# FACULTY OF ENGINEERING

# MASTER'S IN HEALTH, SAFETY AND ENVIRONMENT ENGINEERING

**MASTER DISSERTATION**

# ENVIRONMENTAL SUSTAINABILITY OF DRILLING WASTE TREATMENT: THE CASE STUDY OF NATURAL GAS EXPLORATION WELLS

**By**

Néusia Dinis Chilaúle

Maputo, June 2023

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**Supervisor:**

Prof. Doutor João Chidamoio, PhD

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## RECOMMENDATION OF THE BOARD OF EXAMINERS

The undersigned certify that they have read and recommend to the Faculty of Engineering a thesis entitled "**ENVIRONMENTAL SUSTAINABILITY OF DRILLING WASTE TREATMENT: THE CASE STUDY OF NATURAL GAS EXPLORATION WELLS**" submitted by **NÉUSIA DINIS CHILAÚLE**, in partial fulfillment of the requirements for the degree of Master Program in **HEALTH, SAFETY AND ENVIRONMENT ENGINEERING.**

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## DECLARATION

I hereby certify that this material, which I now submit in part fulfilment of the requirements for the award of Master's in Health, Safety and Environment Engineering is entirely my own work and has not been taken from the work of others save to the extent suck work has been cited and acknowledged within the text of my work.

(Néusia Dinis Chilaúle)

## DEDICATION

*This dissertation is dedicated to my Lord and Savior Jesus Christ for all graces in my life, for my dear grandparents Xavier Macaringue and Irene Langa (in memory), for their great and tireless dedication and wise teachings, to my mother Estrela Dos Anjos X. Macaringue for her great love.*

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## NOMECLATURE

| **ABBREVIATIONS** | **DESCRIPTION** |
|---|---|
| BOD | Biochemical Oxygen Demand |
| DC | Drilling Cuttings |
| DM | Drilling Mud |
| DO | Dissolved Oxygen |
| DS | Dissolved Solids |
| COD | Chemical Oxygen Demand |
| CTT | Central Térmica Temane |
| EC | Electrical Conductivity |
| EHS | Environment, Health and Safety |
| EMP | Environment Management Plan |
| ESO | Environment Site Officer |
| ESP | Exchangeable Sodium Percentage |
| ETA | Event Tree Analysis |
| FTA | Fault Tree Analysis |
| FMEA | Failure Method, Effect and Critical Analysis |
| LD | Lethal Dose |
| LC | Lethal Concentration |
| MITADER | Ministry of Land, Environment and Rural Development |
| PRN | Priority Risk Number |
| PS | Performance Standard |
| SAR | Sodium Adsorption Ratio |
| SOP | Standard Operating Procedure |
| TDU | Thermal Desorption Unit |
| THC | Total Hydrocarbon Content |
| TSS | Total Suspended Solids |
| VOC | Voltaic Organic Compounds |
| WMP | Waste Management Plan |
| WBM | Water Based Mud |
| WHO | World Health Organization |

## ABSTRACT

Almost every process in the finding and production of natural gas generates many types of wastes which impacts the environment negatively. The resulting residue has several compounds containing potential pollutants, which if incorrectly disposed can pose several risks to terrestrial, aquatic, and aerial environments, including reducing soil fertility, affecting negatively the flora and fauna and causing health problems due to the volatilization of hazardous gas components such as methane, benzene, toluene, ethylbenzene and xylene into the atmosphere. This study aimed to evaluate what can go wrong in the drilling waste treatment plant, the landscape components of chemical pollution with metals, gas, and polycyclic aromatic hydrocarbons, from the discharge of drill cuttings. In this context the regulators have established that the disposal of non-treated drilling waste containing free gas is not allowed, therefore, the treatment of drilling residues generated in exploration activities is an essential task. On the drilling plant samples were carefully labeled, well preserved, and sent to the laboratory for chemical analysis, in-situ measurements of physical parameters, pH, EC, total dissolved solids (TDS), and DO were carried out at the using portable digital pH meter, Conductivity, TDS meter, model CO150, and DO meter Orion. The samples sent to the laboratory were tested for COD, BOD, total suspended solids (TSS), total hydrocarbon content (THC), and heavy metals. THC, TSS, and COD were determined by titrimetric method using the relevant reagents. The Failure mode and effect analysis (FMEA), fault tree analysis (FTA) and Event tree analysis (ETA) were also applied for the assessment of what can go wrong especially in the chemical treatment with incorrect dosage of chemicals; the results revel that this factor becomes the 1st rank to get attention improvement in order to meet the quality standards determined by the Ministry of Health. Through the fault tree analysis (FTA), showed that human factors, especially human error had a great effect on top event occurrence. According to ETA, if all systems fail in the waste treatment plant it can result in major effect to the environment and the probability of consequence is 0.516 and if the system work is 0.114. The statistical correlation and distributions of the ions shows that EC, TSS and $Cr^{3+}$, turbidity, THC, BOD, COD, $Zn^{2+}$, $Cu^{2+}$, and $Hg^{2+}$ have positive correlation indicating that the ions are derived from the same source and are qualified to be potential pollutant that can cause environmental hazards in the study area.


**Keywords:** Drilling waste; Physical-Chemical parameters; FMEA and FTA.

## RESUMO

Quase todos os processos de descoberta e produção de gás natural geram muitos tipos de resíduos que impactam negativamente o meio ambiente. O resíduo resultante possui diversos compostos contendo potenciais poluentes, que se descartados incorrectamente podem trazer diversos riscos aos ambientes terrestres, aquáticos e aéreos, inclusive reduzindo a fertilidade do solo, afectando negativamente a flora e a fauna e causando problemas de saúde devido à volatilização de componentes perigosos do gás como metano, benzeno, tolueno, etil-benzeno e xileno para a atmosfera. Este estudo teve como objectivo avaliar o que pode dar errado na estação de tratamento de resíduos de perfuração, os componentes da poluição química com metais, gás e hidrocarbonetos aromáticos policíclicos, provenientes do descarte de cascalhos de perfuração. Neste contexto, os reguladores estabeleceram que não é permitida a disposição de resíduos de perfuração não tratados contendo gás livre, portanto, o tratamento dos resíduos de perfuração gerados nas actividades de exploração é uma tarefa essencial. As amostras da usina de perfuração foram cuidadosamente etiquetadas, bem preservadas e enviadas ao laboratório para análise química, medições in-situ de parâmetros físicos, pH, EC, sólidos totais dissolvidos (TDS) e DO foram realizadas no laboratório digital portátil Medidor de pH, condutividade, medidor de TDS, modelo CO150 e medidor de OD Orion. As amostras enviadas ao laboratório foram testadas para COD, BOD, sólidos suspensos totais (TSS), teor de hidrocarbonetos totais (THC) e metais pesados. THC, TSS e COD foram determinados pelo método titrimétrico usando os reagentes relevantes. A análise de modo e efeito de falha (FMEA), análise de árvore de falhas (FTA) e análise de árvore de eventos (ETA) também foram aplicadas para a avaliação do que pode dar errado especialmente no tratamento químico com dosagem incorrecta de produtos químicos; os resultados revelam que este factor passa a ser o 1º escalão a receber melhorias na atenção para atender aos padrões de qualidade determinados pelo Ministério da Saúde. Por meio da análise da árvore de falhas (FTA), mostrou que os factores humanos, principalmente o erro humano, tiveram grande influência na ocorrência do evento topo. De acordo com a ETA, se todos os sistemas falharem na estação de tratamento de resíduos, isso pode resultar em grande impacto ao meio ambiente e a probabilidade de consequência é de 0,516 e se o sistema funcionar é de 0,114. A correlação estatística e as distribuições dos iões mostram que EC, TSS e Cr3+, turbidez, THC, BOD, COD, Zn2+, Cu2+ e Hg2+ têm correlação positiva, indicando que os iões são derivados da mesma fonte e são qualificados como poluentes potenciais que podem causar riscos ambientais na área de estudo.


**Palavras-chave:** Resíduos de perfuração; Parâmetros Físico-químicos; FMEA and FTA.

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# CHAPTER I: CONTEXTUALIZATION

## 1.1. Introduction

Environmental issues such as air pollution, global warming, toxicity of water and food sources, biodiversity loss and climate change have become growing global concerns. Today, industrialization is considered as the main culprit posing serious risks to ecosystems. At the forefront of industry, the extraction and use of fossil fuels continues to play the critical role. However, a large amount of wastes generated during a typical gas and/or oil fields' life cycle, negatively impacts the environment. Efforts to shift exploitation toward more eco-friendly methods and minimize the release of hazardous waste are now a high priority.

Onshore gas reserves in the Mozambique Basin, Inhambane Province, have been used since 2004 and are currently a supply of gas for industrial use and electricity generation. The small amount of oil was probably also recently in Inhambane, with production starting (MIREME, 2017). As the number of shale gas wells in Mozambique increases, waste associated with water extraction may contain various levels of gas designated solids for such and may also contain organic chemicals, inorganic chemicals, metals and materials.

This project reviews environmentally friendly waste treatment methodology and provides insights to various waste management strategies applicable to most gas (and oil) field operation. The significance of sustainability in fluid management is highlighted, identifying possible environmental problems arising from drilling muds. Advances in the development of sustainable green additives, effective waste management approaches and disposal methods are described. Several case studies are included to reveal the toxicity risks of discarded wastes from wells, field applications of green muds, and appropriate drilling fluid waste management. Banner headline Drilling fluids are vital for facilitating the production of natural gas (and oil) from subsurface reservoirs. However, they pose significant challenges to the sustainability of natural gas drilling because of the environmentally unfriendly chemical additives traditionally used in them, and the contaminated rock cuttings they contain, when they return from the wellbore (MISWACO Broacher, 2003). Continued efforts to replace additives with eco-friendly biodegradable materials, recycle drilling wastes, and generally improve wastewater treatment and treatment processes have become essential.

The study considered information collected related to treatment technologies (their associated costs), discharge resources, financial resources and other relevant data and information.

### 1.2. Problem Statement

Natural gas production, refining and chemical operations generate waste that requires treatment before discharge or disposal. Treatment methodologies range from removal of suspended hydrocarbons and solids from produced water to biological treatment systems for refinery wastewater. Produced water, a byproduct of natural gas production operations, is typically managed onshore by injection into deep underground reservoirs, in accordance with applicable regulatory requirements (International Association of Oil and Gas Producers, 2003).

Natural gas and shale gas extraction operations can result in a number of potential impacts to the environment, including:

- Stress on surface water and ground water supplies from the withdrawal of large volumes of water used in drilling and hydraulic fracturing;
- Contamination of underground sources of drinking water and surface waters resulting from spills, faulty well construction, or by other means;
- Adverse impacts from discharges into surface waters or from disposal into underground injection wells; and
- Air pollution resulting from the release of volatile organic compounds, hazardous air pollutants, and greenhouse gases.

### 1.3. Motivation

The three Reduce, reuse, and recycle - are three approaches and the most environmentally preferred. Reducing, reusing, and recycling waste helps save landfill space by keeping useful materials out. The amount of energy and natural resources needed to produce or collect the raw materials and manufacture the product are reduced. Unfortunately, not all waste can be reduced, reused, or recycled, which brings us to the fourth approach - proper disposal. Through processing, if necessary, and proper disposal, we can prevent harmful contamination from those waste materials. In some cases, operators use surface storage tanks and pits to temporarily store hydraulic fracturing fluids for re-use or until arrangements are made for disposal. In addition, other wastes are generated during the well drilling, stimulation, and production stages. States, tribes, and some local governments have primary responsibility for adopting and implementing programs to ensure proper management of these wastes, (Sharif MDA, Nagalakshmi NVR, Reddy SS, Vasanth G, Uma Sankar K, 2017).

1. Reduction in the volume of wastewater: less sent offsite for disposal
2. Less fresh water needed for hydraulic fracturing operations: reduced impact on local supplies
3. Reduced truck traffic on public roads (less fresh water hauled): lower impact on public roads, noise, air quality
4. Filtration process used is inexpensive and does not require substantial amounts of energy like other processes that remove salts (reverse osmosis membranes, distillation)
5. Helps reduce the cost of operations, materials, waste management and disposal, energy, and facility clean-up
6. Improved operating efficiency;
7. Reduced regulatory compliance concerns;
8. Reduced potential for both civil and criminal liability.

## 1.4. Objectives

### 1.4.1. General Objectives

To evaluate the drilling waste treatment system in the natural gas exploration wells.

### 1.4.2. Specific Objective

- To propose a system approach for quality waste treatment during drilling operations;
- To identify the probability failure of drilling waste treatment methodology in terms of have sustainable environment;
- To identify the mitigation measures to reduce the probability of failure;
- To determine the correlation between the physical parameters and chemical parameters of drilling waste in the environment.

## 1.5. Project Questions

1. How Waste treatment could be sustainable to the Environment in drilling operations?
2. What are the existing approaches to treat drilling waste which can interact more effectively with state regulations, requirements, sustainable technics and cost operations?
3. Which is the based approach to minimize the environmental footprint of drilling operations activities regarding to waste treatment?
4. Which is the collaboration of the application of sustainable waste treatment to the local community?

# CHAPTER II: LITERATURE REVIEW

## 2.1. General aspects about environmental sustainability of drilling waste treatment

### 2.1.1. Drilling waste

All activities related to Oil & Gas Exploration, Production, Storage and Transportation involve waste generation associated to potential risk to environment. Waste types are related to Exploration and Producing (E&P) activities. These activities are: Drilling operations, Production operations, Completion operations, Work-over operations, Gas plant operations, (Sharif MDA, Nagalakshmi NVR, Reddy SS, Vasanth G, Uma Sankar K, (2017).

**Composition/content of drilling fluid**

A drilling fluid is an essential part of drilling operation in oil and gas industry. Drilling fluids serve some purposes such as controlling the hydraulic pressure to protect well blowouts, lubricating and cooling the drill bit and cleaning and removing drill cuttings from the downhole (Caenn et al., 2011). Drilling fluids are classified according to the type of base fluids used; water-based, oil-based, and synthetic based or pneumatic fluids. The term fluid is interchangeably used with mud. For this review, focus was only on water and oil-based muds. Water based drilling muds or fluids (WBM or WBF) contain fresh or salt water with a weighting agent (usually barite - $BaSO_4$), clay or organic polymers, several inorganic salts, inert solids, and organic additives which helps adjust the physical properties of the mud for optimal functionality (Neff, 2005). The total mass of WBM and cuttings discharged per exploratory well is about 2000 metric tons/well, and to some extent less for most development wells (Neff, 2005).

### 2.1.2. Toxicity of drilling waste

The toxicity of a substance is a measure of how it reduces the life and health of living organisms following exposure to the substance. Toxicities are determined through bioassays by exposing laboratory animals to different amounts of the substance in question (MISWACO Broacher, 2008). The resulting effects on the health of the animals are observed.

Two types of toxicity measurements are commonly used: dose and concentration. The dose is the concentration of a substance that has been absorbed into the sample tissue of the test species, while the concentration is measure of the concentration of a substance in the environment that the species lives in. Toxicity measurements using concentration also include a time interval of exposure. A dose that is lethal to 50% of the animals is called LD50, whiles the dose resulting in the first death is called LDLO. The dose levels required for any particular effect also depend on how the animals are exposed - by injection, ingestion, or inhalation. Similarly, a lethal concentration that kills 50% of the animals within a given period of time is called as LC50 whiles the lowest lethal concentration for the same period of time is called LCLO. Concentration is the toxicity measure most commonly used for materials associated with the oil and gas industries. If a material is highly toxic, then only a small concentration will be lethal and the numerical values of the lethal doses and concentrations - LD50 and LDLO, would be low. Conversely, a high value of these parameters indicates low toxicity. LC50 values on the order of 10 are normally considered highly toxic.

### 2.1.3. Impacts of drilling waste on the environment

Many of the materials and wastes associated with drilling activities have the potential to impact on the environment negatively. The potential impact depends primarily on the material, its concentration after release of the biotic community that is exposed. Some environmental risks may be significant whiles others are very low. The major impacts of great concerns are pollution of water bodies, pollution of land, as well as air pollution. Improper disposal of contaminated drill cuttings into water bodies (ocean) exposes marine life to danger. Excessive release of air pollutants from internal combustion engines makes the air unsafe for both humans and animals and some of their effects includes respiratory difficulties in humans and animals, damage to vegetation and soil acidification. Release of hydrogen sulphide, of course, can be fatal to those exposed (Table 1), (Environmental Resources Management and Consultec, 2005).

**Table 1**. Elemental Composition of Drilling Fluid Constituents (Mg/Kg). Source: (Sharif MDA, Nagalakshmi NVR, Reddy SS, Vasanth G, Uma Sankar K, (2017).

| Element | Water | Cutting | Barite | Clay | Lignite | Caustic |
|---|---|---|---|---|---|---|
| Aluminum | 0.3 | 40,400 | 40,400 | 88,600 | 6,700 | 0.013 |
| Arsenic | 0.0005 | 3.9 | 34 | 3.9 | 10.1 | 0.039 |
| Barium | 0.1 | 158 | 590,000 | 640 | 640 | 0.26 |
| Calcium | 15 | 240,000 | 7,900 | 4,700 | 16,100 | 5,400 |
| Cadium | 0.0001 | 0.08 | 6 | 0.5 | 0.2 | 0.0013 |
| Chromium | 0.001 | 183 | 183 | 8.02 | 65.3 | 0.00066 |
| Cobalt | 0.0002 | 2.9 | 3.8 | 2.9 | 5 | 0.00053 |
| Copper | 0.003 | 22 | 49 | 8.18 | 22.9 | 0.039 |
| Iron | 0.5 | 21,900 | 21,950 | 37,500 | 7,220 | 0.04 |
| Lead | 0.003 | 37 | 685 | 27.1 | 5.4 | 0.004 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Magnesium | 4 | 23,300 | 3,900 | 69,800 | 5,040 | 17,800 |
| Mercury | 0.0001 | 0.12 | 4.1 | 0.12 | 0.2 | 4 |
| Nickel | 0.0005 | 15 | 3 | 15 | 11.6 | 0.09 |
| Potassium | 2.2 | 13,500 | 660 | 2,400 | 460 | 51,400 |
| Silicon | 7 | 206,000 | 70,200 | 271,000 | 2,390 | 339 |
| Sodium | 6 | 3,040 | 3,040 | 11,000 | 2,400 | 500,000 |
| Strontium | 0.07 | 312 | 540 | 60.5 | 1030 | 105 |

**Effects of exposure to spent drilling fluid**

Drilling wastes contain organic, inorganic and heavy metal elements. Adewole et al., (2010) reported that lead content of the disposed drill wastes from the two off-shore wells studied were significantly higher than the recommended 0.005 mg/l by DPR and the established international threshold level of 0.05 mg/l (Table 2). These substances, generally classified as the hazardous substances occurring in drilling wastes can be toxic, corrosive, reactive, carcinogenic, teratogenic, and mutagenic, among other hazards (Zhou et. al, 2014).

The most significant environmental impact of drilling operation emanate from the discharge of drilling waste including drill cuttings to the seabed. The toxicity of drilling fluid is mainly due to its base fluid (Ismail et. al., 2017). They also added that besides the toxicity of base fluid, additives such as foralyst and resinex can contribute to drilling fluid toxicity and pollution. Direct discharge of drilling fluid can affect the local ecosystem in three ways; direct toxic effects of drilling waste, by smothering organisms and through anoxic conditions caused by microbial degradation of the organic components in waste.

Bashat (2002) reported, that both spent contaminated water-based mud and spent contaminated oil-based mud contain heavy metals and hydrocarbons (Table 2). These constituents have been implicated by several researchers to be hazardous to the environment, other organisms and humans (Adewole et. al., 2010).

**Figure 2.** Wastes components and environmentally significant constituents from drilling activities.

| **Type of waste** | **Main components** | **Possible environmentally significant constituents** |
|---|---|---|
| Spent/Contaminated water-based muds (including brine) | Biodegradable matter, whole mud and mineral oil | Inorganic salts, hydrocarbons, heavy metals, biocides, BOD, organics, solids/cutting, hydrocarbons and surfactants |
| Oil-based muds cuttings, | Whole mud mineral oil | Hydrocarbons, heavy metals, inorganic salts, solids, BOD, organics, |

| | | |
|---|---|---|
| Spent bulk chemical | Cement, bentonite, barites, thinners, | Heavy metals, hydrocarbon, organics, solids |
| Spent special products | $H_2S$ scavengers, defoamers, tracers | Zinc carbonates, iron oxides, hydrocarbons, silicon oils, potassium |
| Water Based Mud cuttings (WBM) | Bentonite clay (gel), additives such as Barium sulfate (Barite), Calcium carbonate (chalk) or Hematite | Heavy metals, inorganic salts, biocides, hydrocarbons |
| Waste lubricants. | Lube oil, grease | Organic compounds and heavy metals |
| Spent/Contaminated oil-based muds | Mineral oil, water-based muds and formation solids | Biocides, heavy metals, solid/cutting, inorganic salts, BOD, surfactants and hydrocarbons |
| Spacers | Mineral oil, detergents, surfactants | Alcohol, aromatic and hydrocarbon |

### 2.1.4. Treatment and disposal of spent drilling fluid

Many elements contribute, singly or in combination to the pollution associated with drilling fluid wastes, some of those are reservoir fluids, biocides, stimulation or completion fluid components, chemical components of drilling fluids, corrosion inhibitors and oil. If not well managed, wastes generated during drilling have the potential to negatively impact on the health, soil quality, water, and entire ecosystem (Sharif et. al., 2017).

Drilling process produces two major wastes; drilling fluid waste and drilling cuttings, which are disposed in one of these three ways; offshore disposal, onshore disposal and drill cutting re-injections (Ismail et. al., 2017). Wastes like the spent drilling fluids generated from drilling processes are meant to be controlled, collected, processed, stored, transported, and disposed of in a safe and acceptable environment in line with current regulatory standards. Various waste management options, such as underground injection, land application, biological processes and thermal treatment are used for drilling wastes remediation and management (Furukawa et al., 2017).

Drilling wastes are treated to reduce their volume and/or toxicity to make them fit for final disposal. The choice of treatment and disposal options depends largely on the waste characteristics and regulatory requirements. There are various practices to get rid of drilling wastes in the oil and gas industry today (Onwukwe and Nwakaudu, 2012); they are: onsite burial, land farming, incineration, thermal treatment, slurry injection and bioremediation (or vermiculture). Other researchers have also reported on the different types of drilling wastes treatment; thermal desorption, incineration, composting, bioremediation, land spreading/farming etc. (Shariff et. al., 2017) compared onsite land burial of drilling wastes with drill wastes that are land-farmed or land-spread where aerobic conditions predominate and reported that onsite burial usually results in anaerobic conditions, which limits further degradation.

### 2.1.5. Risk assessment of exposure to spent drilling fluid

Borgert et. al. (2004), defines mechanism of action as the response shown by an organism exposed to a pollutant or the key features of the mechanism needed for the production of a biological response. In risk assessment, to estimate toxicity of mixtures of toxicants, the means of action is needed (Anyanwu et. al., 2018). Pollutants in drilling mud may be said to be in trace amounts and one could be tempted to conclude that they do not pose risk to health. It is important however, to consider that these pollutants can interact with each other to produce synergistic impacts that could be deleterious to human health and the health of the ecosystem they are disposed.

Anyanwu et. al. (2018) reported that substances can increase or decrease each other's toxicity, by this, they meant that substances may interact to produce adverse impact or reduce potency when combined in a mixture. The idea of external exposure, which was shown by Spurgeon et.al. (2010) by proposing a biologically based framework, explains the interaction of mixtures of substances in the environment, its exposure and uptake by the host organism – toxicokinetic, to the expression of toxicity in the host organism – toxicodynamics and finally, to the combined toxic effect known as toxicogenomics – a field which shows how genomes respond to environmental pollutants.

Toxicogenomics is important because environmental pollutants such as heavy metals contain more than one mechanism of action and may interact with more than one specific site along an adverse outcome pathway. This adverse outcome pathway contains aspects of molecular interactions, issues of responses to stress due to exposure to the toxicant and deleterious effects resulting from exposure to the combined mixtures. Monocyclic aromatic hydrocarbons (BTEX: benzene, toluene, ethyl benzene, xylene), polycyclic aromatic hydrocarbons (PAH), and related heterocyclic aromatic compounds are considered major toxicants in drilling wastes (Neff et al., 2011). Some PAH are known to be potent carcinogens and this class of contaminants is therefore given high priority for environmental pollution regulation and in risk assessment of industrial discharges (Bakke et al., 2013). BTEX, a group of mono-aromatic volatile organic compounds are often considered carcinogenic. Exposure to benzene and ethylbenzene has been linked with an increased risk of leukaemia and hematopoietic cancers (Schnatter et al., 2012).

Okoro et al., (2020) while assessing the risk of human exposure to radionuclides and heavy metals in oil-based mud samples used for drilling operation, reported that cancer risk obtained from their study were $1.1 \times 10^{-3}$ and $7.7 \times 10^{-3}$ for the drilling crew, which they stated was above the acceptable risk range considered by the environmental and regulatory agencies. They also reported that the carcinogenic risk calculated for the heavy metals; Pb, Cd, Hg, Cu, As, Cr, and Ni showed that nickel followed by cadmium, chromium and arsenic are the likely major contributors to cancer risk. In the same study, Okoro et al., (2020) also reported that the Hazard Index or Quotient for chromium were equal to 1, and that the hazard indices for the analyzed metals decrease in the sequence of Ni > Al > Hg > As > Pb > Cr > Cd > Cu > Zn. Although the reported hazard quotient of chromium and arsenic demonstrate that there was an undesirable health risk (non-cancer effects), they opined that exposure to any of these pathways in the absence of safety measures may lead to cancerous chronic fatal diseases after prolong exposure.

Although there is limited information on a clear-cut impact of drilling mud on humans and its direct implications for chronic non communicable diseases including cancer risk; there is evidence that the contaminant mixture of drilling mud may be injurious to animals and humans to human health risks. While there is paucity in epidemiological evidence, likely due to low study power, increased exposure to heavy metals, hydrocarbons, and other constituents of the drilling wastes, are likely to adversely impact on cancer risk. With established relationship between heavy metal and the increasing cancer risk from available research evidence, there is greater likelihood that heavy metals and hydrocarbon pollution play significant role in cancer risk. It is clear also from reviewed literature that though hydrocarbons may be found in trace amounts in drilling wastes, they still pose danger to the health of the ecosystem in which they are disposed of and inferably humans due to the presence of the non-threshold genotoxic carcinogens.

### 2.1.6. Drilling Waste Assessment and Toxicity Requirements

According to Alberta Energy Regulator (AER) Directive 050: Drilling Waste Management sets out the requirements for the treatment and disposal of drilling waste generated in Alberta as presented below.

1. Licensees must ensure analyses for EC, SAR (sodium, calcium, magnesium), and forms of nitrogen (including ammonium-nitrogen [NH3-N], nitrate-nitrogen [NO3-N], and nitrite nitrogen [NO2-N]) are done:
   a) In oversaturated drilling waste samples using as-received filtrate; clarified filtrate generated by filtration or centrifuging to pass through a Whatman no. 1 filter paper or equivalent;
   b) In under saturated drilling waste samples using a saturated paste extract.
2. Screening methods can be used to determine hydrocarbon content in drilling waste samples. However, hydrocarbon content in soils and soil-waste mixtures must be determined using the procedures and methods referenced in the latest edition of Alberta Tier 1 Soil and Groundwater Remediation Guidelines.
3. The pass threshold for a drilling waste to be considered nontoxic is 75 per cent for an EC50(15) (i.e., a drilling waste aqueous concentration that halves the initial light output of luminescent bacteria after 15 minutes must be 75 per cent or higher). See appendix 6 for reference methods and procedures for toxicity testing using luminescent bacteria.
4. If the EC50(15) value of the toxicity test is less than 75 per cent, licensees must have a lab treat the drilling waste sample with coarse activated carbon (charcoal) and test the charcoal treated sample for toxicity using luminescent bacteria (see appendix 6 for more information).
5. If analysis identifies the presence of hydrocarbons and they are the likely source of toxicity, the disposal may only proceed once all relevant criteria for the disposal method are met. Charcoal treatment is to be done by lab analysis before land disposal.
6. Toxicity un-attributable to hydrocarbon content indicates the need to treat and retest drilling waste before disposal. Toxicological information should be reviewed for all additives and mud products used to formulate the drilling mud; where information about an additive or

product is unknown, its contribution to toxicity cannot be dismissed. Operating practices at the well site should be reviewed to determine whether other circumstances could have caused toxicity to develop (e.g., adding camp sewage or rig waste, such as chain oil, pipe dope, or rig wash, to the storage system).

7. If in-field treatments are conducted (e.g., pH adjustment) to reduce drilling waste toxicity, licensees must resample and retest the drilling waste to determine if it meets the toxicity requirements. Additional lab testing may be required to determine whether field treatment methods will reduce toxicity.

**Applications of drilling waste reuse**

**Road spreading:** Drilling wastes are mixed with other construction materials and spread over gravel roads. The oily waste acts as an effective binding material which helps hold the road materials together and making such wastes an effective dust suppressant. Research has shown that the environmental impact of road spreading is low for properly prepared wastes. The metal contents of most oily wastes can be lower than that of asphalt; a common road paving material. Most of the wastes used for road spreading are of high volume, low toxicity solids; hence, disposal by road spreading reduces that volume of waste has must be disposed of in overused landfills. Nevertheless, the lack of control over the spread of wastes is expected to limit and may even prohibit its future use, (IPIECA, (2009).

**Re-use of cuttings as construction materials:** After treating drilling wastes to remove all the liquid contents, the clean solid residue are employed in the manufacturing of construction rural roads. Some of the possible applications include the use of drill cuttings as a fill material, aggregate or filler in concrete, brick or block manufacturing. The economics of this technique must not be based on the value of the finished product but on the cost of other disposal methods. Usually, the cost of treating waste to remove all possible liquid contaminants makes this method less preferable to other methods like land-farming and composting, (IPIECA, (2009).

## 2.2. Waste management hierarchy

Generally, the waste hierarchy refers to the "3 R" Reduce, Reuse and Recycle (figure 1), which classify waste management strategies according to their desirability in terms of waste minimization. It is usually represented by an inverted triangle with reduction occupying the upper portion, followed by reuse and finally recycling. In some instances waste treatment and disposal is incorporated as the least preferred option in the hierarchy. Proper management of wastes begins with pollution prevention. Pollution prevention refers to the elimination, change or reduction of operating practices which result in discharges to land, air or water. If elimination of a waste is not possible, then minimizing the amount of waste generated should be investigated.


**Figure 1**. Waste management hierarchy. Source: (Sharif MDA, Nagalakshmi NVR, Reddy SS, Vasanth G, Uma Sankar K, (2017).

The philosophy of the waste hierarchy is that if less waste is disposed then it is less likely that there will be a potential impact on the environment. The waste hierarchy encourages measures to be put in place to reduce waste generated though more efficient processes and technologies, or at least to encourage the potential for waste that is generated to be reused or recycled. Failing this, the hierarchy requires that waste be treated where possible to reduce its volume or hazardous properties, or finally be disposed or incinerated.

Responsible waste management can be accomplished through the hierarchical application of the practices of source reduction, re-use, recycling/recovery, treatment, and responsible disposal. This is provided for in article 4 of Hazardous Waste Management Regulation, Decree 83/2014 of 31 December and Regulations on Urban Solid Waste Management, Decree 94/2014 of 31 December. At all stages of the camp construction and operation, the first priority in terms of waste management will be to minimize the amount and toxicity of all waste streams generated. Reducing the volume and toxicity of waste generated will reduce the risks associated with the handling, storage, transport, treatment and disposal of the waste, (Moz Power Invest, S.A. and Sasol New Energy Holdings (Pty) Ltd, 2009). Waste minimization can be accomplished applying the principles below:

1) **Reduce -** source reduction or 'waste avoidance' requires that waste managers examine ways of eliminating or reducing waste at source. This is the first step in responsible waste management. In the event of choices, this is the preferred alternative.

2) **Reuse** - where waste can be reused this is a preferred option. Reuse is different from recycling insofar as it involves the reuse of a resource without changing its original form. The reuse of water would be an example of this. Wherever possible, unused or partially used materials which are surplus should be returned to the original suppliers.

3) **Recycling** - involves the collection of materials that can be re-processed for further use. The separated material can be used as a product or raw material. . The segregation between cuttings and water would be an example of this.

4) **Resource recovery** - involves the capture of energy or some other valuable benefit from the waste.

5) **Incineration** - involves the destruction of wastes, leaving a small quantity of ash to be disposed, and it is found at the most advanced level of waste disposal/treatment.

6) **Landfil**l - this is the final (least desirable) alternative which should only be used when all other reasonable alternatives have been considered.

The Environment Site Officer (ESO) shall identify and implement waste minimization opportunities for waste generated on site as part of the environmental audits and inspection process. Similarly, good housekeeping can minimize the amount of waste generated by ensuring that, where possible, materials are used more than once, and the use of general supplies is maximized before they are discarded, e.g. not discarding half full refuse bags.
To manage the project's camps waste streams, it is necessary to identify disposal routes in accordance with the waste category assigned to the specific waste stream. Some waste may need to be stored temporarily while the most appropriate treatment or disposal facility is identified, and arrangements made for transfer (e.g. lead acid and dry cell batteries light bulbs and solvents).

## 2.3. Waste Management Plan (WMP)

The success of the implementation of the WMP should be In line with the Principle of Extended Producer Responsibility, as described in Decree 83/2014, the responsibility for implementing the waste management measures remains with the Proponent; however, where contractors appointed to perform certain activities, the contractor shall be responsible to ensure that these measures are adhered to. Annexes 1 and 2 present the procedural steps to be adopted when collection, segregating, storing, transporting and disposing of wastes as generated by project activities. Responsibilities are also denoted accordingly, (Sasol Exploration and Production International, 2017).

### 2.3.1. Wastewater Management

The Environment Site Officer (ESO) has to inspect the Contractor periodically to ensure compliance with waste management requirements in relation with project activities, (Sasol Exploration and Production International, 2017).

1. **Training and Inductions**

Training is a critical component to raise awareness on the various impacts and associated management functions of the Plan. Contractor shall ensure that all personnel responsible who are involved in activities that could result in an environmental impact(s) and responsible for the execution of the tasks and requirements contained within this Plan receive training and are competent.

Training shall take the form of, but not be limited to: induction training, use of educational posters and daily environmental discussion topics prior to the start of each shift, (Osisanya S, 2011). During these training sessions, the following principles shall be presented / discussed:

- The Proponent’s corporate environmental, health and safety policies and applicable Mozambican environmental regulations.
- Their roles and responsibilities in achieving conformity with the requirements of the Camp
- Camp Environmental Permits and their conditions; and

- The Waste Management Plan and its procedures for managing identified environmental (and social) impacts arising from Camp operations. ▪ Restrictions and procedures for collection, treatment and disposal of waste and hazardous substances.
- Need to refrain from destruction of animals and plants, indiscriminate defecation, waste disposal and/or pollution of local soil and water resources.

The contractor shall:

- Describe the training and awareness requirements necessary for the effective implementation of the Plan; and
- Document training activity associated with the Waste Management Plan by means of a training needs assessment, training matrix/plan and records of training undertaken.

## 2. Inspections, auditing, reporting, and review

### a. Inspections

An internal inspection schedule shall be developed and maintained. A record of all internal inspections results shall be recorded and maintained. Actions arising from internal inspections shall be tracked until their close out. Performance in respect of waste management shall be included in the monthly ESO reports.

### b. Internal and External Auditing

An internal Audit Schedule shall be developed and maintained for the project. A record of all internal audits and the audit outcomes will be maintained. Actions arising from internal audits will be tracked until their close-out. Audits and/or inspections undertaken by external regulators will be facilitated via the Proponent's Environmental Manager. The findings of external regulatory audits will be recorded, and actions and/or recommendations will be addressed. Additionally, an annual compliance audit report will be submitted to Government as set by Government regulation for Category A projects.

### c. Review of the Plan

The Proponent is committed to conduct activities in an environmentally responsible manner and aims to implement best practice environmental management as part of a program of continuous improvement. This commitment to continuous improvement means that the

Proponent will review this Waste Management Plan every 3 years or more often as required (e.g. in response to new information).

Reviews will address matters such as the overall design and effectiveness of the Plan, progress in waste management performance, changes in environmental risks associated with waste management, changes in business conditions, and any relevant emerging waste environmental issues appropriately covered by the Plan, or measures that are identified to improve the Plan.

## 2.4. Legal framework of waste management

This section summarizes the current national and international legislation, standards and guidelines that regulate environmental matters relevant to the management of waste, (Sasol Exploration and Production International, 2017).

### 2.4.1. Mozambican legal framework

**Regulatory authorities**

Ministry of Land, Environment and Rural Development (MITADER) is responsible for directing the implementation of environmental policy, coordinating, advising and auditing. Under waste management, it is the Ministry's responsibility for the following:

a. To issue and disseminate binding rules on the procedures to be followed under waste management;
b. To carry out the environmental licensing of facilities or places of storage and / or disposal waste;
c. To monitor compliance with the provisions of the regulations and the rules on waste management;
d. To ensure public participation in the licensing process provided in paragraph of this number, as well as access to relevant information on waste management.

### 2.4.2. International guidelines and conventions

The following are international conventions and guidance related to waste management as is applicable to the CTT project: World Bank Group (OP4.03) Performance Standards and World Bank Environmental, Health and Safety (EHS) Guidelines.

The WB EHS guidelines provide guidance for the following:

- Information in support of actions for avoiding, minimizing, and controlling EHS impacts during the construction, operation, and decommissioning phases of a project or development of a facility;
- The implementation of the Performance Standards, particularly on those aspects related to Performance Standard 3: Pollution Prevention & Abatement and aspects of occupational and community health and safety;
- Assisting decision makers with relevant industry background and technical information;
- Management of produced water/wastewater – guidelines for reduction, reuse and disposal; and
- Treatment and disposal of general waste waters (sewage, drainage and storm water). In the event of a host country's regulations differing from the levels and measures presented in the Guidelines, projects will be expected to comply with whichever is more stringent. If less stringent levels or measures are appropriate in view of specific project circumstances, a full and detailed justification for any proposed deviation/alternatives should be provided.
- Performance Standard (PS) PS3: Resource Efficiency and Pollution Prevention. This PS requires the investor to avoid or minimize adverse human impacts on human health and the environment by avoiding or minimizing pollution from project activities.
- Air Quality - Air emissions guidelines are outlined in the World Health Organization (WHO) Air Quality Guidelines Global Update. EHS guidelines for air quality management include the identification of possible risks and hazards associated with the project as early on as possible and understand the magnitude of the risks; the potential consequences to workers, communities, or the environment if these hazards are not adequately managed or controlled. Impacts to air quality should be prevented or minimized by ensuring that emissions to air do not result in pollutant concentrations exceeding the relevant ambient air quality guidelines or standards.

**General guidelines:**

Environmental Waste Management These guidelines apply to projects that generate, store, or handle any quantity of waste across a range of industry sectors. It provides guidance in terms of general non-hazardous waste, hazardous waste and waste monitoring options. The Proponents' commitment to waste minimization, reuse and recycle is audited against the intent of these general EHS guidelines. Sludge and other discarded material, including solid, liquid, semi-solid, or gaseous material resulting from industrial operations needs to be evaluated on a case-by-case basis to establish whether it constitutes a hazardous or a non-hazardous waste. Facilities that generate and store wastes should practice the following:

- Establishing waste management priorities at the outset of activities;
- Establishing a waste management hierarchy that considers first prevention then reduction, reuse, recovery, recycling, removal and finally disposal of wastes;
- Avoiding or minimizing the generation of waste materials, as far as practicable; and
- Where waste generation cannot be avoided, minimize, recover and reuse waste.

Recommended measures to prevent, minimize, and control the volume of solid wastes from thermal power plants include recycling of solid wastes in uses such as cement and other concrete products, construction (roads), disposal of solid wastes in permitted landfills and dry handling of solid wastes, in particular fly ash.

**South African National Standard (SANS) 101031**

Mozambique has not promulgated its own noise regulations and reference is usually made to other standards and guidelines in cases where noise impacts need to be assessed. SANS 101031 is aligned with World Health Organization (WHO) 2 guidelines.

**Conventions**

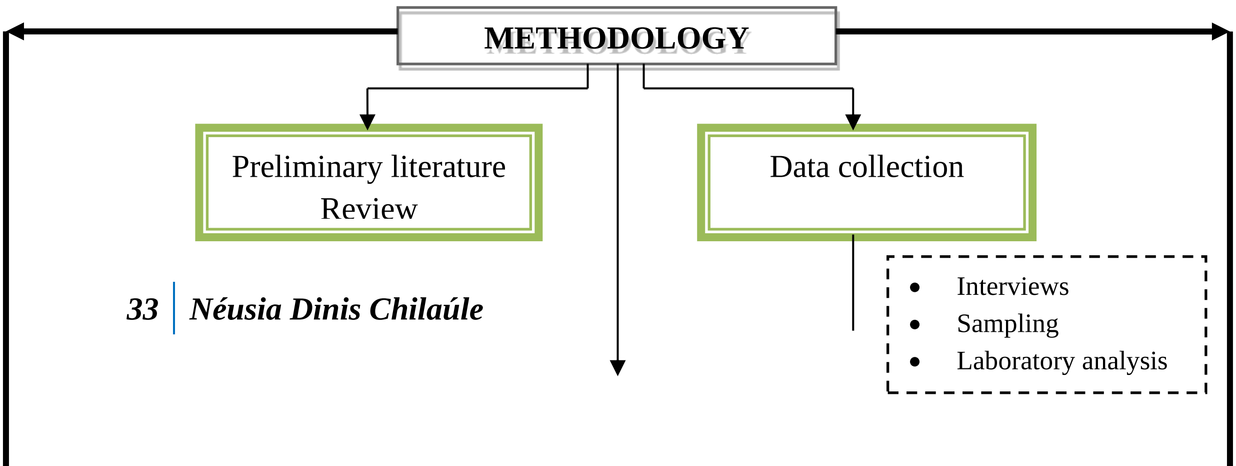
- The Basel Convention (1992) (on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal) to which Mozambique has acceded (1997), controls the movement, storage, transport, treatment, reuse, recycling, recovery and final disposal of hazardous waste as well as requiring producers of hazardous waste to dispose of their waste in an environmentally responsible manner close to where it is generated.
- The Bamako Convention (1991) is supplementary to the Basel Convention and specifically covers the movement of hazardous waste into or between signatory African countries. Mozambique acceded this convention in 1999.
- The Stockholm Convention (2004) on Persistent Organic Pollutants is a global treaty to protect human health and the environment from chemicals that remain intact in the environment for long periods, become widely distributed geographically, accumulate in the

fatty tissue of humans and wildlife, and have harmful impacts on human health or on the environment. Mozambique acceded this convention in 2006.

- Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade (1998).
- The European Waste Incineration Directive, Directive 2000/76/EC on the Incineration of Waste. This directive provides regulations for the incineration of household and hazardous waste in Europe. The aim of the Waste Incineration Directive is to prevent or to reduce, as far as possible, negative effects on the environment caused by the incineration and co-incineration of waste.
- Basel Convention Technical Guidelines on Incineration on Land, 2002. These guidelines focus on the disposal of hazardous waste by thermal processes.

## CHAPTER III: METHODOLOGY

The project research will take a holistic, risk-based approach that can minimize the environmental footprint of drilling operations activities regarding to drilling waste. The methodology will be based on quality and quantitative analysis to provide a better understand of the system approach proposed in this project (figure 2).



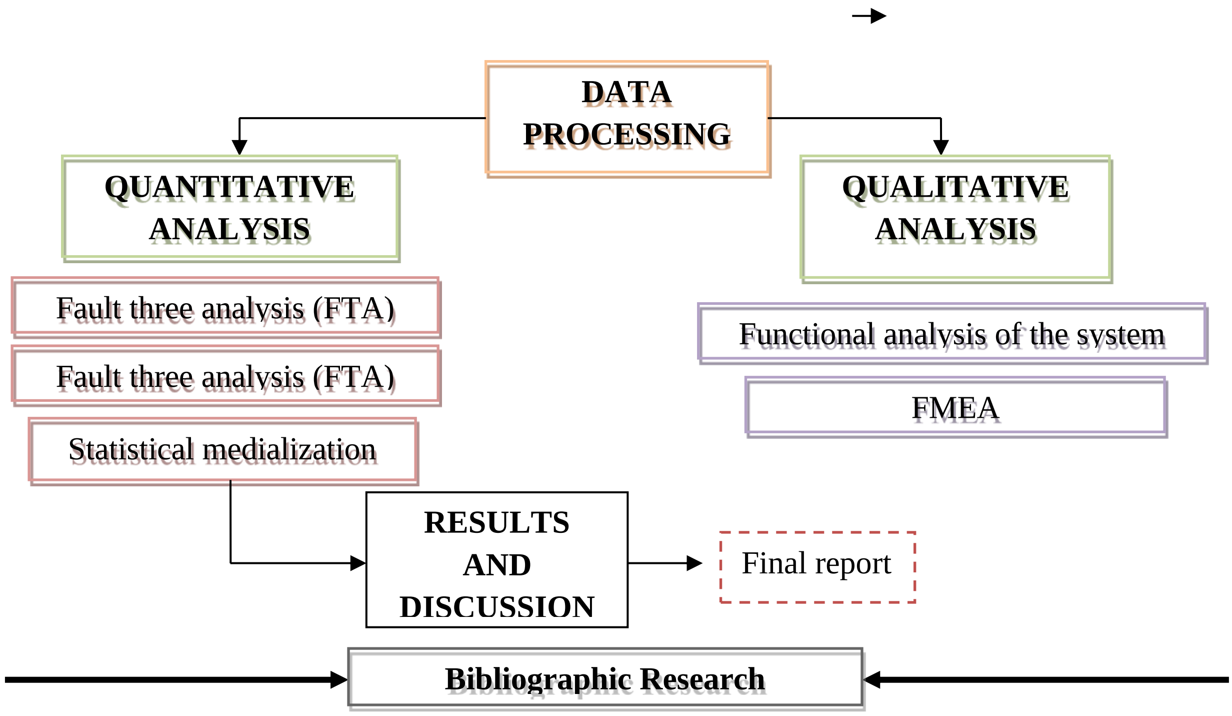



**Figure 2.** Flowchart of the project research methodology. Source: Author

### 3.1. Bibliographic review

Bibliographic review is part of the process in all steps until the compilation of the final report, were published and unpublished literature is reviewed, and also the available professional papers discussing drilling fluids, books, dissertations, scientific papers, and reports from the company itself, relevant standards and environmental regulations of the oil and gas waste disposal, historical data of probability and frequency of the basic events.

### 3.2. Field work

The present study was carried out as part of internship program at SLB, in Inhambane-Pande. All relevant data's regards to drilling waste treatment system was provided by dewatering supervisor by interviews in terms of how is process the system, how they do the analysis of the cuttings, how they treat the waste and how they process for the final disposal. From several interviews and assistances, all relevant information for the system definition and function analysis was provided.

Laboratory analysis

### 3.3. Laboratory Analysis

The laboratory activity was focused on primary dewatering of solid and fluids waste from the rig location and the respective water treatment process, taking in account standards whish meet for release to the environment or compatibility for re-use on the rig. The method used for water treatment was Chemical, Chemical oxidation, chemical precipitation, chromium reduction, coagulation, cyanide destruction, dissolved air flotation electrochemical oxidation, flocculation, hydrolysis, and neutralization (pH control).

### 3.4. Data Processing and analysis

To start the study of the following project will propose the system approach and describe the functionality of the system approach propose, subsystem and its components.

#### 3.4.1. Qualitative analysis

FMEA also is described and analyzed to determine the level of the risk that can result from the potential failure mode. The laboratory analysis is the data set to be able to study the physical parameters and chemical parameters in the drilling waste treatment which can cause serious impacts in the environment after non-treated waste disposal.

1. **Preliminary analysis**

Preliminary analysis is a simple, inductive method of analysis whose objective is to identify the hazards and hazardous situations and events that can cause harm for a given activity, facility or system. It is most commonly carried out early in the development of a project when there is little information on design details or operating procedures and can often be a precursor to further studies or to provide information for specification of the design of a system. It can also be useful when analyzing existing systems for prioritizing hazards and risks for further analysis or where circumstances prevent a more extensive technique.

**Inputs include:**

- Information on the system to be assessed;
- Such details of the design of the system as are available and relevant.

**Outputs include:**

- A list of hazards and risks;
- Recommendations in the form of acceptance, recommended controls, design specification or requests for more detailed assessment.

**Process** A list of hazards and generic hazardous situations and risks is formulated by considering characteristics such as:

- Materials used or produced and their reactivity;
- Equipment employed;
- Operating environment;
- Layout;
- Interfaces among system components, etc.

**Strengths and limitations**

Strengths include:

- That it is able to be used when there is limited information;
- It allows risks to be considered very early in the system lifecycle.

**Limitations include:**

- A preliminary analysis provides only preliminary information; it is not comprehensive, neither does it provide detailed information on risks and how they can best be prevented.

2. **Failure modes and effects analysis (FMEA)**

In FMEA, a team subdivides hardware, a system, a process or a procedure into elements. For each element the ways in which it might fail, and the failure causes and effects are considered. FMEA can be followed by a criticality analysis which defines the significance of each failure mode. For each element the following is recorded:

- Its function;
- The failure that might occur (failure mode);
- The mechanisms that could produce these modes of failure;
- The nature of the consequences if failure did occur;
- Whether the failure is harmless or damaging;
- How and when the failure can be detected;
- The inherent provisions that exist to compensate for the failure.

For FMEA, the study team classifies each of the identified failure modes according to its criticality. Several different methods of criticality can be used. The most frequently used are a qualitative, semi-quantitative or quantitative consequence/likelihood matrix or a risk priority number (RPN). A quantitative measure of criticality can also be derived from actual failure rates and a quantitative measure of consequences where these are known. The RPN is an index method that takes the product of ratings for consequence of failure, likelihood of failure and ability to detect the problem (detection). A failure is given a higher priority if it is difficult to detect.

The Priority Risk Number (PRN) results from the product of the three indices referred to previously (S – Severity; O – Occurrence; D – Detection), according to equation 1:

$$PRN = S * O * D$$

**Equation 1.** Priority risk number equation.

Where:

**PRN** - The Priority Risk Number

**S** - Severity

**O** - Occurrence

**D** - Detection

The PRN works as an indicator of the criticality of failures, that is, the higher the PRN, the greater the risks for the worker and the company, therefore, the greater the Most Urgent Risk Priority Number is to solve or minimize the failure.

### Strengths and limitations

Some strengths of FMEA are listed below:

- It can be applied widely to both human and technical modes of systems, hardware, software and procedures.
- It identifies failure modes, their causes and their effects on the system, and presents them in an easily readable format.
- It avoids the need for costly equipment modifications in service by identifying problems early in the design process.
- It provides input to maintenance and monitoring programs by highlighting key features to be monitored.

Some Limitations of FMEA are listed below:

- FMEA can only be used to identify single failure modes, not combinations of failure modes.
- Unless adequately controlled and focused, the studies can be time consuming and costly.
- FMEA can be difficult and tedious for complex multi-layered systems.

### 3.4.2. Quantitative analysis

Quantitative analysis is focused on fault three (FTA) analyses which will give us a better understand of the failure of the top event and each causes. From the FTA we will be able to understand which cause can have more effect to the system and after that some recommendations should be than to mitigate the risk environment impacts and for the system to be controlled.

1. **Fault tree analysis (FTA)**

FTA is a technique for identifying and analyzing factors that contribute to a specified undesired event (called the "top event"), **(Altabbakh, 2013)**. The top event is analyzed by first identifying its immediate and necessary causes. This analysis is used primarily at operational level and for short- to medium-term issues. It is used qualitatively to identify potential causes and pathways to the top event, or quantitatively to calculate the probability of the top event. For quantitative analysis strict logic has to be followed. This means that the events at inputs of an AND gate have to be both necessary and sufficient to cause the event above and the events at an OR gate represent all possible causes of the event above, any one of which might be the sole cause.

**Inputs for fault tree analysis are:**

- An understanding of the system and the causes of failure or success is required, as well as a technical understanding of how the system behaves in different circumstances. Detailed diagrams are useful to aid the analysis;
- For quantitative analysis of a fault tree, data on failure rates, or the probability of being in a failed state, or the frequency of failures and where relevant repair/recovery rates, etc. are required for all base events;
- For complex situations, software and an understanding of probability theory and Boolean algebra are recommended so inputs to the software are made correctly.

**The outputs from fault tree analysis are:**

- a pictorial representation of how the top event can occur, which shows interacting pathways each of which involves the occurrence of two or more (base) events;
- a list of minimal cut sets (individual pathways to failure) with, provided data is available, the probability that each will occur;
- In the case of quantitative analysis, the probability of the top event and the relative importance of the base events.

**Strengths and limitations**

**Strengths of FTA are listed below:**

- It is a disciplined approach which is highly systematic, but at the same time sufficiently flexible to allow analysis of a variety of factors, including human interactions and physical phenomena;
- It is especially useful for analyzing systems with many interfaces and interactions. It provides a pictorial representation leading to an easier understanding of the system behavior and the factors included;
- Logic analysis of the fault trees and the determination of cut sets is useful in identifying simple failure pathways in a complex system where particular combinations of events and event sequences which lead to the top event could be overlooked;
- It can be adapted to simple or complex problems with the level of effort dependent on complexity.

**Limitations of FTA are listed below:**

- In some situations, it can be difficult to ascertain whether all important pathways to the top event are included; for example, including all ignition sources in an analysis of a fire. In these situations, it is not possible to calculate the probability of the top event;
- Time interdependencies are not addressed;
- FTA deals only with binary states (success/failure);
- While human error modes can be included in a fault tree, the nature and extent of such failures can be difficult to define;
- FTA analyses one top event. It does not analyze secondary or incidental failures.
- An FTA can get very large for large scale systems.

## 2. Event tree analysis (ETA)

ETA is a graphical technique that represents the mutually exclusive sequences of events that could arise following an initiating event according to whether the various systems designed to change the consequences function or not. The tree can be quantified to provide the probabilities of the different possible outcomes. The tree starts with the initiating event then for each control lines are drawn to represent its success or failure. A probability of failure or success can be assigned to each control, by expert judgement, from data, or from individual fault tree analyses. The probabilities are conditional probabilities. For example, the probability of an item functioning is not the probability obtained from tests under normal conditions, but the probability of functioning under the conditions of the initiating event.

The frequency of the different outcomes is represented by the product of the individual conditional probabilities and the probability or frequency of the initiation event, given that the various events are independent.

ETA can be used qualitatively to help analyze potential scenarios and sequences of events following an initiating event, and to explore how outcomes are affected by various controls (equation 2). It can be applied at any level of an organization and to any type of initiating event. Quantitative ETA can be used to consider the acceptability of the controls and the relative importance of different controls to the overall level of risk. Quantitative analysis requires that controls are either working or not (i.e. it cannot account for degraded controls) and that controls are independent. This is mostly the case for operational issues. ETA can be used to model initiating events which might bring loss or gain. The probability of occurrence of the events in one year was calculated according to equation 2.

$$\boldsymbol{p}=\mathbf{1}-\boldsymbol{e}-\lambda\boldsymbol{t}$$

**Equation 2.** Probability of occurrence of the events in one year.

Where:

**p** - Annual probability of occurrence

$\boldsymbol{\lambda}$ - Annual frequency

**t** - Time period (i.e., 1 year)

### Strengths and limitations

Strengths of ETA are listed below:

- Potential scenarios following an initiating event are analyzed and the influence of the success or failure of controls shown in a clear diagrammatic way that can, if required, be quantified;
- It identifies end events that might otherwise not be foreseen;
- It identifies potential single point failures, areas of system vulnerability and low payoff counter-measures, and hence can be used to improve control efficiency;
- The technique accounts for timing and for domino effects that are cumbersome to model in fault trees.

**Limitations ETA are listed below:**

- For a comprehensive analysis, all potential initiating events need to be identified. There is always a potential for missing some important initiating events or event sequences;
- Only success and failure states of a system are dealt with, and it is difficult to incorporate partially operating controls, delayed success or recovery events.

### 3.5. Final report and Compilation

The diagram, illustrations, graphic and tables were prepared using Microsoft office software (word, excel and publish). At this stage, the preparation of the final report consisted of the compilation of all information from the literature review, information from data processing, analysis and interpretation of results obtained and the bellow sequence is followed (figure 3):

**Step 1:** The methodology starts with analyzing the process flow diagram of the drilling waste treatment plant. It is crucial to study the process flow to understand the interaction among different components and their potential vulnerability to failure.

**Step 2:** Identifying the major risk factors and understanding how these factors can bring adverse outcomes is necessary. The historical data gives an overall idea about the persistent failure causes. However, it is impossible to obtain all the factors from the data since many of them may not have been experienced during the considered time frame. The experts can aid in this context by sharing their operational experience. They can suggest additional factors on top of the ones from historical data. This step aims to find all the possible factors that may result in complete or partial failure.

**Step 3:** The qualitative model is constructed based on risk factors, their dependencies, causal relationships and consequences determined in step 2.

**Step 4:** The qualitative network needs to be inserted with the prior and conditional probabilities for quantitative risk assessment.

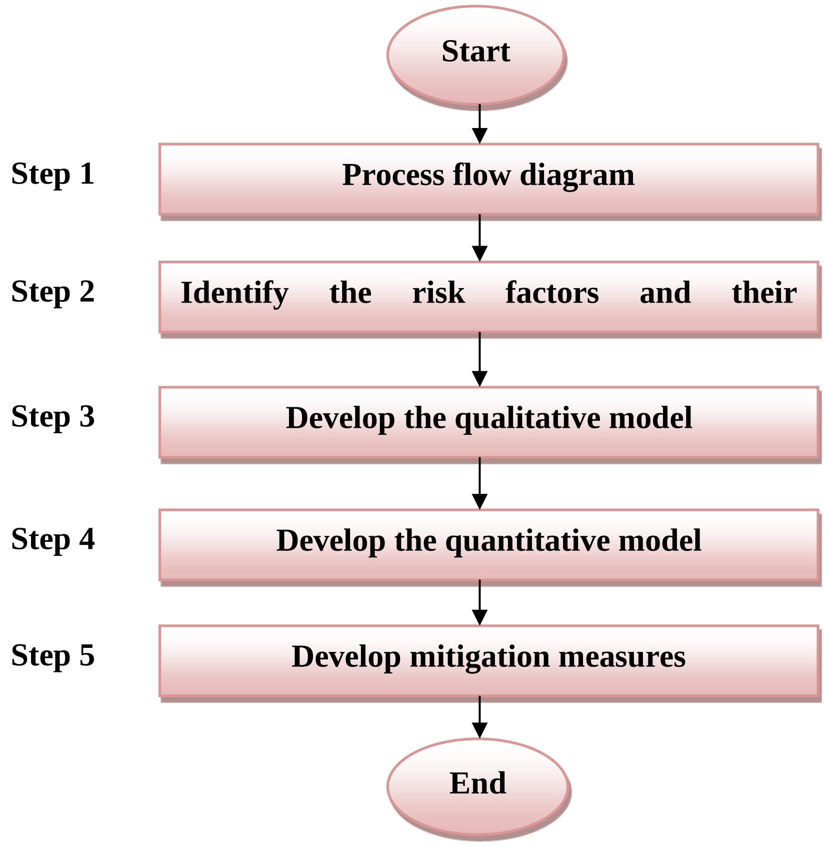



**Figure 3.** The framework of the proposed model. Source: Author

# CHAPTER IV: RESULTS AND DISCUSSION

## 4.1. System definition

The system defined and described is a set of subsystem, components, humans and mechanical functions connected by interfaces to provide a functionality of the drilling waste treatment which is shown in figure 2.

The system was designed for the purpose of treat the drilling waste with the main objective to reduce waste and consequently environment impacts. To have this objective successes its necessary to operate under certain conditions in its environment, which are: good equipment's, qualified operators, good design of the waste pit, good supervision and monitoring of the operation, chemicals, treatment standards in place and application of regulations, (figure 4).

The following is a description of the functions of each subsystem and system components:

- **Subsystem 1 - Mechanical treatment:** with the function of primary treatment of the cutting prior coming from the well, were occurring the sedimentation and segregation process of fluids and cuttings.
- **Subsystem 2 - Physical and chemical treatment:** with function to treat the cuttings and remove water from the mud.
- **Subsystem 3 – Waste quality management:** with the function to do risk assessment control and document control of the laboratory analysis.
- **Subsystem 4 - Regulatory Inspection:** function of providing test and treatment inspection of the parameters analyzed prior to dispose the waste.

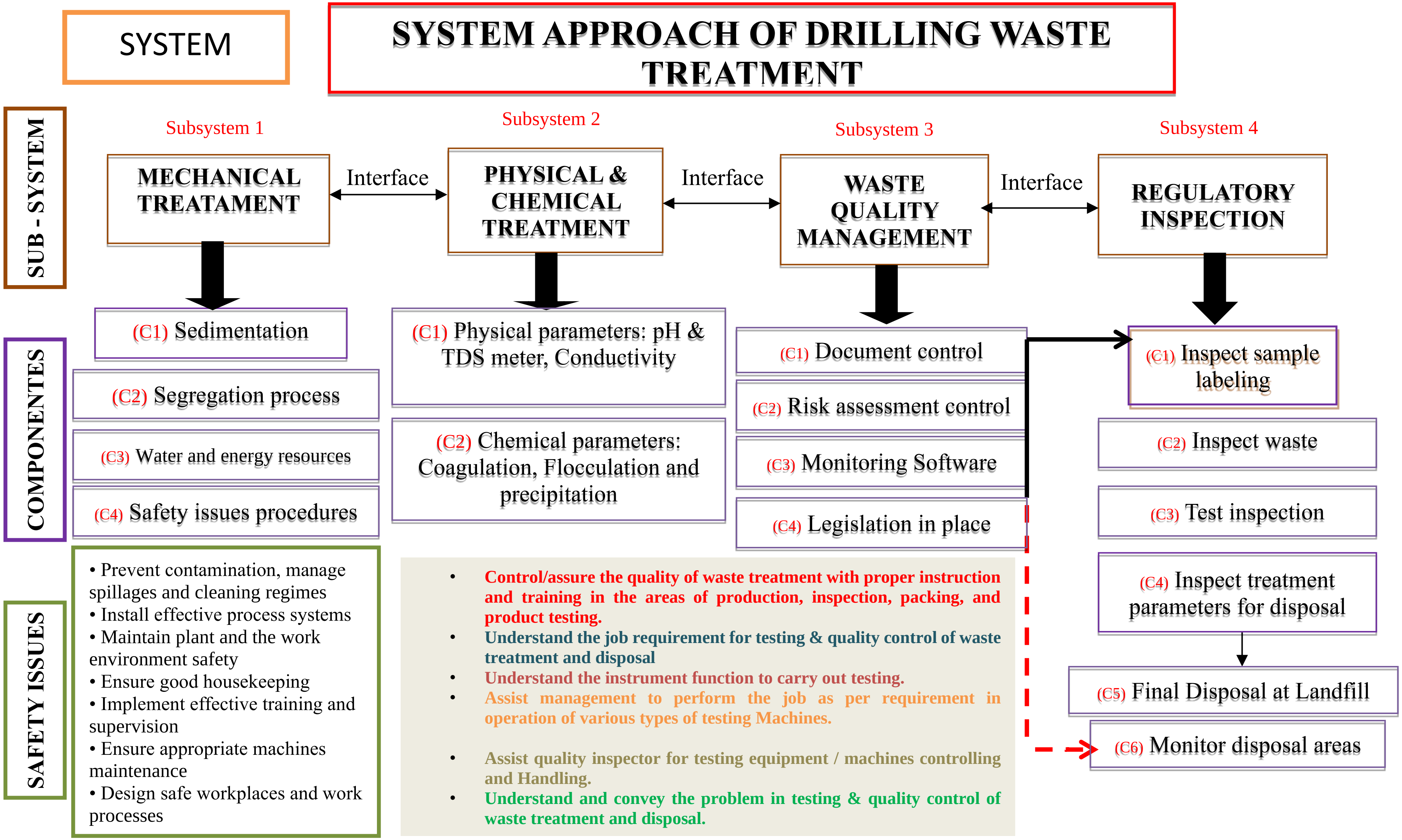



**Figure 4.** Drilling waste treatment system. Source: Author

### 4.2. Function Analysis system

After describing the system and its boundary defined, functional analysis can begin in two levels of analysis.

#### External functional analysis

The first stage consists of understanding why the system exists. To do this, on the one hand we must bring out any relationships that exist between two elements outside the system and which pass through the system itself. These relationships are supports for the main functions that express the system's objective, (figure 5). On the other hand, interactions between the system's constituent elements and outside environments must also be determined. These interactions reveal constraint functions and these functions express the requirements of an outside element in relation to the system (table 2).

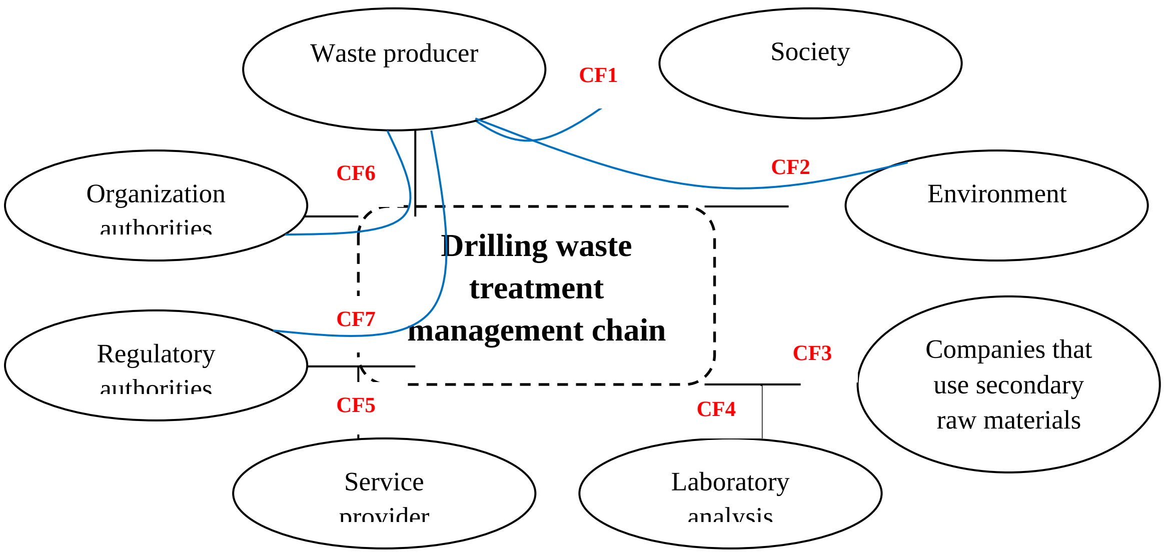



**Figure 5.** External functional block diagram of a drilling waste treatment management system. Source: Author

To achieve the latter, we have listed the main functions as well as the constrained functions of the system:

**Table 2.** Main functions of the system. Source: Author

| | |
|---|---|
| CF1 | Meet society's expectation in terms of sanitation, health and safety |
| CF2 | Limit effects of waste on the environment |
| CF3 | Take account of world market evolutions for choosing the system process |
| CF4 | Apply SOP standards to guaranty well done waste treatment and reduce the environment impacts |
| CF5 | Encourage producers to reduce the waste they generate by means different standardization and rule-making tools. |
| CF6 | Meet control organization requirements |
| CF7 | Comply with regulations. |

### The functional specifications

**Table 3.** Table summarizing the different choices for the flexibility of the system components. Source: Author

| Function | | Criteria | Level | Flexibility |
|---|---|---|---|---|
| CF1 | Meet society's expectation in terms of sanitation, health and safety | HSE policies and procedures | 1 per day | F1 |
| CF2 | Limit effects of waste on the environment | Reduce and recycle waste | Every operation | F2 |
| CF3 | Take account of world market evolutions for choosing the system process | Functional process system | < 6 months | F0 |
| CF4 | Apply SOP standards to guaranty well done waste treatment and reduce the environment impacts | Existing writing procedures | < 6 months | F2 |
| CF5 | Encourage producers to reduce the waste they generate by means different standardization and rule-making tools. | Sustainable methods | Every operation | F1 |
| CF6 | Meet control organization requirements | Supervise the operation | Every operation | F0 |
| CF7 | Comply with regulations. | Comply system approach with standards regulations | <6 month | F1 |

### Internal functional analysis

Secondly, the flow movements through or inside the system and its constituent elements must be determined. These flows define the functions that enable the system to attain its objective and in this way give a description of the system's internal operation (Peyras, 2002). Indeed, each constituent elements of the system can operate as a subsystem of the system. It also can be broken down into components. For these reasons, this method has been applied to a waste management system. The main results of this analysis are presented in the figure 6 and 7.

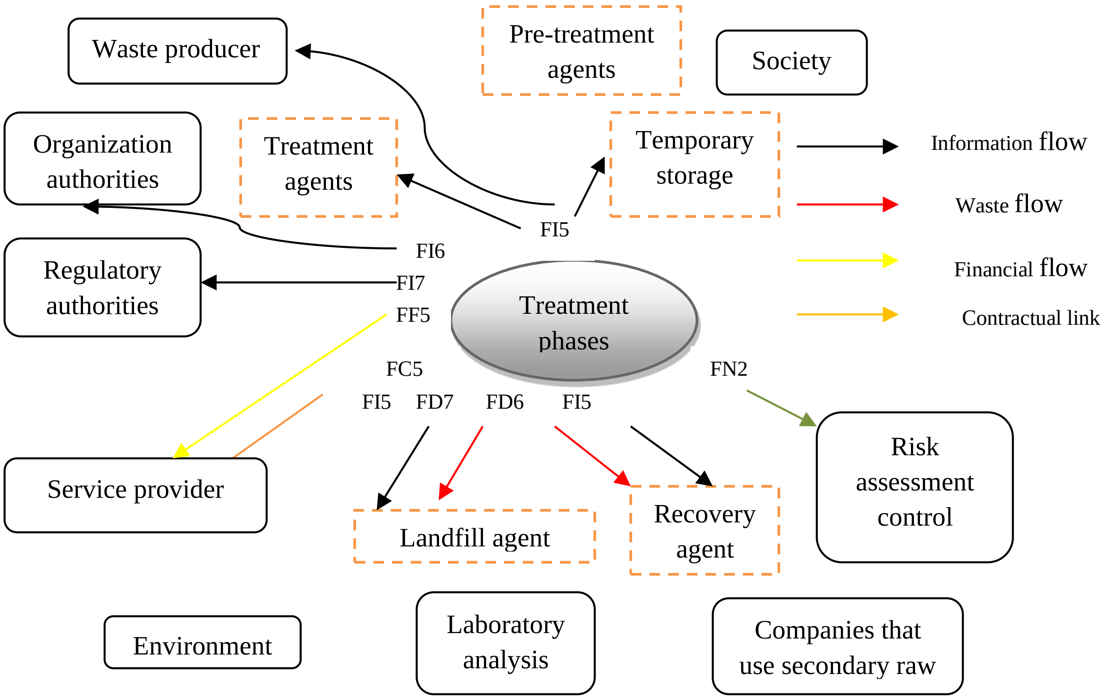



**Figure 6.** The functional block diagram of relationships generated by a "treatment phases". Source: Author

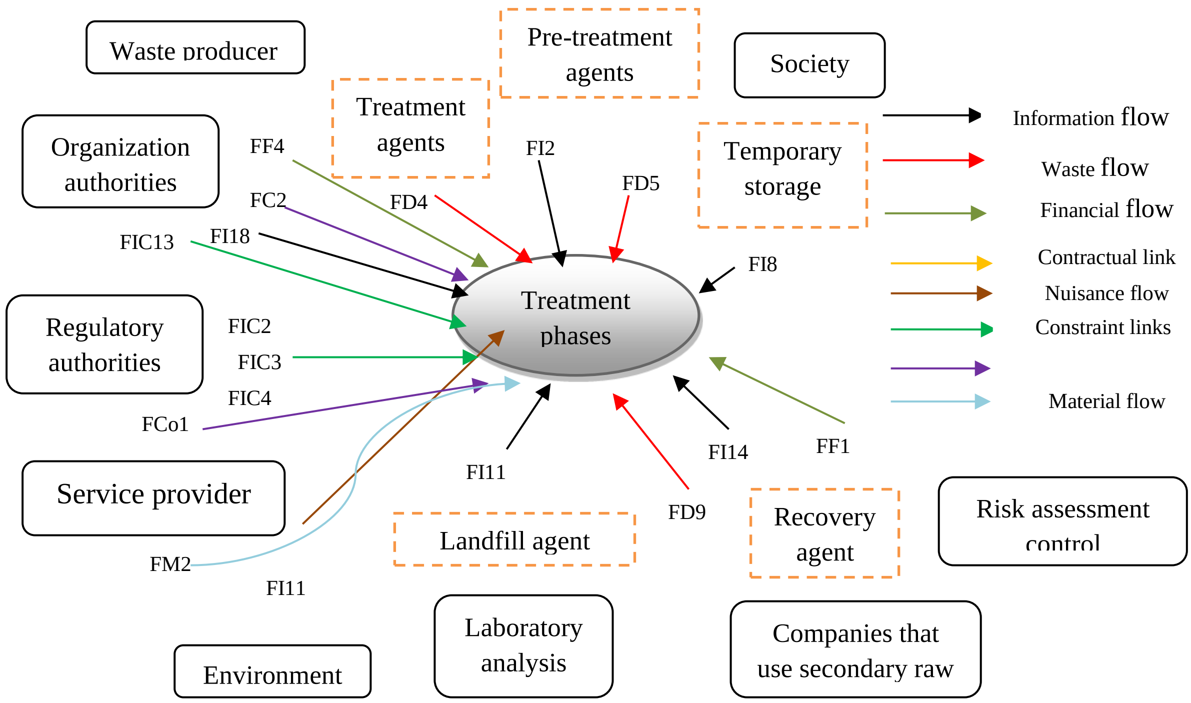



**Figure 7.** The functional block diagram of relationships generated by other constituent elements toward a "treatment phases" subsystem. Source: Author

FF.1: remunerating personnel; FF.2: purchasing and renewing equipment required for the activity; FI.3: handling evolutions in the quality and quantity of waste flows. : FI5: being in contact with partners in front of and behind waste management in order to manage evolutions in waste flows; FD6: Once it has been transformed, sending waste to its energy recovery facility; FC4: concluding service or supply contracts for carrying out the activity. FI2/FI8/FI11/FI14: being in contact with partners in front of and behind waste management in order to manage evolutions in waste flows; FIC2: having regulations followed concerning waste storage; FD4/FD5: sending waste to its point of transformation

### 4.2. Preliminary risk analysis

The purpose of this step is to highlight all the possible malfunctions of the system in identifying potential accidents that could affect the system, highlight the possible causes of potential accidents providing the probability of occurrence of potential accidents and the seriousness of damage they might cause, determining the measures that will reduce the probability of accidents potential or the severity of the damage they could cause (table 5).

**Table 4.** Preliminary Hazard Analysis of the drilling waste treatment system. Source: Author

| Subsystem | Fared event | Probability | Consequences | Intrinsic risk | Control on site | Recommendations |
|---|---|---|---|---|---|---|
| **Mechanical treatment** | Equipment damage | Possible (C) | Minor (1) | Moderate | Pre job safety meeting, checklist before start the job and after, and verbal and written handover for crew change. | Ensure appropriate machine maintenance by providing work sheet before and after the job. |
| **Physical and chemical treatment** | Inappropriate dosage of chemicals | Possible (C) | Major (4) | Critical | Work procedures on place and supervision. | Install effective system, design safe work place and implement effective training and supervision. |
| **Waste quality management** | Ground water contamination | Likely (B) | Major (4) | Critical | Document control and all standards information's provided | Prevent contamination, manage spillage and cleaning regimes. |
| **Regulatory inspection** | Dispose of non-treated waste | Possible (C) | Serious (3) | High | Personnel on site to provide regular inspection. | Regular inspection on disposal sites and document control of waste test and disposal authorization. |

### 4.3. Failure Mode and Effect Analysis (FMEA)

The FMEA method is used as a model in this project. The level of risk variables in the FMEA method is determined based on the expert opinion of drilling waste treatment. These variables include severity (S) indicating the degree of failure of failure that will occur (table 6), occurrence (O) indicating the probability of failure, detection (D) indicating the detection rate of failure. FMEA inputs are values of Severity (S), Occurrence (O) and Detection (D). The values of S, O and D are assessed by the input variables of the 1-10 scale and are grouped into five categories of linguistic levels: Very Low (VL), Low (L), Moderate (M), High (H) and Very High (VH).

**Table 5.**Ranking of the Severity Index. **Source: Carmignani (2009)**

| Severity index | Classification |
|---|---|
| 1-2 | Secondary |
| 3-5 | Important |
| 6-7 | Very important |
| 8-9 | Critical |
| 10 | Catastrophic |

The Occurrence indicates the probability that the failure will occur, that is, it determines the probability that once the cause occurs, it will cause the failure mode. Table 7 represents the values assigned to the occurrence index.

**Table 6.** Ranking of the Occurrence Index. Source: Carmignani (2009)

| Occurrence Index | Classification | Frequency |
|---|---|---|
| 1 | Remote | Once per two years |
| 2 | Very Low | Once a year |
| 3 | Low | Once per semester |
| 4 | Moderate | A few times a year |
| 5 | | A few times per semester |
| 6 | | Once in quarter |
| 7 | High | A few times per quarter |
| 8 | | Often in quarter |
| 9 | Very High | Often in a month |
| 10 | | Often a week |

The Detection estimates the probability that the control means detecting the cause or effect of the failure mode before the customer is affected (Carmignani, 2009). Table 8 represents the values assigned to the cause/effect detection index.

**Table 7.** Ranking of the Severity Index. Source: Carmignani (2009)

| Detection index | Classification | Criterion |
|---|---|---|
| 1-2 | Almost certain | Very high probability of detecting the error: Inspections and checks will almost certainly detect the error |
| 3-5 | High | High probability of detecting the error: Inspections and checks will most likely detect the error |
| 6-7 | Moderate | Moderate probability of detecting the error: Inspections and checks are likely that inspections and checks will detect the error |
| 8-9 | Very Low | Low probability of detecting the error: Inspections and checks are unlikely that inspections and checks will detect the error |
| 10 | Remote | Very low probability of detecting the error: Inspections and checks fail to detect the error; there is no detection system |

**Table 8.** Scoring Ranges and the Meaning of Risk Index. Source: Antunes (2009).

| Risk Priority Number | Score range |
|---|---|
| **Low** | 1–90 |
| **Medium** | 91–190 |
| **High** | 251–500 |
| **Very High** | 501–1800 |

Below is the definition of the different FMEA columns:

1. **Process step:** Activity to be studied
2. **Potential failure mode:** decomposition of the activity into sub-parts to break it down
3. **Potential failure effect:** Find the elements that could compromise the achievement of the process. What will be the effects of the failure modes on the achievement of the process?
4. **Potential causes:** Look for all the causes that could cause the failure modes. To find the causes, it is often useful to ask the question “why this mode of failure? The causes of **a failure mode can be multiple.**
5. **Detection:** How will we detect that a failure mode has occurred
6. **Risk priority number (RPN):** Level of the risk

**Table 9.** Definition of cause-effect of waste treatment. Source: Author

| No. | Process step | ID Failure | Potential Failure Mode | Potential Failure Effect | Severity (S) | Potential Causes | Occurrences (O) | Current Control | Detection | RPN | Action Recommended |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Man | 1 | Not implementing SOP properly | Irregularities in the work | 5 | Low level of concern and knowledge | 7 | None | 4 | 140 | Skills training for operators |
| 2 | Material | 2 | The raw waste quality parameters cannot be controlled | Raw water quality that does not meet the standard | 6 | Groundwater pollution by Industry | 4 | Coordinate with operation supervisor | 8 | 192 | Regular monitoring and coordination with administrator of the site |
| 3 | Machine | 3 | Lack of regularly maintenance of pumping machines | Easy breakdown machine | 8 | Lack of machine maintenance SOP | 2 | Technician | 8 | 128 | Perform the periodic maintenance schedule |
| 4 | | 4 | Working hours of the pumping machine exceed the limit | Fast machine damaged | 4 | No machine replacement | 4 | Technician | 7 | 112 | Replacement with a new engine to fit the budget funds |
| 5 | Method | 5 | The dosage of chemicals is not appropriate | Not perform preliminary calculations | 8 | Not perform preliminary calculations | 9 | Coordinate with operation supervisor | 8 | 576 | Preparation of SOPs on formula of dosage of addition of chemicals that adjusted to waste quality standard |
| 6 | | 6 | Chemical concentrations are not calculated | Parameter clean water that does not comply with quality standards | 5 | Lack of chemical dosage SOP | 2 | Existing written procedures sheet control | 3 | 30 | |

**Severity rating grid (estimating the severity of the effect on the treatment process or, caused by the fault):**

- 1: Minor effect.
- 4: Medium effect causing only slight discomfort. No noticeable degradation.
- 7: Effect with major impacts/serious impacts

**Probability of occurrence / frequency - the frequency of risk to which the process is exposed:**

- Low probability, very few defects in the process. The fault rarely occurs.
- Moderate probability, defects appearing regularly.
- High or even very high probability, faults appearing very regularly

**Detection scoring grid (probability of non-detection): Estimate the risk that the monitoring plan has of letting a defect pass:**

- Low probability of not detecting the defect before the as finally treated, the defect is obvious. Some faults will escape detection (control unitary by an operator).
- Moderate probability of not detecting the defect before the treatment has been completed, meaning difficult control.
- High or even very high probability of not detecting the defect before the treatment process fails, meaning that the control is subjective, poorly adapted.

The results of risk identification for waste treatment stakeholders in the form of disturbance, cause and effect can be seen in Table 10. The results are analyzed based on risk factor group consisting of human, material, method, and machine. Risk assessment is carried out on the risk occurrence of the identified outcome. Assessment is given by the decision maker who knows about the risk issues on drilling waste treatment through the questionnaire provided. The risk assessment includes how serious the impact of the risk (severity rating), the frequency of occurrence of the cause of the risk (occurrence rating) and whether the cause is detected (detection rate), using a scale of 1-10.

Based on the results of RPN calculation it can be seen that the method factor, especially the element of incorrect dosage of chemicals has the highest potential risk of failure because it has a value of RPN 576. This factor becomes the 1st rank to get attention improvement in order to meet the quality of clean water which is in accordance with the quality standards determined by the Ministry of Health. Furthermore, the raw waste quality parameters cannot be controlled also has a moderate potential risk of failure with the value of RPN around 192. Low maintenance of the pump machine due to the absence of a regular maintenance schedule. In addition, other activities can be checked condition of the machine on a regular basis daily, weekly or monthly. Thus, the company may provide the inspection and maintenance schedule such as intake pumps, distribution pumps and other pumps in waste treatment plants.

Furthermore, in the medium risk category obtained source water parameters difficult to control and does not implement SOP properly. Additionally, in the low-risk category there is the working hour of the pumping engine exceed the limit and Lack of regularly maintenance of pumping machines and Working hours of the pumping machine exceed the limit. Thus, to be able to have quality waste management and to meet the quality standards of the Ministry of Health, the company can emphasize improvement on the potential risks that have the highest category. With the improvement is expected to be able to improve the quality of clean water produced.

### 4.4. Fault tree analysis (FTA)

Fault Tree Analysis (FTA) is a top-down probabilistic risk assessment technique. It is a deductive method that investigates the factors and conditions that contribute to adverse events in a system. The strength of the FTA is that it is a visual model that clearly depicts the cause and-effect relationship between the root cause events to provide both qualitative and quantitative results (Altabbakh, 2013).

Through the 4 levels of causes that will allow us to find the causes roots, we will perform a probabilistic analysis on these causes. The tree of failure is composed of “OR gate” which relate the different causes that allows us to go back to the final problem. The top event (level 1) is connected directly to the failure events in implementation of SOP properly failure and chemical concentration calculations failure (level 2). Subset events in (level 3) are such as Irregularities in the work procedures, raw water quality that does not meet the standard, parameter clean water that does not comply with quality standards, inappropriate dosage of chemicals and raw waste quality parameters cannot be controlled. All events in level 3 (E011 to E015) are interconnected with OR gate. Lack of supervision (O1) and low level of concern and knowledge may cause irregularities in the work procedures (E011). Raw water quality that does not meet the standard (E012) is an event which can be caused by ground water contaminated by industry (O3) and lack of application of regulatory standards. So the parameter clean water that does not comply with quality standards (E013) can be generated by lack in performs preliminary calculation (O5) and lack of adequate producer by operator (O6). Inappropriate dosage of chemicals (E014) can be caused by lack of chemical dosage SOP (O7) and lack of experience and appropriate training (O8). Failure in labeling the samples (O9) and lack of regulatory inspector in the field (O10) are the basic events that can failure in raw waste quality parameters (E015). According to the fault tree diagram in Fig 7 the minimal cut sets are determined as follows: So minimal cut sets are (O1, O2, O3, O 4, O5, O6, O8, O9 and O10) to calculate the probability of top event, the probabilities of basic events must be known (figure 8) .

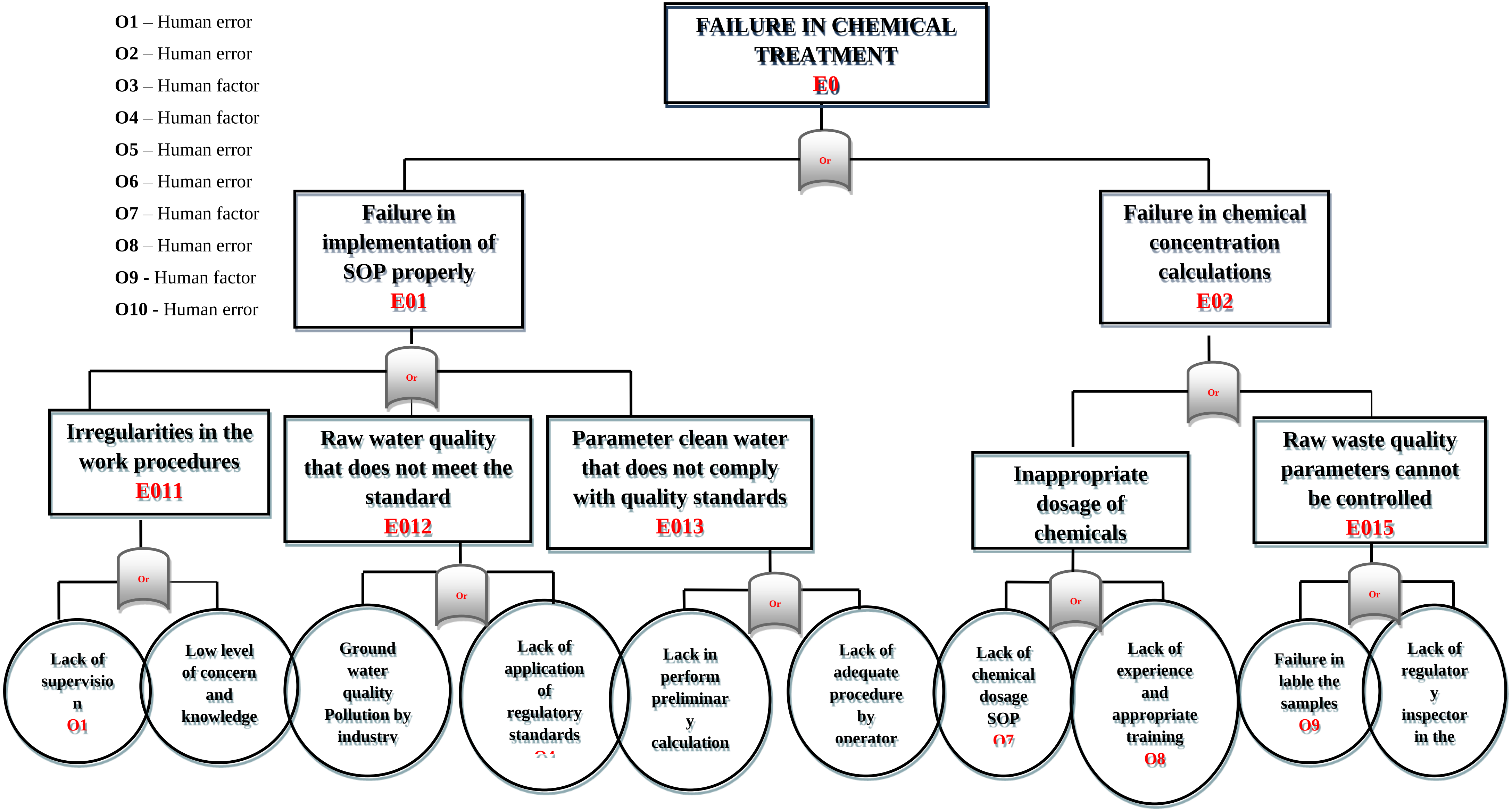



**Figure 8.** Fault tree diagram of waste chemical treatment. Source: Author

### 4.4.1. Probability analysis

After creating a fault trees, each roots of the events are taken to assign them a law of probability. The case study has mainly two laws:

- **Gamma law:** law characterized by two parameters which affect the shape and the scale uses to model a large number of phenomena.
- **Beta law 1:** law whose support is bounded (sup and inf, [0; +oo[) and dependent on two shape parameters.

Now that the level 4 root causes are defined, we can model a sample. For some failures, it will not be easy to define their probability, as for example in the case of human error. For each root cause, we defined which law we were going to use.

As defined the probability law of the root cause and each questions (table 11), it is possible to calculate for each root cause the probability of answering its question and being able to see which event had the most impact on the correspondent event calculating the probability of each event to Occure. It was also then possible to draw the critical path of the fault tree.

The probability of the failure of each event has been calculated and reflected in fault tree (figure 9). So, now it is possible to propose solutions and possible improvements. This result is obtained by the union of the 2 causes of each Level composition. If we go down the tree, we get our root cause which has the highest probability of failure.

**Table 10.** Definition of law and which question we were going to use in the probability analysis. Source: Author

| Ref. | Root cause | Root cause factor | Probability law | Question |
|---|---|---|---|---|
| **O1** | Lack of supervision | Human error | Beta 1 | The probability of the operator have not been supervised in performing the job be less than 5% when the average is 10 % |
| **O2** | Low level of concern and knowledge | Human error | Beta 1 | The probability of doing at least 1 training and pre-job safety meeting when the average number is 2 |
| **O3** | Ground water quality Pollution by industry | Human factor | Gamma | The average probability of treat and monitor all effluent is 5% |
| **O4** | Lack of application of regulatory standards | Human factor | Gamma | The probability to operator apply the standard and implementation process more than 3% when the average is 2% |
| **O5** | Lack in perform preliminary calculation | Human error | Beta 1 | The probability of the operator does not perform preliminary calculation is 5% |
| **O6** | Lack of adequate procedure by operator | Human error | Beta 1 | The probability of inadequate procedure be less than 5% |
| **O7** | Lack of chemical dosage SOP | Human factor | Gamma | The probability of lack of written procedures be less than 5% |
| **O8** | Lack of experience and appropriate training | Human error | Beta 1 | The probability of the operator have less than 1 years of experience when the average is 5% |
| **O9** | Failure in lable the samples | Human factor | Gamma | What is the probability of inadequate lable of samples be more than 5% |
| **O10** | Lack of regulatory inspector in the field | Human error | Beta 1 | What is the probability of the inspection process failure more than 5% |

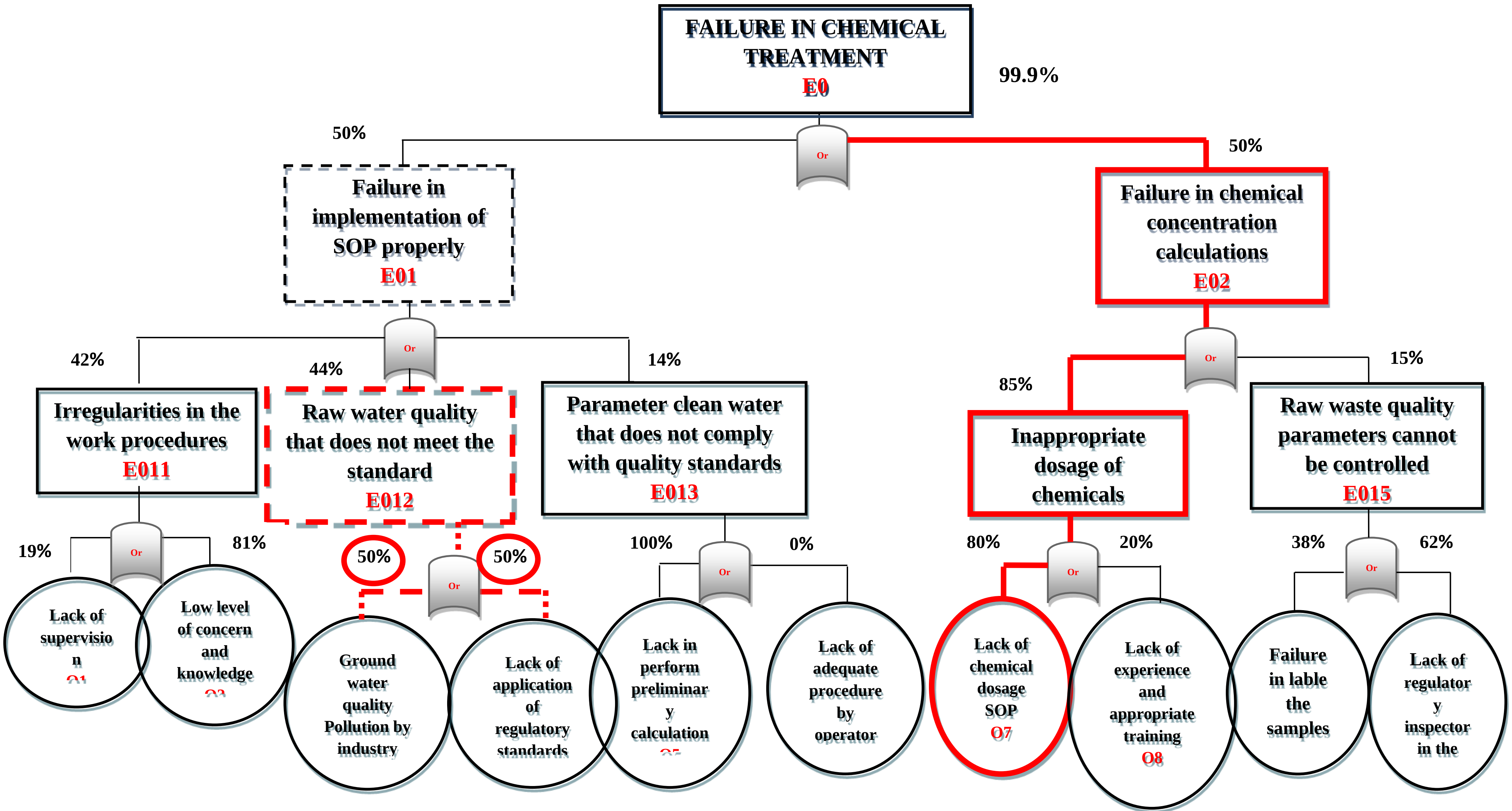



**Figure 9.** Fault tree diagram with the probability of the failure of each event. Source: Author

After generating probabilities for each of my root causes (level 4), I was able to trace the different probabilities from levels 3 to 1. I obtained an average probability (calculated on a sample of size n=1000) of my feared event with the following parameters:

Moyene: 99.79%

Ecart type: 0.26%

Through the probability study I obtained the following results:

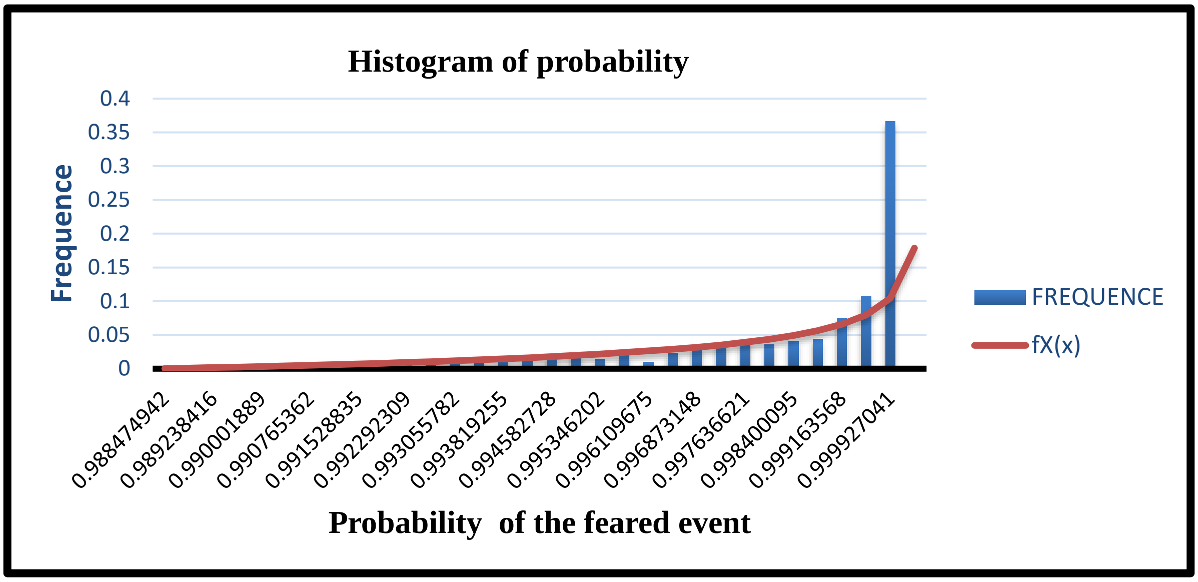



**Figure 10.** Histogram probability of failure in chemical treatment. Source: Author

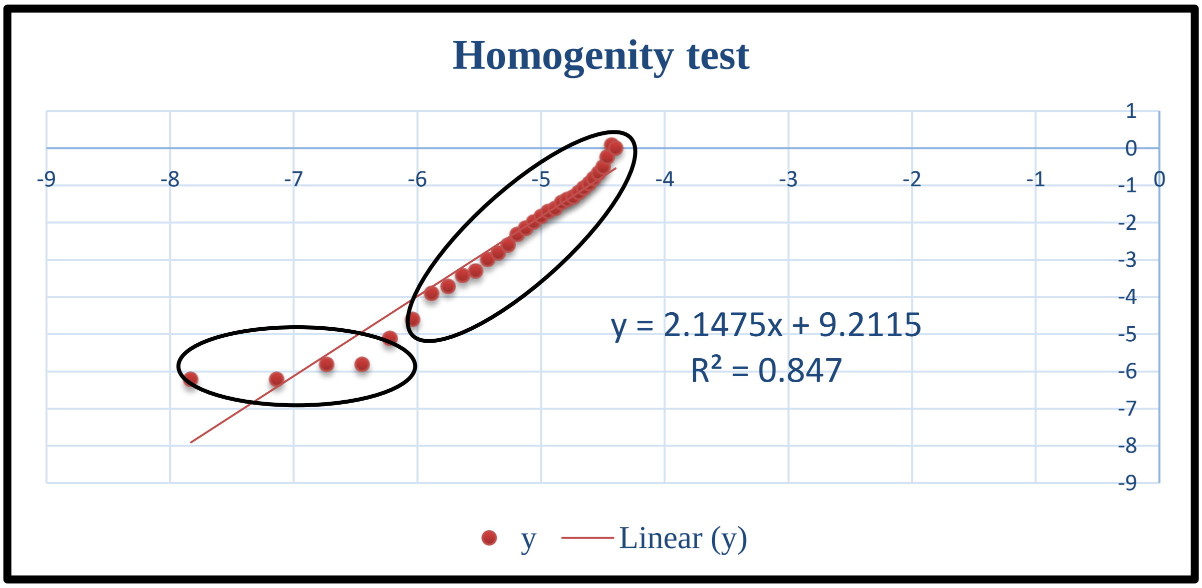



**Figure 11.** Homogeneity test of the probability study. Source: Author

The probability study and statistical correlation is giving coefficient of 0.847 for the feared event, from the parameters u and y has a downward concavity and is mostly a beta 1 and part of the sample represent a gamma law, which corresponds to human error and human factor respectively (figure11).

The curve of feared event is not perfectly homogeneous; however, this study shows that the sample is not heterogeneous. So, the experience can consider the sample homogeneous, it is possible to approximate the distribution. The probability of the system fail is between 0.9885 to 0.99, meaning that the company must follow all the procedures strictly and apply all stages of supervision and inspections (figure 10).

To reduce the probability of the top event the company need to develop and apply a computer model to determine the chemical dosage and do regular monitoring of the data base storage and the system. Furthermore, the operators must be trained for the specific to insure that the all function works properly and all components of the system are in good conditions before the use. To reduce the contribution of events Conjunction failure, contact failure, and half disconnection on the probability of the top event, the company must consider use of a backup data base.

#### 4.4.2. Mitigation measures to reduce the impact of inappropriate chemical treatment

The suggested mitigation measures are presented in Table 12, considering the risk priorities as the operator error that played the most pivotal role in creating and growing the risk of the inappropriate chemical dosage, getting the highest priority, and several mitigation measures have been proposed based on the discussion with the industrial experts. When it comes to wastewater treatment, the most important persons are operators because of their responsibilities for treating the wastewater to meet available standards. Thus it seems logical to pay special attention to decreasing operator errors; one of the effective solutions is to use modern technology and automatic devices for wastewater treatment plants. However, it is worth noting that human factor analysis is a specialized field obtaining significant attention due to humans' role in several accidents in the past few decades.

**Table 11.** The proposed risk-mitigating measures of the impact of inappropriate chemical dosage. Source: Author.

| Risk Factors | Proposed Risk-Mitigation Measures |
|---|---|
| **Operator error** | Precise definition of the skills trainings for the operators |
| | Precise definition on formula of chemical dosage in the SOP that comply with quality standard |
| | Precise definition of the qualities required to perform the chemical analysis |
| | Implementation of work sheet control and periodic schedule analysis |
| | Mandatory presence of the service supervisor during the operations |
| | Perform pre-safety job meeting before start the operation |
| | Implementation of standards must be mandatory |

### 4.5. Event Tree Analysis (ETA)

The event tree of the case of chemical treatment is presented in figure 12, the system is composed by failure in chemical dosage, and operator/inspection failure and system check failure. We can see that when all systems fail or are not present in the waste treatment plant it can lead to major effect to the environment and the probability of consequence is 0.516, if all the system works the probability of consequences reduce to 0.114. Therefore, if system f system checks woks the probability of consequences is 0.057. That means that the company may adjust and make sure all the events are in place and working properly specially the contribution of the operator/inspector with probability of 0.019 of consequences when he works properly.

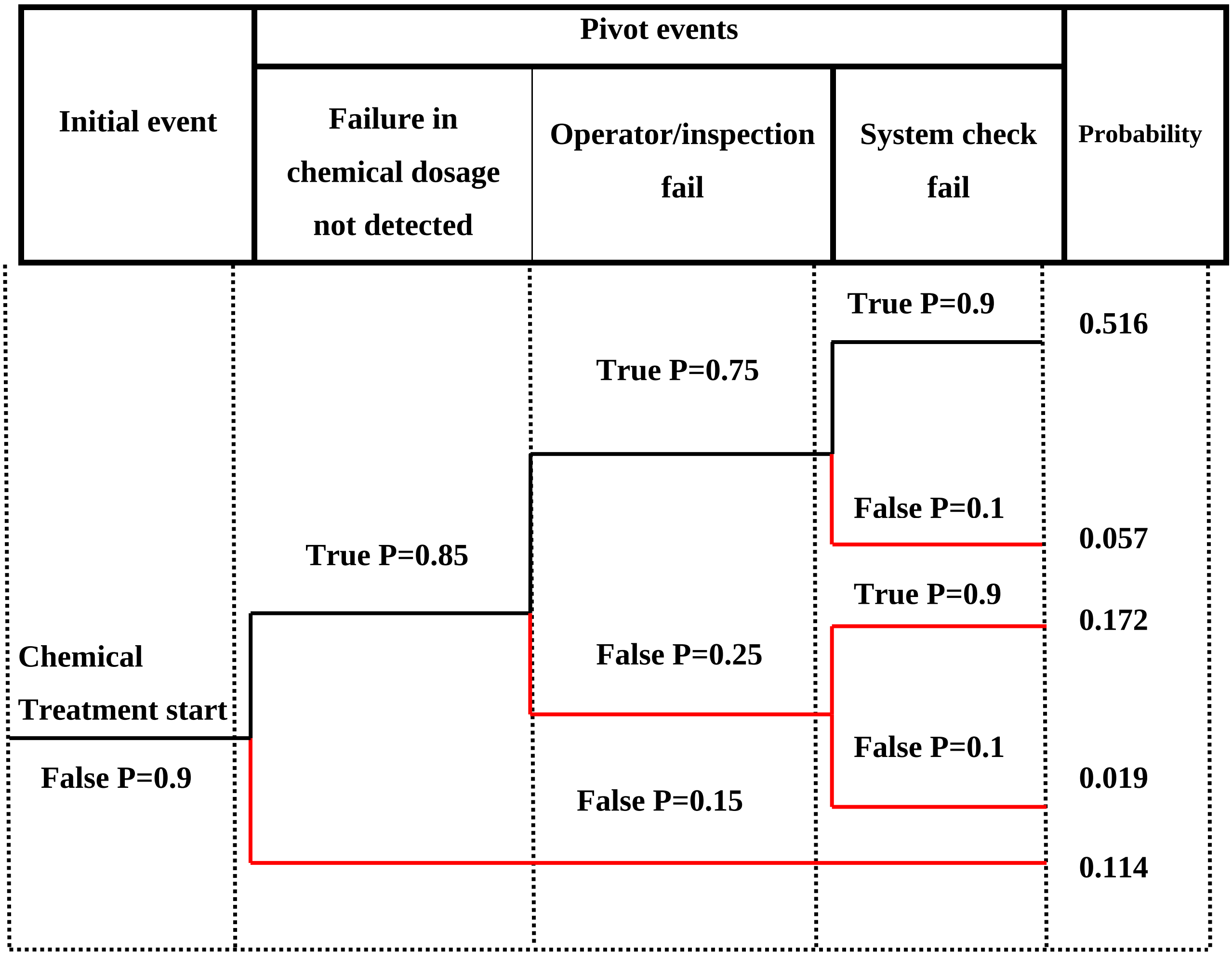



**Figure 12.** Event tree of mitigation measures of waste treatment failure. Source: Author

### 4.6. Physiochemical analysis of drilling waste

The samples were carefully labeled, well preserved, and sent to the laboratory for chemical analysis. In-situ measurements of pH, EC, total dissolved solids (TDS), and DO were carried out at the field using portable digital pH meter, Conductivity, TDS meter, model CO150, and DO meter Orion model 830 which has a sensitivity of 0.01 mg/l and calibrated with Winkler reagents A and B. The samples sent to the laboratory were tested for COD, BOD, total suspended solids (TSS), total hydrocarbon content (THC), and heavy metals. The heavy metals were determined using Buck Model 210/211 AAS 220GF graphite Furnance and 220 AS autosampler. BOD content was determined by Colorimetric using ascorbic acid molybdate blue method with Colorimeter (model spectrum 20D plus spectrophotometer). THC, TSS, and COD were determined by titrimetric method using the relevant reagents. All measured parameters followed standard analytical procedures recommended by DPR/FMEnv guidelines (2002).

Results of heavy metals analysis of DCs and DM at different drilling depths, results of geochemical analysis of drilling waste pit in respect of some selected physical parameters and heavy metals and results of analysis on sample after TDU operation, were compared with guideline of DPR/ FMEnv (2002) to enable qualitative and quantitative assessment of the waste.

**Heavy metals analysis**

Heavy metals analysis of DCs and DM at different drilled depths pH values ranged from 9.67 to 12.5 with an average of 10.74 in the DC and 9.35 to 12.9 in the DM as shown in Figure 11. Sample at depths of 1400 and 800m in both DC and DM recorded the highest value of 12.5 and 12.9, respectively. In addition, the results exceeded the standard acceptable levels of DRP/FMEnv. The elevated concentrations of pH in the DCs and DM are caused by the use of cement and caustic soda in the drilling mud (figure 13).

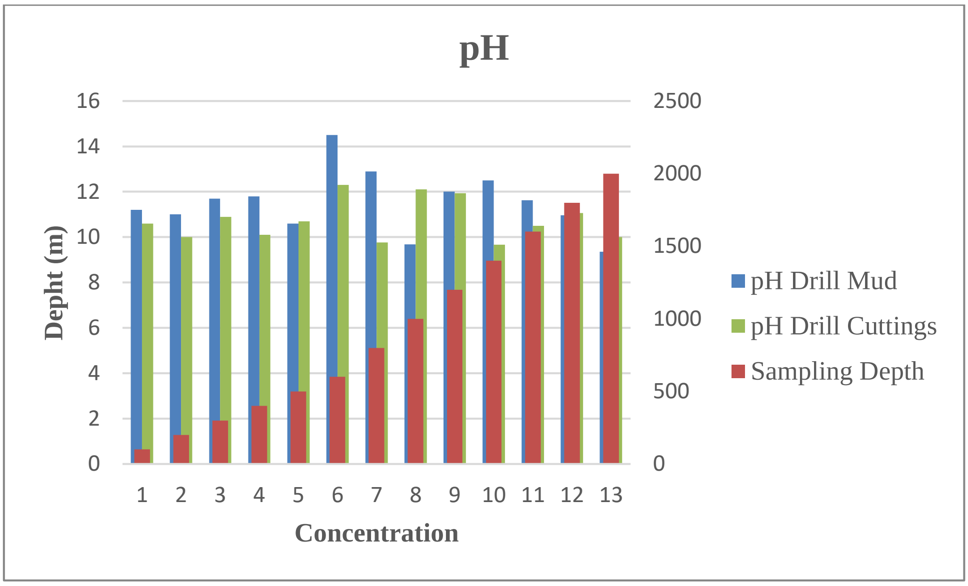



**Figure 13.** pH concentration in the drill cuttings and mud. Source: Author

Copper (Cu2+) showed different values between 6.58 and 20.79 (mg/l) with an average of 14.38 (mg/ l) in the DCs whereas, 4.43–15.6 is observed in the DM. Sample collected at depths of 300 and 400m in both DC and DM recorded the highest value of 20.79 (mg/l) and 15.6 (mg/l), respectively. In addition, the results exceeded the standard acceptable levels of DRP/FMEnv. The anomalous concentrations of Cu2+ in the DCs and DM are attributed to the drilling mud composition and its availability in the subsurface.

Lead (Pb+ ) in the drill cuttings analyzed ranged 4.29– 16.1 mg/l with average of 7.69 mg/l and 3.14–7.22 mg/l in the DM with an average of 4.57 mg/l. Highest values of 16.1 and 7.22 mg/l were measured from both DCs and DM at depth of 100 ft (Figure 12(b)). The DRP/FMEnv guideline value for lead shows (0.05 mg/l) and this indicates that Pb has reached pollution level in the study area. High value of lead in the area is attributed to the drilling mud composition and its availability in the subsurface. Lead can also be from dissolution of iron or manganese oxides or from weathering of pyrite (iron sulfide).

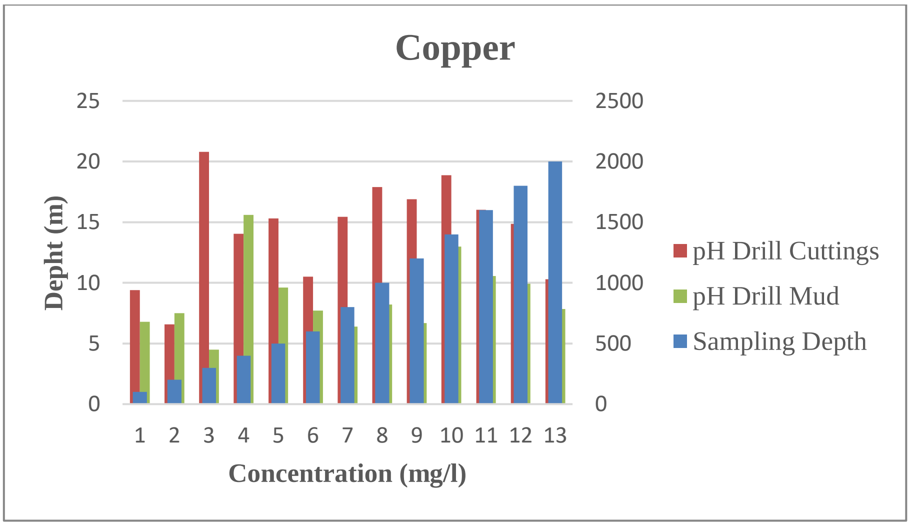
Nickel (Ni+) concentration in DCs ranges from 16.5 to 50.9 mg/l with an average of 34.79 mg/l. In DM, Ni+ varies from 10.3 to 22.5 mg/l with an average of 14.70 mg/l (Figure 12(c)). No guideline value is recommended for nickel by DPR/FMEnv.

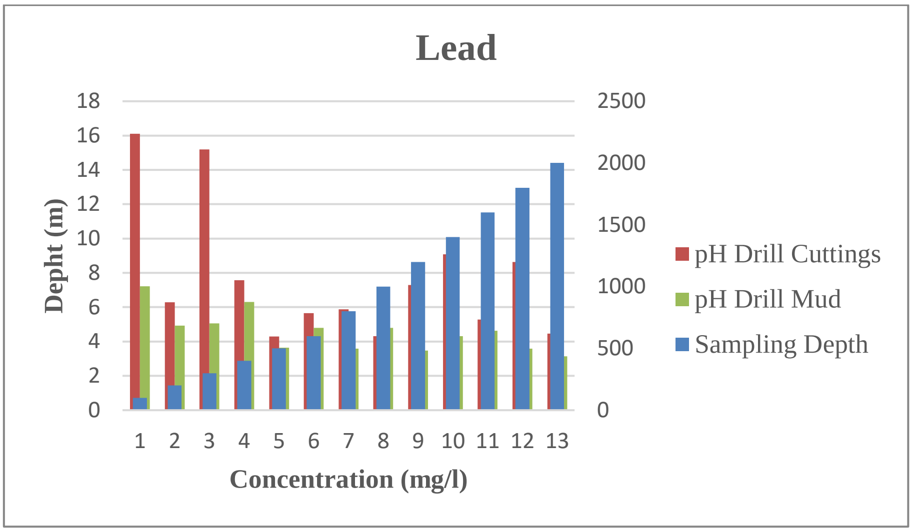
Iron (Fe2+) values varied between 10.4 and 19.81 mg/ l with an average 15.78 mg/l in the DCs. Sample analyzed at depth of 1800m recorded highest Fe2+ value of 19.81 mg/l in the DCs. In a similar manner, Fe2+ values ranged from 5.57 to 16.8 mg/l with an average of 11.45 mg/l in the DM. At depth of 500m, elevated value of 16.8 mg/l was measured from the DM samples. The guideline value of Fe2+ is 1 mg/l. Results show that Cd exceeded DRP/FMEnv threshold value; hence, it is a potential health risk to environment.

Vanadium (V+ ) concentrations of DC samples ranged between minimum 13.89 mg/l at depth of 6000 ft and maximum 28.6 mg/l at depth of 400m with an average of 20.39 whereas in DM, they ranged between minimum 10.1 mg/l at depth of 200m and maximum 19.11 mg/l at depth of 1400m with an average 14.83 mg/l. No guideline value is recommended for vanadium by DRP/ FMEnv.

Barium (Ba) concentrations ranged from 20.35 to 101.3 mg/l with an average of 60.97 mg/l in the DC and 28.35 to 106.4 mg/l with an average of 54.11 mg/l in the DM. The highest value of barium in the DCs was recorded at depth of 400m. On the other hand, the maximum concentration of barium in the DM was observed at depth of 1200m. These values generally exceed the normal level of DRP/FMEnv which is 100 mg/l.

Chromium (Cr) concentrations of the samples were fluctuated between minimum <0.5 mg/l at depth of 1000 and 400m, respectively, and maximum 5.33 mg/l at depth of 6000 ft with an average of 3.48 mg/l in the DC, whereas in the DM, they were fluctuating between minimum <0.003 mg/l at depths between 1600 and 2000m, respectively, and maximum 6.68 mg/l at depth of 2000m with an average of 3.59 mg/l. However, these results are within the standard allowable limit of 5 mg/l stipulated by DRP/ FMEnv except the sample measured at depth of 2000m in the DM.





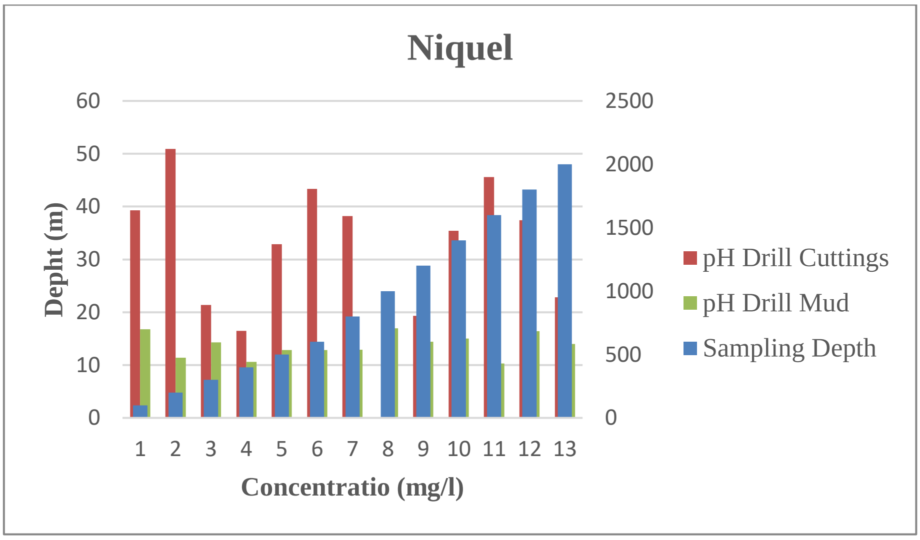




**Figure 14.** Copper, lead, and nickel concentrations in the drill cuttings and mud. Source: Author

The turbidity of the samples varies between 18 and 2076 (NTU), with an average of 630.92 (NTU). DRP/FMEnv established a guideline value of 15 NTU. Based on this value, turbidity level in the area has reached pollution level.

### pH and electrical conductivity

pH value in the area ranges from 6.1 to 9.1, with an average of 6.86. This indicates slightly acidic and strong alkaline water, which is believed to be due to chemicals used during drilling that changed the strong acidic nature of the water to mildly acidic. DPR/FMEnv (2002) established a guideline value of 6.5–8.5 for pH. The electrical conductivity (EC), which is the measurement of concentration of ionized substances in water, in the area ranges from 907 to 27200 µS/cm with an average of 6585.17 µS/cm.

**TDS and dissolved oxygen**

TDS concentration in the area falls between 368 and 14610 mg/l, with an average of 3360.42 mg/l. High values of TDS indicate high degree of dissolved metal constituents in the water. For instance, drilling waste samples from sample 1, 3, 4, 5, 8, and 10 have TDS values above 2000 mg/l stipulated by DPR/FMEnv (2002). Dissolved oxygen (DO) measures the amount of gaseous oxygen dissolved in an aqueous solution.

**Results of analysis on sample after TDU operation**

Drilling fluids (WBM) were subjected to dewatering operation (onsite) to take care of non-compliant parameters before discharge. The average analyzed samples subjected to the TDU show satisfactory compliance with DPR limits.

**Statistical correlation analysis and distributions**

Correlation analysis and distribution is used to assess the relationship between two different variables (Bahar & Reza, 2010). Statistical correlation (r) of +1 shows that two variables are related indicating positive linear correlation, but $r = -1$ shows a negative linear correlation. If $r = 0$, it means that there is no existing relationship between two variables. Two variables having a positive correlation coefficient implies that they have a common source, whereas negative correlation coefficient indicates a different source.

**Table 12.** Correlation matrix between physic-chemical parameters. Source: Author

| | *Turbidity* | *pH* | *TDS* | *EC* | *DO* | *Salinity* | *TSS* | *THC* | *BOD* | *COD* |
|---|---|---|---|---|---|---|---|---|---|---|
| **Turbidity** | 1 | | | | | | | | | |
| **pH** | -0.4096 | 1 | | | | | | | | |
| **TDS** | 0.7936 | -0.4731 | 1 | | | | | | | |
| **EC** | 0.8648 | -0.3326 | 0.9071 | 1 | | | | | | |
| **DO** | -0.3680 | 0.2664 | -0.4809 | -0.3382 | 1 | | | | | |
| **Salinity** | 0.7773 | -0.4758 | 0.9874 | 0.9138 | -0.5417 | 1 | | | | |
| **TSS** | 0.7769 | -0.2749 | 0.8576 | 0.9176 | -0.3977 | 0.8830 | 1 | | | |
| **THC** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 1 | | |
| **BOD** | 0.6321 | -0.4026 | 0.7572 | 0.5440 | -0.4750 | 0.7129 | 0.6796 | 0.0000 | 1 | |
| **COD** | 0.8387 | -0.3994 | 0.7653 | 0.6438 | -0.5904 | 0.7344 | 0.6294 | 0.0000 | 0.835009 | 1 |

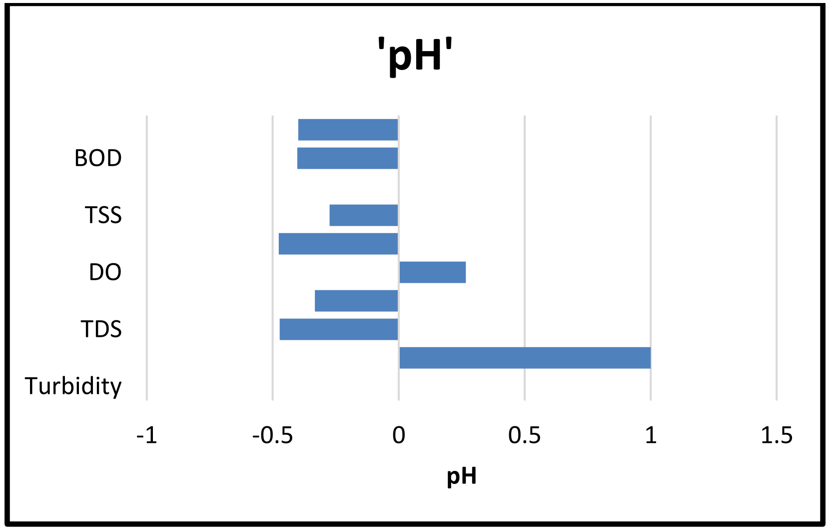



**Figure 15.** Histogram correlation between pH and physical-chemical parameters. Source: Author

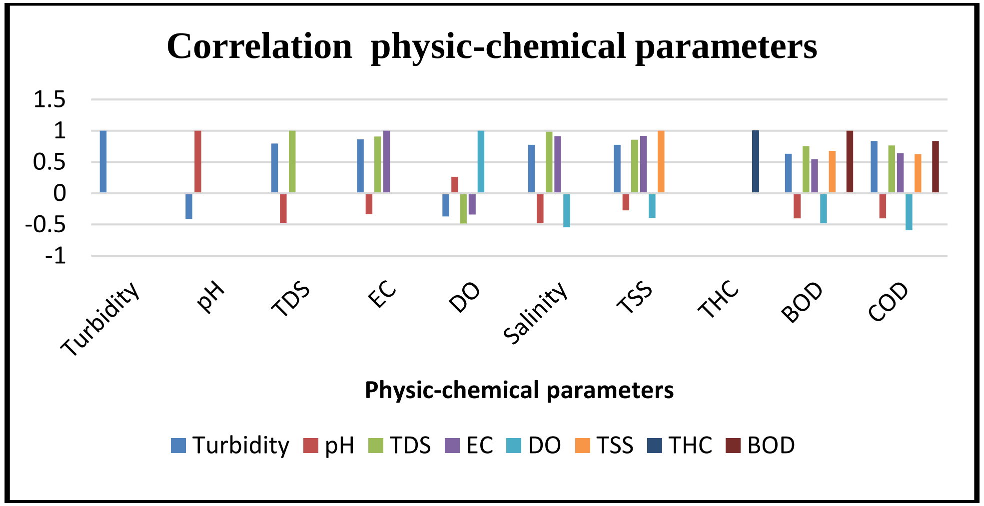



**Figure 16.** Histogram correlation of physical-chemical parameters. Source: Author

**Table 13.** Correlation matrix between heavy metals. Source: Author

| | ***Fe2+ (mg/l)*** | ***Zn2+ (mg/l)*** | ***Pb+ (mg/l)*** | ***Cu2+ (mg/l)*** | ***As3(mg/l)*** | ***Cr3+ (mg/l)*** | ***Ba2+ (mg/l)*** | ***Hg2+ (mg/l)*** |
|---|---|---|---|---|---|---|---|---|
| **Fe2+ (mg/l)** | 1 | | | | | | | |
| **Zn2+ (mg/l)** | 0.3020 | 1 | | | | | | |
| **Pb+ (mg/l)** | -0.6978 | -0.2192 | 1 | | | | | |
| **Cu2+ (mg/l)** | 0.0128 | -0.3387 | 0.3851 | 1 | | | | |
| **As3= (mg/l)** | 0.2190 | 0.3963 | -0.5254 | -0.6349 | 1 | | | |
| **Cr3+ (mg/l)** | 0.5463 | 0.5305 | -0.5357 | -0.4915 | 0.7608 | 1 | | |
| **Ba2+ (mg/l)** | -0.3560 | -0.6382 | 0.4080 | 0.6944 | -0.2578 | -0.5355 | 1 | |
| **Hg2+ (mg/l)** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 1 |

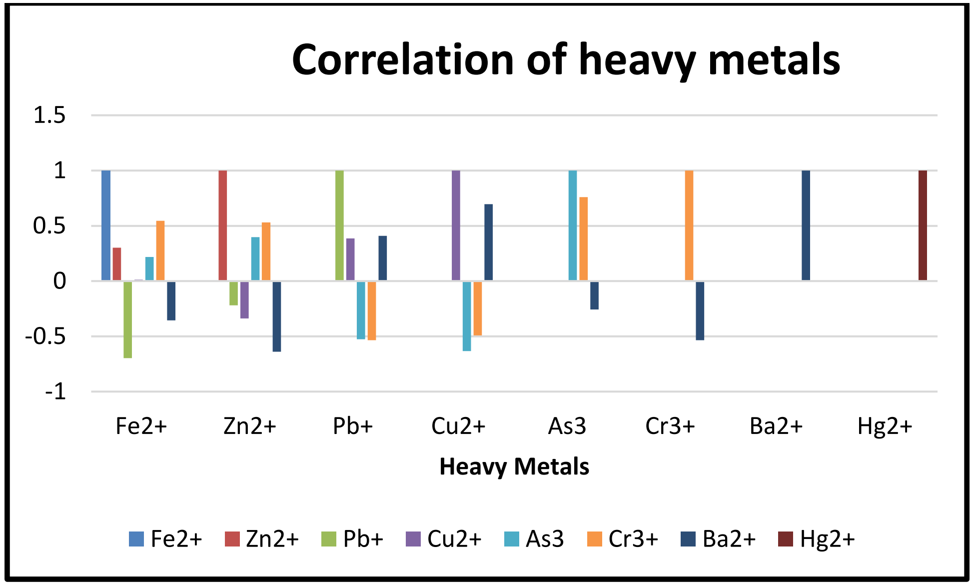



**Figure 17.** Correlation of the heavy metals. Source: Author

Tables 13 and 14 illustrate that EC, TSS, and Cr3+ show statistically high positive correlation at 85% confidence limit with turbidity, THC, BOD, COD, Zn2+, Cu2+, and Hg2+. These correlations indicate that the ions are derived from the same source. The high positive correlation between BOD, COD, Zn2+, Cu2+, and Hg2+ may represent waste lubricant and spent bulk chemicals and the relation between Cr3+ − TSS and COD + Zn2+ may represent contributions from water based mud cuttings (figure 16 and 17).

# CHAPTER V: CONCLUSION AND RECOMMENDATIONS

## 5.1. Conclusions

The aim of the reliability analysis was assessment of the violation of the drilling waste chemical treatment from the standard limit for land disposal. It was assigned as the top event in the fault tree diagram. A systematic approach was applied to investigate the factors influencing the failure of the system. To improve the reliability of the plant, the human factor should be considered as the first priority so the measures such as training, sufficient supervisions, and development of personnel income, along with other actions such as increase the automation level, are the most influential factors.

Based on the results of FMEA it can be seen that the method factor, especially the element of incorrect dosage of chemicals has the highest potential risk of failure because it has a value of RPN 576. Thus, this factor becomes the 1st rank to get attention improvement in order to meet the quality of clean water which is in accordance with the quality standards determined by the Ministry of Health. The improvement factor was defined to show the share of each basic event in the probability occurrence of the top event. The results showed that human factors have the highest impact on failure of the system. ETA results show that the effect of chemical treatment failure in the environment may be prevented with probability of (0.057). The contribution of the operator/inspector has probability of 0.019 of consequences when he works properly. To reduce the probability of the top event the company need to develop and apply a computer model to determine the chemical dosage and do regular monitoring of the data base storage and the system. Furthermore, the operators must be trained for the specific to insure that the all function works properly and all components of the system are in good conditions before the use. To reduce the contribution of events Conjunction failure, contact failure, and half disconnection on the probability of the top event, the company must consider use of a backup data base.

The study reveals that the water of the drilling waste is turbid; with TDS values are higher than 2000 mg/l stipulated by DPR/FMEnv. The results of DO and COD reflect the importance of the content of biodegradable wastes at the drilling waste pit which ranges from 0.37 to 3.95 and 23 to 1700 mg/l, respectively. The high values of BOD indicate the effectiveness of contaminated water-based muds of the waste waters.

The analysis of total iron, zinc, lead, copper, arsenic, chromium, barium, and mercury indicate pollution from drilling wastes such as waste lubricant, spent bulk chemicals, contaminated water- and oilbased muds. The statistical correlation and distributions of the ions shows that EC, TSS and Cr3+, turbidity, THC, BOD, COD, Zn2+, Cu2+, and Hg2+ have positive correlation indicating that the ions are derived from the same source. The physiochemical and heavy metals of waste water qualities of the study area are far from the DPR/FMEnv guidelines values and are qualified to be potential pollutant that can cause environmental hazards in the study area. Further treatment of the DCs and drilling mud using the thermal desorption technique addressed the non-compliant parameters and toxic level of drilling waste. This is confirmed by the results of physicochemical analysis from the TDU operation as they met with the required limits.

### 5.2. Recommendations

The present research was focused to analyze the risk of failure in drilling waste treatment and show by the results it's sustainability to the environment. Taking a base in the topics discussed all along the research, to keep moving in improvements to achieve desirable sustainability and profitability through waste treatment, is recommended to:

- Improve the monitoring of the treatment plant while drilling and application of computer models for analyzing dosage chemicals calculations and the fate of the soil chemicals;
- Have a safety officer specialized regulatory inspection on site to monitor and make sure that all procedure and risk tools are being applied in a right way regarding to the treatment versus disposal.

For future studies is recommended to apply more different tool and explore more this area in Mozambique, because the number of drilling operations in the country is increasing and as all know the oil and gas industry exploration cause several impacts to the environment and consequently to social community. Different areas of science could be studied, such as:

- Medicine: to study different diseases could be cause by the use of water contaminated by the drilling fluids;
- Veterinary and agronomic engineering: to study the impact caused in the soil by the water spreading and cutting reuse with inappropriate treatment.

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# ANNEX

**Annex 1.** Required Management and Monitoring Actions for Hazardous Waste.

| Description | Requirements / specifications | Responsibility | Scheduling | Performance indicator(s) | Relevant Activities |
|---|---|---|---|---|---|
| Compliance with legislation | Comply with the Mozambique Regulations for the management of Hazardous Wastes (Decree 83/2014 of 31 December).<br>The specifications below cover key requirements, but a full listing should be obtained from the regulations themselves. | Workshop Managers | From project initiation and at all times. | Compliance with Decree 83/2014 of 31 December | Camp sites |
| Hazardous waste method statement | Prepare a Method Statement for Management of Hazardous Waste in accordance with Article 11 of Decree 83/2014 of 31 December, including the relevant information required by Annexure II. The plan shall include but not be limited to:<br>• An inventory of all hazardous waste, together with estimated quantities, documented in accordance with the classification system in Annexures III and IX of the regulations.<br>• Measures to comply with waste hierarchy requirements for | Workshop Managers | Before project initiation as a basis for licensing of the activity | Authorisation by MITADER | Camp sites |

| | | | | | |
|---|---|---|---|---|---|
| | minimizing hazardous waste generation and recycling of waste<br>• Measures to safely contain and temporarily store hazardous waste prior to collection.<br>• Measures to label hazardous waste in accordance with Annexure IV of the regulations.<br>• Measures to transport hazardous waste in accordance with Annexures VI and VIII of the regulations.<br>• Details of the licensed disposal site. | | | | |
| **Description** | **Requirements / specifications** | **Responsibility** | **Scheduling** | **Performance indicator(s)** | **Relevant Activities** |

| | | | | | |
|---|---|---|---|---|---|
| Waste generation and recycling | • Develop waste inventories. These inventories must be updated throughout the project.<br>• Stipulate the storage and disposal requirements for each waste stream.<br>• Develop waste management strategies for each waste stream based on the waste management hierarchy.<br>• Prepare waste management procedures for their specific scope of work and expected waste types and volumes.<br>• Manage controlled waste as required by the Mozambican waste management Decree and Proponent's SHE policy.<br>• Demonstrate efforts to reduce waste volumes.<br>• Recycle used oils and greases, where possible, or dispose of them appropriately according to the regulation (Decree 83/2014). | • Process Engineers<br>• Workshop Managers | • Before establishment on site<br>• At all times during the project | • Record of waste reduction and recycling initiatives.<br>• Recycling bins on site | • Construction<br>• Camp sites |

| | | | | | |
|---|---|---|---|---|---|
| Waste storage and handling | • Comply with applicable regulatory requirements and standards regarding the design and operation of all waste storage areas (Decree 83/2014).<br>• Segregate all waste streams at source, where practicable.<br>• Line hazardous waste containers or construct of materials those are compatible with the wastes to be stored. Keep containers in good condition, free from corrosion, leaks or ruptures and sealed to prevent spillage.<br>• Label hazardous waste in accordance | • Contractor<br>• Process Engineers<br>• Stores Managers Workshop Managers,<br>• Hazardous Waste Transportation Contractor | At all times<br>Within 7 days | • Evidence of waste storage containers.<br>• Evidence of inspection waste storage facilities/containers<br>• Manifest of waste removal from site | |
| **Description** | **Requirements / specifications** | **Responsibility** | **Scheduling** | **Performance indicator(s)** | **Relevant CTT Project Activities** |
| | • with the labelling system required by Annexure IV of Decree 83/2014 of 31 December (Appendix C)<br>• Keep Material Safety Data Sheets for stored hazardous waste, where available, at the following locations: the hazardous waste storage area at the Camps the office of the Contractor's site manager the EC/ESO's office | | | | |

| | | | | | |
|---|---|---|---|---|---|
| | • Regard any unidentified wastes as hazardous waste and handle and store such waste.<br>• Locate spill kits at hazardous liquid waste storage areas.<br>• Handle waste chemicals in accordance with the appropriate Material Safety Data Sheet (MSDS).<br>• Keep temporarily stored hazardous waste at the work sites on pallets underlain by a plastic liner. All waste stored in this manner shall be removed to the Base Camp within 7 days.<br>• Ensure that storage at the Camps is a concrete floored, bunded, facility, covered to provide shade and prevent ingress of rain. Bunded areas shall include a trap to collect wash-down water from cleaning of the area. If this water is likely to contain hydrocarbons, then the washdown shall be treated as POC water.<br>• Fully secure the storage area, with lockable gates, to prevent unauthorised access. | | | | |

| Description | Requirements / specifications | Responsibility | Scheduling | Performance indicator(s) | Relevant Activities |
|---|---|---|---|---|---|
| Waste transport and disposal | • Comply with Mozambican waste management regulations regarding waste disposal, as described in Decree 94/2014 of 31 December.<br>• Dispose of hazardous waste at a licensed hazardous waste disposal site.<br>• Stipulate the disposal requirements for each waste stream must be signed by the Site Engineer.<br>• Correlate the waste manifest with the contractor's waste documentation.<br>• Maintain the waste manifest for at least 3 years.<br>• Collect waste sufficiently frequent to ensure that there is no overloading of the temporary storage at the site.<br>• In accordance with the legislation, ensure that waste to be transported off site is removed by a transporter that is certified.<br>• Securely contain all wastes during transport to hazardous waste disposal sites or other means.<br>• Have in place the means to respond appropriately to spillages of waste | • Contractor<br>• ESO<br>• Process Engineers<br>• Stores Managers<br>• Workshop Managers | At all times | • Record of waste manifest signed by ESO<br>• Certificates of safe disposal | • Construction<br>• Camp sites |

| | | | | | |
|---|---|---|---|---|---|
| | anywhere along the transport route within a time limit acceptable to the Proponent.<br>• Provide certificates of safe disposal to the Site Engineer for all wastes disposed at the licensed waste site. | | | | |
| **Description** | **Requirements / specifications** | **Responsibility** | **Scheduling** | **Performance indicator(s)** | **Relevant Activities** |
| Specific requirements – bioremediation of contaminated soils | Treat small quantities of soils contaminated by hydrocarbons (less than 20kg) in-situ using bioremediation. Where large quantities of contaminated soils are involved (greater than 20kg) or if there is the potential to cause pollution to groundwater, surface water or community water facilities, remove to the area allocated by the EC at the Base Camp for longer-term bioremediation (over a surfaced hard standing area).<br><br>Monitoring of surface and ground water in the areas with potentially impacted soils will be necessary, a monitoring programme is recommended for inclusion in the o-EMP. Contractors shall be responsible for the bioremediation of their own contaminated soil until the following standards are met: | • Proponent<br>• Contractor<br>• ESO<br>• Process Engineers<br>• Stores Managers<br>• Workshop Managers<br>• WWTP operators | At all times | | • Construction<br>• Camp sites. |

| | | | | | |
|---|---|---|---|---|---|
| | • There is no hydrocarbon odour.<br>• The soil particles do not coagulate as a result of hydrocarbon contamination.<br>• There is no visual evidence of hydrocarbons in the soil.<br>• Where there is uncertainty the soil shall be sent for analysis.<br>• Where soils are contaminated by other hazardous chemicals they shall be removed and disposed of as per hazardous waste disposal requirements, indicated in the MSDSs. | | | | |
| **Description** | **Requirements / specifications** | **Responsibility** | **Scheduling** | **Performance indicator(s)** | **Relevant Activities** |
| Specific requirements - disposal of unused chemical waste | Chemicals that are no longer used, or are past their shelf-life date, shall be stored in the hazardous waste storage area at the Camps for interim storage until disposal (toxic chemicals are normally sent to incineration). | • Contractor,<br>• ESO<br>• Process Engineers<br>• Stores Managers<br>• Workshop Managers<br>• WWTP operators | At all times | Records of disposal | • Construction<br>• Camp sites. |

| | | | | | |
|---|---|---|---|---|---|
| Specific requirements - cement storage, use and disposal | Cement/aggregate shall be stored and mixed on compacted ground in designated areas. This ground shall be lifted and disposed of in a waste site as cover fill at the end of the construction phase. | • Contractor<br>• ESO<br>• Process Engineers<br>• Stores Managers<br>• Workshop Managers | Cement mixing | As per requirement | Construction |

**Annex 2.** Required Management and Monitoring Actions for Hazardous Waste.

| Description | Requirements / specifications | Responsibility | Scheduling | Performance indicator(s) | Relevant Activities |
|---|---|---|---|---|---|
| Effluent Disposal (oily wastewater) (irrigation) | • Dispose of effluent in line with Mozambican regulations on effluent water disposal requirements and irrigation (amended by Decree 67/2010 of 31 December.) and in line with industry specific WB EHS guidelines for effluent disposal.<br>• Prepare a method statement describing effluent management at Camps that shall include, but not be limited to: | • Workshop Managers<br>• Contractor<br>• ESO<br>• Process Engineers<br>• Stores Managers<br>• Workshop Managers<br>• WWTP operators | Prior to initiation of project activities | Method statement available | • Construction<br>• Camp sites |

| | | | | | |
|---|---|---|---|---|---|
| | - How effluent will be stored prior to treatment.<br>- How the effluent will be treated to meet the standards required under Mozambican legislation: Decree 18/2004 amended by Decree 67/2010 of 31 December, “Regulation on Environmental Quality and Effluents Emission Standards”, and under the EHS guidelines for effluent disposal.<br>- Measures to ensure that there will be no release of polluted runoff from the site.<br>- Measures to prevent erosion at any discharge point.<br>- The duration of the use of the site.<br>• Proponent/Managing Contractor shall approve the Method Statement prior to submission of the effluent management method statement as a part of wastewater licensing requirements. | | | | |
| Brine and Ultrafiltration reject | Evaporation – pond – design and management. HDPE liner. Desludging | • Contractor<br>• ESO<br>• Process Engineers<br>• Stores Managers | Prior to operations and at all times | Approved and implemented method statement. | • Construction<br>• Operation |

| | | | | | |
|---|---|---|---|---|---|
| | | • Workshop Managers<br>• WWTP operators | | | |

**.** Table that summarize different choice for the flexibility Colum.

| K | Importance | F | Flexibility classes |
|---|---|---|---|
| 1 | Desirable | Class F0 | Zero Flexibility - Imperative Level |
| 2 | Necessary | Class F1 | Low Level of Flexibility – Non-Negotiable Level |
| 3 | Important | Class F2 | Good Flexibility – Negotiable Level |
| 4 | Very important | Class F3 | Strong Flexibility – Very Negotiable Level |

**Annex 3.** Physiochemical analysis of drill cuttings at drilling point.

| **Physiochemical analysis of drill cuttings at drilling point.** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Parameter** | **Metals** | | | | | | | |
| **Sampling depht** | **pH** | **Cu (mg/l)** | **Pb (mg/l)** | **Hg (mg/l)** | **Ni (mg/l)** | **Fe (mg/l)** | **V (mg/l)** | **Ba (mg/l)** | **Cr (mg/l)** |
| **100** | 10.6 | 9.4 | 16.1 | <0.01 | 39.3 | 13.4 | 22.4 | 62.9 | <0.5 |
| **200** | 10 | 6.58 | 6.29 | <0.01 | 50.9 | 10.4 | 15.6 | 57.9 | 4.59 |
| **300** | 10.9 | 20.79 | 15.2 | <0.01 | 21.39 | 16.98 | 19.06 | 25.09 | 3.39 |
| **400** | 10.1 | 14.04 | 7.57 | <0.01 | 16.5 | 15.3 | 28.6 | 101.3 | <0.5 |
| **500** | 10.7 | 15.32 | 4.29 | <0.01 | 32.89 | 17.3 | 20.5 | 69.06 | 2.2 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **600** | 12.3 | 10.5 | 5.65 | <0.01 | 43.36 | 16.54 | 13.89 | 89.55 | 5.33 |
| **800** | 9.77 | 15.45 | 5.87 | <0.01 | 38.2 | 13.36 | 16.58 | 20.35 | 2.63 |
| **1000** | 12.1 | 17.89 | 4.32 | <0.01 | 49..26 | 19.81 | 19.5 | 56.51 | 3.38 |
| **1200** | 11.94 | 16.9 | 7.3 | <0.01 | 19.33 | 16.03 | 22.05 | 52.6 | 4.08 |
| **1400** | 9.67 | 18.88 | 9.09 | <0.01 | 35.41 | 17.67 | 16.83 | 57.29 | 2.51 |
| **1600** | 10.5 | 16.03 | 5.29 | <0.01 | 45.56 | 16.31 | 28.3 | 3.07 | 0 |

**Annex 4.** Physiochemical analysis of drilling mud at drilling point.

| **Physiochemical analysis of drilling mud at drilling point.** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Parameter** | **Metals** | | | | | | | |
| **Sampling depht** | pH | Cu (mg/l) | Pb (mg/l) | Hg (mg/l) | Ni (mg/l) | Fe (mg/l) | V (mg/l) | Ba (mg/l) | Cr (mg/l) |
| **100** | 11.2 | 6.8 | 7.22 | <0.01 | 16.8 | 5.57 | 15.9 | 106.4 | <0.5 |
| **200** | 11 | 7.5 | 4.93 | <0.01 | 11.4 | 10.1 | 58.7 | 6.68 | 4.59 |
| **300** | 11.7 | 4.48 | 5.05 | <0.01 | 14.29 | 9.25 | 14.82 | 45.8 | 0.51 |
| **400** | 11.8 | 15.6 | 6.3 | <0.01 | 10.6 | 9.45 | 13.03 | 97.02 | <0.03 |
| **500** | 10.6 | 9.6 | 3.64 | <0.01 | 12.85 | 11.29 | 12.7 | 35.41 | <0.03 |
| **600** | 14.5 | 7.7 | 4.8 | <0.01 | 12.85 | 11.29 | 12.7 | 35.41 | <0.03 |
| **800** | 12.9 | 6.4 | 3.59 | <0.01 | 12.93 | 10.6 | 14.37 | 54.57 | <0.03 |
| **1000** | 9.68 | 8.22 | 4.8 | <0.01 | 16.93 | 15.19 | 12.78 | 50.03 | <0.03 |
| **1200** | 12 | 6.67 | 3.47 | <0.01 | 14.39 | 11.35 | 14.37 | 30.51 | <0.03 |
| **1400** | 12.5 | 13 | 4.32 | <0.01 | 15.01 | 13.2 | 19.11 | 28.35 | <0.03 |
| **1600** | 11.62 | 10.56 | 4.62 | <0.01 | 10.3 | 13.13 | 19.3 | 40.03 | <0.003 |
| **1800** | 10.97 | 9.93 | 3.58 | <0.01 | 16.4 | 10.96 | 17.56 | 39.38 | <0.003 |
| **2000** | 9.35 | 7.84 | 3.14 | <0.01 | 14 | 10.65 | 11.24 | 48.19 | <0.003 |

**Annex 5.** Physiochemical analysis of waste from waste pit.

| Parameters | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Average | DPR/FMENV limit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temp. (°C) | 33.1 | 30.2 | 30.3 | 36 | 36 | 34.3 | 31.9 | 32.8 | 34.7 | 35.7 | 34.7 | 31.2 | 32.98 | 25-35 |
| Odor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Turbidity (NTU) | 1100 | 41 | 1815 | 2076 | 174 | 869 | 399 | 371 | 605 | 605 | 18 | 18 | 630.92 | 15 |
| pH | 6.3 | 6.4 | 6.2 | 5.9 | 6.1 | 7.2 | 6.8 | 9.1 | 6.7 | 6.7 | 7.4 | 6.9 | 6.86 | 6.5-8.5 |
| EC (µS/cm) @ 25°C | 5080 | 1772 | 12,700 | 27,200 | 10.250 | 2610 | 2340 | 5380 | 8160 | 8160 | 907 | 916 | 6585.17 | - |
| TDS (mg/l) | 2930 | 888 | 6380 | 14,610 | 5660 | 1326 | 1183 | 2380 | 3540 | 3540 | 368 | 397 | 3360.42 | 2000 |
| DO (mg/l) | 0.45 | 1.28 | 1.42 | 0.38 | 0.37 | 0.97 | 0.53 | 0.87 | 0.76 | 0.76 | 2.31 | 1.83 | 1.26 | - |
| Salinity mg/l | 2130 | 462 | 3106 | 8875 | 3195 | 1065 | 1065 | 1331 | 2751 | 2751 | 284 | 240 | 2072.33 | 600 |
| TSS (mg/l) | >1.100 | 57 | 889 | 2845 | 192 | 1011 | 471 | 448 | 855 | 855 | 25 | 25 | 640.45 | 30 |
| THC (mg/l) | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 10 |
| BOD (mg/l) | 43 | 15 | 423 | 613 | 520 | 389 | 241 | 108 | 43 | 133 | 12 | - | 230.91 | 10 |
| COD (mg/l) | 1131 | 62 | 1290 | 1700 | 1002 | 921 | 747 | 554 | 98 | 469 | 23 | 86 | 673.58 | 10 |
| Heavy metals | | | | | | | | | | | | | | |
| Fe2+ (mg/l) | 0.52 | 1.24 | 1.2 | 1.72 | 1.37 | 1.2 | 1.4 | 2.73 | 0.39 | 0.26 | 0.26 | 0.44 | 1.17 | 1 |
| Zn2+ (mg/l) | 0.38 | 0.61 | 0.5 | 0.24 | 0.41 | 0.58 | 0.44 | 0.56 | 0.43 | 0.44 | 0.44 | 0.22 | 0.45 | 1 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pb+ (mg/l) | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.04 | 0.66 | 0.58 | 0.58 | 0.38 | 0.14 | 0.05 |
| Cu2+ (mg/l) | 0.73 | 0.009 | 0.009 | 1.33 | 1 | 1.3 | 1.5 | 1.4 | 1.4 | 1.3 | 1.3 | 1.2 | 1.02 | 1.5 |
| As3= (mg/l) | 0.09 | 0.09 | 0.049 | 0.009 | 0.009 | 0.009 | 0.049 | 0.049 | 0.009 | 0.009 | 0.009 | 0.009 | 0.03 | - |
| Cr3+ (mg/l) | 0.004 | 0.009 | 0.009 | 0.0009 | 0.0009 | 0.0009 | 0.009 | 0.009 | 0.0009 | 0.0009 | 0.0009 | 0.000 9 | 0.003 | 0.03 |
| Ba2+ (mg/l) | 2.47 | 1.32 | 0.46 | 2.5 | 1.64 | 1.53 | 2.3 | 1.58 | 2.3 | 2.2 | 2.2 | 2.3 | 1.83 | - |
| Hg2+ (mg/l) | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | - |

**Annex 6.** Results of analysis on sample after TDU operation. SAR: Sodium adsorption ratio; ESP: exchangeable sodium percentage.

| Parameters | DPR max limit | Result |
|---|---|---|
| Moisture content (%) | <50% by Wt or zero-free | 5.327 |
| Ph | 6–9 | 7.9 |
| Electric conductivity (Mmhos/cm) | 8.0 | 6.974 |
| SAR | 12.0 | 4.752 |
| ESP | 15% | 2.09 |
| Oil and grease (mg/l) | 100 | 4.871 |
| Chloride (mg/l) | 5000 | 1527.32 |
| Arsenics (mg/l) | 5 | Below detection limit of 0.001 of AAS |
| Barium (mg/l) | 100 | 38 |
| Cadmium (mg/l) | 1 | 0.305 |

| | | |
|---|---|---|
| Total chromium (mg/l) | 5 | 2.985 |
| Lead (mg/l) | 5 | BDL |
| Mercury (mg/l) | 0.2 | BDL |
| Selenium (mg/l) | 1 | BDL |
| Silver (mg/l) | 5 | BDL |
| Nickel (mg/l) | 1.0 | BDL |
| Zinc (mg/l) | 50 | 43.63 |
| Vanadium (mg/l) | 1 | BDL |