 © IWA Publishing 2010 Journal of Water Supply: Research and Technology—AQUA | 59.6–7 | 2010

Practical Paper

Cost effective way to harvest estuarine water: variable salinity desalination concept

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ABSTRACT

Singapore, a small island city-state with some 700 km^2 in land area and a population of 4.5 million, is always looking for innovative ways to find new water sources to meet its growing need for water. Rain falling in the urban fringe catchments is not harvested; these areas experience bouts of heavy rain but dry up during the dry season and, as such, the conventional approach of constructing large dams for storage to support large water treatment plants is not economically viable. This paper explores the viability of a newly developed variable salinity water desalination treatment plant to harvest water from estuarine catchments. The plant is able to treat estuarine waters which vary gradually from low salinity river water into high salinity seawater. When the river water has high salinity or dries up, treatment is maintained with the plant operating in seawater desalination mode instead of remaining idle, thus affording high plant utilisation. The treated water is of high grade with energy consumption half that of seawater desalination plants. The average unit production and capital cost of such variable salinity desalination plants is significantly lower than that of seawater desalination plants.

Key words | desalination, estuaries, membranes, sea, variable salinity, water production

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INTRODUCTION

High population density in towns and cities needs to be supported by clean water. Singapore is an island city-state with some 700 km^2 of land area and a population of 4.5 million. It has to continually seek new water resources to meet its growing population and increasing demand for clean water. The mainstay of raw water supply for Singapore is the water catchments, which will be expanded to occupy approximately two-thirds of the island in 2011. The remaining part of the island consists of small catchments around the fringes which experience bouts of heavy rain that reduces to a trickle or dries up during the dry season. Rain falling in the fringe catchments is currently not harvested and flows into estuaries and sea.

Feasibility studies showed that using conventional treatment concepts to harvest water from the fringe estuarine catchments is not viable. Small reservoirs were only able to provide small reliable yields and support very small water treatment plants. The low storage capacities resulted in high loss of storm water. Unit production cost was high and exceeded that of desalination plants.

On the other hand, large capacity water treatment plants suffered from low plant utilisation as only about 20% of the days in the year have heavy rainfall which usually lasts for a few hours. Insufficient water during the dry season means the large plants will have low utilisation resulting in high overall unit cost which is greater than that of desalination.

doi: 10.2166/aqua.2010.011

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The variable salinity water desalination (VSD) concept allows medium-sized water treatment plants to be built and operated at high plant utilisation, providing a balance between the extremes as described earlier. Adjustable weirs can be constructed across the mouths of canals and rivers to maximise fresh water harvesting. In the absence of fresh water, the plant will switch its operation mode to treat seawater. The VSD concept hence provides flexibility in terms of the source of feedwater that can be treated, which greatly enhances plant utilisation. Besides, by treating brackish water, at significantly lower salinity, when it is available, the average unit production cost and capital cost of such VSD plants would be significantly lower than desalination plants that treat high salinity seawater all the time.

If successful, such VSD plants will enable Singapore to tap the surface runoff from the remaining third of the island and increase its water catchments to 90% of the island.

DEVELOPMENT OF THE VSD PLANT

The variable salinity technique R&D started with a pilot scale VSD plant of 240 m^3/d (seawater) in 2004 to test the feasibility of the concept, which was the first of its kind. The pilot plant incorporated microfiltration for pre-treatment before reverse osmosis (RO) membranes for the final product water that meets WHO and USEPA Drinking Water Guidelines and Standards, respectively. The pilot testing was successful with reduced chemical usage for pH correction, anti-scaling in RO and bio-fouling. This led to a medium-sized demonstration plant of projected production capacity at 4,500 m^3/day (seawater desalination mode) and 9,000 m^3/day (brackish water desalination mode) located at Pasir Ris, along Tampines River, to treat water with widely variable salinity (brackish water and seawater), producing potable water. Figure 1 shows the location of the VSD demonstration plant. The urban catchment is about 730 ha for fresh water abstraction. Currently the product water is supplied to supplement existing NEWater supply. NEWater is Singapore's high-grade reclaimed water from secondary effluent.

The VSD plant comprises four stages of treatment, screening, microfiltration, reverse osmosis and disinfection, as shown in Figure 2. These stages are common to both seawater and brackish water operation.

Screening

- 6 mm autorake for removal of large objects.
- 1 mm drum screen (separate drum screens for seawater and brackish water process streams) before MF (microfiltration) feed tank.
- 100 μm autostrainer (before MF).

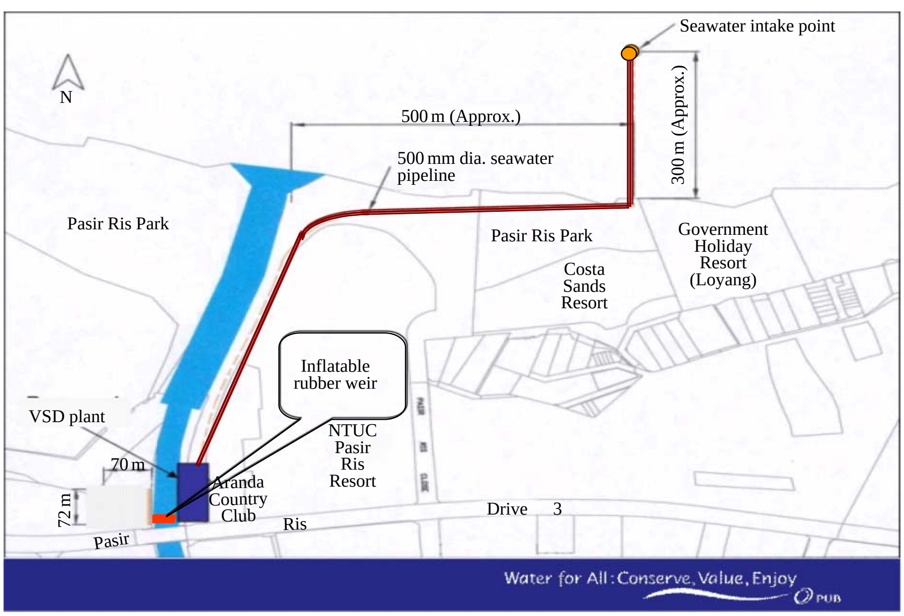

Figure 1 | Site plan of variable salinity desalination plant at Tampines River.

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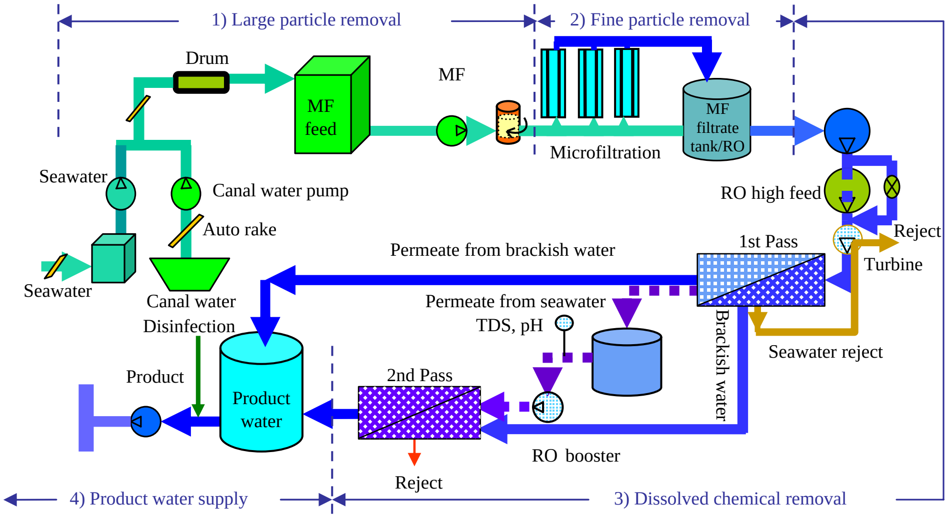

Figure 2 | VSD plant treatment processes.

Microfiltration

- Pressurised MF system, with both seawater and brackish water process streams using the same membranes.
- PVDF membrane with pore size 0.1 μm for removal of suspended solids and some colloidal particles to ensure consistent RO feedwater quality of less than 0.1 NTU and SDI <3.
- MF system includes sodium hypochlorite injection during backwash for disinfection and to mitigate MF fouling.

Reverse osmosis

- For removal of dissolved salts (TDS) and organics to ensure that the product water is well within WHO and USEPA Drinking Water Guidelines and Standards respectively.
- SWRO and BWRO membranes are common to both seawater and brackish water operation:
  - Seawater operation: 2-pass system, 1st pass (single stage) uses SWRO membrane, 2nd pass (2-stage) uses BWRO membrane.
  - Brackish water operation: Single pass, 3-stage system, 1st stage uses SWRO membrane, 2nd and 3rd stages use BWRO membrane.

Disinfection

Disinfection via sodium hypochlorite dosing is an added safety barrier before the water is pumped into the distribution pipelines.

RESULTS AND DISCUSSION

Water quality

The product water is well within World Health Organisation (WHO) Drinking Water Guidelines and the United States Environmental Protection Agency (USEPA) Drinking Water Standards. The typical feedwater and product water qualities are provided in Tables 1 and 2, respectively.

Energy consumption and production cost

The VSD plant treated brackish water with TDS that varied from 30 to 250 ppm and seawater with TDS that varied from 30,000 to 35,000 ppm. In both modes, the plant was able to produce potable water that meets the WHO and USEPA Drinking Water Guidelines and Standards, respectively.

The overall production cost of the VSD plant is about half that of a seawater desalination plant and power

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Table 1 | Feedwater characteristics at the VSD plant

Water quality parameters	Seawater feed	Brackish water feed
Physical		
Turbidity (NTU)	2.0–18.0	2.3–65
Conductivity ($\mu S\,cm^{-1}$)	37,000–42,000	33–426
pH value	7.4–7.9	7.2–7.9
Total dissolved solids ($mg\,l^{-1}$)	30,000–35,000	27–256
Total suspended solids ($mg\,l^{-1}$)	4–54	47
Total organic carbon ($mg\,l^{-1}$)	1.5–4.7	2–7.36
Total alkalinity ($CaCO_3$) ($mg\,l^{-1}$)	$<$20	
Total hardness ($CaCO_3$) ($mg\,l^{-1}$)	4,600–5,800	13–83
Chemical ($mg\,l^{-1}$)		
Ammonia (as NH_3)	$<$0.6	$<$0.1
Bicarbonate as $CaCO_3$	92–100	35.4
Chloride (Cl)	14,000–17,000	1.2–69
Fluoride (F)	1.6–4.1	$<$0.5
Nitrate (NO_3)	0.3–1.3	0.24–1.87
Silica (SiO_2)	$<$1.5	2.5–10
Sulphate (SO_4)	2,500–3,100	2.1–38
Residual chlorine (Cl, total)	$<$2	0.05–0.44
Total trihalomethanes (as $mg\,l^{-1}$)	$<$0.08	
Metal ($mg\,l^{-1}$)		
Aluminium	$<$0.1	0.11–1.2
Barium (Ba)	$<$0.01	0.009–0.04
Boron (B)	3.7–4.2	0–0.23
Calcium (Ca)	250–350	4.1–25
Copper (Cu)	$<$0.05	0.004–0.006
Iron (Fe)	$<$0.06	0.15–1.99
Sodium (Na)	7,000–11,000	0.6–41
Strontium (Sr)	3.0–6.5	0.01–0.14
Zinc (Zn)	$<$0.1	0.02–0.06
Bacteriological		
Total coliform bacteria 35°C @ 24 h (cfu/100 ml)	31–3,900	2,000–62,000
Faecal coliform (cfu/100 ml)	4–168	40–3,000

consumption is less than half of that required for seawater desalination. This was achieved between January and December 2008 when the plant was treating brackish water 60% of the time and seawater the remaining 40% of the time. The energy consumption figures are shown in Table 3.

The energy consumption figures underscore one of the primary advantages of the variable salinity plant: the ability to treat both seawater and brackish water has reduced the unit energy consumption to a much lower level than that of a typical seawater desalination plant. With energy consumption being the major cost component of a desalination plant, lower energy consumption means that the production costs are reduced tremendously, thus the VSD plant is an attractive and viable option in terms of production costs.

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Table 2 | Product water quality

Water quality parameters	SW mode	BW mode	USEPA/WHO Standards (2007)
Turbidity (NTU)	<0.1	<0.1	5/–
Conductivity ($\mu S\,cm^{-1}$)	48	7	Not specified (–/–)
Total dissolved solids ($mg\,l^{-1}$)	13	<1	500/–
Total organic carbon ($mg\,l^{-1}$)	<0.1	<0.1	–/–
Total alkalinity ($CaCO_3$) ($mg\,l^{-1}$)	4	3	–/–
Total hardness ($CaCO_3$) ($mg\,l^{-1}$)	<1	<1	Not available
Ammonia nitrogen (as N)	<0.1	<0.1	–/1.5
Chloride (Cl)	11	<0.05	250/–
Fluoride (F)	<0.05	<0.05	4/1.5
Nitrate (NO_3)	<0.05	<0.05	10/50
Silica (SiO_2)	<0.1	<0.1	–/–
Sulphate (SO_4)	0.22	<0.05	250/–
Residual chlorine (Cl, total)	0.03	0.01	4/5
Aluminium	<0.05	<0.005	0.05–0.2/0.2
Barium (Ba)	<0.003	<0.003	2/0.7
Boron (B)	0.43	<0.002	–/0.5
Calcium (Ca)	0.05	<0.02	–/–
Copper (Cu)	<0.002	<0.002	1.3/2
Iron (Fe)	<0.003	<0.003	0.3/–
Manganese (Mn)	<0.002	<0.002	0.05/0.4
Sodium (Na)	7.1	<0.02	–/200
Strontium (Sr)	<0.01	–/–	
Zinc (Zn)	<0.005	<0.005	5/–
Total coliform bacteria (counts/100 ml)	<1	<1	Not detectable
Enterovirus	<1	<1	Not detectable

Furthermore, in 2008, because the percentage of time in brackish water operation was higher than the plant was designed for, the average unit energy consumption was consequently lower than expected. Clearly, the more the plant operates in brackish water mode, the more the energy consumption can be reduced. Hence, while each mode of operation can be optimised independently to reduce energy consumption, there is even more room for further energy reduction if the source of brackish water can be utilised in the most optimal way. Thus, the flexibility to treat both seawater and brackish water at the VSD plant has created opportunities for innovation to maximise the length of brackish water operation.

Innovation in the operation of the membrane treatment processes

The VSD plant includes the following innovative features which are being refined to enhance plant operation and reduce operating costs through lower power and chemical consumption:

(i) Refining the operation of the inflatable rubber weir to maximise water retention without compromising risk of flooding upstream.
(ii) The use of MF to provide pre-treatment for seawater instead of conventional multi-media filters and dissolved air flotation (DAF) approach.
(iii) No anti-scalant is required during seawater operation.

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Table 3 | Energy consumption at the VSD plant in 2008

	Design	Actual (2008)
% Time in BW mode	50	60
% Time in SW mode	50	40
	Actual unit energy consumption in 2008 (kWh m^{-3})	
BW operation	1.11	
SW operation	4.86	
Average	1.86	

BW, brackish water mode; SW, seawater mode.

(iv) Online TOC (total organic carbon) analyser for online RO membranes integrity monitoring and pressure decay test for online microfiltration membranes integrity.
(v) Frequent switch from brackish to seawater mode and vice versa every three days to control fouling of the MF and RO membrane units with minimal use of chemicals.

Inflatable rubber weir

The rubber weir in Tampines River was originally built for aesthetic reasons. Currently the rubber weir will deflate via two triggers:

1. Automatic deflation: A hydrostatic sensor in Tampines River gives an indication of the water level. When the water level reaches a pre-set level, the weir will automatically deflate to prevent flooding. During heavy rain, the weir has been known to deflate up to four times daily, releasing several million gallons of water which flows to the sea.
2. Manual deflation: Regular weir deflation is part of a dengue fever prevention strategy by Singapore's National Environment Agency, which aims to minimise breeding grounds of the *Aedes* mosquito. The mosquito is known to breed in the presence of stagnant water. Usually, the rubber weir in Tampines River is deflated weekly.

It may be possible in future to refine the operation of the rubber weir such that the VSD can tap an increased volume of water and for a longer duration, thus allowing more production in brackish water mode, which is more cost-effective. PUB (Singapore's national water agency) is currently carrying out a number of studies into areas such as the proportion of runoff which flows into the canal during different rainfall episodes, the quality and proportion of water in Tampines River which can be treated by VSD, and the volume available during different seasons.

Use of MF for seawater pre-treatment

Unlike most desalination plants, which use conventional pre-treatment, the VSD uses MF as pre-treatment to the RO system. It has been found that the MF is able to achieve reliable quality that is suitable for feed to the RO, without the necessity for multi-media filtration or DAF. Other advantages of MF over conventional pre-treatment include a reduced footprint and a shorter retention time due to minimal flocculation and coagulation requirements. This is due to the small pore size of the MF membrane; coagulant dosing via $FeCl_3$ is minimal relative to conventional pre-treatment as even a small floc can be rejected by the MF.

It was found that a cartridge filter was not required at the RO feed. Initially a 50 μm basket filter was installed at the RO feed, but since the MF filtrate quality was found to be suitable for RO feed quality even before the cartridge filter, it was removed. No detrimental effect on the RO performance following its removal was witnessed.

Anti-scalant

For most plants using RO membranes either for desalination or brackish water treatment, anti-scalant is required to be dosed at the RO feed in order to prevent the formation of scales on the membrane surface, which can impede RO performance via a reduction in permeate flux, higher operating pressures and reduced salt rejection. Scale formation is usually worsened at higher operating pH. Most desalination plants use pH adjustment at the RO feed to achieve enhanced boron rejection.

However the VSD, under seawater operation, can achieve the WHO specification for boron without pH adjustment at the RO feed, because the RO system design and selection of membranes have the specific intention of achieving enhanced boron rejection. Since no pH adjustment for boron rejection takes place, in addition to the presence of strong ionic forces associated with the

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high TDS levels of seawater, scaling components present in the feedwater will not precipitate, thus there is no need for anti-scalant dosing.

Online TOC analyser and pressure decay test

Online TOC monitoring plays an integral role in monitoring the RO membrane performance, and can be used as an indicator of the membrane integrity. Permeate TOC levels (ppb range) as well as permeate TDS levels are compared with the concentration of these parameters in the feedwater (also monitored online) as a way of gauging the RO rejection rates for TOC and TDS. A deterioration in RO rejection may be due to the natural ageing of the membranes, or it may indicate causal damage to the membrane: for example, via excessive feed pressure, back pressure or differential pressure, or exposure of the polyamide membrane surface to an oxidising agent such as free chlorine. As the VSD treats water from different sources, both with differing TOC and TDS levels, a baseline is established over time as to the normal permeate concentrations. A deviation from this baseline may suggest potential membrane integrity issues, the cause of which would require thorough investigation.

The PDT (pressure decay test) forms a critical component of MF performance monitoring. The PDT should be carried out at regular intervals (as recommended by the membrane supplier), and is an additional off-line test which can give a more accurate picture of whether individual membranes within the MF train are damaged. Normally the primary indicator of MF performance is the MF filtrate quality, including parameters such as turbidity, SDI and particle count. These tests should be carried out for individual membrane trains, in addition to monitoring the combined filtrate from multiple trains. However, it is important to note that, despite stable filtrate quality, it is still possible for suspended solids and colloidal materials to pass through the MF and travel to the RO, causing fouling and scaling of the RO. For this reason, membrane integrity testing (including PDT, bubble test, sonic test or vacuum test, depending on the membrane manufacturer) is as important as quality in MF performance monitoring.

Frequent switch between brackish and seawater mode

It has been found that the potential for fouling increases with the duration of time spent in a particular operating mode. This phenomenon may be due to biological matter in the feedwater adapting to a particular environment over an extended period, or the accumulation of organic or inorganic matter on the membrane surface over time. In addition, extended seawater operation can result in the growth of mussels on equipment such as the drum screen or the seawater intake system. The build-up of such materials can be easily prevented at the VSD by switching between seawater and brackish water operation frequently. It has been found that the ideal frequency is approximately every 3 days.

CONCLUSIONS

- The VSD plant has demonstrated that the variable salinity desalination concept is viable for harvesting estuarine water, using microfiltration and reverse osmosis membrane treatment processes.
- The product water meets WHO and USEPA Drinking Water Guidelines and Standards.
- The overall unit energy consumption of the VSD plant is half that of seawater desalination plants.
- The average unit production and capital cost of such variable salinity desalination plants is also significantly lower than that of seawater desalination plants.

First received 30 September 2009; accepted in revised form 20 January 2010

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