraq.

Soltani, S., Mowla, D., Vossoughi, M., & Hesampour, M. (2010). Experimental investigation of oily water treatment by membrane bioreactor. *Desalination, 250*(2), 598-600. doi: 10.1016/j.desal.2009.09.031

Somerville, H. J., Bennett, D., Davenport, J. N., Holt, M. S., Lynes, A., Mahieu, A., . . . et al. (1987). Environmental Effects of Produced Water from North Sea Oil Operations. *Marine Pollution Bulletin, 18*(10), 549-558.

South Oil Company. (2012). from http://www.soc.gov.iq/

Stamatis, D. H. (2003). *Six sigma for financial professionals / D.H. Stamatis*: Hoboken, N.J. : John Wiley & Sons, c2003.

Stephenson, M.T. (1992). Components of Produced Water: A Compilation of Industry Studies. *SPE Journal of Petroleum Technology, 44*(5), 548-550, 602-603. doi: 10.2118/23313-pa

Stewart, Maurice, & Arnold, Ken. (2011). *Produced water treatment field manual [electronic resource] / Maurice Stewart, Ken Arnold*: Waltham, MA : Gulf Professional Pub., c2011.

Stromgren, T., Sorstrom, S. E., Schou, L., Kaarstad, I., Aunaas, T., Brakstad, O. G., & Johansen, O. (1995). Acute toxic effects of produced water in relation to chemical composition and dispersion. *Marine Environmental Research, 40*(2), 147-169.

Subber, A.R.H., Ali, M.A., & Salman, T.M. (2011). Radon Concentration in oily Sludge Produced from Oil Refineries in the Southern oil plant at Basra Governorate-Iraq. *Archives of Applied Science Research, 3*(6), 263-271.

Surace, Domenica, Broccia, Patrizia, Salemi, Youssef, & Iovane, Massimo. (2010). *Installation of a Produced Water Treatment System on Raml Field (Western Desert), Egypt*. Paper presented at the SPE Annual Technical Conference and Exhibition, Florence, Italy.

http://www.onepetro.org/mslib/app/Preview.do?paperNumber=SPE-135725-MS&societyCode=SPE

Systems, isee. (2012). Applying System Thinking and Common Archetypes to Organizational Issues. Retrieved 05\27\2012, 2012, from http://www.pegasuscom.com/course_preview/index.htm

Taghizadegan, Salman. (2006). *Essentials of lean six sigma / Salman Taghizadegan*: Amsterdam ; Boston, Mass. : Elsevier, c2006.

TDS AND pH-Safe Drinking Water Foundation. (2012). Retrieved 04-14-2012, 2012, from http://www.safewater.org/PDFS/resourcesknowthefacts/TDS_AND%20_pH.pdf

Terrens, G.W., & Tait, R.D. (1996). *Monitoring Ocean Concentrations of Aromatic Hydrocarbons from Produced Formation Water Discharges to Bass Strait, Australia*. Paper presented at the SPE Health, Safety and Environment in Oil and Gas Exploration and Production Conference, New Orleans, Louisiana. http://www.onepetro.org/mslib/app/Preview.do?paperNumber=00036033&societyCode=SPE

Tibbetts, P. J. C., Buchanan, I. T., Gawel, L. J., & Large, R. (1993). A Comprehensive Determination of Produced Water Composition. *Environmental Sience Research, 46*, 97.

Tomson, M.B., Oddo, J.E., Kan, A.T. (1992). Brine Management Options to Gas Research Institute (Vol. 92, pp. 253-438).

Toral, S.V. (2011). *Heavy metals removal by a dual media filter inoculated with specific bacteria to treat urban water.* (Master), Delft University of Technology. Retrieved from http://www.citg.tudelft.nl/fileadmin/Faculteit/CiTG/Gezondheidstechniek/doc/Final_thesis_Soledad.pdf

U.S.Energy Information Administration. (2010). *Independent Statistics & Energy*. from http://www.eia.gov/countries/cab.cfm?fips=IZ

United States Environmental Protection Agency. (2012). from http://www.epa.gov/

Veil, J. A., Puder, M., Elcock, D., & Redweik, R. (2004). A White Paper Describing Produced Water from Production of Crude Oil, Natural Gas, and Coal Bed Methane *A White Paper Describing Produced Water from Production of Crude Oil, Natural Gas, and Coal Bed Methane B2 - A White Paper Describing Produced Water from Production of Crude Oil, Natural Gas, and Coal Bed Methane*.

Velmurugan, V., & Srithar, K. (2008). Prospects and scopes of solar pond: A detailed review. *Renewable and Sustainable Energy Reviews, 12*(8), 2253-2263. doi: 10.1016/j.rser.2007.03.011

Wang, Guiqin, Qin, Li, Li, Guoxue, & Chen, Lijun. (2009). Landfill site selection using spatial information technologies and AHP: A case study in Beijing, China. *Journal of Environmental Management, 90*(8), 2414-2421. doi: 10.1016/j.jenvman.2008.12.008

Weber-Scannell, P.K., Duffy, L.K., Weber-Scannell, P.K., & Duffy, L.K. (2007). Effects of total dissolved solids on aquatic organisms: a review of literature and recommendation for salmonid species. *American Journal of Environmental Sciences, 3*(1), 1-6.

Yang, Jiaqin, & Shi, Ping. (2002). Applying Analytic Hierarchy Process in Firm's Overall Performance Evaluation: A Case Study in China. *International Journal of Business, 7*(1), 29-46. doi: http://www.craig.csufresno.edu/IJB/

Yavuz, Ozdemir, Huseyin, Basligil, & Merve, Karaca. (2011). Aircraft Selection Using Analytic Network Process: A Case for Turkish Airlines. *Lecture Notes in Engineering and Computer Science*(1), 1155.