SEAWATER DESALINATION PLANT

Conceptual Design

Abstract

Australia is known to be one of the driest continent in the world. Droughts are well understood and they are integral part of everyday Australian life. In recent months, it was apparent that drought has returned and it continues to affect New South Wales and other the eastern states as Sydney's dam water levels are falling at a rapid rate since late 2017.To combat ongoing droughts and secure water supply to meet future demands from projected population growth, desalination plant is one of the key solutions to the water scarcity problem. Although it is the expensive solution compared to other solutions such as direct portable reuse, it is one of the most widely accepted solution due to the 'yuck', religion, negative public perception and other factors.This report is aimed to determine an optimal RO system design that can achieve boron level of 0.3 mg/L and key issues affecting the cuttlefish.

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Abbreviations

APF	Average Permeate Flux
BOM	Bureau of Meteorology
CIP	Clean In Place
DWEER	Dual Work Exchange Energy Recovery
MF	Microfiltration
NF	Nanofiltration
RO	Reverse Osmosis
TDS	Total Dissolved Solids
UF	Ultrafiltration
WHO	World Health Organization

1. BACKGROUND

Population growth, urbanisation, climate change and increasing community expectations on efficiency of services and use of resources are posing major challenges for authorities and water utilities.

A 2016 projection by NSW Department of Planning shows that Sydney population, with an average annual change of 1.5±0.3%, is expected to reach 6.5 million by 2036, Figure 1. With increased population projections and public awareness of the environment, current aging infrastructure, especially water supply infrastructure, will not have the capacity to meet the increased demands.

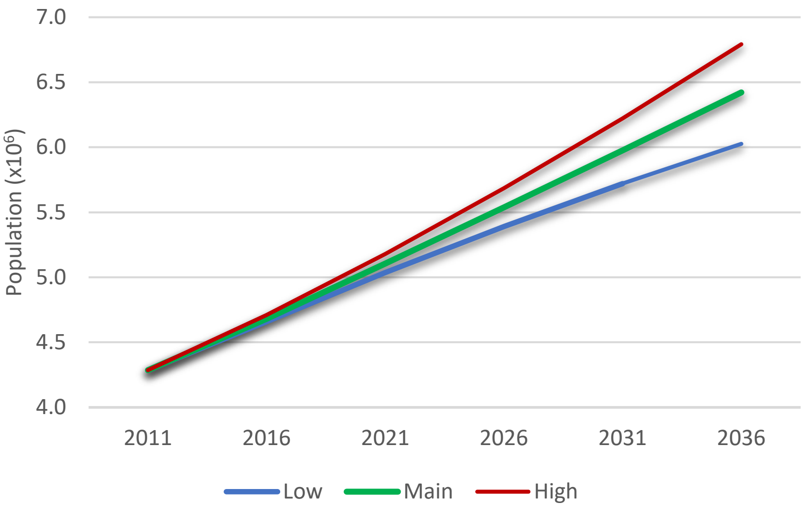


Figure 1: Sydney Population 2016 Projection (NSW DP&E, 2019)

Apart from Antarctica, Australia is known to be the driest continent in the world. Droughts are well understood and they are integral part of everyday Australian life. They can be intense, unpredictable and often have long lasting effects to communities across the country. The Millennium drought was the worst drought recorded in Australia since the European settlement. The event placed extreme pressure on urban water supply and completely changed the way water resources being treated at every community in the country.

Recent rainfall data from the Bureau of Meteorology (BOM) indicates that severe drought has returned with similar characteristics of Millennium drought patterns. Rainfalls in Sydney and other major cities were heading towards record low, especially in Brisbane, Melbourne and Adelaide, Figure 2.

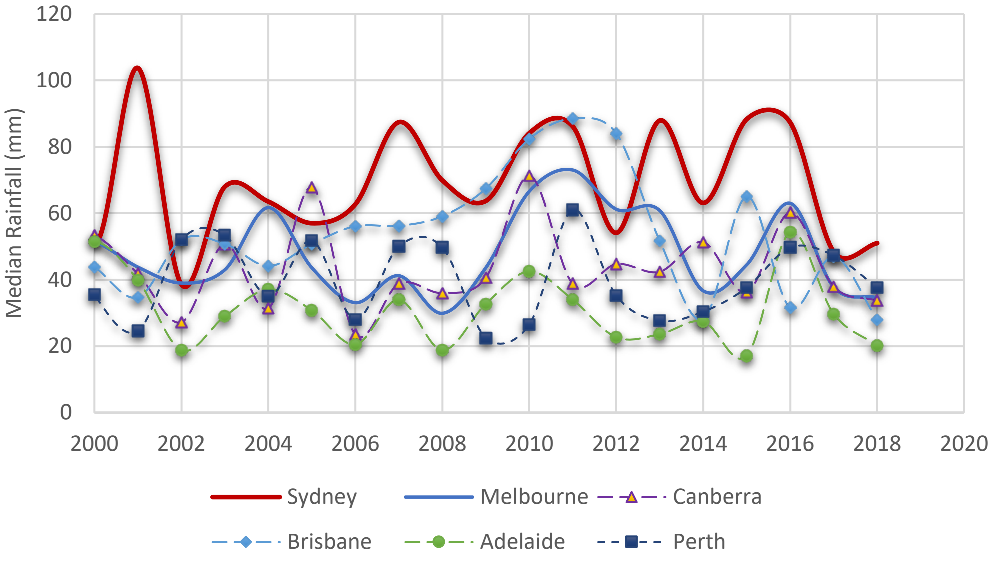


Figure 2: Median Rainfalls in Australia (Source: BOM)

Sydney Water is the largest water utility in Australia with extensive water and wastewater networks capable of servicing a population of more than 5 million people. Recent water storage and demand report indicates the total available water within the networks is fast approaching the 50% threshold. As drought continues to affect New South Wales and other the eastern states, Sydney's dam water levels are falling at a rapid rate since late 2017 compared to the previous declining rate notably between 2000 and 2004 during Millennium Drought, Figure 3Figure 3. Despite a number of existing water saving initiatives such as recycled water, water harvesting and water efficiency through BASIX, long-term drought is placing significant stress on Sydney's freshwater resources. Recent catastrophic problems in Murray-Darling system led to millions of native fishes killed and farmers are struggling to their feed livestock.

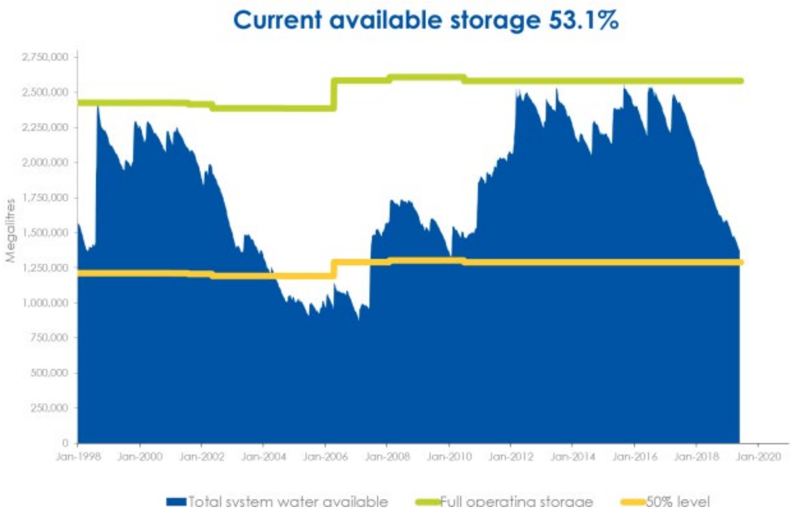


Figure 3: Greater-Sydney-water-storage-and-supply-report June 2019 (WaterNSW, 2019)

The combination of steady population growth and recurrence droughts places significant pressures on authorities and water utilities to find long-term solutions for water security and ensure reliable supply to increased demands.

On of the viable options for addressing water scarcity is direct potable reuse. However, like many other countries around the world, such as United States, Israel and other countries in the Middle East and North Africa, negative public perception of wastewater reuse undermines the implementation of the, otherwise economically and financially viable, direct potable reuse to secure long-term water supply.

The alternative water supply option to the controversial direct potable reuse is desalination in which reverse osmosis (RO) technology is used to extract fresh water from seawater. Although the option is more expensive due to its intensive energy demands in the RO process, it is more widely accepted by the public.

Since the first discovery of RO in the early 1950s and its development at commercial scale in late 1970s, RO technology has become more advanced and widely used in the water industry around the world. Renewable energy has also become more reliable and affordable which helps to reduce the energy demands of desalination plants.

This report examines the design process of a desalination plant, its environmental impacts, including boron and the cuttlefish, and the shut-down procedures.

2. DESALINATION PLANT DESIGN ASSESSMENT

2.1 Seawater Reverse Osmosis Design

There are several steps of extracting fresh water from seawater in the desalination plant using reverse osmosis membrane technology. Large materials are being filtered through the screening process as the raw seawater is drawn into the plant via a series of underground and undersea pipe networks. Seawater enters the plant through screens that filter out larger material. Smaller particles are then being filtered in the pre-treatment process before being pumped into the reverse osmosis treatment system where all the minerals and viruses are being removed. Following the reverse osmosis treatment, fluoride and minerals are added to the treated water and transferred to the holding facility ready for distribution to the drinking water networks. These steps can be grouped into 4 main stages namely Seawater Intake, Pre-Treatment, RO and Drinking Water Treatment. These stages are described below and illustrated in Figure 4.

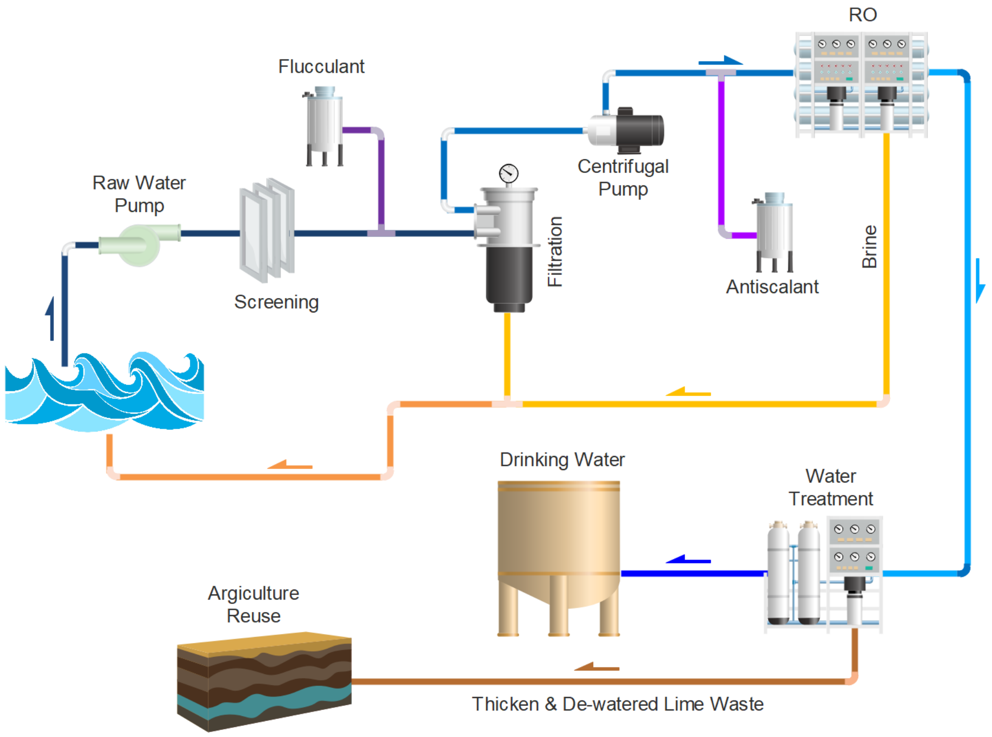


Figure 4: Conceptual RO Process Flow Diagram

3.1.1. Seawater Intake

The seawater intake components consist of risers, gate valve, drum screens, artificial reefs around the inlet structures and concrete tunnel to transfer the water.

The inflow velocity through the intake risers is regulated and controlled at constant 0.1 m/s rate such that it is not exceeding the surrounding currents to prevent marine life from being drawn into the inlet risers and concrete tunnel. Drum screens are used to filter out materials greater than 3 millimetres (Sydney Desalination Plant, 2019).

3.1.2. Pre-Treatment

The pre-treatment process is generally a filtration process where seawater, with added flocculant, is being filtered through a series of Dual Media filters, cartridges filters and layers of filter coal and sand. Centrifugal & high-pressure pumps are used to pump filtered water to the RO system (Sydney Desalination Plant, 2019).

3.1.3. Reverse Osmosis

The RO with automatic Clean in Place (CIP) system is a 2-pass system. At the end of each first pass train, Dual Work Exchanger Energy Recovery (DWEER) devices are installed recover energy in the reject stream. Water pressure is elevated to approximately 5 bar and 60 bar using centrifugal and high-pressure pumps, respectively. The rejection is returned to the ocean via special designed outlet nozzles to neutralise the salinity and temperature of the returned water within 50 to 75 metres of the outlets (Sydney Desalination Plant, 2019).

3.1.4. Drinking Water Treatment

Following the RO treatment process, to ensure compliance with Australian Drinking Water Guidelines, fluoride and minerals are added to the treated seawater. Further testing and disinfection are required to ensure public safety prior to distribution to the drinking water networks. Lime waste from the treatment process is thickened, de-watered and distributed to industries such as agriculture for reuse (Sydney Desalination Plant, 2019).

2.2 Detailed RO Process Design

3.2.1. Key Design Parameters

Plant Capacity:	500,000 m^3/d
Feed Water Quality:	35,000 mg/L TDS
APF:	20L/m^2/h
Salt Rejection:	>95%
Membrane Area:	37 m^2/element
Applied Pressure:	10 bar
Feed Flow Rate (Q_f):	500,000 m^3/d
Recovery Rate (R):	80%

3.2.2. Detailed Design

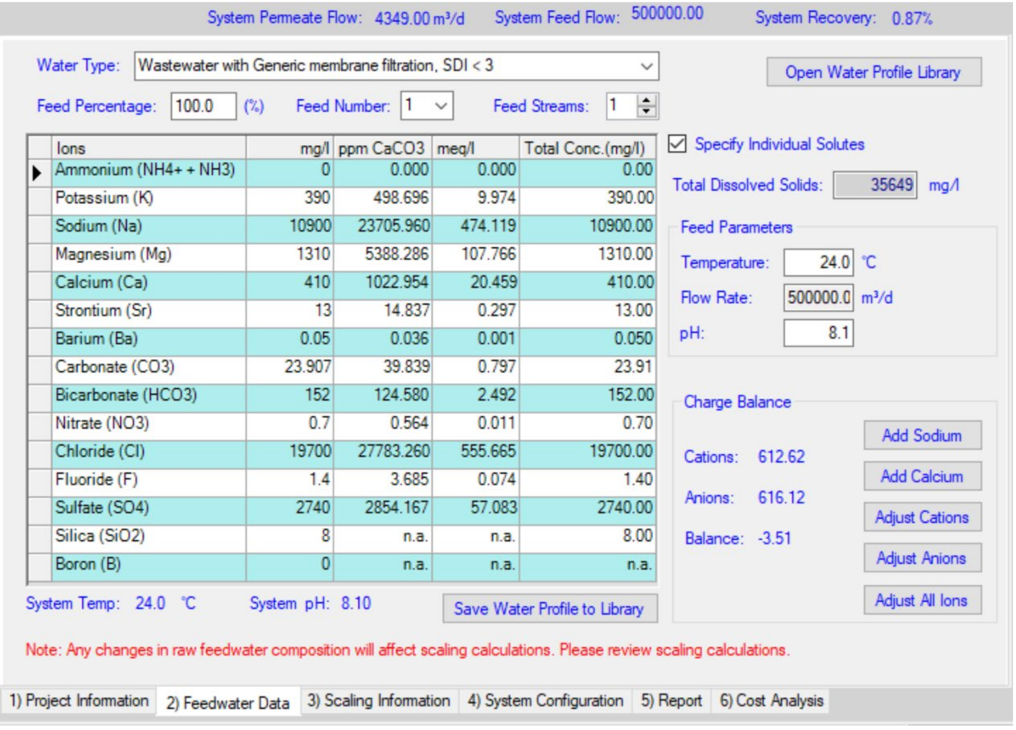
Step	Description	Value
1	Feed Water Quality:	SDI<3 ; Table 1
2	Flow Configuration:	Plug Flow, Double Pass System
3	Membrane & Element:	BW30HR-440i, 40.9m^2 Active Area
4	Average Membrane Flux:	22 L/m^2/h
5	Number of Elements*:	23,154
6	Number of Pressure Vessels:	23,154÷6 = 3,859
7	Number of Stages:	2
8	Staging Ratio:	2:1

$$\text{*Number of Elements} = \frac{Q_f \div 24}{AMF \times 10^{-3}} \div \text{Active Area} = \frac{500{,}000 \div 24}{22 \times 10^{-3}} \div 40.9 = 23{,}154$$

Ion	Concentration (mg/L)
Calcium:	410
Magnesium:	1,310
Sodium:	10,900
Potassium:	390
Barium:	0.05
Strontium:	13
Iron:	<0.02
Manganese:	<0.01
Silica:	0.04-8
Chloride:	19,700
Sulfate:	2,740
Fluoride:	1.4
Bromide:	65
Nitrate:	<0.7
Bicarbonate:	152
Boron:	4-5
TDS:	35,000
pH:	8.1

Table 1: Seawater Composition

3.2.3. *ROSA Design*



System Permeate Flow: 4349.00 m³/d System Feed Flow: 500000.00 System Recovery: 0.87%

Water Type: Wastewater with Generic membrane filtration, SDI < 3

Feed Percentage: 100.0 (%) Feed Number: 1 Feed Streams: 1

Ions	mg/l	ppm CaCO3	meq/l	Total Conc.(mg/l)
Ammonium (NH4+ + NH3)	0	0.000	0.000	0.00
Potassium (K)	390	498.696	9.974	390.00
Sodium (Na)	10900	23705.960	474.119	10900.00
Magnesium (Mg)	1310	5388.286	107.766	1310.00
Calcium (Ca)	410	1022.954	20.459	410.00
Strontium (Sr)	13	14.837	0.297	13.00
Barium (Ba)	0.05	0.036	0.001	0.050
Carbonate (CO3)	23.907	39.839	0.797	23.91
Bicarbonate (HCO3)	152	124.580	2.492	152.00
Nitrate (NO3)	0.7	0.564	0.011	0.70
Chloride (Cl)	19700	27783.260	555.665	19700.00
Fluoride (F)	1.4	3.685	0.074	1.40
Sulfate (SO4)	2740	2854.167	57.083	2740.00
Silica (SiO2)	8	n.a.	n.a.	8.00
Boron (B)	0	n.a.	n.a.	n.a.

☑ Specify Individual Solutes

Total Dissolved Solids: 35649 mg/l

Feed Parameters

Temperature: 24.0 °C

Flow Rate: 500000.0 m³/d

pH: 8.1

Charge Balance

Cations: 612.62

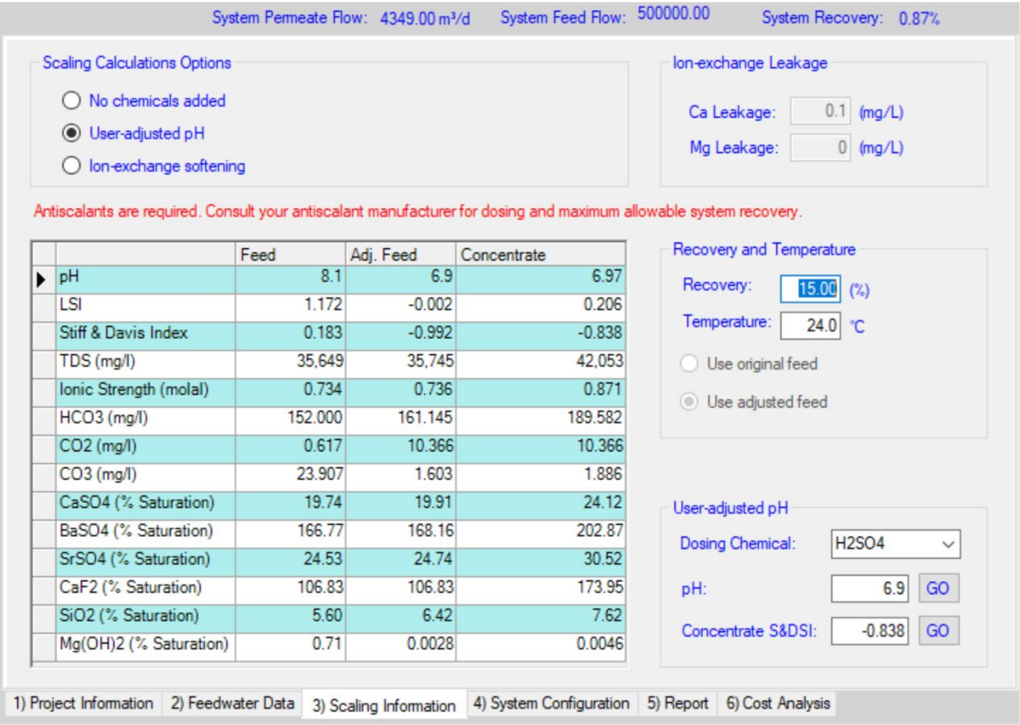
Anions: 616.12

Balance: -3.51

System Temp: 24.0 °C System pH: 8.10

Note: Any changes in raw feedwater composition will affect scaling calculations. Please review scaling calculations.

Figure 5: Feedwater Data



System Permeate Flow: 4349.00 m³/d System Feed Flow: 500000.00 System Recovery: 0.87%

Scaling Calculations Options

○ No chemicals added

● User-adjusted pH

○ Ion-exchange softening

Ion-exchange Leakage

Ca Leakage: 0.1 (mg/L)

Mg Leakage: 0 (mg/L)

Antiscalants are required. Consult your antiscalant manufacturer for dosing and maximum allowable system recovery.

	Feed	Adj. Feed	Concentrate
pH	8.1	6.9	6.97
LSI	1.172	-0.002	0.206
Stiff & Davis Index	0.183	-0.992	-0.838
TDS (mg/l)	35,649	35,745	42,053
Ionic Strength (molal)	0.734	0.736	0.871
HCO3 (mg/l)	152.000	161.145	189.582
CO2 (mg/l)	0.617	10.366	10.366
CO3 (mg/l)	23.907	1.603	1.886
CaSO4 (% Saturation)	19.74	19.91	24.12
BaSO4 (% Saturation)	166.77	168.16	202.87
SrSO4 (% Saturation)	24.53	24.74	30.52
CaF2 (% Saturation)	106.83	106.83	173.95
SiO2 (% Saturation)	5.60	6.42	7.62
Mg(OH)2 (% Saturation)	0.71	0.0028	0.0046

Recovery and Temperature

Recovery: 15.00 (%)

Temperature: 24.0 °C

○ Use original feed

● Use adjusted feed

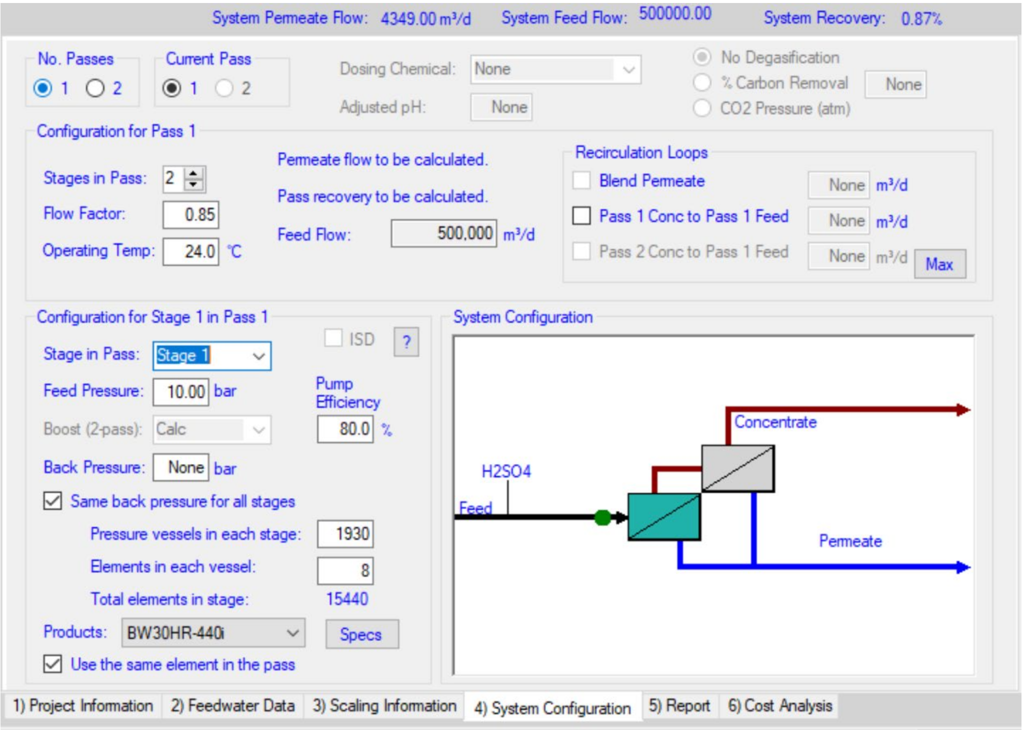
User-adjusted pH

Dosing Chemical: H2SO4

pH: 6.9

Concentrate S&DSI: -0.838

Figure 6: Scaling



System Permeate Flow: 4349.00 m³/d System Feed Flow: 500000.00 System Recovery: 0.87%

No. Passes: ● 1 ○ 2

Current Pass: ● 1 ○ 2

Dosing Chemical: None

Adjusted pH: None

● No Degasification
○ % Carbon Removal None
○ CO2 Pressure (atm)

Configuration for Pass 1

Stages in Pass: 2

Flow Factor: 0.85

Operating Temp: 24.0 °C

Permeate flow to be calculated.

Pass recovery to be calculated.

Feed Flow: 500,000 m³/d

Recirculation Loops

☐ Blend Permeate None m³/d
☐ Pass 1 Conc to Pass 1 Feed None m³/d
☐ Pass 2 Conc to Pass 1 Feed None m³/d

Configuration for Stage 1 in Pass 1

☐ ISD

Stage in Pass: Stage 1

Feed Pressure: 10.00 bar

Pump Efficiency: 80.0 %

Boost (2-pass): Calc

Back Pressure: None bar

☑ Same back pressure for all stages

Pressure vessels in each stage: 1930

Elements in each vessel: 8

Total elements in stage: 15440

Products: BW30HR-440i

☑ Use the same element in the pass

Figure 7: Configuration

2.3 Boron Removal

Naturally occurring chemical element, boron is also known as a "Metalloid" element. It is a combination of oxygen and borates which are widely found in oceans, sedimentary rocks, shale, some soils and coal (GreenFacts, 2019).

In laboratory animals, the male reproductive system is a consistent target of toxicity with signs of testicular lesions when being orally exposed to boric acid or borax in food or drinking water. In human, daily intake of Boron greater than 5 mg can cause symptoms such as nausea, vomiting, diarrhoea and, in some cases, blood clotting. The lethal doses of boric acid in human have been reported to be 29 mg/kg, 640 mg/kg and 8600 mg/kg of body weight when subject to intravenous injection, oral and dermal intakes respectively (WHO, 2009).

The average concentration Boron in the oceans is 4.5 mg/l. For drinking water, the World Health Organization recommends a Boron concentration below 0.5 mg/L (WHO, 2009). In desalination process, boron removal has been widely studied around the world. Generally, Boron can be removed by ion exchange, through RO membranes or sorption–membrane filtration hybrid processes. Ion exchange is a method commonly used in diluted water streams and seawater streams with low salt concentrations (Güler, E. et al., 2014). Considering the high concentration of Boron in seawater, this section of the report examines boron removal only in RO membranes and sorption–membrane filtration hybrid processes.

3.3.1. Factors Influence Boron Rejection

Busch, M. et al., 2003, determined that feed water, membrane element and systemdesign are the thee main aspects of RO in which Boron rejection is being influenced. The possible factors in each of these three aspects include (Busch, M. et al., 2003):

- pH, water temperature & TDS
- Chemistry of membranes & efficiency of elements
- APF, concentration polarisation system recovery & cleanings

3.3.2. Removal of boron by membrane processes *(Güler, E. et al., 2014)*

Despite the above factors influencing boron rejection, the main factors are pH and water temperature. The typical standard High Rejection Seawater Reverse Osmosis membranes can achieve between 73% and 90% removal rates at pH 8, depending on the water temperature, Figure 6. A removal rate of 95% or higher can also be achieved using Special High Boron Removal membrane (Lenntech, 2019).

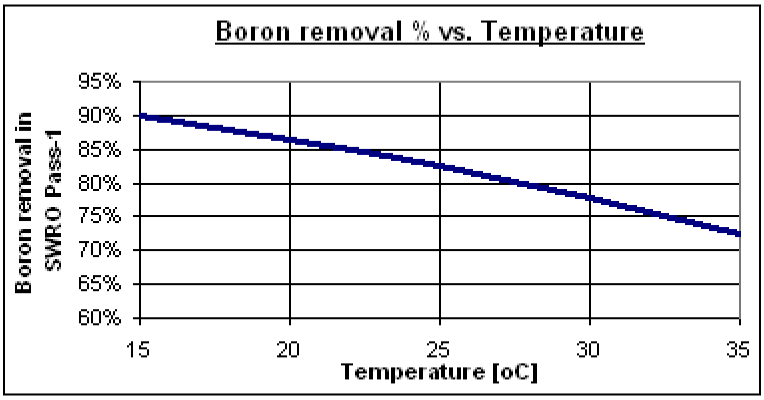


Figure 8: Boron removal rates at pH 8 (Lenntech, 2019)

Güler, E. et al., (2014) indicated that up to up to 84.6% and 87.7% of boron rejection rates can be achieved by using conventional SWRO membranes and high rejection membranes, such as FILMTEC XUS SW30-XHR-2540, respectively. Under a two-pass configuration and without pH adjustment, a 96% boron rejection rate can be achieved using new generation RO membranes (Güler, E. et al., 2014).

There are two options for a two-pass RO system, a full second pass and partial second pass. As the name suggests, in a full second pass design option, 100% of permeate is treated by second pass RO. In this design option, the typical first pass to second pass recovery ratio is 50%:90% and a total 47% with second pass brine recycle. In partial second pass design option, only a portion of the first pass permeate is treated by the second pass and permeate from both passes is blended together. The first and second pass recovery ratio is similar to that of the full second pass design option except for a total recovery of 48.5% with second pass brine recycle. The partial second pass option offers smaller second pass trains, higher total system recovery and lower capital and maintenance costs due to smaller footprints, less number of pressure vessels and membranes and less high pressure piping and fittings (Rybar, S. et al., 2010).

3.3.3. Removal of boron by sorption–membrane filtration hybrid processes

Sorption–membrane filtration hybrid processes are the combined ion exchange and membrane filtration process in which first boron elements are adsorbed by ion exchangers and then membrane filtration, either UF or MF, is used to separate the boron loaded resins from water. Under this system, the main advantage, compared with conventional fixed bed ion exchange processes, is the fast adsorption kinetics of the ion exchange resins, therefore ion exchange efficiency, with small particle size without any significant pressure drop which could translate to lower operational costs (Güler, E. et al., 2014). However, these processes are typically used in high purity applications where boron and other weak acids will be removed to a level of <0.1 mg/L, far below the standard 0.3 mg/L limit for drinking water. Alternatively, these processes are better suit existing treatment plants that were designed without any boron removal process to achieve new boron stringent limits (Busch, M. et al., 2003).

2.4 Impact of Brine Disposal on Cuttlefish

Australian waters are the home of many unique marine species including the Giant Cuttlefish, Sepia apama, which is the world largest cuttlefish species. They can be found from Moreton Bay on the east-coast and on the west-coast up to Ningaloo Reef, Figure 8, (Australian Museum, 2019). From economic perspectives, cuttlefishes are financial opportunities for fisheries, food and pet businesses as well as recreational and ecotourism businesses such as scuba diving and snorkelling.

Cuttlefishes have a relatively short lifespan between two and four years and they are subject to seasonal change in water temperature and conditions. Changes in water conditions and temperature as a direct and indirect result of local industrialisation can cause significant ecological impacts to many marine species including the cuttlefish. Industries such as steelworks, fish farming and seawater desalination are known to be the main source of nutrient pollution in the water.

In relation to seawater desalination, the main problem is the by-product from the treatment processes, which is a high salt concentrated effluent known as brine, being discharged into the ocean. Brine is generally known as water with salt concentration greater than 50 parts per thousand. The optimal salinity level for development of cuttlefish embryos is 28 to 38 parts per thousand (Beeton, 2011). Discharges from desalination plants also affect the dissolved oxygen levels in the water due to the heat treatment causing water temperature to increase. Brine can also contain high concentrations of heavy metals such as lead, copper, zinc and manganese which are toxic to the environment (Dupavillon, J. et al., 2009).

Photo 1: Giant Cuttlefish at Kurnell NSW

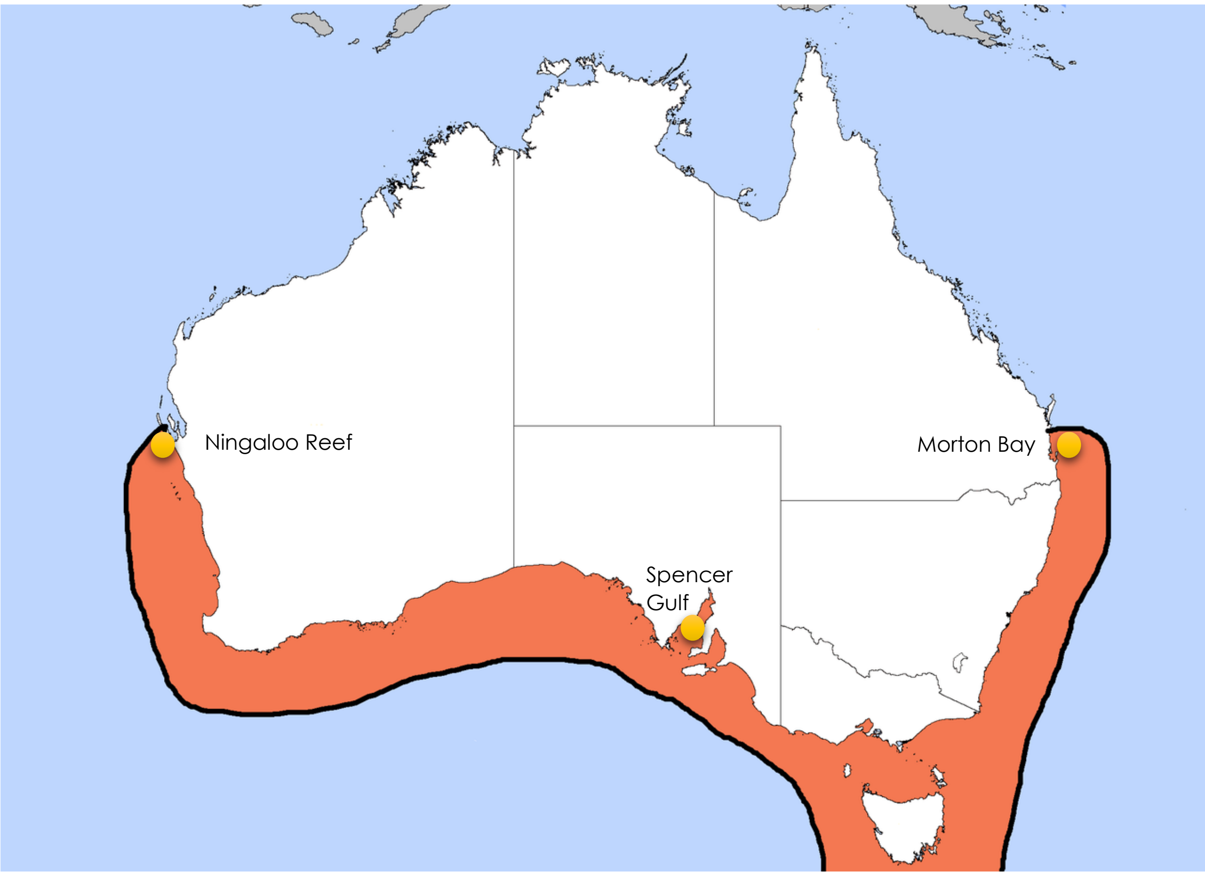


Figure 9: Giant Cuttlefish Distribution (Wikipedia, 2019)

Increases in salinity and water temperature lead to detrimental effects on the embryonic development of the cuttlefish. A study of estuarine crab shown a direct correlation of increased salinity, smaller embryos and egg sizes. The species developed from smaller eggs will have greater physical constraints limiting their ability in swimming and food capturing which reduce their overall chance of survival (Dupavillon, J. et al., 2009).

South of Port Augusta in South Australia, Sundrop Farms expanded their vegetable growing business by constructing a new seawater desalination plant 2016 which has a potential brine concentration of 60 parts per thousand putting the local Upper Spencer Gulf cuttlefish population at risk (Monceaux, 2015). This level of brine concentration will affect the cuttlefish's cephalopod growth rates and dehydration of their eggs.

3. SHUT-DOWN PLANT OF A DESALINATION PLANT

In Sydney, the desalination plant was designed as a backup water supply during drought period. When dam levels rise and conventional water supply systems have exceeded their minimum optimal capacity, i.e. 60% or higher, the desalination plant needs to be shutdown. Proper shutdown procedures must be correctly followed to ensure the elements won't be dried out and the system has adequate protection against bacteria growth. In general, the two main aspects of shutting down a desalination plant are permeate flushing and bacteria growth prevention.

3.1 Permeate Flushing

When shutting down the membrane systems, the salt concentration in the feed water is likely to increase to a level exceeding its solubility. Flushing is, therefore, crucial to remove highly concentrated salt from the vessels using permeate water at low pressure about 3 bar for approximately 15 to 20 minutes. This should be sufficient time for the balance between conductivity out and conductivity in (ROChemicals, 2018).

To prevent scale inhibitors, the water used for flushing the vessels should not contain any chemicals. The feed valves are to be completely closed. To prevent the backpressure from damaging the membrane, a static permeate backpressure must be limited to0.3 bar at all time. In the permeate line, check valves can be used to safeguard the membrane (Applied Membranes, 2007).

3.2 Bacteria Growth Prevention

Biological growth in the RO system must be carefully controlled by using suitable chemical disinfectant or non-oxidising, non-ionic biocides kill bacteria, control biofouling and prevent re-growth. Application rates and frequency of disinfectant/biocides application will be depended on the biological loading and biofilm growth rate (ROChemicals, 2018).

4. CONCLUSIONS AND RECOMMENDATIONS

Australia is known to be one of the driest continent in the world. Droughts are well understood and they are integral part of everyday Australian life. In recent months, it was apparent that drought has returned and it continues to affect New South Wales and other the eastern states as Sydney's dam water levels are falling at a rapid rate since late 2017.

To combat ongoing droughts and secure water supply to meet future demands from projected population growth, desalination plant is one of the key solutions to the water scarcity problem. Although it is the expensive solution compared to other solutions such as direct portable reuse, it is one of the most widely accepted solution due to the 'yuck', religion, negative public perception and other factors.

To ensure successful implementation of the desalination plant, proper studies to be carried out to determine potential short and long-term environmental impacts of such project. Endemic native marine species such as cuttlefishes are sensitive to change in water temperature and conditions. Concentrated brine can affect the embryonic development of the cuttlefish. Brine should be diluted to reduce concentration to around 28 to 38 parts per thousand within the cuttlefish habitats.

A two-pass RO system is to be designed such that boron level is 0.3 mg/L suitable for drinking as recommended by the WHO.

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