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Theme:

Adapting membrane unit for tap water production: Configuration, Sizing and Optimisation using WAVE Software

Prepared by:
Dirwayi Tariro Gift
Mweene Elijah

Supervised by:
Dr Mohamed El Moundir Hadji
Prof Mohamed Wahib Naceur

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ملخص

وتشكل صناعة إنتاج المياه شاغلا رئيسيا للاستهلاك البشري وتشهد نموا كبيرا. يتم تصنيع أنواع مختلفة من المياه (المياه المعدنية ومياه الينابيع، وما إلى ذلك)، مع تركيبات مختلفة تتكيف مع احتياجات السكان. الهدف الرئيسي من هذا العمل هو تصميم وحدة معالجة المياه وتحسينها من أجل تحقيق مياه تجارية معدنية قليلاً مع TDS ثابت يبلغ حوالي 90 ملغم/لتر من مياه الآبار الملوحة. تقنيات فصل الغشاء مثل الترشيح النانوي والتناضح العكسي هي الأكثر جاذبية للتحكم في التركيب المستهدف وإنتاج الماء بجودة محددة. تم استخدام مجموعة واسعة من أغشية التناضح العكسي والترشيح النانوي مع عتبات قطع مختلفة، متوفرة في سوق الغشاء في هذا المشروع.

لتحقيق هذا المشروع، تم إجراء فحص أغشية التناضح العكسي والترشيح النانوي على أساس تكلفة الأغشية والاسترداد والطاقة المحددة.

أتاح برنامج WAVE تحديد تكوينات نظام متقدم يضمن المياه المنتجة ذات الجودة القياسية، وبالتالي من خلال ضمان الاسترداد الأمثل لما يقرب من 70٪، وعدد محدود من الأغشية، وانخفاض استهلاك الطاقة المحدد مما يجعل الاستثمار قابلاً للتطبيق اقتصاديًا.

الكلمات الرئيسية: المحاكاة، برنامج WAVE، الترشيح النانوي، التناضح العكسي، الماء المقوس.

Abstract

The industry of water production is of main concern for human consumption and is experiencing considerable growth. Different types of water are manufactured (mineral water, spring water, etc.), with different compositions adapted to the population needs. The main objective of this work is to design and optimize water treatment unit in order to achieve slightly mineralized commercial water with a constant TDS of approximately 90 mg/L from brackish well water. The membrane separation technics such as Nanofiltration and Reverse Osmosis are the most attractive for controlling a targeted composition and producing water with defined quality. A wide range of Reverse osmosis and nanofiltration membranes with different cut-off thresholds, available on the membrane market were used in this project.

To achieve this project, reverse osmosis and nanofiltration membranes screening was performed on the basis of the cost of the membranes, recovery and the specific energy.

WAVE software has made it possible to define an advanced system configurations which guarantees produced water of standard quality, thus by ensuring an optimal recovery of approximately 70%, a limited number of membranes, and low specific energy consumption making the investment techno-economically viable.

Keywords: simulation, WAVE software, nanofiltration, reverse osmosis, brackish water.

Résumé

L'industrie de la production d'eau est une préoccupation majeure pour la consommation humaine et connaît une croissance considérable. Différents types d'eau sont fabriqués (eau minérale, eau de source, etc.), avec différentes compositions adaptées aux besoins de la population. L'objectif principal de ce travail est de concevoir et d'optimiser l'unité de traitement de l'eau afin d'obtenir une eau commerciale légèrement minéralisée avec un TDS constant d'environ 90 mg/L à partir d'eau de puits saumâtre. Les techniques de séparation membranaire telles que la Nanofiltration et l'Osmose Inverse sont les plus attractives pour contrôler une composition ciblée et produire une eau de qualité définie. Une large gamme de membranes d'osmose inverse et de nanofiltration avec différents seuils de coupure, disponibles sur le marché des membranes, a été utilisée dans ce projet.

Pour mener à bien ce projet, un criblage de membranes d'osmose inverse et de nanofiltration a été réalisé sur la base du coût des membranes, de la récupération et de l'énergie spécifique.

Le logiciel WAVE a permis de définir des configurations de système avancées qui garantissent une eau produite de qualité standard, assurant ainsi une récupération optimale d'environ 70%, un nombre limité de membranes et une faible consommation d'énergie spécifique rendant l'investissement technico économiquement viable.

Mots clés : simulation, software WAVE, nanofiltration, osmose inverse, eau saumâtre.

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We would like to sincerely thank all our families, friends and colleagues who have contributed directly and indirectly to the development of this project and development of our education.

Thank you very much and God bless and protect you!!!

DEDICATION

I have the honour to dedicate this work to my dear, lovely parents Gift Dirwayi and Phoebe Kurarama who brought me on this beautiful world, they have believed in my capabilities and always been on my side.

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Thank you for being with me

DIRWAYI TARIRO GIFT

DEDICATION

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MWEENE ELIJAH

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List of Abbreviations

BOD: Biochemical Oxygen Demand
DAF: Dissolved Air Floatation
DBP: Disinfection By product
DWTP: Drinking Water Treatment Plant
IX: Ion Exchange
MCLs: Minimum Contaminant Levels
MF: Microfiltration
NF: Nanofiltration
NOC: Natural Organic Matter
NWASCO: National Water Supply and Sanitation Council
NTU: Nephelometric Turbidity Units
OSW: Office of Saline Water
PH: Potential Hydrogen
PPM: Parts Per Million
RO: Reverse Osmosis
SADC: Southern African Development Committee
SAZ: Standard Association of Zimbabwe
SDG: Sustainable Development Goal
SDI: Silt Density Index
TARWR: Total Annual Renewable Water Resources
TDS: Total Dissolved Solids
TOC: Total Organic Carbon
TSS: Total Suspended Solids
UF: Ultrafiltration
UV: Ultraviolet
WAVE: Water Application Value Engine
WHO: World Health Organisation
WTP: Water Treatment Plant
ZABS: Zambia Bureau of Standards
ZEMA: Zambia Environmental Management Agency
ZINWA: Zimbabwe National Water Authority

Introduction

Everyone in this world search the best way to live a heathy life with minimum cost, especially by having good clean drinking water.

Water is a fundamental resource in everyday life of humans as the human body of an adult contains 60% water. As it is often said, water is life because it is vital for life. Water is important in regulating the human body temperature and prevents dehydration, a condition that causes unclear thinking, which tends to cause mood change in humans.

Water does not only play an important role in humans only but also in livestock and crops as it helps plants to photosynthesize. Water is also important in industries and also creating and sustaining the ecosystem, where all life depends on.

Our goal is to protect the public health since water contains dissolved solids which in total are called Total Dissolved Solids(TDS) which indicates whether the water is fit for consumption or not.

High dissolved solids cause water hardness, makes water to have odour, and loses its tasteless character, which turns to affect human health. This means that water needs to be treated in order to remove contaminants, which are harmful to health, and the contaminants, which makes water to taste bad. In treatment of water, there is also removal of aesthetic contaminants, which affects the appearance, taste and odour of water, which can lead to problems that can indirectly result in health concerns.

There are different types of water treatment technologies used around the globe to ensure clean water availability. These technologies include reverse osmosis (RO), nanofiltration (NF), Ultrafiltration (UF), Ion exchange (IX) etc.

Clean water concerns have led us to conduct simulations of different kinds of water treatment using water application value engine (WAVE) software.

The goal of this work is to design water treatment systems that can be used to produce clean tap drinking water of TDS 90ppm from well water with TDS of 1220ppm using the cheapest membrane system.

The work is based on a methodological approach in which there is world overview and water treatment survey in chapter one. This chapter discusses on different technics used in water desalination and being followed by chapter two, which explains the methodology of the WAVE Software.

Finally yet importantly, there will be chapter three, which is based on membrane selection and advanced configurations.

CHAPTER I: World Overview and Water Treatment Survey

I.1. Introduction

Water is essential in everyday life of human beings as it is part of life, there is need for the provision of clean and safe water for drinking which is free from things that are a threat to human health.

There is need of good management of water though it is important to our life, yet it can and does transmit diseases in countries in all continents, from developing to developed.

According to World Health Organisation (WHO), the most predominant waterborne disease, diarrhoea, has an estimated annual incidence of 4.6 billion episodes and causes 2.2 million deaths every year. (Guidelines for Drinking Water Quality, 2010)

From the information above, we can conclude that there is need of provision of clean water for drinking to humans in order to conserve the precious gift of life. To fulfil the objectives of the sustainable development goal (SDG) 6, there is need to develop innovative approaches to solve global water scarcity since recent years traditional financing solutions and technologies have proven to be insufficient in addressing these challenges.

I.2. World State of the Art

Water treatment is the process of removing all those substances, whether biological, chemical, or physical, that are potentially harmful to the water supply for human and domestic use. This treatment helps to produce water that is safe, palatable, clear, colourless, and odourless. Water treatment can eliminate potential or certain harmful substances in the water to prevent the consumption of contaminated water sources that can cause potential health problems. Therefore, it is important to establish a water treatment facility with sufficient capacity to remove pollutants according to standards before being supplied to consumers.

Water treatment did not start today but dated back to the ages as some might think water treatment is a modern idea yet it started sometime back.

I.2.1. The History of Water Treatment

Ancient Greek and Sanskrit writings dating as far back as **2000 BC** recommend methods for water treatment. Even then, people knew that water could be purified with heat, and they practiced sand and gravel filtration, boiling, and straining.

Their primary motivation in doing this was to make water taste better, as they couldn’t yet distinguish between water that’s clean and water that’s foul. They knew to try to reduce the turbidity of the water, but didn’t know much about chemical contamination or microorganisms.

Sir Francis Bacon restarted the advancement of water treatment practices in **1627**, when he began experiments in seawater desalination. He tried to use sand filtration to filter salt out of saltwater. His experiment did not succeed, but he laid the groundwork for other scientists to get involved in the field.

Water softening was invented in **1903** for desalinating water. In the 1980s, researchers developed the first membranes for reverse osmosis systems. Soon after, water treatment plants began regularly running risk assessments of the water.

During World War II, it was felt that desalination technology - ‘desalting’ as it was called then should be developed to convert saline water into usable water, where fresh water supplies were limited. Subsequently, Congress passed “The Saline Water Act”, in 1952 to provide federal support for desalination. The U.S. Department of the Interior, through the Office of Saline Water (OSW) provided funding during the 1950s and 60s for initial development of desalination technology, and for construction of demonstration plants.

Desalination is a relatively new science that has developed largely during the latter half of the 20th century, and continues to undergo technological improvements even at the present time.

It is interesting to note that one of the first seawater desalination demonstration plants t built in the United States was at Freeport, Texas in 1961. (Krishna).

I.2.2. Water Treatment Processes

There are two types of water treatment processes, namely conventional water treatment and unconventional water treatment. Conventional water treatment uses a combination of physical, chemical, and biological processes and operations. Preliminary, main, secondary, and tertiary and/or advanced water treatment are all words that are used to describe various levels of treatment in order to increase the treatment level. The basic unit processes employed in a conventional system include coagulation, flocculation, sedimentation and filtration. Conventional treatment systems are capable of producing a final effluent turbidity of less than 0.1 NTU.

Non-conventional method water treatment is simpler than the conventional method of water treatment.

Non-conventional technologies have lower environmental impacts and reduce contaminant loads at lower costs than conventional treatments. Compared to the conventional method, the non-conventional method uses more advance equipment and technology. The use of technology depends on the quality of the water source. Non-conventional will be used if and only the conventional water treatment is no longer feasible due to factors such as extreme water contamination. (Pakharuddin1, 2021)

(htt)

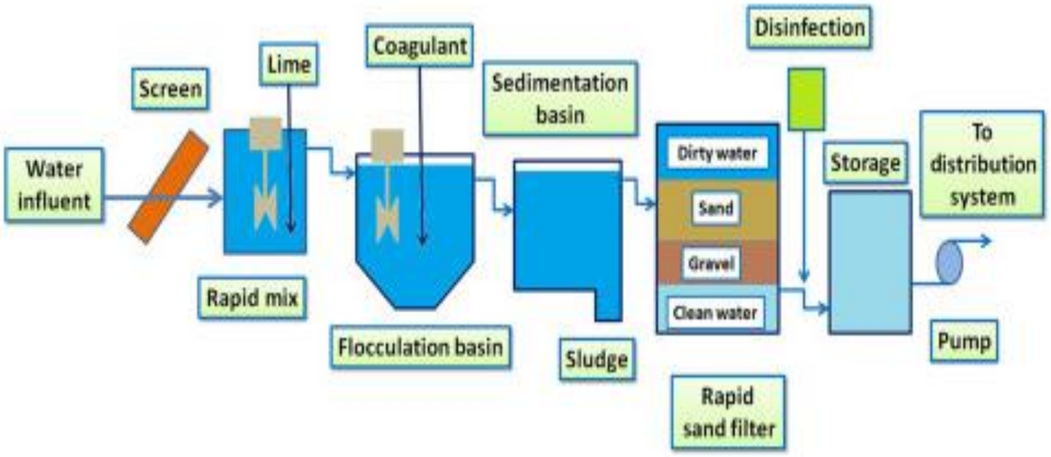


Figure I.1: The typical conventional water treatment
https://sciencedirect.com

Desalination process is done for all different types of water sources:

- Conventional Water
- Non-Conventional Water

I.2.3. Conventional Water Resources and Non-Conventional Water Resources

The conventional water resources include the part of the water cycle that corresponds to run-off, the so-called “useful rain”, that is, surface water, rivers and lakes, and groundwater that could be naturally available.

Non-conventional water resources refer primarily to recycled and desalinated water. Water can be used more than once, provided that, after is it used, it is returned to the environment with a quality that enables other uses afterwards.

I.3. Case Study of Zimbabwe

Zimbabwe is a landlocked country and therefore its major water supplies are lakes, rivers, and aquifers. The two major rivers in Zimbabwe are the Zambezi River in the north, and the Limpopo River in the south. Several other rivers with significant watershed areas that flow through Zimbabwe are the Save, Manyame, and Sanyati Rivers. The biggest lake in Zimbabwe is Lake Kariba , which is on the border with Zambia. There are several large aquifers in Zimbabwe.

In urban centres of Zimbabwe, the majority of the water supply comes from piped water. In rural areas, Zimbabweans predominantly rely on wells and boreholes that tap into Zimbabwe's groundwater supply. Several promising technological innovations have greatly improved the access to and quality of water supply in Zimbabwe. For example, the Zimbabwean Bush Pump has been highlighted as a "fluid" technology that has greatly expanded access to cleaner water throughout the country. The diffusion of this technology can be understood because of its remarkable adaptability. The implementation, operation, and repair of the bush pump is determined by the input and choices of local communities, and as such this technology has no "hard boundaries" since it can adapted, utilized, and personalized by communities throughout Zimbabwe (The Zimbabwean bush pump mechanics of a fluid technology, 2000)

I.3.1. Water Sources in Zimbabwe

Zimbabwe is perched on top of the Central Plateau of Southern Africa and her wetlands are small in size but very diverse and unique in natureThe main wetlands in Zimbabwe include the floodplains, riverine systems, dambos, pans, swamps and artificial impoundments. Due to its geographical location and the physiographic nature of its surface and drainage, Zimbabwe lacks large floodplains, extensive swamps and coastal wetlands. Wetland ecosystems perform functions, provide products and possess attributes that are beneficial to almost all forms of life. They are linked to other systems through the cycles of energy, matter and water.. (Wetlands Ecology and Priorities for Conservation in Zimbabwe)

I.3.1.1. Floodplains and Riparian wetlands

Very small floodplain areas exist in Zimbabwe. These are confined to the MidZambezi Valley (around the Mana Pools region) and around the Save- Runde River confluence in southeastern Zimbabwe (Chiredzi). Notable riverine wetlands of national importance are the Save- Runde system, Manyame, Gwayi- Shangani, Mazowe and Sanyati systems.These riverine wetlands are usually characterised by riparian vegetation such as Acacia albida, Azima tetracantha, Cordyla Africana. The Save-Runde system drains 21 administrative districts with diverse population characteristics and land use.

I.3.1.2. Artificial impoundments

Zimbabwe does not have natural lakes but has over 8,000 impoundments. The major artificial impoundments are the Kariba, Mutirikwi, Chivero, Manyame and Mazvikadei Dams. All the dams except for Kariba were constructed for domestic water and/or irrigation. Although Kariba Dam was constructed for hydroelectric power supply, the lake has assumed other functions of water supply, fisheries and tourism. (Wetlands Ecology and Priorities for Conservation in Zimbabwe).

Lake Kariba is the largest dam in Zimbabwe and is shared with Zambia. The dam covers 536,130 ha, of which 294,930 ha belong to Zimbabwe. The lake has a maximum depth of 119 m and a mean depth of 29.2 m.

I.3.2. Water Treatment Methods in Zimbabwe

The total annual freshwater resources withdrawal in Zimbabwe is estimated at 4.21km3 /yr. or 21.05% of total annual renewable water resources (TARWR) meaning that Zimbabwe is water-stressed in terms of a water intensity use index greater than 20%.

. Conventional sewerage systems are used to collect and convey the sewage to wastewater treatment plants and have inter-connected sewer outfall drains that make it difficult to quantify domestic and industrial effluent separately.

There are 137 wastewater treatment plants in Zimbabwe and of these, 101 are waste stabilization ponds.

However, in terms of volumes of wastewater treated, the largest amount of volume is treated by modified activated sludge systems with biological nutrient removal in Harare and Bulawayo as an attempt to conform to effluent discharge regulations. The second dominant type of wastewater treatment in terms of treatment capacity is the conventional trickling filter system. (T.A Thebe)

Surface water is water from river, rainwater, lake or fresh water wetland, which can be treated using different methods, such as Ultrafiltration Systems, Media Water Filters, and Brackish Water RO.

Ground Water or brackish water is from water located in the pore space of soil and rock "Borehole well", which can be treated using Reverse Osmosis Systems, Media Water Filters, Chemical Dosing, UV Sterilizers.

Government water supply, which could have high level of hardness or high level of chlorine, can be treated with Water Softener Systems, Media Water Filters.

I.3.3. Regulations and Water Standards in Zimbabwe

In Zimbabwe according to section 77 of Zimbabwe's 2013 constitution, every person has the right to safe, clean and potable water.

According to Water Act of 2003 no person shall be entitled to ownership of any water in Zimbabwe and no water shall be stored, abstracted, apportioned, controlled, diverted, used or in any way dealt with except in accordance with this Act

According to section 66 of the Public Health Act, all water works vested in any local authority are maintained by the local authority in a condition for the effective distribution of a supply of pure water for drinking and domestic purposes.

Zimbabwe National Water Authority (ZINWA) was created to manage the national water resources.

ZINWA manages water resources on a catchment basis with involvement of stakeholders in each catchment area. Other responsibilities of ZINWA includes the management of the water permit system, the pricing of water, operating and maintaining existing infrastructure, and executing development projects.

ZINWA carries out and publish hydrological and geographical surveys, including water related research, for the purposes of planning, development, and exploitation of water resources.

The Standards Association of Zimbabwe (SAZ) is the National Standards Body for Zimbabwe. SAZ's mission is to facilitate the development and use of national standards in order to enhance Zimbabwe's competitiveness and safeguard the welfare of communities.

SAZ provides technical services for the testing of manufactured goods and raw materials and calibration of equipment to encourage the use of Zimbabwe Standards by operating Certification / Registration schemes.

SAZ has also the mandate to ensure the right standards of water for drinking, i.e. the required TDS for drinking water to enhance public health. According to SAZS 560:1997 has no specified a limit for TDS but WHO recommended 1000 mg/L. Water containing TDS level below 1000 mg/litre is usually acceptable to consumers. (E & al, 2019)

I.4. Case Study of Zambia

Zambia is a landlocked country in Southern Africa that is home to a variety of water sources, including rivers, lakes, groundwater, and wetlands. These water sources are essential for drinking water, agricultural irrigation, and hydropower generation. However, many of these water sources are often contaminated with pollutants, making them unsafe for consumption. (Standards, 2010)

I.4.1. Water Sources in Zambia

Zambia has extensive surface water resources, with a number of large perennial rivers. The major dammed surface water reservoirs are used primarily for electricity, but also provide water supplies. Much of the population relies on groundwater for domestic water supplies, both directly and via urban municipal water supply schemes, and groundwater is also used for irrigation and livestock watering.

I.4.1.1. Rivers and Wetlands

Zambia is home to many rivers, which are a main source of water. The rivers include Zambezi River, a major river in Africa, flowing through six countries including Zambia, where it is located. The Zambezi River is the fourth-longest river in Africa and the largest river flowing into the Indian Ocean from Africa. There is also Kafue River, one of the longest rivers in Zambia, and it is the largest tributary of the Zambezi River.

Wetlands are an important source of water in Zambia, especially during the dry season when other water sources may be limited. Wetlands are areas where water covers the soil or is near the surface, and they are often characterized by diverse vegetation and wildlife.

I.4.1.2. Groundwater

Zambia also has significant groundwater resources, with estimates suggesting that it holds approximately 70 billion cubic meters of groundwater. Groundwater is an important source of water for domestic, agricultural, and industrial purposes in Zambia, particularly in rural areas where surface water is limited or unreliable.

According to the World Bank, approximately 50% of Zambia's population relies on groundwater for drinking water, and 70% of rural water supply comes from groundwater sources. However, groundwater resources in Zambia face several challenges, including over-abstraction, pollution, and declining water tables.

I.4.2. Water Treatment Methods in Zambia

In Zambia, various water treatment methods are employed to ensure access to safe and clean drinking water. These methods are crucial to desalinate and remove impurities from water and to make the water suitable for consumption. Water treatment methods used in Zambia vary depending on the source and quality of the water. Here are some common water treatment methods used in Zambia:

Coagulation and Flocculation. This is a chemical treatment process where chemicals such as aluminium sulphate or ferric chloride are added to water to create tiny particles called flocs. These flocs bind with suspended particles and sediment in the water, forming larger particles that can be removed through filtration.

Sedimentation. This is the process of allowing the water to sit in a tank or basin so that the heavier particles settle to the bottom of the tank. The settled particles can then be removed using a sludge collector.

Filtration. This process involves passing water through a filter media, such as sand, gravel, or activated carbon. The filter media removes suspended particles and impurities in the water.

Disinfection. This is a process that involves adding chlorine or other disinfectants to the water to kill bacteria, viruses, and other microorganisms.

Reverse Osmosis. This is a process that uses a semi-permeable membrane to remove impurities and contaminants from water. The water is forced through the membrane, leaving behind the contaminants. In Zambia, these methods and techniques are used in combination to treat water from various sources, such as boreholes, rivers, lakes, and dams. The quality of the treated water is monitored regularly to ensure it meets the standards set by the World Health Organization (WHO) and the Zambia Environmental Management Agency (ZEMA). (agency, 2011)

I.4.3. Regulation and Water Standards

In Zambia, the National Water Supply and Sanitation Council (NWASCO), which was established under the Water Supply and Sanitation Act of 1997, oversee the regulation of drinkable water. The primary role of NWASCO is to regulate the provision of water supply and sanitation services in the country, ensuring that the services are of good quality, affordable, and accessible to all. Under the Act, all water supply and sanitation service providers are required to obtain a license from NWASCO in order to operate in Zambia.

The regulations require that all drinking water sources, whether from surface or groundwater, must be treated to meet certain quality standards before being distributed to consumers. These standards are set by the Zambia Bureau of Standards (ZABS), which is responsible for developing and enforcing standards for various products and services, including drinking water. ZABS It is a statutory body established under the Standards Act No. 4 of 2017, and is responsible for the development, promotion, and implementation of standards in Zambia. ZABS is mandated to promote standardization and quality assurance in industry, commerce, and the public sector.

The Zambia Bureau of Standards (ZABS) has set regulations and standards for drinkable water in Zambia. These regulations are aimed at ensuring that the water consumed by the public is safe and of high quality. Some of the key regulations set by ZABS include:

- Maximum Contaminant Levels (MCLs) – These are the maximum allowable levels of various contaminants in drinking water. ZABS has set MCLs for various substances, including bacteria, viruses, nitrates, fluoride, and heavy metals.
- Treatment and disinfection – ZABS requires that all public water supplies be treated and disinfected to remove any contaminants and pathogens that may be present. Water treatment plants are required to meet certain standards in terms of their design, operation, and maintenance

- Monitoring and testing – ZABS requires that water suppliers regularly monitor and test their water supplies to ensure that they meet the required standards. This includes testing for various contaminants and pathogens, as well as ensuring that the water meets certain aesthetic standards, such as colour and taste.
- Chemical quality: The water must not contain harmful levels of chemicals such as pesticides, heavy metals, and other toxic substances.
- Conducting water quality tests: ZABS regularly conducts water quality tests to ensure that the water meets the required quality standards. These tests cover various parameters, including microbiological, physical, and chemical properties

I.5. Water Treatment Technologies

There are different technologies which are used in the treatment of drinking water .There have been some advancement in technology hence the methods for treatment of water are becoming more modern compared to the past years.

Water treatment and water treatment technologies are an essential line of defence to remove contaminants and bacteria before the delivery of clean, potable water supplies for consumption. Water sources can be subject to contamination and therefore require appropriate treatment to remove disease-causing agents. Public drinking water systems use a variety of methods to provide safe drinking water for their communities. Depending on the continent, country and region, different water treatment systems may be in operation depending on regional regulations and raw water input. There are three different processes for treatment of water, which are primary, secondary and tertiary processes.

1. Primary Treatment

The purpose of primary treatment is to settle material by gravity, removing floatable objects, and reducing the pollution to ease secondary treatment. Primary Treatment aims to reduce the Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS) in the wastewater.

The methods include sedimentation

2. Secondary Treatment

Secondary treatment involves the removal of biodegradable organic matter (BOD) and suspended solids (TSS) using biological processes.

3. Tertiary Treatment

Tertiary treatment in wastewater is the third and final advanced treatment process used to disinfect water that has already been treated by primary and secondary processes for removing harmful material in a wastewater plant. This produces high quality, usable water. This treatment removes phosphorous, nitrogen and other nutrients, as well as any organic and other suspended material from the water.

Tertiary methods can be termed desalination technologies. A desalination process essentially separates saline water into two parts - one that has a low concentration of salt (treated water or product water), and the other with a much higher concentration than the original feed water, usually referred to as brine concentrate or simply as ‘concentrate’.

I.5.1. Membrane Treatment

Membranes are used in water treatment to separate contaminants from water based on properties such as size or charge. Common membrane processes include microfiltration, ultrafiltration, nanofiltration, reverse osmosis. Membrane filtration methods include a diverse group of processes, with the most common ones being pressure-driven membranes. During pressure-driven membrane filtration, a pressure difference is imposed on the two sides of a semi-permeable membrane, with the kinds of solutes permeating the membrane, further defining the membrane types.

I.5.1.1. Nanofiltration

Nanofiltration (NF) is a membrane liquid-separation technology sharing many characteristics with reverse osmosis (RO). Unlike RO, which has high rejection of virtually all dissolved solutes, NF provides high rejection of multivalent ions, such as calcium, and low rejection of monovalent ions, such as chloride. Nanofiltration has properties in between ultrafiltration (UF) and reverse osmosis (RO), NF membranes possess pore size typically of 1 nm which corresponds to molecular weight cut-off (MWCO) of 300–500 Da. NF membranes in contact with aqueous solution are also slightly charged due to the dissociation of surface functional groups or adsorption of charge solute. These properties have allowed NF to be used in niche applications in many areas especially for water and wastewater treatment, pharmaceutical and biotechnology, and food engineering. (AW & al, 2015)

Typical applications of nanofiltration membrane systems include:

- The removal of colour and total organic carbon (TOC) from surface water
- The removal of hardness or radium from well water
- The overall reduction of total dissolved solids (TDS).
- The separation of organic from inorganic matter in specialty food* and wastewater applications.

I.5.1.2. Reverse Osmosis

Reverse osmosis is a water purification process that uses a semi-permeable membrane (synthetic lining) to filter out unwanted molecules and large particles such as contaminants and sediments like chlorine, salt, and dirt from drinking water. Osmosis is a natural phenomenon by which water from a low salt concentration passes into a more concentrated solution through a semi-permeable membrane. When pressure is applied to the solution with the higher salt concentration solution, the water will flow in a reverse direction through the semi-permeable membrane, leaving the salt behind. This is known as the Reverse Osmosis process or RO process.

RO membrane technology has developed for both brackish and seawater applications. Brackish water RO membranes typically have higher product water (permeate) flux, lower salt rejection, and require lower operating pressures (due to the lower osmotic pressures of less saline waters), while seawater RO membranes require maximum salt rejection. (Greenlee & al, 2009)

Reverse osmosis is used for:

- Desalination of seawater.
- Desalination of brackish water
- The production of ultrapure water
- Process water production

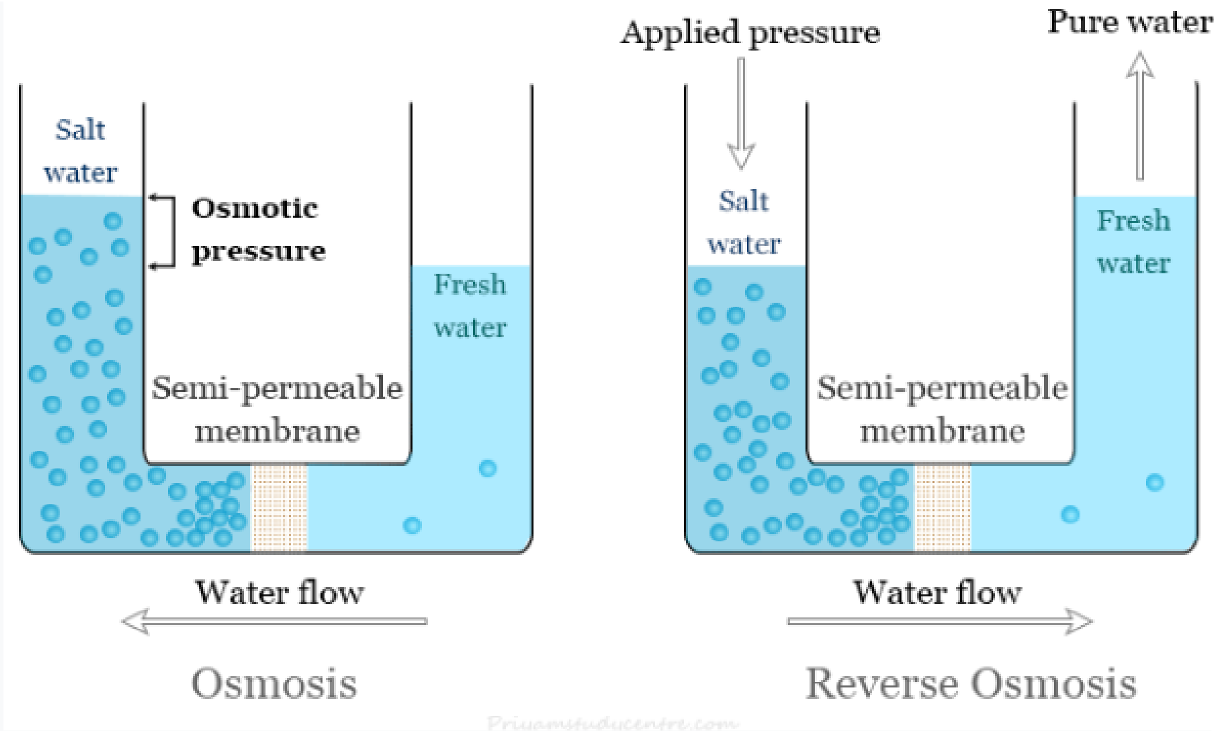


Figure I.2: Principle phenomenon of Osmosis and Reverse Osmosis
https://www.priyamstudycentre.com

I.5.1.3. Types of Reverse Osmosis Membranes

RO membranes for desalination generally come in two types: Spiral wound and Hollow fibre. Spiral wound elements are actually constructed from flat sheet membranes. Membrane materials may be made of cellulose acetate or of other composite polymers. In the spiral wound design, the membrane envelope is wrapped around a central collecting tube. The feed water under pressure flows in a spiral path within the membrane envelope, and pure (desalinated) water is collected in the central tube. As a portion of the water passes through the membrane, the remaining feed water increases in salt content. A portion of the feed water is discharged without passing through the membrane. Without this discharge, the pressurized feed water would continue to increase in salinity content, causing super-saturation of salts.

Another type of membrane is the hollow fibre design, which places a large number of hollow fibre membranes in a pressure vessel. The pressurized saline water is introduced into the vessel along the outside of the hollow fibres. Under pressure, desalinated water passes through the fibre walls, and flows in the hollow fibres for collection. This type of design is not as widely used now as the spiral wound membranes for desalination. (Krishna)

(Alsarayreh & al, 2020)

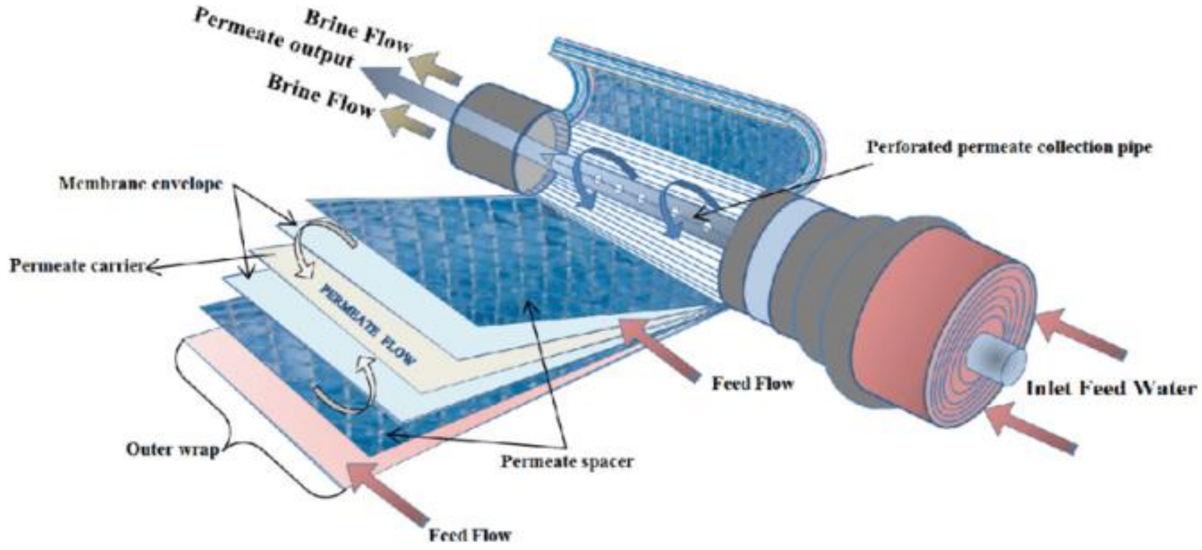


Figure I.3: A cross-sectional view of a pressure vessel with a spiral-wound RO membrane

I.5.1.4. Reverse Osmosis Plant Unit Description

An Industrial RO (Reverse Osmosis) system is a manufacturing plant, which purifies contaminated water through the process of reverse osmosis. The Industrial RO Water plant requires a variety of pre-treatment methods such as softening, dechlorinating as well as antiscalant treatment. After the pre-treatment process, a high level of pressure is used to send water through a semipermeable membrane, which retains all the contaminants from the water and passes pure water through. Depending upon the concentration of salts and contaminants in the water, energy levels are determined.

An RO desalination plant essentially consists of four major systems:

a) Pre-treatment system
b) High-pressure pumps
c) Membrane systems
d) Post-treatment

In the RO Water plant, there are two compartments; one, which contains high concentration water (seawater) and the other compartment, contains low concentration water (pure water). The semi-permeable membrane separates both the compartments.

When we apply a high level of pressure on the high concentration water compartment, the water moves into the low concentration compartment through the semipermeable membrane. The water we collect out is called reverse osmosis water.

An Industrial RO plant contains raw water pump, dosing pump, activated carbon filter, high-pressure pump, RO membrane, sand filter, control panel box etc.

Upon passing through the cartridge filters, the water is pumped with high-pressure pumps into the RO production units for primary treatment. When the feed water travels across the RO membrane elements, it is separated into usable (product) and non-usable (concentrate) water.

The amount of concentrate removed in the RO process is approximately 20% of the feed water entering the system. The concentrate water is not drinkable nor is it suitable for irrigation due to the high dissolved solids concentration. After the RO units separate the water into product and concentrate, the product water flows toward the degasifiers.

Product water coming out of the RO units is of such high purity that it has little or no hardness. Prior to entering the degasifiers, some raw water is blended with the product water to increase alkalinity and hardness to a moderate level. This produces a more stable finished water for corrosion control. At this point, the water is called blend product. Approximately 20% of the total blend product is blend water. The blend product water now enters the degasifiers where a final contaminant needing removal, hydrogen sulphide, is stripped from the water. Hydrogen sulphide produces sulphur or “rotten egg” odour often found in well water. (2012 Annual Consumer Report on the Quality of Tap Water)

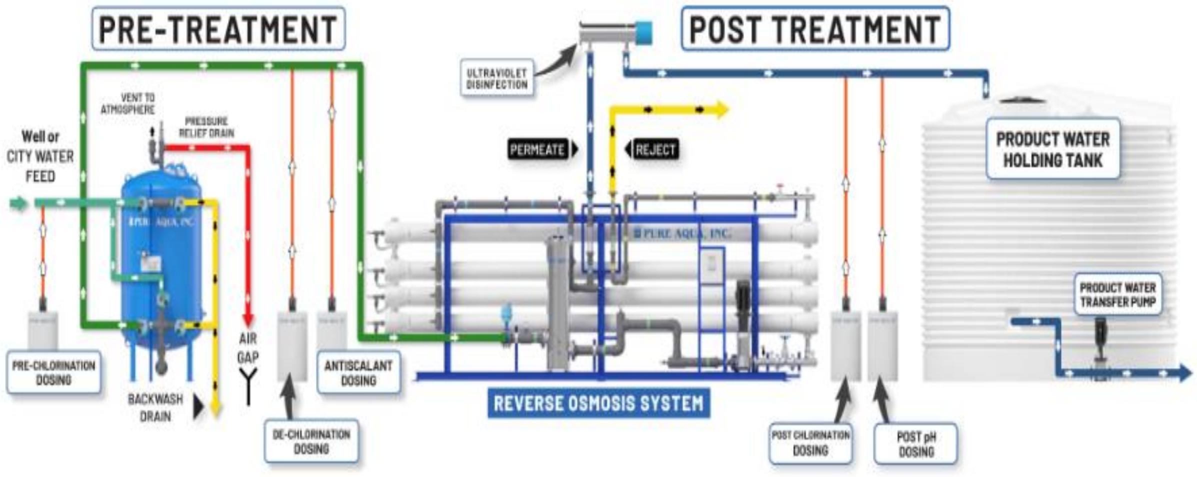


Figure I.4: Industrial Reverse Osmosis System

https://pureaqua.com

I.5.1.5. Difference between Reverse Osmosis and Nanofiltration

Nanofiltration removes bacteria, protozoa and some viruses from the water as well as most natural organic matter and some natural minerals, especially divalent ions that cause hard water. Nanofiltration, however, does not remove dissolved compounds. Reverse osmosis removes turbidity, including microbes and virtually all dissolved substances. However, while reverse osmosis removes many harmful minerals, such as salt and lead, it also removes some healthy minerals, such as calcium and magnesium. This is why water that is treated by reverse osmosis benefits by going through a magnesium and calcium mineral bed. This adds calcium and magnesium to the water, while also increasing the pH and decreasing the corrosive potential of the water. Corrosive water may leach lead and copper from distribution systems and household water pipes.

Between nanofiltration and reverse osmosis, reverse osmosis is the best because it filters out up to 99% of contaminants, which cannot be done by nanofiltration.

Table I.1: Differences between Nanofiltration and Reverse Osmosis

Particular	**Nanofiltration**	**Reverse Osmosis**
Membrane	Finely porous Asymmetric/composite	Non porous Asymmetric/composite
Pore size	1-5nm	-------------------
Transfer Mechanism	Sieving/electrostatic Hydration/diffusive	Diffusive
Law governing Transfer	Fick’s law	Fick’s law
Typical Solution Treatment	Ions, small molecules	Ions, small molecules
Typical pure water flux($Lm^{-2}h$)	20-200	10-100
Pressure requirement(atoms)	7-30	20-100

I.5.2. Pre-treatment for Reverse Osmosis

Reverse Osmosis thin film composite membranes are subject to fouling by many substances so there is need of pre-treatment to avoid membrane fouling. An antiscalant solution should be dosed before the reverse osmosis membranes to disperse calcium carbonate and sulphates precipitates in order to avoid scaling.

Proper pre-treatment plays a critical role in the performance, life expectancy and the overall operating costs of RO system. Pre-treatment is very important in RO because the membrane surfaces must remain clean. Therefore, all suspended solids must be first removed, and the water pre-treated so that salt precipitation or microbial growth does not occur on the membranes. Pre-treatment may involve conventional methods such as a chemical feed followed by coagulation/flocculation/sedimentation, and sand filtration, or pre-treatment may involve membrane processes such as microfiltration (MF) and ultrafiltration (UF).

The primary objective of pre-treatment is to make the feed water to the RO compatible with the membrane. Pre-treatment is required to increase the efficiency and life expectancy of the membrane elements by minimizing fouling, scaling and degradation of the membrane. (Pretreatment for Membrane Processes)

I.5.2.1. Ultrafiltration in Pre-treatment

As with most conventional filtration methods, sand filters and media filtration require consistent raw water quality to deliver quality effluent, which is not always possible. They also do not provide an absolute barrier. Traditional media filters typically remove particles to down to about 5 microns.

Ultrafiltration (UF), however, does not suffer from those limitations. This technology uses an ultrafiltration membrane barrier to exclude particles 0.02 to 0.05 microns, including bacteria, viruses, and colloids, meeting increasingly stringent water-quality standards around the world, and providing a stable, reliable, and consistent water quality.

Ultrafiltration (UF) is theoretically the best pre-treatment before an RO system, removing from the feed water most of the potential elements responsible for membrane fouling such as particles, turbidity, bacteria and large molecular weight organic maters.

The UF acts as a barrier filter, retaining any particles over 0.1 micron. This allows the RO to operate at a higher design flux and therefore higher total flow, to increase production, or to produce the same flow as before but with less energy. With UF pre-treatment, the RO has reduced requirements for membrane cleaning, meaning that chemical usage and wastewater discharges are reduced. Longer membrane life is also a benefit.

The UF pre-treatment also provides filtered water with high and constant quality that enhances the reliability of the RO desalination plant. UF membrane has been shown to be very efficient in removing turbidity and non-soluble and colloidal organics contained in the source seawater. In contrast to MF membrane, UF membrane can also effectively remove viruses and prevent biofouling. (Lau & al, 2014)

UF with a nominal pore size of around 0.02 µm is known to be the most effective in removing potential elements such as silt, algae, bacteria, and large molecular weight of organic matters responsible for RO fouling and consistently producing permeate with turbidity below 0.1 NTU.

Ultrafiltration (UF) is a pressure-driven barrier to suspended solids, bacteria, viruses, endotoxins and other pathogens to produce water with very high purity and low silt density.

I.5.2.2. Microfiltration

Microfiltration (MF) is a filtration process and generally applied for water treatment process. Different suspended solids or colloidal components remove through micro porous membrane with applied pressures range of 0.1–2 bar from an inlet fluid stream. A standard MF membrane is having the pore size range between 0.1 to 10 µm (Khan & al, 2021)

The advantage of MF is that its large pore size enables operation at relatively low transmembrane pressures. MF is used widely in variety of surface water purification processes and membrane bioreactors, and as a pre-treatment method in seawater desalination plants. (Sillanpaa & al, 2023)

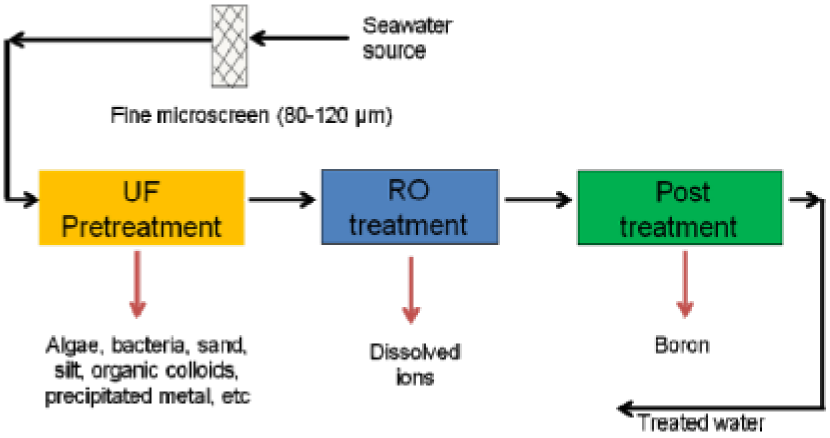


Figure I.5: Typical integrated membrane system for seawater desalination process

I.5.3. Post Treatment

Post-treatment is needed for municipal water treatment before the membrane-treated water is delivered to the distribution system as finished water. The objectives of post-treatment are:

- Correction of water aggressiveness
- Correction of corrosivity
- Final disinfection

1. Aggressiveness and corrosivity of water

Water aggressiveness refers to the ability of water to corrode, i.e., to disintegrate and deteriorate materials that the water is in contact with. Corrosion can be accelerated by low or high pH.

Langelier Index

$$\boxed{LSI = pH - pHs}$$

pH – potential hydrogen

pHs – saturation pH

- If pH <pHs ,LSI<0 then the water is aggressive
- If pH >pHs , LSI>0 then there is water scaling

The objective of correction of water aggressiveness is to eliminate the CO_2 from water by neutralisation of CO_2 by NaOH or $Ca(OH)_2$. (M Alain Maurel, M Jean Christophe Schtrotter, & Prof Michel Rumeau, 2004)

2. Final Disinfection

Normally, post-treatment disinfection is accomplished with chlorine. As in conventional treatment, disinfection is required, but the chlorine demand is reduced greatly by the desalting process, resulting in minimal formation of disinfection by-product.

If the desalting process allows the blending or bypass of water that contains disinfection by product (DBP) precursors, then chloramines, or some additional post-treatment of the blended water (or a reduction in the quantity bypassed or blended) may be required to comply with DBP drinking-water quality standards. Desalinated waters constitute a relatively easy disinfection challenge because of their low TOC and particle content, low microbial loads, and minimal oxidant demand after desalination treatments.

Final disinfection is typically the final step to remove organisms from the treated water before the effluent is released back into the water system. Disinfection prevents the spread of waterborne diseases by reducing microbes and bacterial numbers to a regulated level. (VRABLÍKOVÁ & al, 2014)

I.5.4.Types of Membranes

Membrane configuration’ refers to the geometry of the membrane and its position in space in relation to the flow of the feed fluid and of the permeate. There are four membrane configurations: modules with plane membranes, modules with tubular membranes, modules with spiral membranes, and modules of hollow fibre.

I.5.4.1. Modules with plane membranes

This configuration is no longer in use due to its high price. It typically provides 50–100 m^2/m^3 and pressure drops of 3–6 kg/cm^2. A preliminary filtration is required to remove suspended solids, and the membrane must be supported. The regeneration requires high-pressure water or the use of chemicals. The product purity is high.

I.5.4.2. Modules with tubular membranes

Tubular membrane modules are tube-like structures with porous walls. Tubular modules work through tangential crossflow and are generally used to process difficult feed streams such as those with high dissolved solids, high-suspended solids, and/or oil, grease, or fats. These membranes are allocated inside porous tubes that provide support. Tubular modules consist of a minimum of two tubes: the inner tube, called the membrane tube, and the outer tube, which is the shell. These modules can be regenerated chemically, mechanically, or using pressurised water. The cost is also typically high.

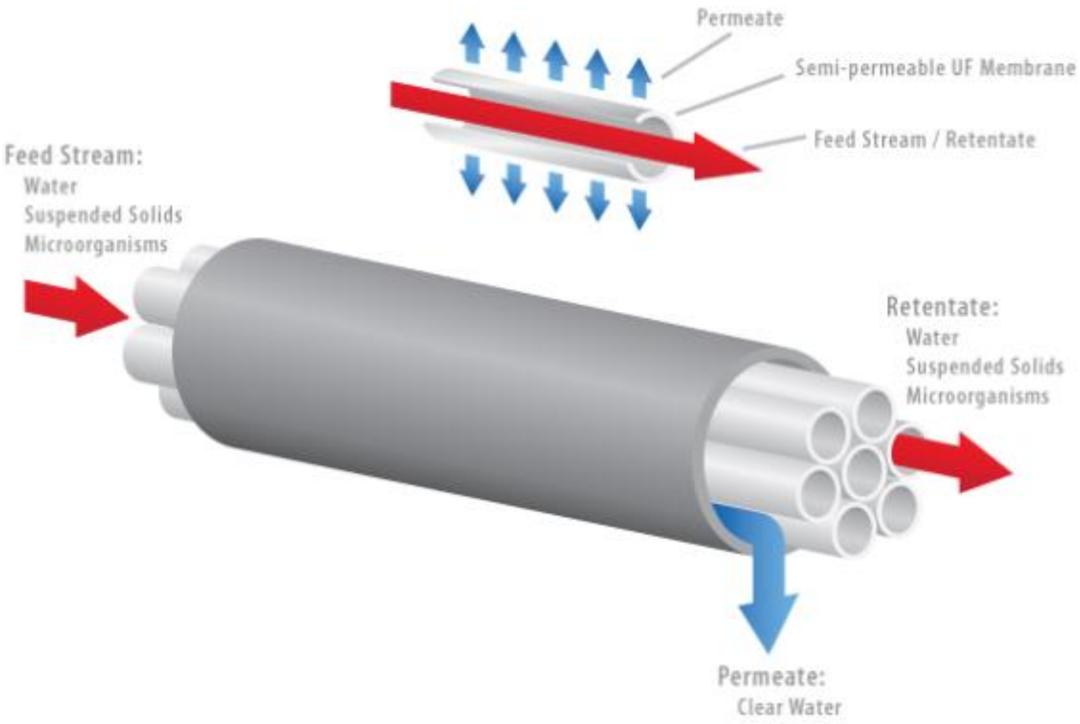


Figure I.6: Model Configuration-Tubular Module
https://synderfiltration.com

I.5.4.3. Modules with spiral membranes

These modules are built by surrounding a permeable tube with the membranes separated by porous material. They allow good purification, and different structures and materials are employed such as spiral polyamide and spiral cellulose acetate and triacetate. The modules can be standard or for high rejection. The surface area provided is 600–800 m^2/m^3 for a pressure drop of 3–6 kg/cm^2. They require preliminary filtration to remove particles from 10 to 20 μm. Membrane cleaning can be carried out with pressurized water or using chemicals. The cost is lower than the modules with tubular membranes.

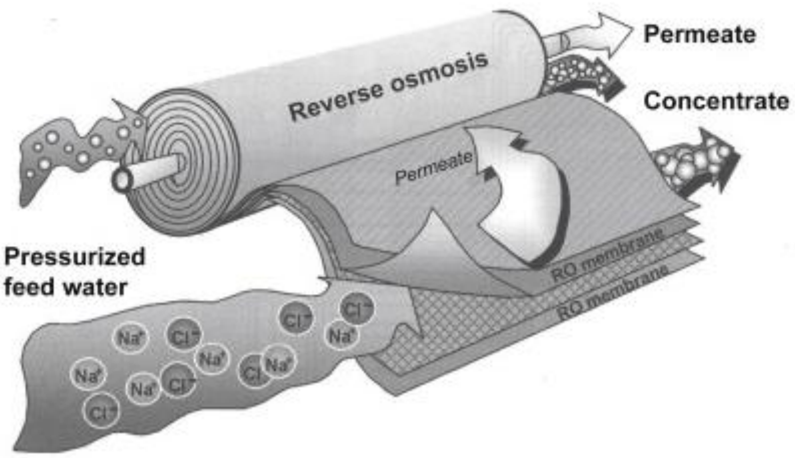


Figure I.7: Module with spiral
https://www.aquanext-inc.com

I.5.4.4. Modules of hollow fibre

The surface area they provide is large, 6000–8000 m2/m3, with a low-pressure drop of 0.2–0.5 kg/cm2. These modules require preliminary filtration to remove particles from 5 to 10 µm. They can be cleaned chemically or with pressurized water. The cost is low and they do not need support for the membrane. (Water, 2016)

I.5.5. Membrane Fouling

Membrane fouling refers to the adsorption and deposition of constituents on a membrane surface or in the membrane pores. Consequently, fouling leads to a reduction in membrane permeability. Fouling in general is divided into two subgroups:

- Reversible fouling, usually formed on the membrane surface. It can be removed by physical cleaning.
- Irreversible fouling, which designates internal fouling in the membrane pores and can be removed only by chemical cleaning.

I.5.5.1. Types of Membrane Fouling

1. **Particulate fouling**

Small particles can accumulate on the membrane surface, consequently forming a filter cake. This type of fouling is common in MBRs using MF and UF.

2. Organic fouling

This involves the adsorption of dissolved organics on membrane surface resulting in membrane fouling. Natural organic matters (NOMs), e.g. humic substances, in drinking water filtration processes have a significant role. In membrane processes for wastewater treatment, organics remaining after biodegradation also can contribute to fouling.

3. Biofouling

This refers to the adhesion and growth of microorganisms on the membrane surface. It results in a loss of membrane performance. Membrane processes other than MF and UF commonly used in MBRs and post treatment after conventional ASP, NF, and RO may have more biofouling.

4. Scaling

This occurs when dissolved salts exceed their solubility product. This phenomenon is of main concern in the operation of NF and RO with regard to the deposition of salts such as $CaCO_4$, $CaSO_4$, $BaSO_4$, $SrSO_4$, $MgCO_3$, and SiO_2. (Sadr & al, 2015)

I.5.6. Cleaning of Membranes

Membrane cleaning is based on the foulants removal from the membrane surface, and there are numerous membrane cleaning strategies. Membrane cleaning is especially used when there is an increase in the transmembrane pressure or when a decrease in permeate flux is observed. A good pre-treatment system is essential to achieve a long reverse osmosis membrane life. During a chemical cleaning process, membranes are soaked with a solution of chlorine bleach, hydrochloric acid or hydrogen peroxide. First, the solution soaks into the membranes for a number of minutes and after that a forward flush or backward flush is applied, causing the contaminants to be rinsed out.

There are different membrane cleaning methods such as forward flush, backward flush and air flush. (Hanife Sari Erkan, 2018).

Repeated cleaning gradually degrades reverse osmosis membranes, generally, this is done once or twice a year, but more often if the feed is a problem water. (Baker, 2004)

1. Backward Flush

Is a reversed filtration process. Permeate is flushed through the feed waterside of the system under pressure, applying twice the flux that is used during filtration. When backward flush is applied, the pores of the membrane are flushed inside out. The pressure on the permeate side of the membrane is higher than the pressure within the membranes, causing the pores to be cleaned. A backward flush is executed under a pressure that is about 2.5 times greater than the production pressure.

A consequence of backward flush is a decrease in recovery of the process. Because of this a backward flush must take up the smallest possible amount of time, however the flush must be maintained long enough to fully flush the volume of a module at least once.

2. Forward Flush

When forward flush is applied in a membrane, the barrier that is responsible for dead-end management is opened. At the same time the membrane is temporarily performing cross-flow filtration, without the production of permeate. The purpose of forward flush is the removal of a constructed layer of contaminants on the membrane through the creation of turbulence.

3. Air Flush or Air/Air Water Flush

Using air flush means flushing the inside of membranes with an air/water mixture.

During an air flush, air is added to the forward flush causing air bubbles to form, which cause a high turbulence. Because of this turbulence, fouling is removed from the membrane surface. The benefit of air flush over forward flush is that, it uses a smaller pumping capacity during cleaning,

I.5.6.1. Membrane Cleaning Procedure

Generally, low pH solutions are used to clean metallic scales while alkaline solutions are used to clean biological and organic fouling. Relatively high flow with low pressure is recommended. System cleaning follows the following basic steps:

- Preparation of the cleaning solution and adjustment of temperature and pH.
- Displacement of the solution in RO modules by pumping the cleaning solution.
- Recycling and soaking of the element. Soaking time may vary from few hours to overnight depending on the fouling level.
- Flushing the unit with RO permeate water (El-Dessouky & al, 2002)

I.5.7. Calculations of Installation

The calculations include all the input data necessary in order to effectuate water treatment using the WAVE Software, in order to get the desired results.

I.5.7.1. Calculation 1: Water quality to be delivered and detailed inlet water analysis with temperature range

These include:

- Simple pass or double pass
- Approximate pass conversion rate
- Type of module(seawater, brackish water, nano)

Example

Feed water:

- TDS 2035ppm
- Temperature:15-20 ˚C

Permeate quality required: TDS<70ppm

- Simple pass
- Two or three stages(Y: 75-85%)
- BW30LE440 of DOW or ESPA2 of hydranautics

I.5.7.2. Net flow to be produced

- Total number of elements required
- Total number of pressure tubes required

Examples

Calculation of number of elements required

$$\text{Total number of elements} = \frac{\text{Permeate flow}}{\text{Sizing flow} \times \text{Active membrane surface}}$$

For example

Well water SDI <3

Net permeate flow required = $60m^3/h$

Selected element: BW30-LE440 ($40.9m^2$) or ESPA2 ($37.2m^2$)

Sizing flow= $20.5l/hm^2$

Number of elements required =72(BW30-LE440) or 78(ESPA2)

Example for calculation of the pressure tubes required

Total number of pressure tubes required

$$=\frac{Total\ number\ of\ elements}{Number\ of\ elements\ that\ can\ be\ intergrated\ in\ one\ pressure\ tube}$$

Number of elements required: 72(BW30-LE440) or 78(ESPA2)

Number of elements per tube: 6

Number of pressure tubes: 12 or 13

I.5.8. Membrane Classification

Membranes are classified by membrane structure. The membranes include isotropic membranes, anisotropic membranes, ceramic and metal membranes, and liquid membranes.

I.5.8.1. Isotropic Membranes

Isotropic membranes have a uniform composition and structure throughout; such membranes can be porous or dense.

Dense nonporous isotropic membranes are rarely used in membrane separation processes because the transmembrane flux through these relatively thick membranes is too low for practical separation processes.

Isotropic microporous membranes have much higher fluxes than isotropic dense membranes and are widely used as microfiltration membranes. Further significant uses are as inert spacers in battery and fuel cell applications and as the rate-controlling element in controlled drug delivery devices. (Baker, 2004)

I.5.8.2. Anisotropic Membranes

Anisotropic membranes are layered structures in which the porosity, pore size, or even membrane composition change from the top to the bottom surface of the membrane. Usually anisotropic membranes have a thin, selective layer supported on a much thicker, highly permeable microporous substrate. Because the selective layer is very thin, membrane fluxes are high. The microporous substrate provides the strength required for handling the membrane.

I.5.8.3. Metal Membranes and Ceramic Membranes

Ceramic and metal membranes can be either isotropic or anisotropic.

Ceramic membranes have the advantages of being chemically inert and stable at high temperatures, conditions under which polymer membranes fail. This stability makes ceramic microfiltration/ultrafiltration membranes particularly suitable for food, biotechnology and pharmaceutical applications.

I.5.8.4. Liquid Membranes

The selective barrier in these membranes is a liquid phase, usually containing a dissolved carrier that selectively reacts with a specific permeant to enhance its transport rate through the membrane. Liquid membranes are used almost exclusively in carrier facilitated transport processes. (Baker, 2004)

I.6. The Economic Aspect

The cost of water varies significantly from country to country. Factors such as availability, population density and economic conditions can influence the price of water. Some countries use a metre system to estimate the cost of water used by households, industries etc. In most cases, the responsible municipality of a city or town is in charge of putting up the metres and the cost of the water.

In the last decade there was a significant decrease of capital and operating cost .This decrease of water cost is even more remarkable if one considers, that on the average, the permeate water quality requirements are more stringent now than they were five years ago. The drivers behind these economical improvements are competition and improvement of process and membrane technology.

The water cost is composed of capital cost, power consumption, maintenance and parts, membrane replacement, consumables and labour.

The system cost is calculated through cost contribution of major system components: site preparation and building, intake and outfall, pre-treatment, RO trains, RO membrane elements, piping, high-pressure pumps and power recovery turbines, electrical, permeate post-treatment and storage, membrane cleaning system, instrumentation and control system. (Wilf)

Table I.2: Summary of estimation of product water cost components for a large capacity

Product water cost component	\$/m^3
Capital cost, including land fee (25 years @ 6.0% interest)	0.203 – 0.338
Electric power (\$0.060/kWhr)	0.180 – 0.240
RO membrane replacement (5 years membrane life)	0.025 – 0.035
MF membrane replacement (7 years membrane life)	0.000 – 0.030
Chemicals	0.020 – 0.025
Maintenance and spare parts	0.023 – 0.038
Labour	0.030
Total cost	0.481 – 0.706

I.6.1. Potential for future cost reduction

The future reduction of desalted water cost can be achieved by reduction of capital cost and optimization of the process parameters. The most likely future development that can result in cost reduction will be introduction of large size membrane element. Current evaluation by consortium of membrane manufacturers indicated possibility of up to 10% reduction of capital cost of seawater systems if element diameter will be increased to 16”. It is difficult to envision other significant development, beside large diameter element, than would affect equipment cost, especially in seawater applications.

. On the operating cost side the most promising directions is optimization of process parameters through more advanced automation. The cost contribution parameters that potentially could be optimized by more advanced automations are electric power, RO membrane replacement, MF membrane replacement, chemicals usage and possibly maintenance (frequency of membrane cleaning). It is expected that in the future “smart” automation system will control plant operation to optimize process parameters to produce water at the lowest cost according to water demand, conditions of the plant equipment, condition and availability of feed water and local economic parameters. (Wilf)

CHAPTER II: METHODOLOGY

II.1. Introduction

The work consists in carrying out a series of systematic simulations of well water treatment by the reverse osmosis and Nano-filtration technics, in the goal of achieving pure quality water. The simulation was carried out with the software specialized in water treatment “WAVE: Water Application Value Engine” from the DUPONT Water Solutions industry. The first step is to select (screening) the most effective Reverse osmosis and Nano filtration membranes in terms of recovery, feed pressure, affordable price and energy efficiency (specific energy). After the membrane screening step, the second step consists in determine the optimal configurations of a reverse osmosis and Nano filtration water treatment system. The aim is to compare the reverse osmosis and Nano filtration membranes and determine the best membrane which can produce the water quality that is close or same as our target water at the lowest price possible.

II.2. Presentation of the WAVE 1.82 software

WAVE software is a software launched by DUPONT Water Solutions, it is a multi-technology design software that allows the design of water treatment systems while optimizing the performance and increasing the productivity of the system. WAVE makes it possible to estimate the performance of ultrafiltration (UF), reverse osmosis (RO) and ion exchange (IX) technologies in water treatment systems, either individually or combined. Similarly, the WAVE software makes it possible to carry out a technical and economic study and an estimate of the cost of treated water (OPEX). Using a common interface, it simplifies the design process and ultimately helps reduce the time needed to manage your water-treatment system. Moreover, it provides information on actual mass balance volumes and fluxes that reflect changes in density due to temperature, compressibility and water composition. (company, 2021)

WAVE is an integrated expert modeling software for water-treatment plant design, including wastewater-treatment plant design, offering:

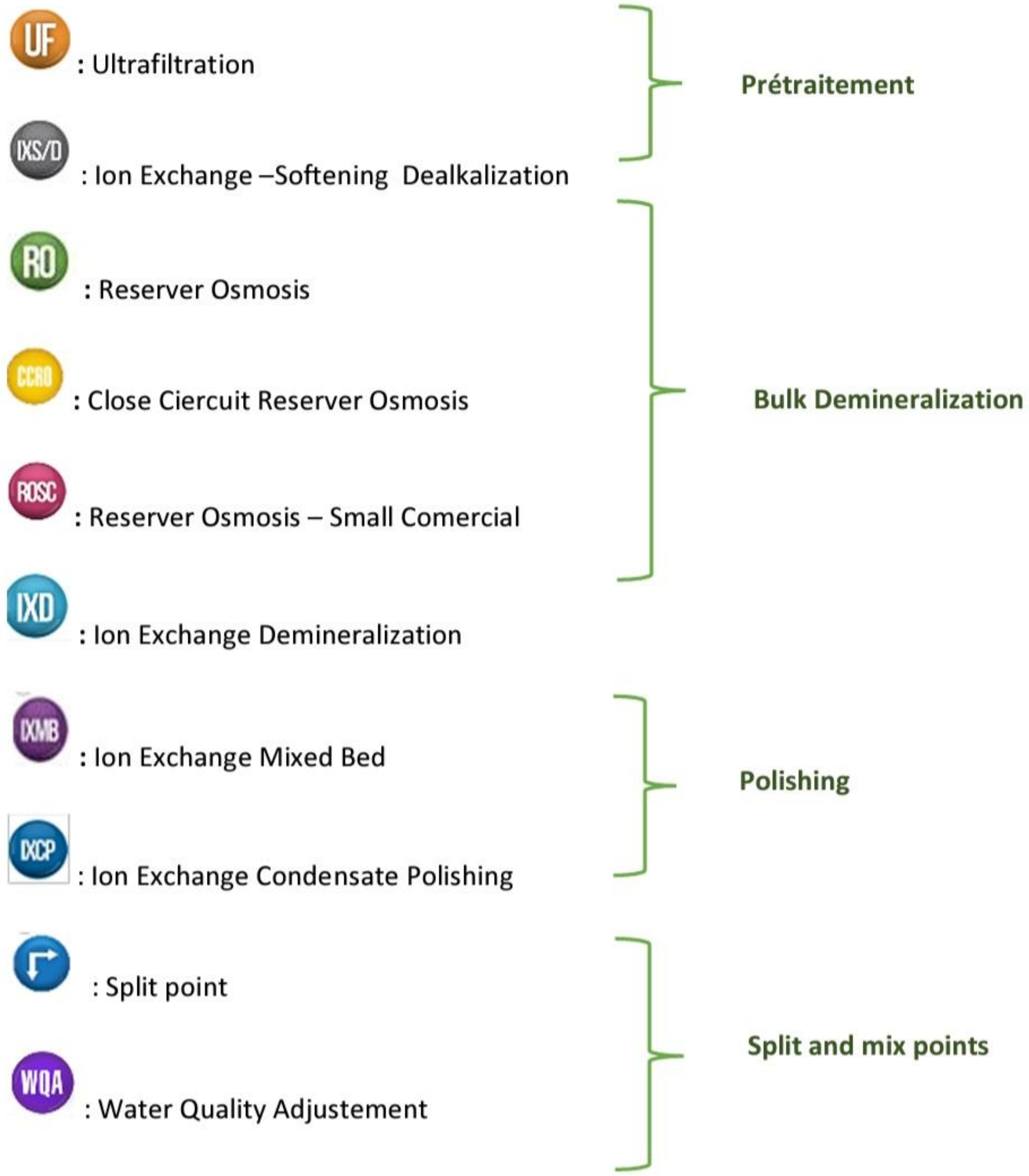
- Flexible design using three technologies, with multiple-unit operation combinations, plus the option to specify system-feed or net-product flow rate.
- A powerful calculation engine with the capacity to run complex designs at high levels of accuracy.
- Improved water-equilibrium calculations and interface.

- True mass-balance volumes and flows that reflect changes in density due to temperature, water composition, and water compressibility.
- Consistent hydraulic constraints and regeneration parameters, which reflect best practices and state-of-the-art product performance and application.
- Default values for most parameters, allowing you (or your designer) to create a design quickly.
- The capability to introduce project-specific parameters to increase the accuracy of operating-expense calculations.

Among the advantages of this software:

- Use of three main technologies in combination as well as related technologies.
- Use of improved and efficient algorithms.
- Simple interface and quick handling of processing processes.
- Presence of database for all products and processes.

II.2.1. Water treatment technologies on the WAVE software



II.2.2. The design equations of an RO system on WAVE software

The performance of a specified RO system is defined by its feed pressure (or permeate flow rate, if feed pressure is not specified) and salt passage. In its simplest terms, the permeate flux Q through an RO membrane is directly proportional to the wetted area S multiplied by the net driving pressure (ΔP – Δπ). The proportionality constant is the membrane permeability coefficient, known as the A-value. The familiar equation for water permeation has the form:

$$Q = (A)(S)(\Delta P - \Delta\pi) \qquad \text{Equation 1}$$

The passage of salt is by diffusion, so the flux of salt N_A is proportional to the difference in salt concentration between the two sides of the membrane. The proportionality constant is the salt diffusion coefficient, known as the B value.

$$N_A = B\,(C_{FC} - C_P) \qquad \text{Equation 2}$$

Where:

C_{FC}: average feed concentrate concentration

C_{P}: permeate concentration

Table II.1. Design equations for projecting reverse osmosis system performance: performance of individual elements

Object	Equation	Equation Number
Permeate flow	$Q_i = A_i \overline{\pi}_i S_E (TCF)(FF)\left(P_{fi} - \frac{\Delta P_{fci}}{2} - P_{pi} - \overline{\pi} + \pi_{pi}\right)$	3
Mean side osmotic pressure Concentrate	$\overline{\pi} = \pi_i \left(\frac{\overline{C_{fc}}}{C_f}\right)\overline{pf}$	4
Average osmotic pressure on the permeate side	$\overline{\pi} = \pi_i (1 - R_i)$	5
Ratio: arithmetic mean side concentrate to feed the concentration for element i	$\frac{C_{fc\,i}}{C_{f\,i}} = \frac{1}{2}\left(1 + \frac{C_{ci}}{C_{fi}}\right)$	6
Ratio: concentrate to feed the concentration for element i	$\frac{C_{c\,i}}{C_{fi}} = \frac{1\text{-}Y_i(1\text{-}R_i)}{(1\text{-}Y_i)}$	7
Osmotic pressure of water Feeding	$\pi_f = 1.12(273 + T)\sum m_i$	8

Temperature correction factor for RO and NF membrane	$TCF = EXP\left[2640\left(\frac{1}{298}-\frac{1}{273+T}\right)\right]; T \geq 25°C$ $TCF = EXP\left[3020\left(\frac{1}{298}-\frac{1}{273+T}\right)\right]; T \leq 25°C$	9 10
Concentration polarization factor for 8 inch elements	$pf_i = EXP\left[0.7Y_i\right]$	11
System recovery	$Y = 1-\left[(1-Y_1)(1-Y_2)\ldots(1-Y_n)\right] = 1-\prod_{i-1}^{n}(1-Y_i)$	12
Permeate concentration	$C_{pj} = B\left(C_{fc\,j}\right)\left(pf_i\right)\left(TCF\right)\frac{S_E}{Q_i}$	13

Table II.2: Design equations to project system performance RO: average system performance

Object	Equation	Equation Number
Total permeate flow	$Q = N_E S_E \bar{A}\bar{\pi}(TCF)(FF)\left[P_f - \frac{\overline{\Delta P_{fc}}}{2} P_p - \pi_f\right]\left[\frac{\overline{C_{fc}}}{C_f} p_f - \left(\bar{1}-\bar{R}\right)\right]$	14
Ratio: average concentration between side concentrate and charge for the system	$\frac{C_{fc}}{C_f} = \frac{-\bar{R}\ln\left(1-Y/Y_L\right)}{Y-(1-Y_L)\ln\left(1-Y/Y_L\right)}+\left(1-\bar{R}\right)$	15
System Recovery Limitation	$Y_L = 1-\frac{\pi_f\left(\overline{pf}\right)\left(\bar{R}\right)}{pf-\overline{\Delta P_{fc}}-P_p}$	16

Approximate log-mean concentration ratio concentrate side on feed for the system	$\frac{C_{fc}}{C_f}=-\frac{\ln(1-Y)}{Y}$	17
Average element recovery	$Y_i=1-(1-Y)^{1/n}$	18
Average polarization factor	$\overline{pf}=EXP\left[0.7\overline{Y_i}\right]$	19
Average concentrate-side osmotic pressure for the system	$\bar{\pi}=\pi_i\left(\frac{\overline{C_{fc}}}{C_f}\right)\overline{pf}$	20
Average concentrate-side system pressure drop for 8-inch elements; 2 steps	$\overline{\Delta P}_{fc}=0.04\bar{q}_{fc}^{\ 2}$ $\Delta P_{fc}=\left[\frac{0.1\left(Q/1440\right)}{YN_{V2}}\right]\left(\frac{1}{N_{VR}}+1-Y\right)$ $\Delta P_{fc}=0.01n\bar{q}_{fc}^{\ 1.7}$	21 22 23
Individual 8 inch element or single stage concentrate side pressure drop	$\bar{A}(\pi)=0.125;\pi\leq 25$ $\bar{A}(\bar{\pi})=0.125-0.011\left(\frac{\bar{\pi}-25}{35}\right);25\leq\bar{\pi}\leq 200$ $\bar{A}(\bar{\pi})=0.070-0.0001(\bar{\pi}-200);200\leq\bar{\pi}\leq 400$	24 25 26
Permeability of the membrane as a function of the average osmotic pressure on the concentrate side	$C_p=BC_{fc}\overline{pf}(TCF)\left(\frac{N_ES_E}{Q}\right)$	27

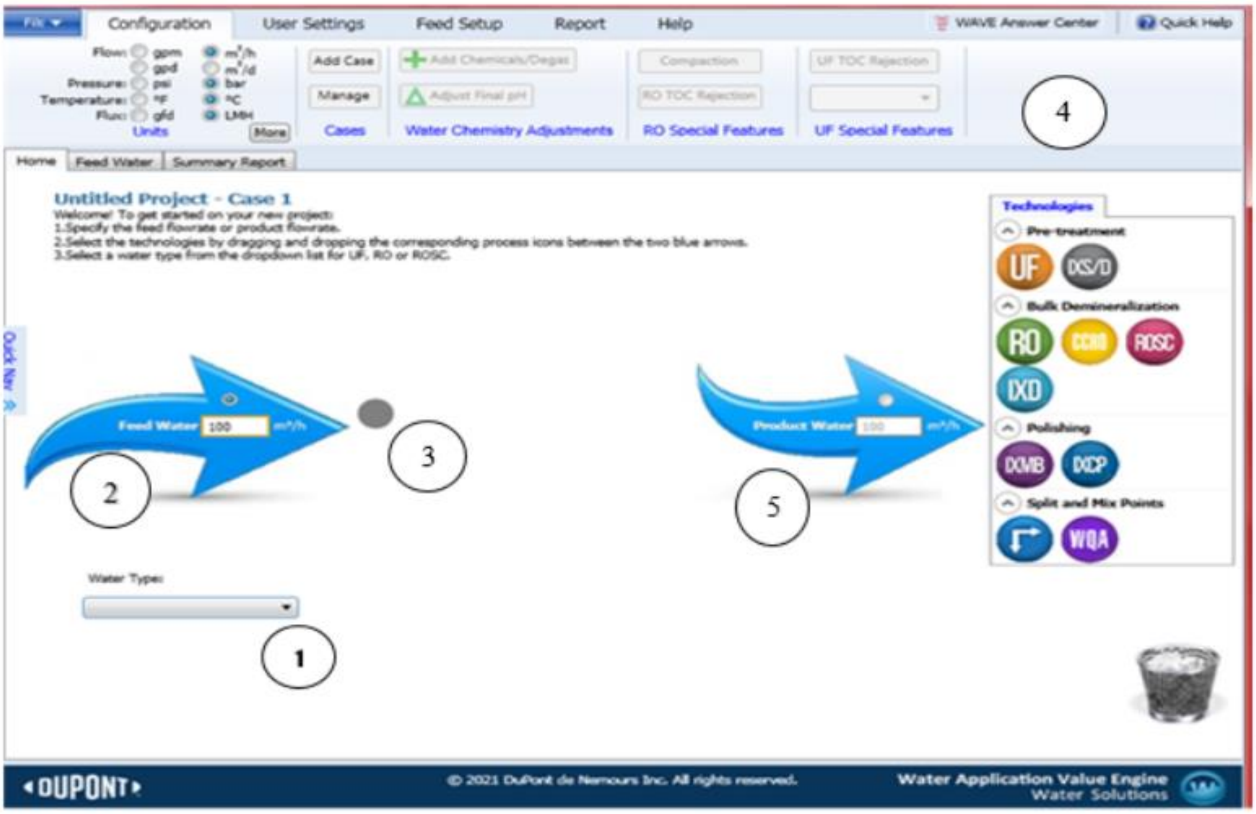
Table II.3: Symbol definition

Q_i: Permeate flow of element i (gpd)	$\sum_j$: Summation of all ionic species
$A_i\pi_i$: Membrane permeability at 25°C for element i, a function of the average concentrate-side osmotic pressure (gfd/psi)	Y : System recovery (expressed as a fraction) = permeate flow/feed flow
S_E : Membrane surface area per element (ft^2)	$\prod_{i=1}^{n}$: *multiplication of n terms in a series*
TCF : Temperature correction factor for membrane permeability	N_E : Number of element in system
FF : Membrane fouling factor	Q : System permeate flow (gpd)
P_{fi} : Feed pressure of element i (psi)	n : Number of elements in system
ΔP_{fci} : Concentrate-side pressure drop for Element i (psi)	$\bar{Q}_i$: Average element permeate flow (gpd) = Q/NE
P_{pi} : Permeate pressure of element i (psi)	$\bar{A}\pi$: Average membrane permeability at 25°C: a function of the average concentrate-side osmotic pressure (gfd/psi)
$\bar{\pi}_i$: Average concentrate-side osmotic pressure (psi)	$\bar{C}_{fc}$:Average concentrate-side concentration for system (ppm)
π_{fi} : Feed osmotic pressure of element i	$\bar{R}$: Average fractional salt rejection for system
π_{pi} : Permeate side osmotic pressure of element i	$\bar{\pi}$:Average concentrate-side osmotic pressure for system (psi)
Pf_i : Concentration polarization factor for element i	$\Delta\bar{P}_{fc}$: Average concentrate-side system pressure drop (psi)
R_i : Salt rejection fraction for element i $= \frac{feed\ concentration - permeate\ concentration}{\text{feed concentration}}$	Y_L : Limiting (maximum) system recovery (expressed as a fraction)
C_{fci} : Average concentrate-side concentration for element i (ppm)	$\bar{Y}_i$: Average element recovery (expressed as a fraction)
C_{fi} : Feed concentration for element i (ppm)	$\overline{pf}$: Average concentration polarization factor
C_{ci} :Concentrate concentration for element i (ppm)	$\bar{q}_{fc}$: Arithmetic average concentrate-side flowrate (gpm) [= (1/2)(feed flow + concentrate flow)]
Y_i : Recovery fraction for element i	N_V : Number of six-element pressure vessels in system (≈ $N_E/6$)
π_f : Treated feed water osmotic pressure (psi)	N_{V1} : Number of pressure vessels in first stage of 2-stage system (≈ 1/3 NV)
T : Feed water temperature (°C)	N_{V2} : number of pressure vessels in second stage of 2-stage system (≈ $N_V/3$)

m_j : Molal concentration of j th ion species	N_{VR} : stage ratio (=N_{V1}/N_{V2})

II.3. WAVE Software Interfaces

The handling of the Wave DOW software is simple, not requiring a lot of input parameters (input) and allows to generate very reliable results. The interface is clear, as shown in figure (II.1), it is therefore sufficient to know the quality of water to be filtered, such as the ionic composition of water to be treated, the type of water, the temperature, the pH and finally the turbidity, as well as the flow (either the inlet flow to the membrane, or the outlet flow) which makes this computer tool efficient and precise. The type of water to be treated can be carefully chosen: well water, permeate, softened water, municipal water, surface water, sea water or discharges. WAVE has an up-to-date database on membranes (RO, NF and UF), which makes it possible to carry out a simulation on a wide range of membranes with various characteristics and therefore to choose the most appropriate membrane according to the goals and needs. Figures (II.1), (II.2) and (II.3), represent respectively the interface of the software for the choice of technology, the introduction of the characteristics of the treated water and finally the configuration of the unit.



Untitled Project - Case 1

Welcome! To get started on your new project:

1.Specify the feed flowrate or product flowrate.
2.Select the technologies by dragging and dropping the corresponding process icons between the two blue arrows.
3.Select a water type from the dropdown list for UF, RO or ROSC.

Figure II.1: Window 1: choice of technology, flow rate and type of water

1. Type of water	2. Input flow
3. Input area for the type of treatment	4. Configuration(control) Panel
5. Output flow	

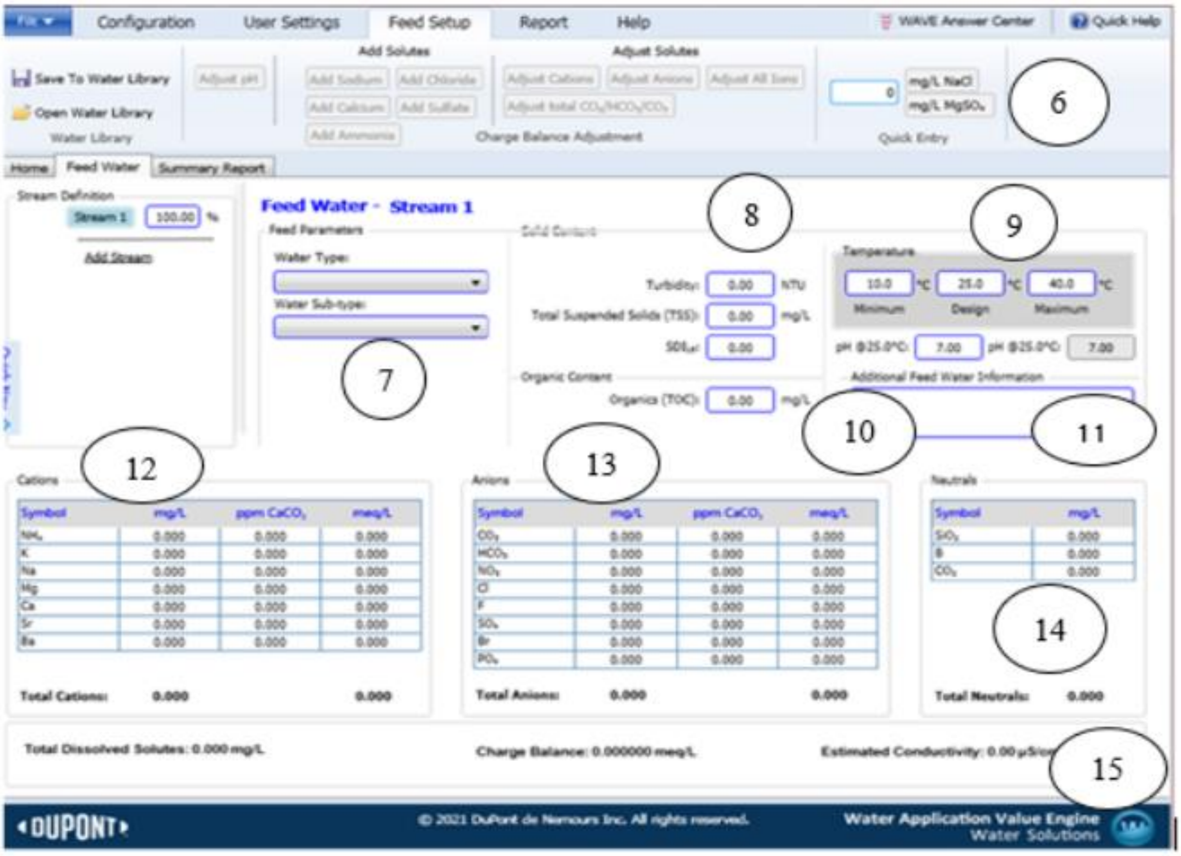
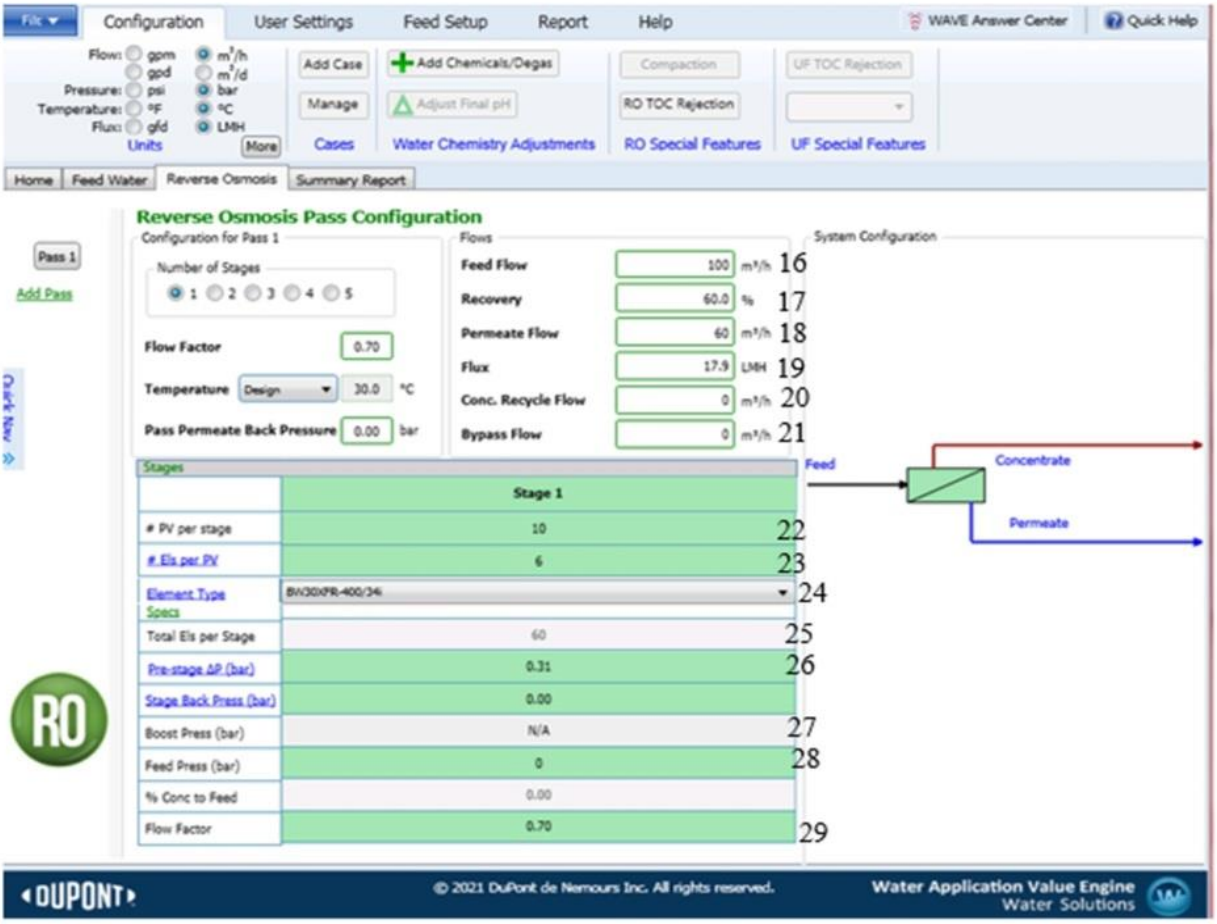


Figure II.2: Window 2: feed water characteristics

6. Water Balance Adjustment Parameters	7. Type of water
8. Water characteristics (TSS, Turbidity and SDI)	9. Temperatures
10. Water TOC	11. Solution pH
12. Concentrations of cations	13. Concentrations of anions
14. Concentrations of neutral ions	15. Conductivity and balance of water



Units: Flow: ○ gpm ○ gpd ● m³/h ○ m³/d; Pressure: ○ psi ● bar; Temperature: ○ °F ● °C; Flux: ○ gfd ● LMH

Reverse Osmosis Pass Configuration

Configuration for Pass 1

Number of Stages: ● 1 ○ 2 ○ 3 ○ 4 ○ 5

Flow Factor: 0.70

Temperature: Design 30.0 °C

Pass Permeate Back Pressure: 0.00 bar

Flows

Feed Flow	100	m³/h
Recovery	60.0	%
Permeate Flow	60	m³/h
Flux	17.9	LMH
Conc. Recycle Flow	0	m³/h
Bypass Flow	0	m³/h

Stages

	Stage 1
# PV per stage	10
# Els per PV	6
Element Type Specs	BW30XFR-400/34
Total Els per Stage	60
Pre-stage ΔP (bar)	0.31
Stage Back Press (bar)	0.00
Boost Press (bar)	N/A
Feed Press (bar)	0
% Conc to Feed	0.00
Flow Factor	0.70

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Figure II.3: Window 3: choice of membranes and configuration of the unit

16. Feed flow	17. Conversion rate
18. Permeate flow	19. Flow: permeate flow in LMH
20.Conc. Recycle Flow: recycle concentrate flow	21. Remineralization flow
22. Module number	23. Number of membrane per module
24. Membrane type	25. Total number of membranes
26. Pressure loss per stage	27. Permeate pressure
28. Feed Pressure	29. Flow factor

(Naila & al, 2022)

II.4. Characteristics of Raw and Target water

These characteristics represent the data necessary for the feasibility of the simulation.

II.4.1. Raw Water

The raw water in this research is well water. Well water is untreated groundwater stored in aquifers (underground layers of porous rock). Wells get drilled as far down as 1,000 feet into the rock to access the water. Just as water from other water sources, untreated well water is saline and contains very high mineral content which is not safe for drinking due to its bad odour, its negative health effects such as kidney stones etc. Therefore, it has to be treated so as to have acceptable salt and mineral content levels, good odour and normal total dissolved solids (TDS). (Organisation(WHO), 2011)

Table II.4: Raw Water Specifications

Substance	**Composition(mg/L)**
Calcium(Ca)	200
Chloride(Cl^-)	250
Copper(Cu)	1
Iron(Fe)	0.3
Magnesium(Mg)	150
Sulphate($SO^{2-}{}_4$)	400
Zinc(Zn)	3
Sodium	200
Phenolic Compounds(as phenol)	0.002
Detergents(alkyl benzene sulphonate)	1.0
Aluminium(Al)	0.2
Arsenic(As)	0.01
Cadmium	0.003
Barium	0.7
Chromium(Cr)	0.05
Cobalt(Co)	0.5
Cyanide(CN^-)	0.01
Fluoride(Fe^-)	1.5
Lead(Pb)	0.01
Mercury(Hg)	0.001
Manganese(Mn)	0.1
Nitrates($NO_{-3-}N$)	10
Nitrites($NO_{-2-}N$)	1
Selenium(Se)	0.01
Silver(Ag)	0.05
TDS	1220ppm

(Standards, 2010)

II.4.2. Target Water

It is reported by health experts that the longer you drink demineralized water (water without any mineral content) with very low TDS such as distilled water, the more you are at risk of developing multiple mineral deficiencies and placing your body in an acidic state. In the same manner, one who drinks water with very high TDS risks suffering multiple health effects due to unacceptable levels of mineral content. Therefore, a TDS of 90ppm is the best due to its recommended and acceptable mineral content levels for drinking water as shown in table 2.5 below.

Table II.5: Specification for Target Water

Element	**Composition(mg/L)**
Calcium(Ca)	20
Bicarbonates(HCO_3)	39.4
Magnesium(Mg)	1.2
Chlorides(Cl)	5
Sodium	3.5
Iron(Fe)	<0.09
TDS	90ppm
pH	6.97

(Zambia, 2021)

Example of the target water

CHAPITER III: PRACTICAL PART

In order to achieve the goal of producing drinkable water of 90 ppm from well water initially of 1220 ppm, the framework is described as follows:

1- NF and RO Membrane selection
2- NF and RO Advanced Configuration
3- Comparison

III.1. Membrane Selection (Membrane Screening)

Several membranes with wide range of specifications are included in the WAVE application; the purpose of this section is to screen different membranes according to the following criteria:

- Number of membrane
- TDS
- Specific energy
- Recovery

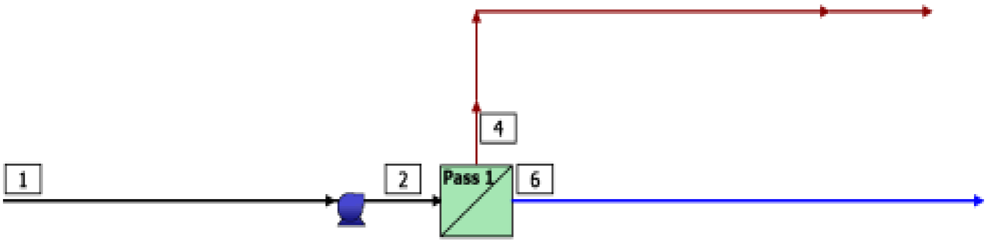


Figure III.1: Basic configuration of Reverse Osmosis

The membrane screening was performed according to a basic configuration of only one pass and one stage (no recirculation) for both reverse osmosis and Nanofiltration. Two membranes will be selected for the next step of advanced configuration.

- For membrane 1, it must have the lowest TDS, least number of membranes, low specific energy and a good recovery
- For membrane 2,it must have the highest TDS, least number of membranes, low specific energy and a good recovery

Membrane 1 having lowest TDS and membrane 2 having the highest TDS is because there will be need to compare the variations of these two membranes with regards to how they converge to the targeted TDS.

III.1.1. Reverse Osmosis membrane selection

Table III.1 shows the results of the different parameters (Number of element, TDS, specific energy, recovery, feed pressure). The number of the RO membrane required to desalinate 10 m^3/h are most likely 6 except for XLE-4040, XLE-2540,BW30 PRO-365 ,BW30-365,BW30-4040 and BW30-2540. This is due to the difference of the active surface area, which is one of the main properties affecting the flow rate and then the number of elements.

In terms of specific energy, all the membranes were in the range of 0.32-0.75kWh/m^3. Most of the membranes had a recovery of 60% except for BW30 PRO-365 and BW30-365 which display a recovery of 40%.

The TDS for most of the membranes was below 10mg/l except for XLE-440, XLE-B-440, XLE-440i, XLE-4040 and XLE-2540, this decisive parameter of TDS is tightly dependent on the selectivity.

All the membranes had feed pressure, which ranged from 4.3 to 12.9 bars.

Table III.1: Reverse Osmosis Membranes

Membrane Name	Numb of Elements	Specific Energy(kwh/m^3)	Recovery(%)	TDS(mg/L)	Feed Pressure(bars)
Eco Pro-400	6	0.41	60	8.42	7.0
Eco Pro-400i	6	0.41	60	8.42	7.0
Eco Pro-440	6	0.40	60	9.50	6.9
Eco Pro-440i	6	0.39	60	9.53	6.7
Eco Platinum-440	6	0.38	60	9.43	6.6
Eco Platinum-440i	6	0.37	60	9.45	6.4
XLE-440	6	0.34	60	26.23	5.9
XLE-B-440	6	0.34	60	26.23	5.9
XLE-440i	6	0.34	60	26.19	5.9
XLE-4040	30	0.32	60	26.17	5.5
XLE-2540	78	0.37	60	22.45	6.4
BW30HRLE-440	6	0.40	60	9.80	6.9
BW30HRLE-440i	6	0.39	60	9.82	6.7
BW30XFR-400/34	6	0.58	60	3.52	10.10
BW30XFR-400/34i	6	0.57	60	3.53	9.90
BW30FR-400/34	6	0.61	60	4.86	10.60
BW30FR-400/34i	6	0.60	60	4.86	10.4
BW30XHR PRO-440	6	0.56	60	2.78	9.60
BW30XHR PRO-400/34	6	0.58	60	2.49	10.10
BW30 PRO-365	12	0.38	40	8.24	4.3
BW30HR-440	6	0.56	60	3.92	9.6
BW30HR-440i	6	0.55	60	3.96	9.4
BW30XFRLE-400/34	6	0.41	60	8.60	7.0
BW30XFRLE-400/34i	6	0.40	60	8.96	6.90

BW30-365	12	0.39	40	10.23	4.4
BW30-400	6	0.66	60	4.98	11.4
BW30 PRO-400 IG	6	0.63	60	4.4	10.9
BW30 PRO-400	6	0.63	60	3.95	10.9
BW30 PRO-400/34	6	0.63	60	3.98	10.9
BW30 PRO-400/34i	6	0.60	60	3.98	10.40
BW30-400/34	6	0.64	60	4.89	11.10
BW30-400/34i	6	0.64	60	4.90	10.90
BW30-4040	30	0.58	60	10.45	9.90
BW30-2540	66	0.75	60	8.10	12.90

According to our screening criteria cited above, the following RO membranes were selected:

- XLE-B-440
- BW30XHR PRO-400/34

Tables III.2 and III.3 are describing respectively the typical properties and suggested operating conditions of the two selected membranes.

Table III.2: Typical Properties for the selected RO membranes

Membrane Name	Active Area (m^2)	Feed Spacer Thickness(mm)	Permeate flow rate (m^3/d)	Stabilized Salt Rejection (%)	Minimum Salt Rejection (%)
BW30XHR PRO-400/34	37	34-LDP	43.5	99.8	99.6
XLE-B-440	41	28	53	99.0	97.0

LDP- Low Differential Pressure

From the above table the two membranes exhibits different properties. The main difference which affect the TDS of the permeate water according to the table III.1 is the salt rejection. Higher is rejection lower is the TDS.

Table III.3: Suggested Operating Conditions of the selected RO membranes

Properties	Membrane Name	
	BW30XHR PRO-400/34	XLE-B-440
Membrane Type	Polyamide Thin-Film Composite	Polyamide Thin-Film Composite
Maximum Operating Temperature [1]	45°C	45°C
Maximum Operating Pressure	41bar	41bar
Maximum Pressure Drop Per Element	1.0bar	1.0bar
Per Pressure Vessel(Minimum 4 Elements)	3.5bar	Nil
pH Range Continuous Operation [1]	2-11	2-11

Short Term Cleaning (30min)[2]	1-13	1-13
Maximum Feed Flow [3]	17m^3/hr	Nil
Maximum Feed Silt Density Index	SDI 5	SDI 5
Free Chlorine Tolerance [4]	<0.1ppm	<0.1ppm

The two membranes have the same operating conditions except for maximum pressure drop per pressure vessel and maximum feed flow.

III.1.2. Nanofiltration Membrane Selection

The table III.4 shows the results of the different parameters (Number of elements, specific energy, recovery, TDS, feed pressure).Compared to RO, nanofiltration requires more elements to desalinate 10m^3/h of feed water.

Unlike reverse osmosis, nanofiltration requires less specific energy, which ranged from 0.19 to 0.26 kWh/m^3, thus makes nanofiltration more energy efficient compared to the reverse osmosis. The specific energy contrast between the reverse osmosis and nanofiltration, is mainly related to the operating pressure parameter, in fact and due to higher permeability, the required operating pressure for NF system is less than the RO system. It worth to remind that the transport mechanism for the NF and RO system is respectively potential flow mechanism and solubility-diffusion. .

Table III.4: Nanofiltration

Membrane Name	Number of Elements	Specific Energy(kWh/m^3)	Recovery(%)	TDS	Feed Pressure(bars)
NF90B-400	12	0.20	40	100.50	2.40
NF90-400/34i	12	0.19	40	96.04	2.20
NF90-4040	36	0.25	55	61.12	4.00
NF90-2540	96	0.26	55	56.17	4.60
NF90-400/34	12	0.19	40	96.01	2.20
NF200-4040	48	0.24	45	468.20	3.10
NF200-2540	144	0.24	45	472.10	3.00
NF270-400/34	6	0.23	60	492.10	4.00
NF270-400/34i	6	0.22	60	507.90	3.80
NF270-440	6	0.20	60	512.80	3.50
NF270-4040	30	0.21	60	490.90	3.70
NF270-2540	78	0.24	60	473.80	4.10

Unlike reverse osmosis, nanofiltration results divide the table into two. Some membranes had TDS above 100mg/l and the others had TDS below 100mg/l.

According to our screening criteria, (low specific energy, high recovery, number of elements) two NF membranes were selected:

-NF90-4040

- NF270-440

The tables III.5 and III.6, are describing respectively the typical properties and suggested operating conditions of the two selected membranes.

Table III.5: Typical Properties for Nanofiltration

Membrane Name	Active Area (m^2)	Feed Spacer Thickness(mil)	Permeate flow rate (m^3/d)	Stabilised Salt Rejection (%)	Minimum Salt Rejection (%)
NF90-4040	7.6	-	7.6	>97	97
NF270-440	41	28-LDP	52	>97	97

From the above table, the membrane NF270-440 has properties, which are much higher than that of NF90-4040.

Table III.6: Suggested Operating Conditions

Properties	Membrane Name	
	NF90-4040	NF270-440
Membrane Type	Polyamide Thin-Film Composite	Polypiperazine Thin-Film Composite Membrane
Maximum Operating Temperature [1]	45°C	45°C
Maximum Operating Pressure	41bar	41bar
Maximum Pressure Drop	1	1
Per Element		
Per Pressure Vessel(Minimum 4 Elements		
pH Range		
Continuous Operation [1]	2-11	3-10
Short Term Cleaning (30min)[2]	1-12	1-12
Maximum Feed Silt Density Index	5	5
Free Chlorine Tolerance [4]	<0.1ppm	<0.1ppm

The two membranes have almost the same operating conditions

Conclusion

According to these results, the basic configuration failed to reach the target water of 90 ppm. Regarding the reverse osmosis the permeate TDS is lower than the targeted water and advanced configurations such remineralisation or different stages are required. For some of the nanofiltration membranes had TDS lower than the targeted water, in which advanced configurations such as remineralisation or different stages are required.

Regarding Nanofiltration the permeate TDS for most of the membranes is higher than the targeted water and advanced configuration such as double pass is required.

III.2. Advanced Configuration

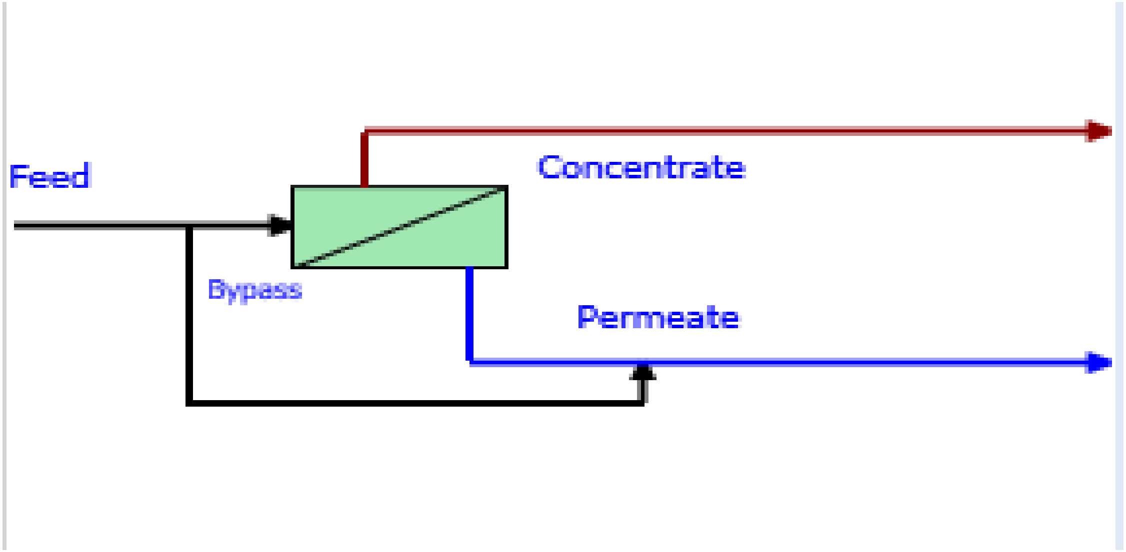
III.2.1. Advanced Configuration for Reverse Osmosis

III.2.1.1. Bypass/one stage Configuration

Bypass refers to a temporary or intentional diversion of water from the normal treatment process. It involves redirecting the flow of water around the treatment system, either partially or completely, without subjecting it to the usual treatment process.

Bypass is done to analyse, measure and increase the values of various aspects of water quality such as TDS and mineral content.

The bypass is described by the scheme below.



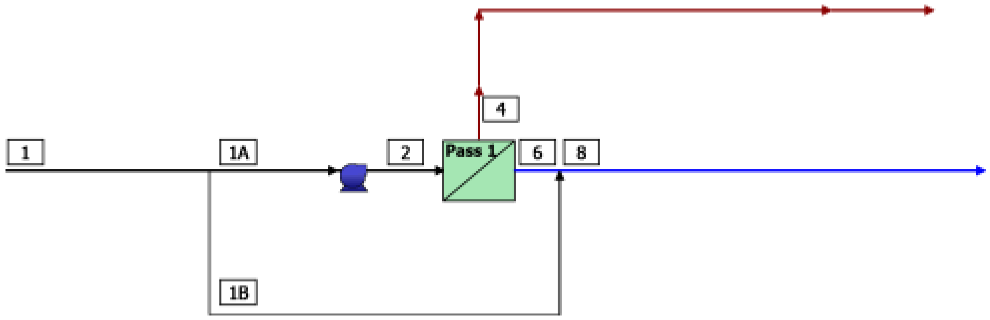


Figure III.2: Bypass Configuration for one stage

Key

1: Raw Feed to RO System **1A**: Feed to Pass 1 after Bypass **1B**: Bypass from Pass 1Feed to Pass1 Permeate **2**: Net Feed to Pass1 **4**: Total Concentrate from Pass1 **6**: Net Product from RO System **8**: Blend of Pass 1 Permeate and Bypassed Pass1 Feed

In order to find the fraction required to reach the target permeate of 90 ppm, the figures III.3 and III.4 are displaying the variation of TDS vs the feed water fractions.

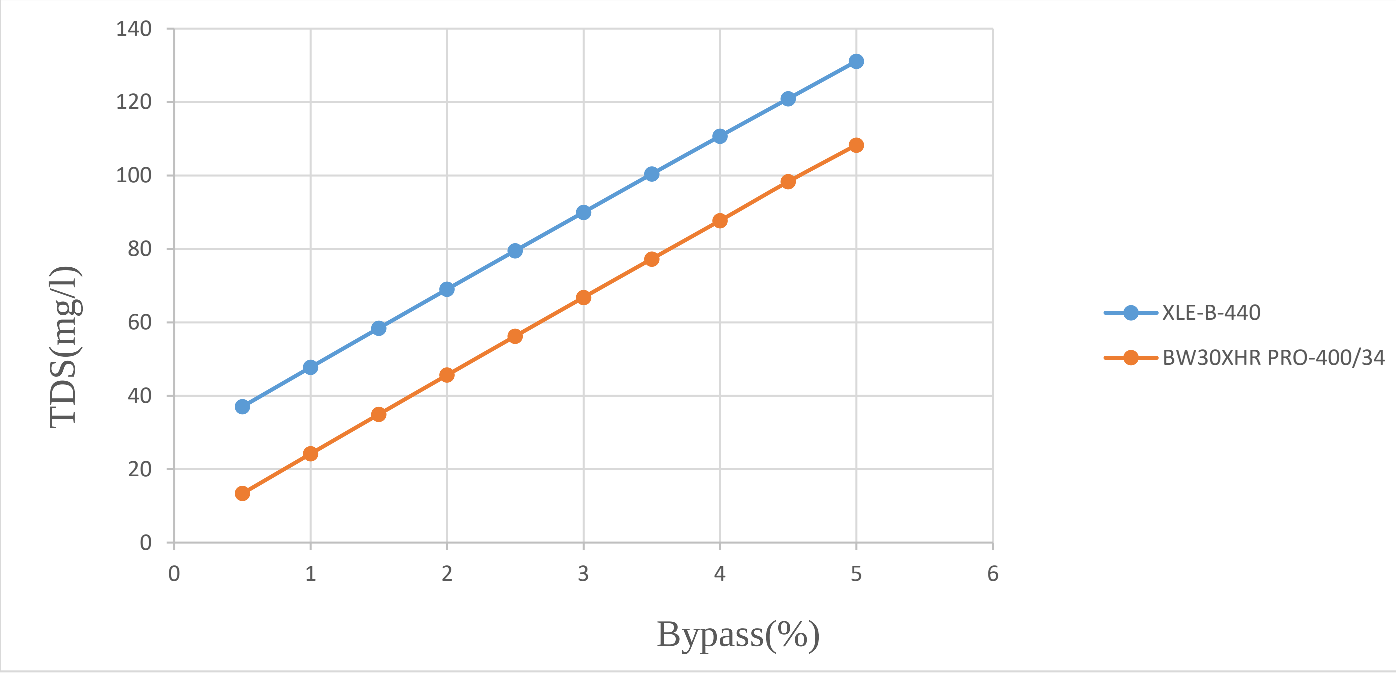


Figure III.3: Variation of TDS vs the feed water fractions for one stage bypass

From the figure above of variations of TDS vs feed water fractions, the membrane XLE-B-440 needed a fraction of 3.02% whereas the membrane BW30XHR PRO-400/34 needed a fraction of 4.15% to reach the target of 90ppm.This concludes that XLE-B-440 required less of remineralisation compared to BW30XHR PRO-400/34.

Table III.7: Results for one stage with bypass

Pass 1	XLE-B-440	BW30XHR PRO-400/34
Number of Elements	6	6
Total Active Area (m^2)	245	223
Feed Flow per Pass(m^3/h)	9.70	9.58
Feed TDS (mg/l)	1313	1313
Feed Pressure(bar)	5.7	9.6
Permeate Flow per Pass(m^3/h)	5.82	5.75
Pass Average Flux (LMH)	23.7	25.8
Permeate TDS(mg/l)	26.94	2.58
Pass Recovery	60%	60%
Average NDP(bar)	3.7	7.8
Specific Energy(kWh/m^3)	0.31	0.52
Temperature (˚C)	25	25
Chemical Dose	-	-
RO System Recovery	61.2%	61.7%
Net RO System Recovery	61.2%	61.7%
Blend bypassed TDS (mg/l)	90.39	90.78

From the table we remark that, both membranes were able to reach the targeted TDS of 90ppm, which is shown by the blend bypassed TDS. Other observations that were made are:

- The specific energy for both membranes decreased compared to the ones without bypass
- Most of the parameters for the membrane XLE-B-440 were lower than those of BW30XHR PRO-400/34

III.2.1.2. Advanced Configurations for RO Second Stage before Bypass

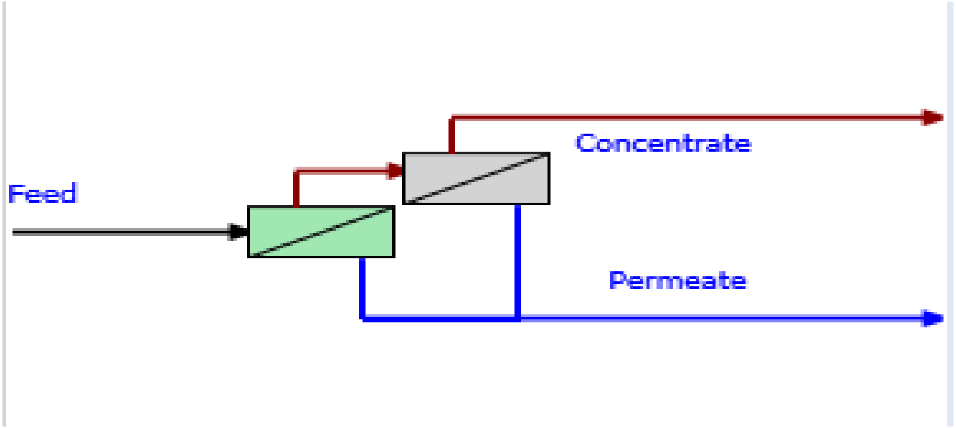


Figure III.4: Configuration for Second Stage

Table III.8: Results for second stage before bypass

Pass 1	XLE-B-440	BW30XHR PRO-400/34
Number of Elements	9	10
Total Active Area (m^2)	368	372
Feed Flow per Pass(m^3/h)	10.0	10.0
Feed TDS (mg/l)	1313	1313
Feed Pressure(bar)	5.4	7.7
Flow Factor per Stage	0.85 ; 0.85	0.85:0.85
Permeate Flow per Pass(m^3/h)	7.00	7.0
Pass Average Flux (LMH)	19.0	18.8
Permeate TDS(mg/l)	38.14	3.92
Pass Recovery	70%	70%
Average NDP(bar)	3	5.6
Specific Energy(kWh/m^3)	0.27	0,38
Temperature (˚C)	25	25
Chemical Dose	-	-
RO System Recovery	70%	70%
Net RO System Recovery	70%	70%

According to the results obtained from second stage without bypass, we can note that for both membranes, there was an increase in recovery by 10% and a decrease in specific energy. This makes second stage a better option compared to first stage although the number of elements increased from 6 to 9 and 10 for XLE-B-440 and BW30XHR PRO-400/34 respectively.

We also remark for both membranes that, the TDS increased and almost doubled the ones for first stage.

Despite all the increase in TDS, both membranes failed to reach the targeted TDS of 90ppm.This leads to a conclusion that the advanced stage of bypass is required for both membranes.

III.2.1.3. Advanced Configurations for RO Second Stage with Bypass

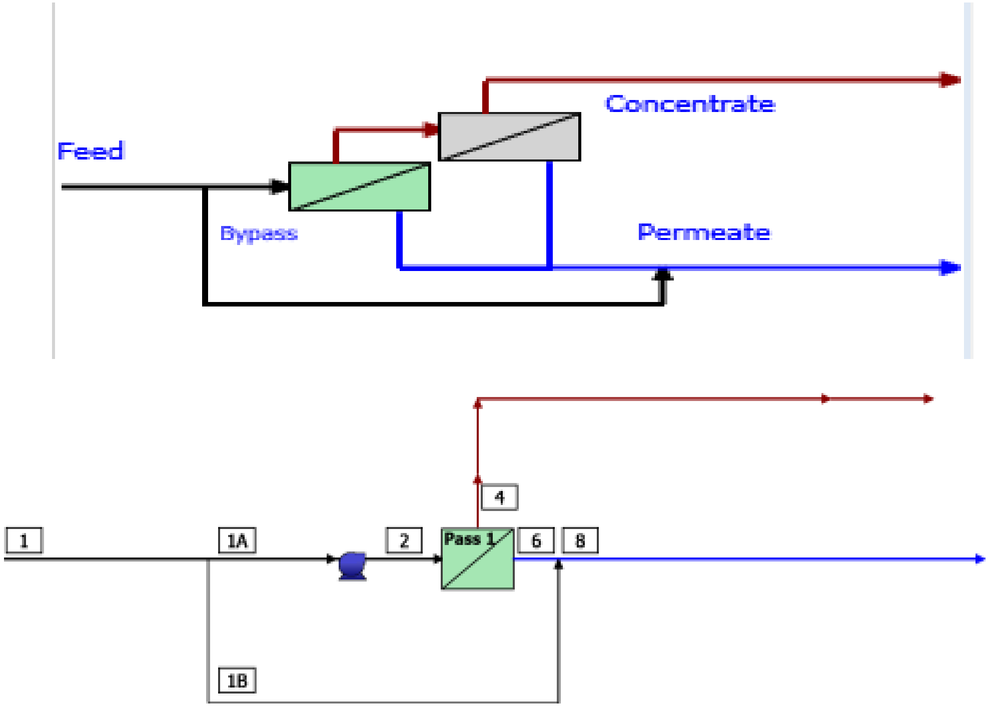


Figure III.5: Configuration for RO Second Stage with Bypass

Key

1: Raw Feed to RO System **1A**: Feed to Pass 1 after Bypass **1B**: Bypass from Pass 1 Feed to Pass 1 Permeate **2**: Net Feed to Pass 1 **4**: Total Concentrate from Pass 1

6: Net Product from RO System **8s**: Blend of Pass 1 Permeate and Bypassed Pass 1 Feed

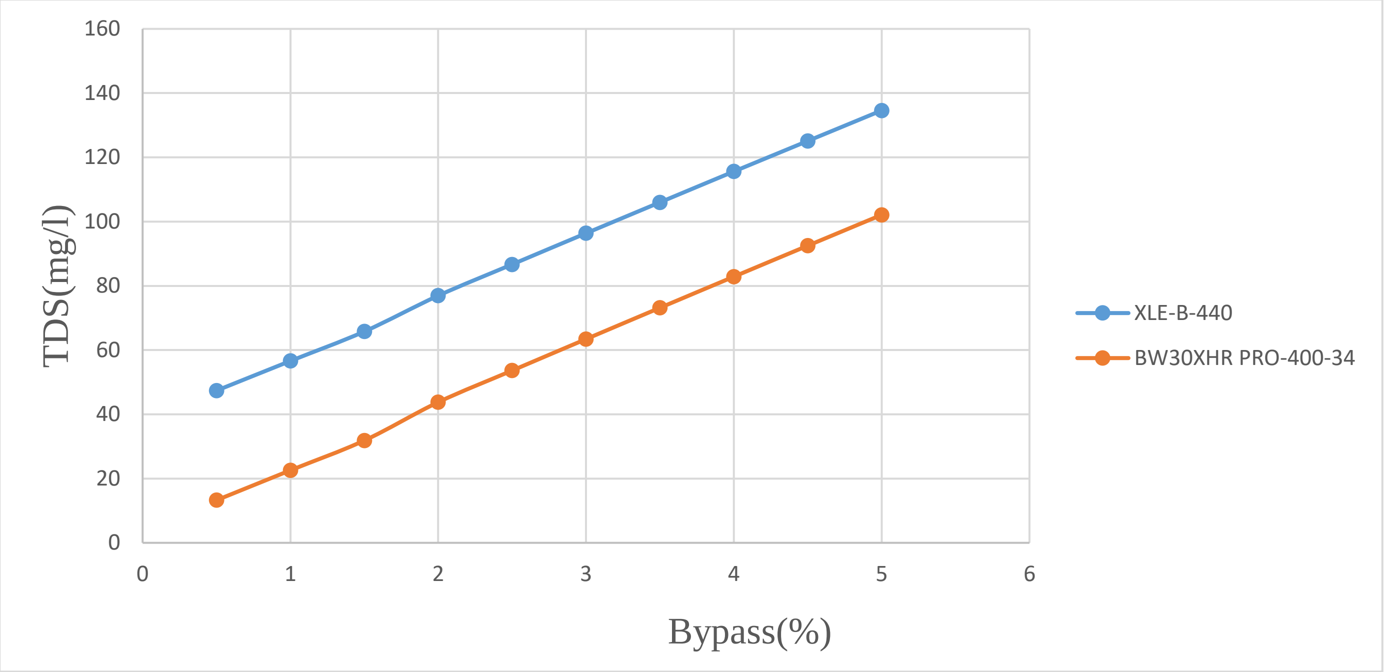


Figure III.6: Variation of TDS vs the feed water fractions for two stage bypass

From the figure above of variations of TDS vs feed water fractions, the membrane XLE-B-440 needed a fraction of 2.7% whereas the membrane BW30XHR PRO-400/34 needed a fraction of 4.37% to reach the target of 90ppm.This concludes that XLE-B-440 required less of remineralisation compared to BW30XHR PRO-400/34.

Table III.9: Results for second stage with bypass

Pass 1	XLE-B-440	BW30XHR PRO 400/34
Number of Elements	9	10
Total Active Area (m^2)	368	372
Feed Flow per Pass(m^3/h)	9.73	9.56
Feed TDS (mg/l)	1313	1313
Feed Pressure(bar)	5.0	6.9
Flow Factor per Stage	0.85:0.85	0.85;0.85
Permeate Flow per Pass(m^3/h)	6.32	6.22
Pass Average Flux (LMH)	17.2	16.7
Permeate TDS(mg/l)	38.38	4.02
Pass Recovery	65%	65.1%
Average NDP(bar)	2.7	4.9
Specific Energy(kWh/m^3)	0.26	0.35
Temperature (˚C)	25	25
Chemical Dose	-	-
RO System Recovery	65.9%	66.5%
Net RO System Recovery	65.9%	66.5%
Blend bypassed TDS (mg/l)	90.57	90

According to the results in the table above, it is evidenced that, both membranes were able to reach the targeted TDS of 90ppm, which is shown by the blend bypassed TDS. Other observations that were made are:

- The specific energy for both membranes decreased compared to the ones without bypass
- The recovery decreased whilst TDS increases therefore TDS and recovery are inversely proportional
- Most of the parameters for the membrane XLE-B-440 such as specific energy, total active area etc were lower than those of BW30XHR PRO-400/34, which makes the membrane XLE-B-440 a better option.

Table III.10: Comparison between first stage and second stage

Parameters	First Stage		Second Stage	
	XLE-B-440	BW30XHR PRO-400/34	XLE-B-440	BW30XHR PRO-400/34
Number of Elements	6	6	9	10
Specific Energy(kWh/m^3)	0.31	0.52	0.26	0.35
Recovery (%)	60	60	65	65.1
Feed Pressure (bar)	5.7	9.6	5.0	6.9
Total Active Area (m^3)	245	223	368	372

According to the table, it is noted that for both membranes number of elements increased in second stage but the specific energy dropped gradually. This means that second stage uses less energy compared to first stage despite increase in number of stages.

There is also an increase in recovery and total active area in second stage for both membranes.

The two membranes showed a decrease in feed pressure in second stage.

In summation, second stage can be considered a better option compared to first stage due to its increase in recovery and decrease in specific energy inspite of a slight increase in number of membranes.

III.2.2. Advanced Configuration for Nanofiltration

III.2.2.1. Nanofiltration with Bypass First Stage

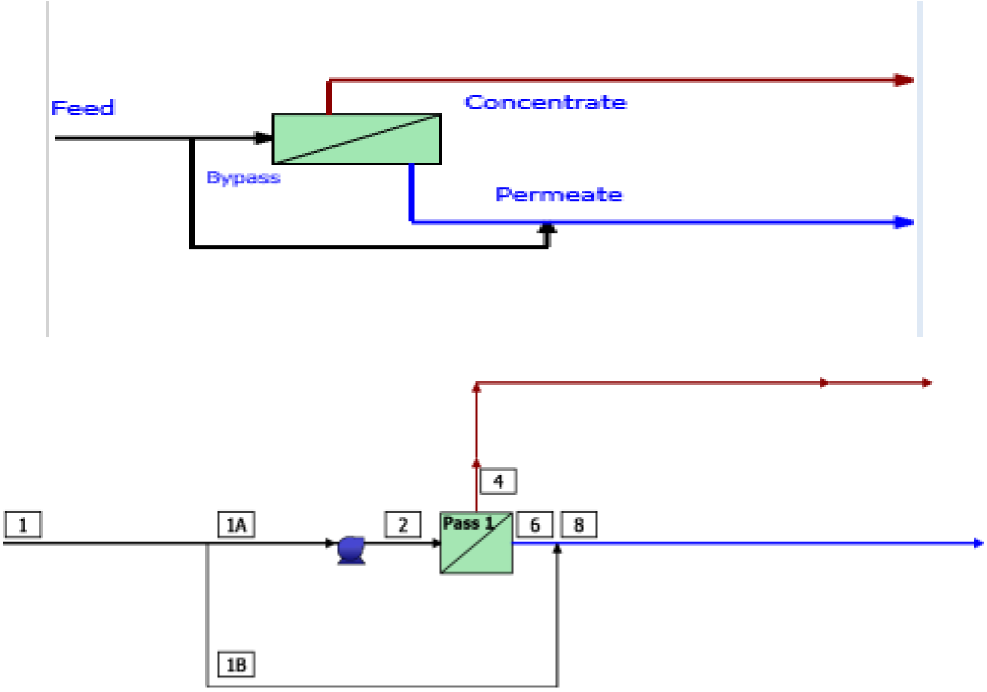


Figure III.7: NF90-4040

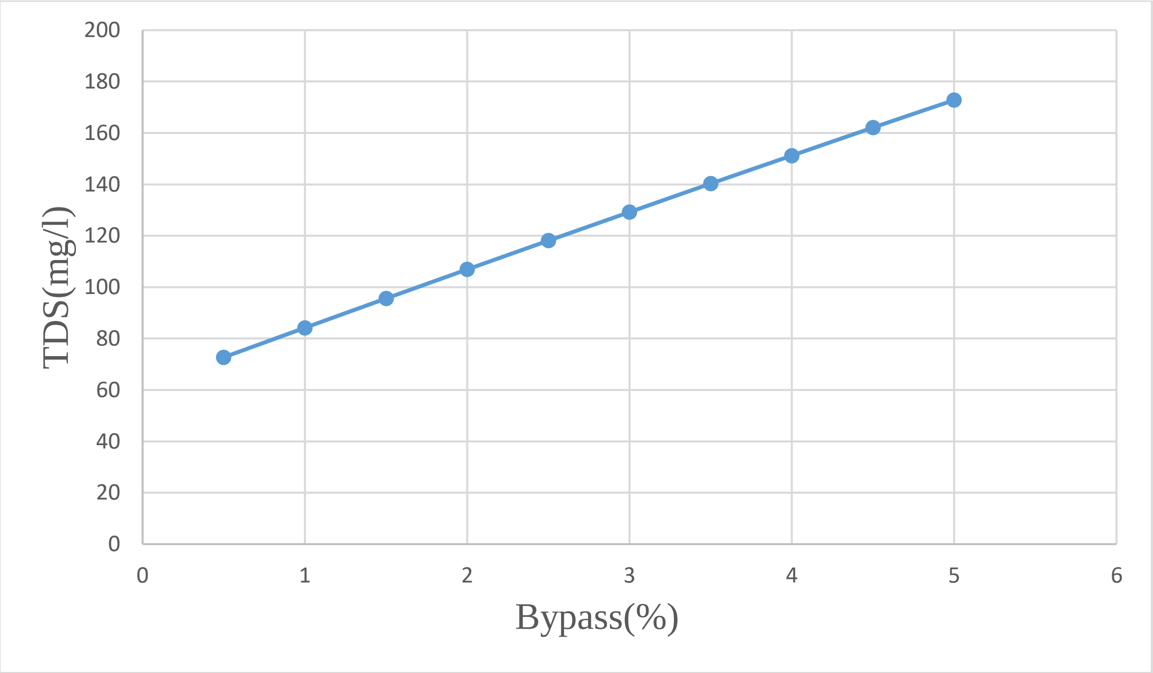


Figure III.8: Variation of TDS vs the feed water fractions for NF90-4040

The fraction giving the desired TDS of 90ppm was 1.27%. This shows that NF membrane needed a small percentage of remineralisation compared to RO membranes.

Table III.11: Results for NF90-4040

Pass	Pass 1
Number of Elements	36
Total Active Area (m^2)	274
Feed Flow per Pass(m^3/h)	9.87
Feed TDS (mg/l)	1313
Feed Pressure(bar)	3.9
Permeate Flow per Pass(m^3/h)	5.43
Pass Average Flux (LMH)	19.8
Permeate TDS(mg/l)	61.77
Pass Recovery	55%
Average NDP(bar)	2.3
Specific Energy(kWh/m^3)	0.24
Temperature (˚C)	25
Chemical Dose	-
RO System Recovery	55.6%
Net RO System Recovery	55.6%
Blend bypassed TDS (mg/l)	90.36

According to the figures shown in the table above, we remark that the NF membrane had increased number of elements compared to RO membranes. The number of membranes tripled those of RO.

Although increase in number of elements, the specific energy was way lower than that of RO membranes.

We can remark also that there was a decrease in recovery, which makes the RO membranes have better recovery.

III.2.2.2. Nanofiltration before bypass Second Stage

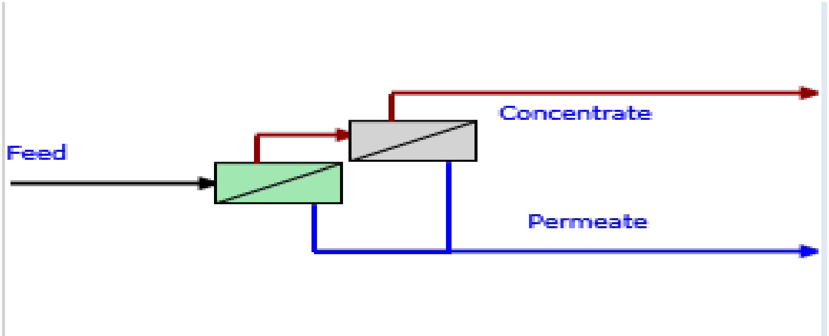


Figure III.9: NF90-4040

Table III.12: Results for NF90-4040

Pass	Pass 1
Number of Elements	54
Total Active Area (m^2)	411
Feed Flow per Pass(m^3/h)	10
Feed TDS (mg/l)	1313
Feed Pressure(bar)	4.2
Pass Average Flux (LMH)	17.0
Permeate TDS(mg/l)	86.68
Pass Recovery	70%
Average NDP(bar)	2
Specific Energy(kWh/m^3)	0.21
Temperature (˚C)	25
Chemical Dose	-
RO System Recovery	70%
Net RO System Recovery	70%

According to the results obtained from second stage without bypass, we can note that, there was a gradual increase in recovery and a decrease in specific energy. This makes second stage a better option compared to first stage although the number of elements increased from 36 to 54.We also remark that, the TDS increased gradually in second stage compared to first stage. Despite all the increase in TDS, the membrane failed to reach the targeted TDS of 90ppm.This leads to a conclusion that the advanced stage of bypass is required.

III.2.2.3. Nanofiltration Second Stage with Bypass

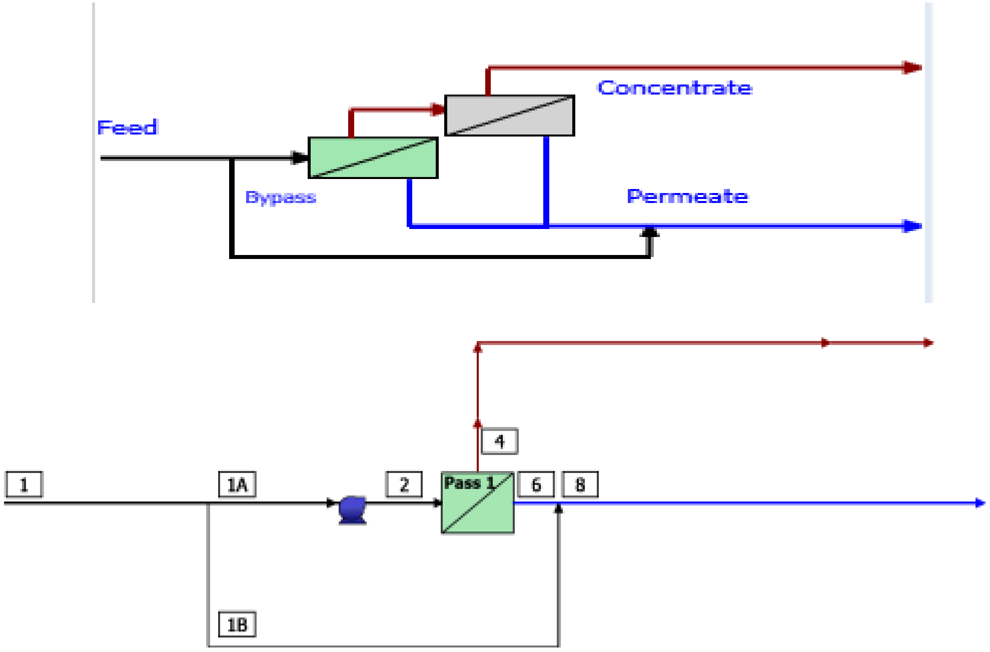


Figure III.10: NF90-4040

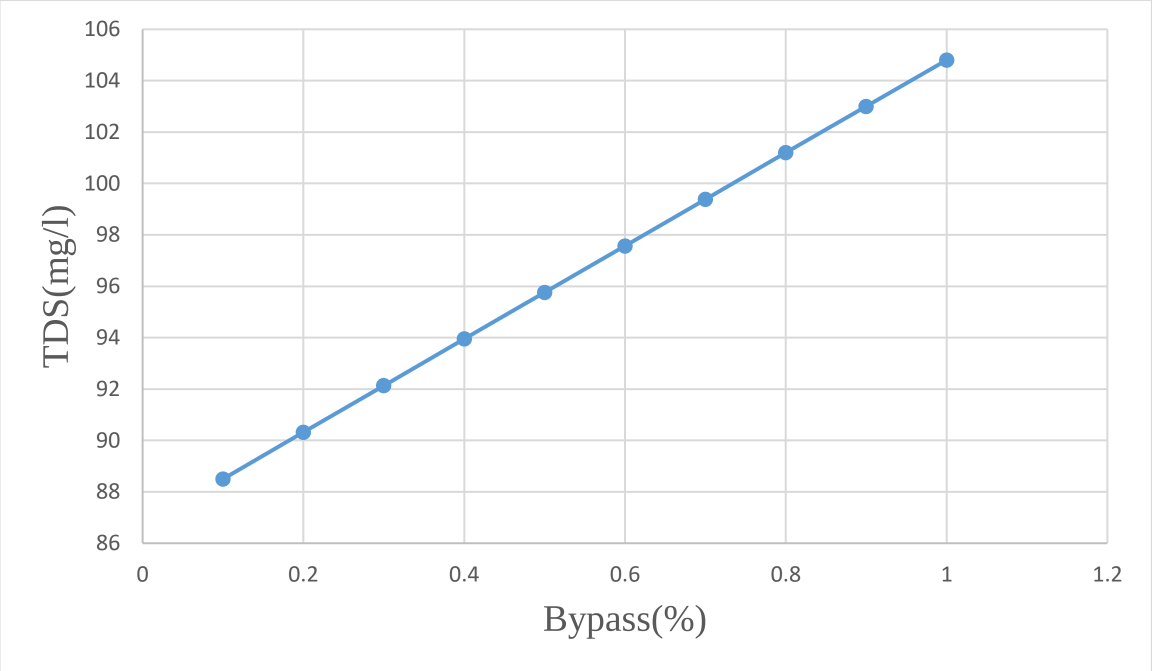


Figure III.11: Variation of TDS vs the feed water fractions for NF90-4040

From the graph, the fraction giving the targeted TDS was 0.2%. This means that the membrane NF90-4040 required less remineralisation in the second stage with bypass.

Table III.13: Results for NF90-4040

Pass	Pass 1
Number of Elements	54
Total Active Area (m^2)	411
Feed Flow per Pass(m^3/h)	9.98
Feed TDS (mg/l)	1313
Feed Pressure(bar)	4.2
Flow Factor per Stage	0.85;0.85
Permeate Flow per Pass(m^3/h)	6.99
Pass Average Flux (LMH)	17
Permeate TDS(mg/l)	86.82
Pass Recovery	70%
Average NDP(bar)	2
Specific Energy(kWh/m^3)	0.21
Temperature (˚C)	25
Chemical Dose	-
RO System Recovery	70.1%

Net RO System Recovery	70.1%
Blend bypassed TDS (mg/l)	90.32

According to the figures shown in the table above, we remark that the NF membrane had increased number of elements compared to RO membranes.

We can remark also that there was a decrease in specific energy compared to RO membranes, which makes NF membranes less energy consumers.

In comparison to first stage with bypass, second stage with bypass had a gradual increase in recovery despite the increase in number of elements.

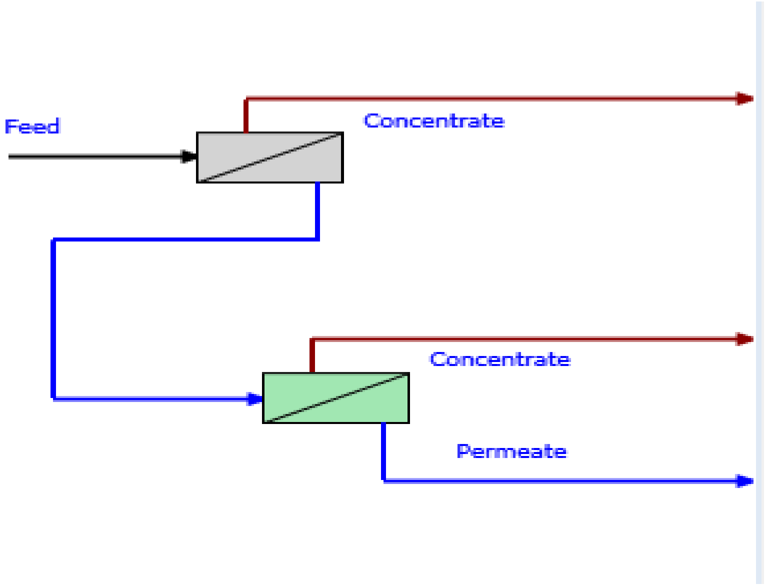
From the observations made, we can conclude that second stage with bypass is a better option.

Table III.14: Variation of Specific Energy with Bypass

Bypass (%)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Specific Energy(kWh/m^3)	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.20	0.20

III.2.2.4. Nanofiltration with Double Pass

Double pass refers to a specific process or configuration that involves passing water through a treatment process twice (Water undergoes two sequential treatment steps). It is often employed in situations where a higher level of treatment is required to meet specific water quality standards.



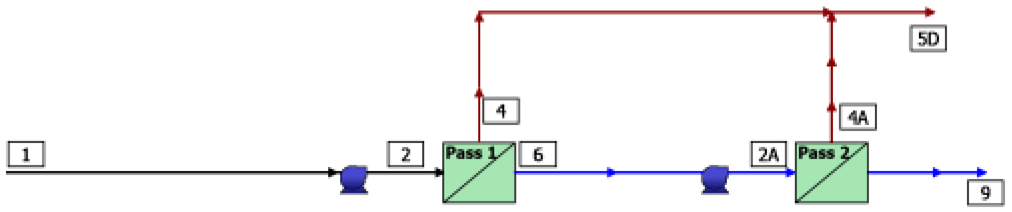


Figure III.12: NF270-440 with double pass

Key

1: Raw Feed to RO System **2**: Net Feed to Pass1 **4**: Total Concentrate from Pass 1

6: Total Permeate from Pass1 **2A**: Net Feed to Pass2 **4A**: Total Concentrate from Pass2

5D: Net Concentrate from RO System **9**: Net Product from RO System

Table III.15: Results for Double Pass

Pass	Pass 1	Pass 2
Number of Elements	6	3
Total Active Area (m^2)	245	123
Feed Flow per Pass(m^3/h)	10	6
Feed TDS (mg/l)	1313	512.8
Feed Pressure(bar)	3.5	2.5
Flow Factor per Stage	0.85	1
Permeate Flow per Pass(m^3/h)	6	3.3
Pass Average Flux (LMH)	24.5	26.9
Permeate TDS(mg/l)	512.8	338.6
Pass Recovery	60%	55%
Average NDP(bar)	2.2	1.9
Specific Energy(kWh/m^3)	0.20	0.16
Temperature (˚C)	25	25
Chemical Dose	-	-
RO System Recovery	33.0%	
Net RO System Recovery	33.0%	
Specific Energy (kWh/m^3)	0.52	

Contrary to RO, the primary results for the membrane NF270-440 surpassed the targeted TDS of 90ppm. In this case, the membrane required a different configuration, which is double pass. The number of membranes increased as well as the specific energy. This renders double pass a more energy-consuming configuration.

After the performance of double pass, the final TDS of 338,6ppm was obtained as indicated in Pass 2 column.

In summation the membrane NF270-440 failed to converge to the targeted TDS, this concludes that this membrane is not suitable for our project.

III.3. Comparisons

Table III.16: Specific Energy in function of Configuration

Configuration	1	2	3	4
Specific Energy	0.26	0.35	0.21	0.52

Key

Configuration 1: XLE-B-440 **Configuration 2**: BW30XHR PRO-400/34

Configuration 3: NF90-4040 **Configuration 4**: NF270-440

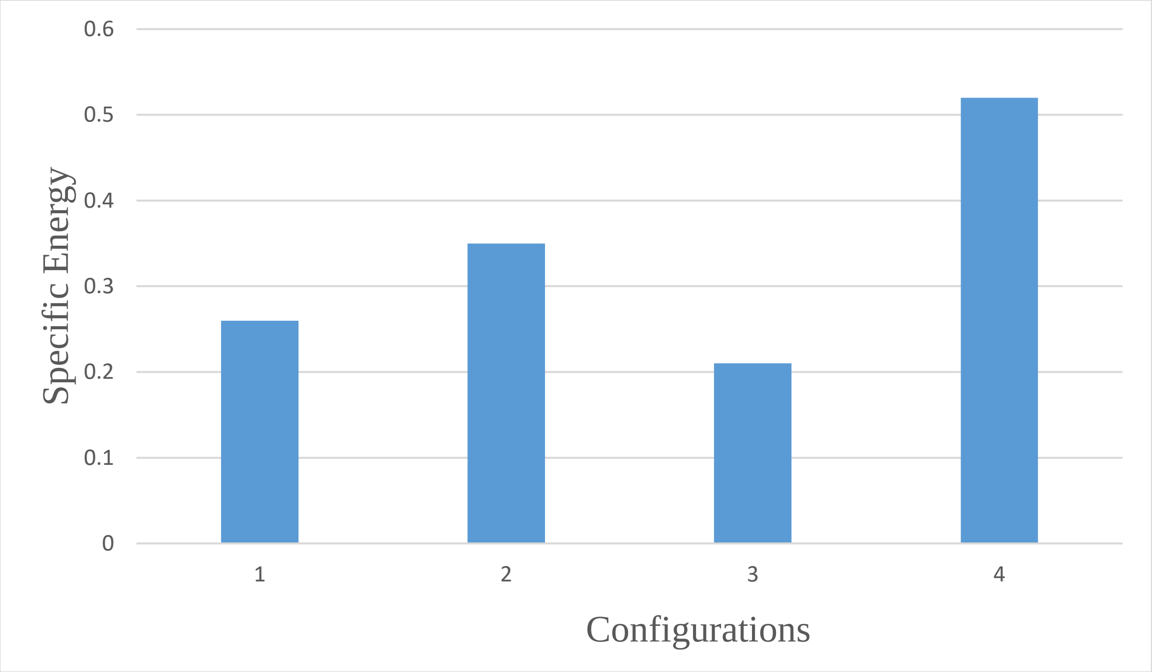


Figure III.13: Histogram of the variation of Specific Energy with the Configurations

From the diagram, we can remark that, the configuration that underwent double pass consumed a lot of energy compared to those that did not undergo double pass.

Among the bypass configurations (1, 2, 3), we remark that the RO configurations consumed more energy compared to NF configuration.

Table III.17: Number of Elements in function of Configuration

Configuration	1	2	3	4
Number of Elements	9	10	54	9

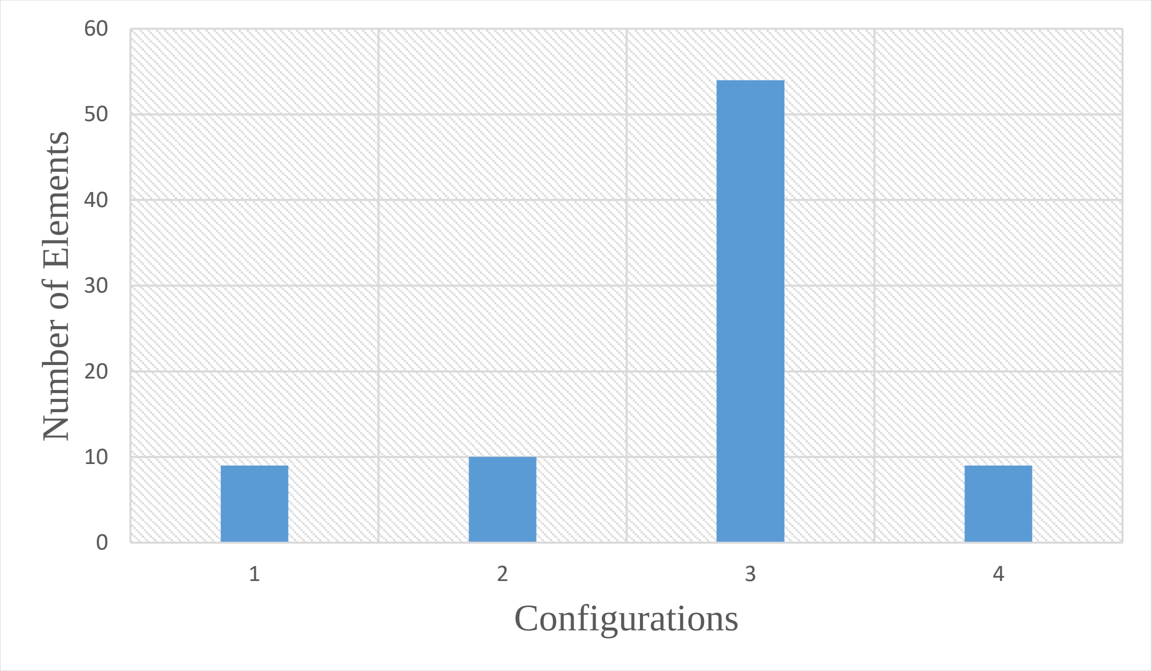


Figure III.14: Histogram of the variation of Number of Elements with the Configurations

According to the results shown above, the configuration that underwent double pass (Configuration 4) required almost the same number of elements with the configurations of RO bypass (Configurations 1, 2) whereas NF bypass required a lot of elements.

Table III.18: Recovery in function of Configuration

Configuration	1	2	3	4
Recovery	65	65.1	70	55

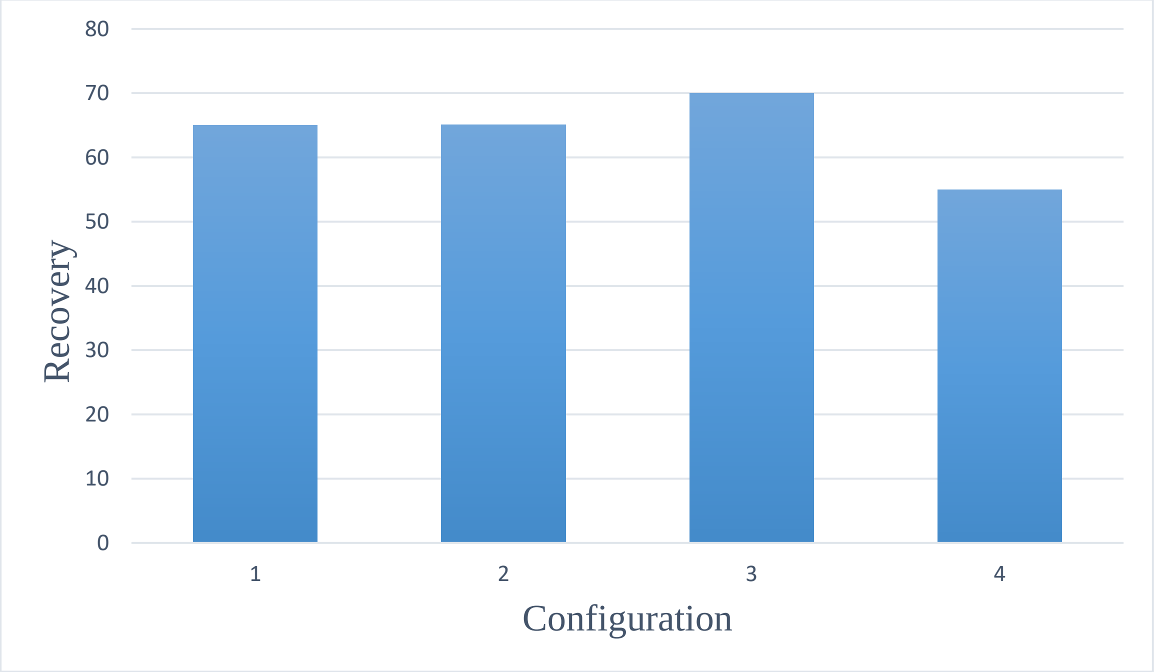


Figure III.15: Histogram of the variation of the Recovery with the Configurations

We can note that the RO configurations had similar recovery while in contrast to NF membranes, one had a higher recovery and the other had a lower recovery.

Table III.19: Price in function of Configuration

Configuration	1	2	3	4
Price	820	980	468	1046

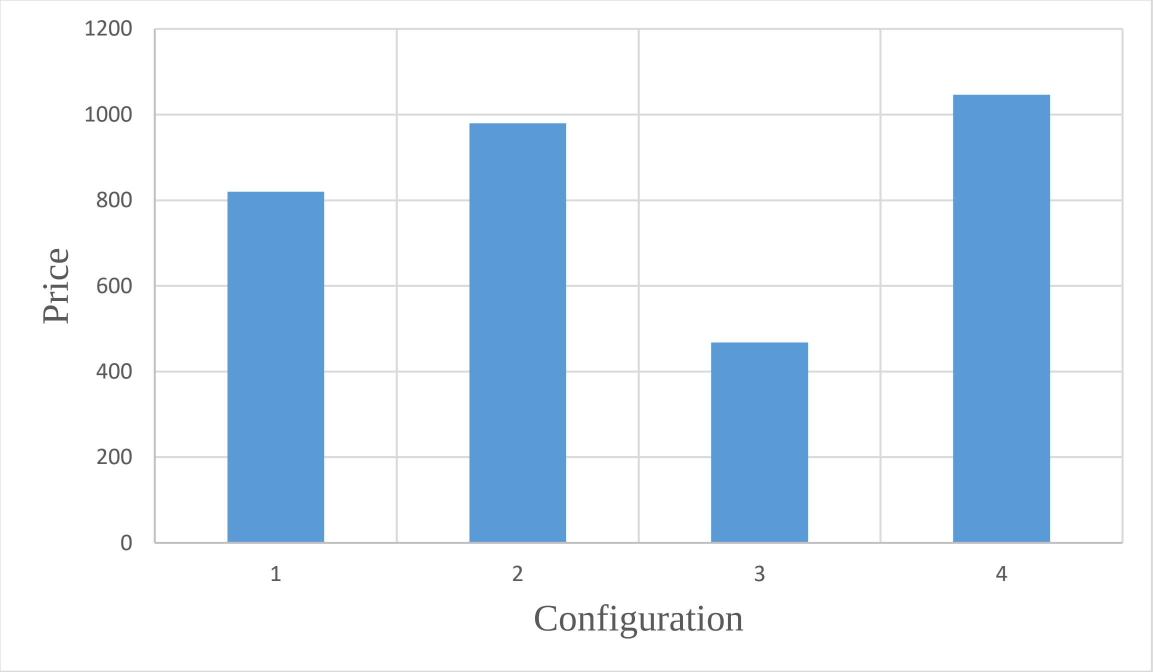


Figure III.16: Histogram of the variation of the Price with the Configurations

Taking the number of elements required into account, we can conclude that the membranes that required less number of elements, their prices were very high compared to the ones that required a lot of number of elements.

Everything considered, we can strongly conclude that the number of elements required is indirectly proportional to the price.

Calculation of cost of energy according to Zambia

1kWh costs \$0.044

Example for Configuration 1

1m^3=0.26kWh then for 10 m^3 =2.6 kWh

Therefore the total cost for electricity =\$0.1144

Note: *All the costs are for 1hour only*

Table III.20: General Comparisons

Configuration	Number of Elements	Specific Energy(kWh/m^3)	Price for Elements $USD
1	9	0.26	7380
2	10	0.35	9800
3	54	0.21	25272
4	9	0.52	9414

Considering all factors, we can note that configuration 1 had the lowest number of elements and the least price, which makes it the suitable membrane for this project.

We learn that all parameters (number of elements, specific energy) should be put in consideration, as we can see in configuration 3 that, it had the least specific energy but had the highest number of elements, which made the total price to escalate. In addition to previous point, we can observe that, configuration 4 had lower number of elements but had the highest specific energy, which makes the total price to be high, resulting in the company having a deficit in its budget.

Conclusion

The goal of this work was to design and optimize water treatment unit with NF and RO membrane in order to produce commercial drinking water, slightly mineralised of 90ppm.

The selected raw water is a brackish well water type specifically of Zambian origin with TDS of 1220ppm.

The most viable configuration is based the best compromised of the different criteria such as ; Low specific energy, low number of element with lowest expenses and finally a unit which converges quickly to the targeted TDS.

The Primary results from the screening criteria which describe the membrane efficiency, it appears that the RO membrane XLE-B-440 is showing the best performance among all and low expenses, which makes a company/enterprise to operate on a favourable, profitable budget.

From the obtained results, RO and NF unit single pass with two stages and remineralization system (Raw water Bypass) configurations are displaying the best compromise and thus the most techno-economically viability.

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