SIMULATION AND OPTIMISATION OF A SWRO SYSTEM IN CAPE TOWN, SOUTH AFRICA

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ABSTRACT

A SWRO system was designed to fulfil 50% of the population water demand in Cape Town, South Africa, which can lead up to 383,353 m^3/day in the next 15 years. The total dissolved solid (TDS) within the product (i.e. drinking water) must be lowered than 600 ppm by referring to standard guideline stated by the World Health Organization (WHO). The design flowrate was set at 766,704 m^3/day and the parameters such as feed, permeate, concentrate flowrate, number of vessels, number of membrane elements, number of stages, seawater chemical composition, temperature, pressure, and system configuration were considered in this study. Reverse Osmosis System Analysis (ROSA) 2017 software was used to determine how different parameters affect one another in the SWRO system. The TDS product concentration obtained from ROSA pre-optimisation simulation results was 74 ppm, which was too low compared to the standard set. Therefore, a ROSA post-optimisation was done to increase TDS value to 181 ppm, which was closer to the standard. The efficiency of the SWRO system recovery rate was 76% and specific energy consumption (SEC) was 6.18 kWh/m^3, greater than the previous value of 50% and lower than 9.7 kWh/m^3 in terms of recovery percentage and SEC respectively. The a lower amount of feed and energy resulting in major savings in terms of operating cost for the SWRO system.

Keywords: Seawater reverse osmosis (SWRO) system, Reverse Osmosis System Analysis (ROSA), Optimisation, Energy consumption

1.0 INTRODUCTION

2.1 billion people (i.e. 29% of the population) does not have the privilege to access safe drinking water that are free from contamination [1]. Without clean water, diseases will be likely to linger, illness and death caused by cholera, polio, typhoid, and others are inevitable. The chaos caused by unclean water will not only stop at diseases, but development of agriculture will also be on a standstill and economy of the country will eventually plummet in the long run.

With the effect of climate change not in favour, water will be more valuable than ever in the next decade. And from there many scientist and engineers have been trying to figure out ways to deal with water scarcity. Over the years, technologies to fight water crisis or to obtain clean water have been invented. Some of them are solar powered water filtration, fog catchers, the life straw, etc. These technologies are extremely innovative and have helped many people around the world. However, they have limitations such as low water production, expensive, unreliable, and unfriendly to the environment.

Cape Town, which is located at the Southwestern most part of South Africa has experienced many water shortages before with an average of at least once per year. Between 2015 and 2018, the town was hit by the worst water crisis the nation has ever faced. During the early 2018, its dam was below 25% of its capacity due to less rainfall at the end of 2017 and 2018 [2]. With 4 million residents relying on water to survive and the approaching of 'Day Zero', the government had issued a statement where each person has only a limited amount of water that can be use per day [2]. Consumers have to reduce their household water usage from 540 L to 280 L per day for more than 36 months [3]. The water crisis was then eliminated not due to the efforts of people from Cape Town or the government, but because of heavy rainfall in the next few weeks. The water level of the dams had risen and 'Day Zero' was delayed until an indefinite time. However, many people speculate that if heavy rainfall did not happen the worst is yet to come. Incidents like this may happened again with a few very persuasive reasons, climate change, every increase of population in the area and limited fresh water supply. Hence the idea of desalination plant may help the community from ever going into another water crisis again.

Desalination is the process of removing minerals from a volume of water. The objective is to turn highly salt contaminated water into a safe useable water. It can be achieved using the membrane filter based desalination (e.g. nanofiltration, electrodialysis) and non-membrane based filters (e.g. multistage flash, multieffect distillation) [4]. Nanofiltration was one of the methods to desalinate seawater into drinking water. However, even with today's technologies nanofiltration has a few limitations of which it usually desalinates 5000 ppm of saline water under 9 bars with an excellent salt rejection rate of 95%. However, as the salt content in the water increases to 25000 ppm, it is close to impossible to turn it into drinkable water as the rejection rate is only 41% at the same pressure [5]. According to the World Health Organization TDS guidelines level for a good palatable drinking water is around 600 ppm (mg/L), hence nanofiltration could not serve the purpose of desalinating seawater into drinkable water. Since False Bay has a saline range of 34% to 35%, nanofiltration is not being considered as the main filtration system due to the fact that the cost and effort to achieve drinkable water from high salinity of water is unrealistic. Another way to turn sea water into drinkable water is through filtration via reverse osmosis. The objective of this study is to simulate and optimise the reverse osmosis membrane filter system and model using the Reverse Osmosis System Analysis Software (ROSA) that further improved using Excel software to assess how the parameters changes affect one another.

2.0 METHODOLOGY

2.1 Selection of Saline Water Source

Cape Town of South Africa is close to many water sources within a 50 km radius, such as the Berg River, Palmiet River, mountain dams, ground water, reservoir, etc. False Bay has been chosen as the location for desalination to be taken place because part of Cape Town of South Africa lies beside False Bay, which is partially in contact with the southern part of the Atlantic Ocean and the Indian Ocean. Salinity of False Bay lies between 34 % (34 ppt) and 35% (35 ppt) [6] which is around the average of an ocean salinity. The contamination ranges from short term nutrients enrichment, organic matter and microbial contamination to long term heavy metal (i.e. cadmium, lead and zinc) contamination. Heavy metal contamination is mainly caused by sewage effluent, agricultural, commercial, urban development and marine transportation such as fishing boats and yacht [7]. Estimated seawater characteristics and chemical composition of False Bay are shown in Table 1.

Table 1: Seawater Characteristics and Chemical Composition

Parameters	Values	References
Depth of Seawater	40 m to 120 m	[7]
Average temperature	17 °C	[6]
Salinity	3.45 % (34.5 ppt)	[6]
Chemical Oxygen Demand (COD)	1410 mg/L	[6]
pH	8.9	[6]
Fats and oils	17 mg/L	[6]
Suspended solids	6 mg/L	[6]
Glycerol	0.14%	[6]
Nitrogen	25 mg/L	[6]
Nickel	0.24 mg/L	[6]
Chloride	19545.24 mg/L	[8]
Sodium	10892.58 mg/L	[8]
Magnesium	1303.56 mg/L	[8]
Sulphate	2779.70 mg/L	[8]
Calcium	417.79 mg/L	[8]
Potassium	403.21 mg/L	[8]
Carbon (inorganic)	28.15 mg/L	[8]
Bromide	67.63 mg/L	[8]
Boron	4.49 mg/L	[8]
Strontium	0.09 mg/L	[8]
Fluoride	1.33 mg/L	[8]
Barium	0.005 mg/L	[9]
Phosphorus	52.02 mg/L	[10]
Nitrate	1.53 mg/L	[11]

2.2 Water Demand

The basis of water demand for Cape Town of South Africa used in this study was targeted for 50% population excluding agricultural, commercial, and industrial usage. Referring to the Standard Country Report 2017 [12], the water consumption per person per day are shown in Table 2, where estimated 130 L of water needed per day for each person.

Table 2: Estimated Water Consumption Rate per Person per Day from year 2013 – 2017 extracted from Standard Country Report: 26 utilities in South Africa, 2017 [12]

Year	Water Consumption per Person per Day (L)
2013	112
2014	112
2015	176
2016	136
2017	114
Average	130

For 4.7 milliion people, desalination plant estimated product output as per 2021:

Total Water Consumption (litres) = 611,000 m^3 *per day*
Estimated Desalination Plant Capacity: 50% of Cape Town Population = 305,500 m^3 *per day*
12,730 m^3 *per hour or 3.5* m^3 *per second*
Estimated population of Cape Town in 2035: 5,900,000
Total Water Consumption (litres): 130 x 5,900,000 = 766,705,000 litres per day
Total Water Consumption (m^3) *= 766,705* m^3 *per day*
Estimated Desalination Plant Capacity:
50% of Cape Town Population
766,705 m^3 *x 0.5 = 383,352* m^3 *per day*
15,973 m^3 *per hour or 4.43* m^3 *per second*

2.3 Coagulations and Flocculation

Due to high turbidity of water around the False Bay water are high in turbidity with brown discoloration and milky white green appearance. It was due to the present of diatom *Anaulus australis*. The surf zone blooms present due to high concentration of nutrients presence in nearby rivers which passes through agricultural sectors [13]. As for the milky white-green appearance in some bodies of water, it is studied that plankton community composition were presence in these body of waters causing a rise in turbidity [13]. Further to this, the body of water were warmer, less saline and contains unusual amount of nitrate, silicate, chlorophyll α and calcium [13]. Hence process of coagulation and flocculation were used to remove these suspended solids hidden in the seawater feed.

Coagulant and flocculants water treatment chemicals were added into the stream to remove iron, suspended solids and hardness of water through the effect of bridging mechanism:

dispersion, adsorption, compression and collision [14]. After the effect of bridging mechanism takes place, suspended solid will join together in the form of a bigger solid and sediment at the bottom of the sediment tank. A pump was designed to transfer the solids/sludge for further treatment. Figure 1 shows the overall flow of the first pre-treatment process.

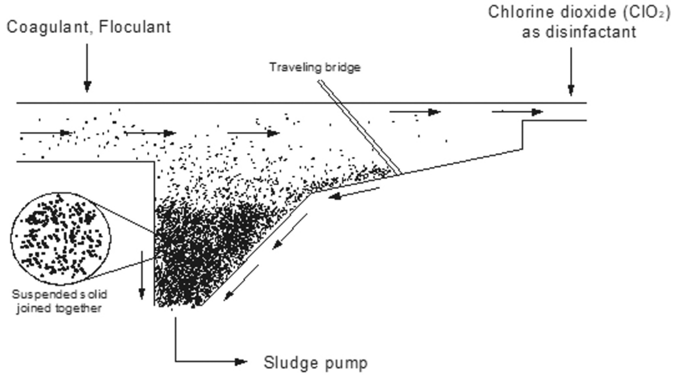


Figure 1: Illustration of Settling Tank process

Water inlet flow: 800,000 m^3 / day
Detention time: 1.5 hours
Estimate tank holds 80% of water inlet flow at any given time
Tank capacity = 40,000 m^3

2.4 Reverse Osmosis System Design Simulation

Recovery ratio of seawater desalination has an average value of 50% or 0.5, hence this value was used to balance energy consumption concerns and avoid accelerated membrane fouling. Based on the recovery ratio, many parameters such as flow of feed water, brine and concentration of brine were calculated. The feed water flow, concentrated water flow, permeate water flow, percent rejection and concentrate water concentration are show in equations (1) to (4).

$$Q_f = \frac{Q_p}{RR} \tag{1}$$

Where Q_f is feed water flow (m^3/day), Q_p is permeate water flow (m^3/day), *RR* is recover ratio.

$$Q_c = \frac{Q_f}{1-RR} \tag{2}$$

Where Q_c is concentrate water flow (m^3/day).

$$Q_p = Q_f - Q_c \tag{3}$$

$$PR = \left[1 - \left(\frac{TDS_p}{TDS_f}\right)\right] x\ 100\% \tag{4}$$

Where *PR* is percentage rejection, %, TDS_p is product total dissolved solids and TDS_f is feed total dissolved solids.

$$C_c = C_c\left(\frac{1}{RR}\right) \tag{5}$$

Where C_c is concentrate water concentration, mg/L and C_f is feed water concentration, mg/L.

2.5 Osmotic Pressure

The osmotic pressure of the feed, π was determined by measuring the concentration of total dissolved salts in the feed solution. The osmotic pressure of feed was obtained from the following equation while obeys a law that resembles the ideal gas equation:

$$\pi = \frac{nRT}{V} = RT \sum X_i \tag{6}$$

Where, π is the osmotic pressure (kpa), R is the universal gas constant, 8.314 kPa m^3/kg mol K, T is temperature (K), $\sum X_i$ is the concentration of all constituents (Table 4) in a solution (kmol/m^3).

2.6 Specific Energy Consumption (SEC)

Recovery ratio of seawater desalination has an average value of 50% or 0.5 based on Seawater desalination power consumption data 2011. It was used a reference for RO energy system configuration. Qiu and Davies (2012) developed different specific energy consumption equations for different configuration. RO system configuration are shown in equations (7) to (11). [15]

Single stage without energy recovery

$$P_{osm} \frac{1}{r(1-r)} \tag{7}$$

Single stage with energy recovery

$$P_{osm} \frac{1}{(1-r)} \tag{8}$$

Two stage without energy recovery

$$\frac{P_{osm}}{r}\left[\frac{2}{\sqrt[2]{(1-r)}} - (2-1)\right] \tag{9}$$

Single stage with energy recovery

$$\frac{P_{osm}}{r}\left[\frac{2}{\sqrt[2]{(1-r)}} - (2)\right] \tag{10}$$

BO batch-RO

$$\frac{P_{osm}}{r}\left[ln \frac{1}{1-r}\right] \tag{11}$$

Where, P_{osm} is π obtained from equation (6)
n is the number of stages.
r is the recovery ratio which is equivalent to 0.5.

2.7 Membrane Specifications

SEAMAXX was selected because it resembles closely to polyethylenimine (FilmTecTM SeamaxxTM-440 Element). Number of membrane elements of SEAMAXX membrane and number of vessels required were determined using equations (12) and (13).

$$Ne = \frac{Qp}{Qe} \tag{12}$$

Where *Ne* is number of membrane elements, *Qp* is permeate flow and *Qe* is membrane element flow capacity.

A typical number of membrane elements per vessel is set at 6. Number of vessels needed for desalination process:

$$Nv = \frac{Ne}{6} \tag{13}$$

Where *Nv* is number of vessels and *Ne* is number of elements.

2.8 Selection for Number of Stages

In reverse osmosis, the number of stages was defined as how many pressure vessels the seawater feed passed through until it exists as a concentrate. For each stage, the elements were arranged in parallel. From the number of stages specification sheet provided by (Dupoint, 2020), the 8 number of serial element and 2 number of stages were selected.

The relation of the number of pressure vessels in the subsequent stages was determined as staging ratio. The staging ratio, R of a system was calculated using the equation (14):

$$R = \left[\frac{1}{(1-r)}\right]^{\frac{1}{n}} \tag{14}$$

Number of pressure vessels in the first stage, *Nv*(1) and second stage, *Nv*(2) was calculated in terms of staging ratio) using equations (15) and (16):

$$Nv(1) = \frac{Nv}{1+R^{-1}} \tag{15}$$

$$Nv(2) = \frac{Nv(1)}{R} \tag{16}$$

2.9 Charge Balance for Seawater Feed

Charge balance was to make sure the validity of the amount of chemical substance in the feed water. An overall charge balance was performed by converting the unit mg/L to meq/L (milliequivalent per litre). Milliequivalent is define as the chemical activity or combining power of an element relative to the activity of 1.0 mg of hydrogen. Molar mass of the chemical entity was multiplied by the number of free electron charges it has, regardless of whether it is positive or negative were determined using equation (17):

$$M_m \text{ x } \frac{number\ of\ valance\ charge}{mol} = \frac{mg}{meq} \tag{17}$$

$$\frac{mg}{L} \div \frac{mg}{meq} = \frac{meq}{L}\ (milliequivalent\ per\ litre)$$

Where M_m is molar mass, $\frac{g}{mol}$.

3.0 RESULTS AND DISCUSSION

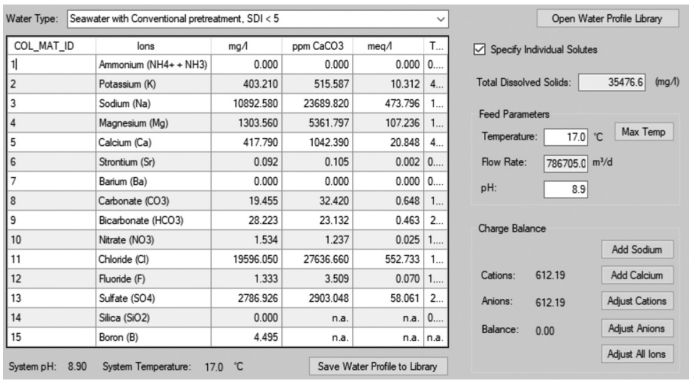
3.1 Simulation Results

The estimated values and simulated results were compared in this study (Table 3). It was found that optimisation change the feed flow rate and made the energy requirement of 9.7 kWh/m^3 lowered compared to the pre-optimized value of 14.14 kWh/m^3 and lower recovery ratio of the overall system. The duty of the pump decreased as a result of lower energy usage. The feed, reject and product flow rate for both manual calculations and ROSA calculations are slightly different because optimisation has been done to increase the recovery ratio and lower down the pressure requirement of the process. This results in a greater RO system efficiency hence a change in flowrate. The product total dissolve solid (TDS) are significantly different. 600 mg/L is a WHO safe drinkable water guideline hence the value was estimated as a benchmark. However, the results on the ROSA software exceeds the expectation of a high purity water with a value of only 73.76 mg/L. Therefore, further optimisation was carried out to increase the product TDS value so that it is close to benchmark standard while at the same time able to lower the energy requirement to achieve a more economical RO system using Excel software. While the TDS of the product is lowered, naturally, TDS of the reject will increase. The specific energy consumption from ROSA software is lower (9.7 kWh/m^3) than the calculated value which is 14.14 kWh/m^3, due to lower recovery rate and optimization. However, the value could be lowered if there is an implementation of ERD [16].

Table 3: Comparison of results between estimated value and ROSA simulation

Properties	Estimated value	ROSA simulation	Percentage difference (%)
Feed flow rate (m^3/day)	766,704	786,705	2.61
Product flow rate (m^3/day)	383,353	378,010	1.39
Reject flow rate (m^3/day)	383,353	408,695	6.61
Recovery ratio (%)	50	48.05	3.90
Product TDS (mg/L)	600	73.76	87.00
Reject TDS (mg/L)	71,091	68,258	4.00
Specific energy consumption (kWh/m^3)	14.14	9.7	31.4
Number of elements required	5,961	6,144	3.07
Number of vessels in 1st stage	583	512	12.18
Number of vessels in 2nd stage	413	512	23.97
Operating pressure (bar)	69	80	15.94
pH value	7	5.37	23.29

Figure 2 shows the feed flow data section of the ROSA software and the seawater quality of False Bay. It includes chemical composition, temperature, pH value. It was found that the TDS value around 35,000 mg/L. The seawater charge was balanced out between the cations and anions.



Water Type: Seawater with Conventional pretreatment, SDI < 5

COL_MAT_ID	Ions	mg/l	ppm CaCO3	meq/l	T...
1	Ammonium (NH4+ + NH3)	0.000	0.000	0.000	0....
2	Potassium (K)	403.210	515.587	10.312	4...
3	Sodium (Na)	10892.580	23689.820	473.796	1...
4	Magnesium (Mg)	1303.560	5361.797	107.236	1...
5	Calcium (Ca)	417.790	1042.390	20.848	4...
6	Strontium (Sr)	0.092	0.105	0.002	0....
7	Barium (Ba)	0.000	0.000	0.000	0....
8	Carbonate (CO3)	19.455	32.420	0.648	1...
9	Bicarbonate (HCO3)	28.223	23.132	0.463	2...
10	Nitrate (NO3)	1.534	1.237	0.025	1....
11	Chloride (Cl)	19596.050	27636.660	552.733	1...
12	Fluoride (F)	1.333	3.509	0.070	1....
13	Sulfate (SO4)	2786.926	2903.048	58.061	2...
14	Silica (SiO2)	0.000	n.a.	n.a.	0....
15	Boron (B)	4.495	n.a.	n.a.	n.a.

System pH: 8.90 System Temperature: 17.0 °C

☑ Specify Individual Solutes

Total Dissolved Solids: 35476.6 (mg/l)

Feed Parameters

Temperature: 17.0 °C

Flow Rate: 786705.0 m³/d

pH: 8.9

Charge Balance

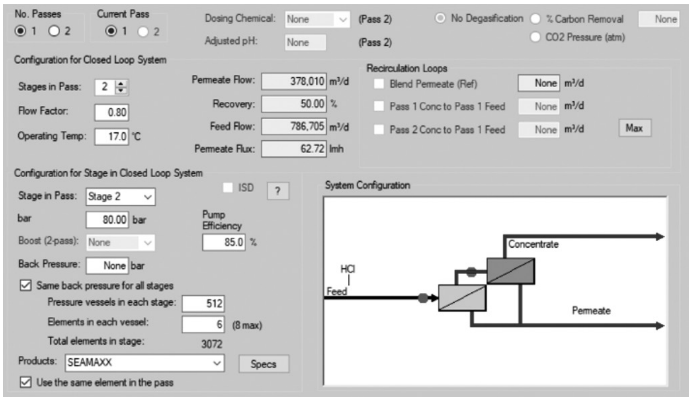
Cations: 612.19

Anions: 612.19

Balance: 0.00

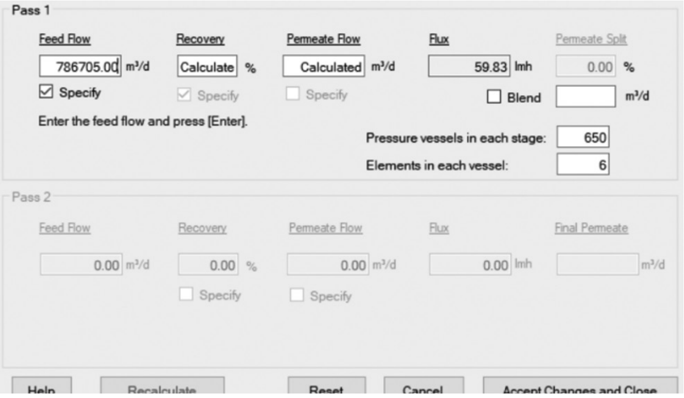
Figure 2: ROSA simulation water feed section

Stages and temperature was set as 2 and 17 °C, respectively for the vessels and element was set to the calculated number (Figures 3a and 3b). The RO process details, chemical compositions, stages and scaling reports are shown in Figures 4 and 5.



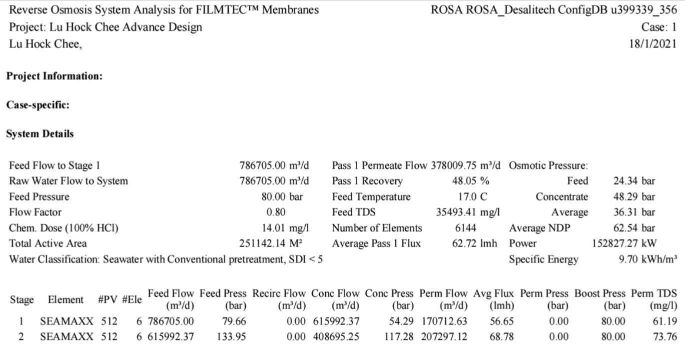
No. Passes: ● 1 ○ 2
Current Pass: ● 1 ○ 2
Dosing Chemical: None (Pass 2)
Adjusted pH: None (Pass 2)
● No Degasification ○ % Carbon Removal None
○ CO2 Pressure (atm)
Stages in Pass: 2
Flow Factor: 0.80
Operating Temp: 17.0 °C
Permeate Flow: 378,010 m³/d
Recovery: 50.00 %
Feed Flow: 786,705 m³/d
Permeate Flux: 62.72 lmh
☐ Blend Permeate (Ref) None m³/d
☐ Pass 1 Conc to Pass 1 Feed None m³/d
☐ Pass 2 Conc to Pass 1 Feed None m³/d
Stage in Pass: Stage 2
bar 80.00 bar
Pump Efficiency 85.0 %
Boost (2-pass): None
Back Pressure: None bar
☑ Same back pressure for all stages
Pressure vessels in each stage: 512
Elements in each vessel: 6 (8 max)
Total elements in stage: 3072
Products: SEAMAXX
☑ Use the same element in the pass

Figure 3 (a): System configuration section



Feed Flow: 786705.00 m³/d ☑ Specify
Recovery: Calculate % ☑ Specify
Permeate Flow: Calculated m³/d ☐ Specify
Flux: 59.83 lmh
Permeate Split: 0.00 % ☐ Blend m³/d
Enter the feed flow and press [Enter].
Pressure vessels in each stage: 650
Elements in each vessel: 6
Pass 2: Feed Flow 0.00 m³/d; Recovery 0.00 % ☐ Specify; Permeate Flow 0.00 m³/d ☐ Specify; Flux 0.00 lmh; Final Permeate m³/d

Figure 3 (b): Flow calculation matrix of ROSA software



Reverse Osmosis System Analysis for FILMTEC™ Membranes ROSA ROSA_Desalitech ConfigDB u399339_356
Project: Lu Hock Chee Advance Design Case: 1
Lu Hock Chee, 18/1/2021

Project Information:

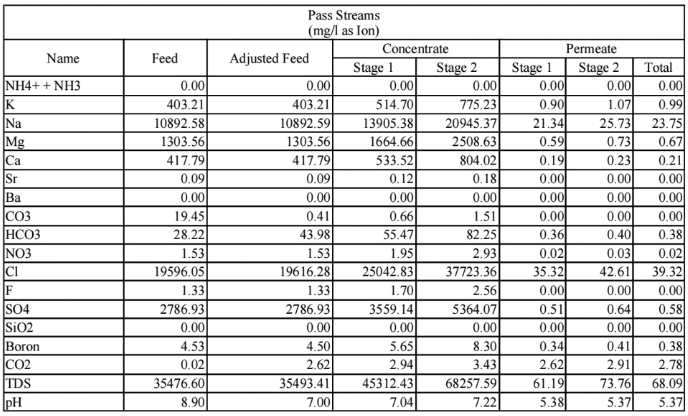
Case-specific:

System Details

Feed Flow to Stage 1	786705.00 m³/d	Pass 1 Permeate Flow	378009.75 m³/d	Osmotic Pressure:	
Raw Water Flow to System	786705.00 m³/d	Pass 1 Recovery	48.05 %	Feed	24.34 bar
Feed Pressure	80.00 bar	Feed Temperature	17.0 C	Concentrate	48.29 bar
Flow Factor	0.80	Feed TDS	35493.41 mg/l	Average	36.31 bar
Chem. Dose (100% HCl)	14.01 mg/l	Number of Elements	6144	Average NDP	62.54 bar
Total Active Area	251142.14 M²	Average Pass 1 Flux	62.72 lmh	Power	152827.27 kW
Water Classification: Seawater with Conventional pretreatment, SDI < 5				Specific Energy	9.70 kWh/m³

Stage	Element	#PV	#Ele	Feed Flow (m³/d)	Feed Press (bar)	Recirc Flow (m³/d)	Conc Flow (m³/d)	Conc Press (bar)	Perm Flow (m³/d)	Avg Flux (lmh)	Perm Press (bar)	Boost Press (bar)	Perm TDS (mg/l)
1	SEAMAXX	512	6	786705.00	79.66	0.00	615992.37	54.29	170712.63	56.65	0.00	80.00	61.19
2	SEAMAXX	512	6	615992.37	133.95	0.00	408695.25	117.28	207297.12	68.78	0.00	80.00	73.76

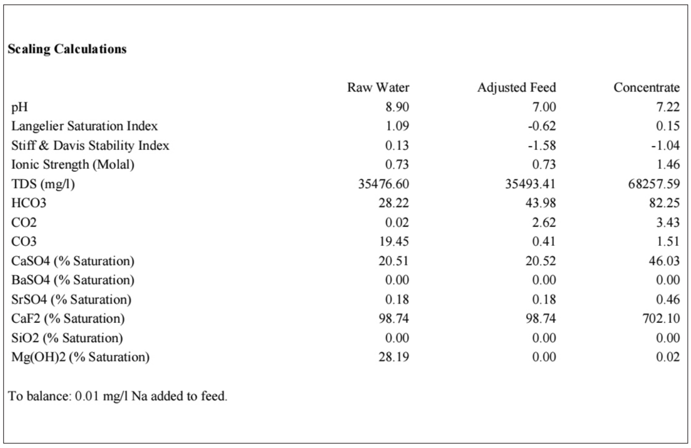
Figure 4 (a): RO process details



Pass Streams
(mg/l as Ion)

Name	Feed	Adjusted Feed	Concentrate		Permeate		
			Stage 1	Stage 2	Stage 1	Stage 2	Total
NH4+ + NH3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	403.21	403.21	514.70	775.23	0.90	1.07	0.99
Na	10892.58	10892.59	13905.38	20945.37	21.34	25.73	23.75
Mg	1303.56	1303.56	1664.66	2508.63	0.59	0.73	0.67
Ca	417.79	417.79	533.52	804.02	0.19	0.23	0.21
Sr	0.09	0.09	0.12	0.18	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO3	19.45	0.41	0.66	1.51	0.00	0.00	0.00
HCO3	28.22	43.98	55.47	82.25	0.36	0.40	0.38
NO3	1.53	1.53	1.95	2.93	0.02	0.03	0.02
Cl	19596.05	19616.28	25042.83	37723.36	35.32	42.61	39.32
F	1.33	1.33	1.70	2.56	0.00	0.00	0.00
SO4	2786.93	2786.93	3559.14	5364.07	0.51	0.64	0.58
SiO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Boron	4.53	4.50	5.65	8.30	0.34	0.41	0.38
CO2	0.02	2.62	2.94	3.43	2.62	2.91	2.78
TDS	35476.60	35493.41	45312.43	68257.59	61.19	73.76	68.09
pH	8.90	7.00	7.04	7.22	5.38	5.37	5.37

Figure 4 (b): Chemical compositions

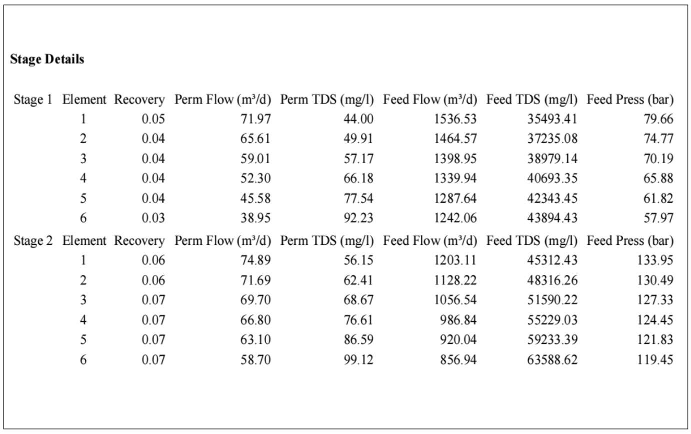


Scaling Calculations

	Raw Water	Adjusted Feed	Concentrate
pH	8.90	7.00	7.22
Langelier Saturation Index	1.09	-0.62	0.15
Stiff & Davis Stability Index	0.13	-1.58	-1.04
Ionic Strength (Molal)	0.73	0.73	1.46
TDS (mg/l)	35476.60	35493.41	68257.59
HCO3	28.22	43.98	82.25
CO2	0.02	2.62	3.43
CO3	19.45	0.41	1.51
CaSO4 (% Saturation)	20.51	20.52	46.03
BaSO4 (% Saturation)	0.00	0.00	0.00
SrSO4 (% Saturation)	0.18	0.18	0.46
CaF2 (% Saturation)	98.74	98.74	702.10
SiO2 (% Saturation)	0.00	0.00	0.00
Mg(OH)2 (% Saturation)	28.19	0.00	0.02

To balance: 0.01 mg/l Na added to feed.

Figure 5 (a): Stage details



Stage Details

Stage 1	Element	Recovery	Perm Flow (m³/d)	Perm TDS (mg/l)	Feed Flow (m³/d)	Feed TDS (mg/l)	Feed Press (bar)
	1	0.05	71.97	44.00	1536.53	35493.41	79.66
	2	0.04	65.61	49.91	1464.57	37235.08	74.77
	3	0.04	59.01	57.17	1398.95	38979.14	70.19
	4	0.04	52.30	66.18	1339.94	40693.35	65.88
	5	0.04	45.58	77.54	1287.64	42343.45	61.82
	6	0.03	38.95	92.23	1242.06	43894.43	57.97
Stage 2	Element	Recovery	Perm Flow (m³/d)	Perm TDS (mg/l)	Feed Flow (m³/d)	Feed TDS (mg/l)	Feed Press (bar)
	1	0.06	74.89	56.15	1203.11	45312.43	133.95
	2	0.06	71.69	62.41	1128.22	48316.26	130.49
	3	0.07	69.70	68.67	1056.54	51590.22	127.33
	4	0.07	66.80	76.61	986.84	55229.03	124.45
	5	0.07	63.10	86.59	920.04	59233.39	121.83
	6	0.07	58.70	99.12	856.94	63588.62	119.45

Figure 5 (b): Scaling calculations

3.2 Further Optimisation

To further optimise the process, an excel sheet was used to compare different parameters such as SEC, recovery rate, cost and temperature. Assumptions made during comparison were cost of each RO membrane was $769 (FILMTECTM MEMBRANES, 2020), efficiency of the pumps were set at 85%, product flow rate 383352.5 m^3/day, number of passes was 1, no back pressures and number of stages was compared with recovery and SEC. At each stage, the ROSA simulation was used to calculate its respective recovery % and SEC value while pressure, flowrate, temperature, number of elements and vessels were kept constant. Percentage ratio was obtained by dividing the respective recovery percentage with achievable recovery percentage. The last recovery stage was stage 5 and the optimum values are shown in Table 4. The optimum number of stages was roughly 2.5 stages ≈ 3 stages (Figure 6). Table 5 shows the pre and post optimisation results and technical drawing of the design membrane elements and vessels are shown in Figures 7 and 8.

Table 4: Number of Stage Optimisation using Excel

No. of stages	Recovery percentage	Percentage ratio	SEC (kWh/m^3)	% ratio
1	21.71	26.93	12.05	100.00
2	48.06	59.62	9.70	80.50
3	69.81	86.60	8.62	71.54
4	80.59	99.98	8.45	70.12
5	80.61	100.00	9.08	75.35

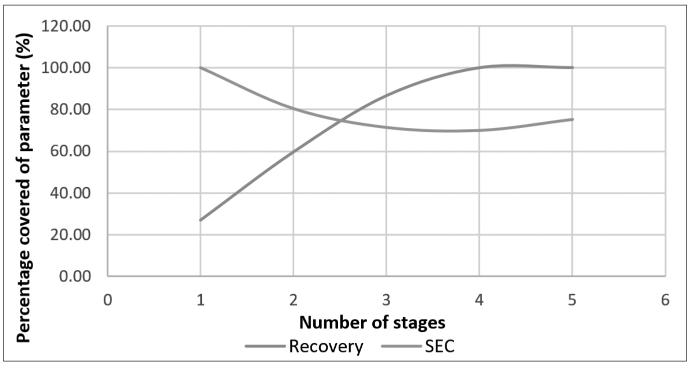


Figure 6: Optimal number of stages

Table 5: Pre and post optimisation results

Properties	ROSA simulation (pre-optimised)	ROSA simulation (post-optimised)	Changes
Number of stages	2	3	+1 stage
Operating pressure (bar)	80	66.5	-13.5 bar
Feed flow rate (m^3/day)	786,705	506,705	-280,000 (m^3/day)
Product flow rate (m^3/day)	378,010	384,417	+6,407 (m^3/day)
Reject flow rate (m^3/day)	408,695	122,288	+286,407 (m^3/day)
Recovery ratio (%)	48.05	75.87	+ 27.82%
Product TDS (mg/L)	74	181.13	+107.13 (mg/L)
Reject TDS (mg/L)	68,258	146,429	+78,171 (mg/L)
Specific energy consumption (kWh/m^3)	9.7	6.18	-3.52 (kWh/m^3)
Number of elements required	6144	8100	+1956
Cost of membranes ($)	4,7242,736	6,228,900	+41,013,836 ($)
Power (kW)	152585	98970	-53,615 (kW)

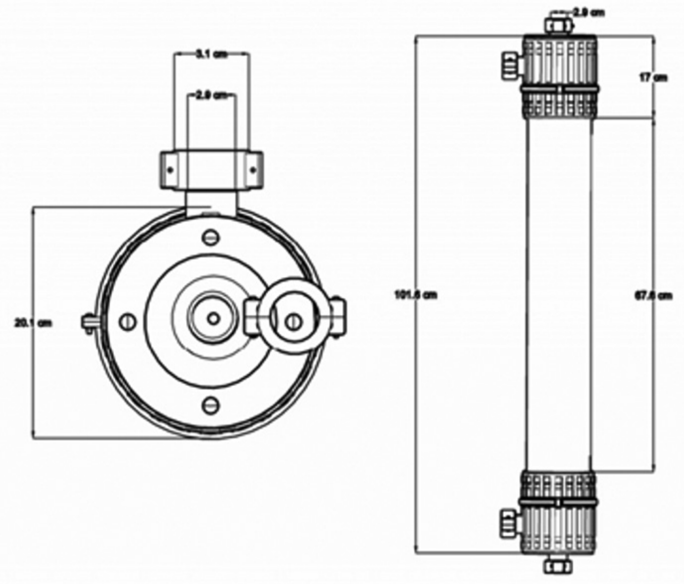


Figure 7: Technical drawing of a RO membrane element

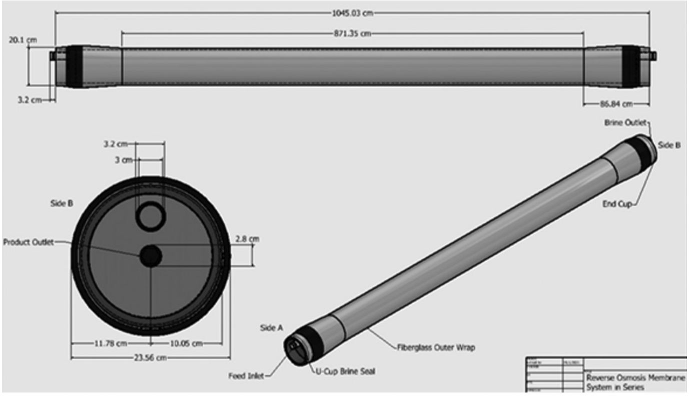


Figure 8: . Technical drawing of a RO vessel

4.0 CONCLUSIONS

A configuration of 3 stages, 1 pass and 6 elements in a vessel achieved an optimum efficiency using the ROSA software after post optimisation. Approximately 8,100 membrane elements were used so that the seawater feed flow of 506,705 m^3/day can achieve a production rate of 384,417 m^3/day and brine flowrate of 122,288 m^3/day. The recovery rate was 75.87 % and the final product TDS simulated was 181 mg/L. In addition, the specific energy requirement was as low as 6.18 kWh/m^3 and the total membrane active area was 251142.14 m^2 at an optimum temperature of 22.5 °C. ■

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