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New entry point of membrane technology for public water treatment plants in Malaysia

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ABSTRACT

Membrane applications in public water treatment plants (WTP) in Malaysia have seen more setbacks than successes. Its early applications in a few locations encountered operational problems which saw many systems cease operations due to high operating expenses, membrane fouling or poor raw water quality. The main issue, however, was financial-related in view of the fact that the water tariff has been regulated and heavily subsidised. Both capital expenses (CAPEX) and operating expenses (OPEX) have not been affordable within such a framework. The power consumption of a 3 million L d^{-1} (MLD) hybrid membrane WTP subjected to study consumed 1.5 kWh m^{-3} of electricity as compared with 0.43 kWh m^{-3} for a conventional system in the same district. Besides that, cartridge filters had to be changed on a weekly basis as compared with filter media which can last more than 5 years. Capital cost of a membrane WTP is at least twice more expensive than conventional systems. Based on the standard of raw water adopted in the Malaysia, it is imperative that operators raise raw water quality standards prior to treatment whether through natural process or forced, physically or chemically. Downstream reservoir, river bank infiltration and radial well system have been applied in several projects in Malaysia and had successfully resulted in the high quality of raw water. However it has always been restricted from being implemented holistically due to financial constraints. Hybrid off-river storage implemented as interim measure to improve raw water quantity had indicated prospect of improving raw water to reach higher standards. This paper compares the raw water quality of various non-conventional raw water abstractions, followed by discussion on the proposed entry point of membrane systems in Malaysia for public WTPs.

Keywords: Raw water; Membrane; Quality; Treatment; River bank filtration

1. Introduction

Membrane applications in public water treatment plants (WTP) in Malaysia had been attempted several times in the water industry since 1980s. However, its early applications faced operational problems which ended up with the cessation of operations due to intolerably poor raw water quality and inadequate pre-treatment processes, resulting in membrane fouling. There were also cases of high operating costs of electricity and maintenance, expensive than conventional water treatment systems. Hence membrane technology had not satisfied the expectations of stakeholders and its usage was not able to grow in the public water supply which is a regulated market. However, it is also important to note that membrane technology especially reverse osmosis (RO) systems had been widely used in water bottling factories in the country as they usually treat public drinking water which was already within World Health Organisation

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(WHO) Drinking Water Quality Standards. In addition, the membrane market in Malaysia has been largely confined to industrial applications for purification and separation purposes.

In a few European countries, there is a high level of awareness on the need to ensure high raw water quality for both surface water and groundwater. This level of awareness has not been attained in Malaysia. The report on the quality of raw water in Europe was made public, as required by Article 13 of the European Union Council Directive [1], indicated that the European Union (EU) adopted a higher treated water quality standards compared with Malaysia. According to Wagner [2], high raw water quality is a prerequisite for acceptance at water intake, prior to public WTPs. Hence the introduction of membrane in such good raw water quality would simplify the complexity of membrane operations and reduce operating costs. Therefore such a framework should be fully adhered to in Malaysia. This is the entry point for membrane technology in public water works.

2. Background

This paper is based on operational experience encountered during the planning, implementation and operation of a number of membrane public water treatment facilities in Malaysia. Although the cases revealed are real, the exact location of the facilities will remain undisclosed. This paper will address various issues related to key enablers for the acceptance of membrane systems in Malaysian public water works.

The interest to depart from conventional water works in Malaysia is associated with the need for higher treated water quality and flexibility of raw water quality and quantity. The conventional system has limitations on flexibility due to its size and operational variables. Membrane has been singled out due to its robustness and footprint. The State Government of Selangor [3] opened the opportunity for membrane technology when the State Chief Minister stated that "The State Government should not be tied to just conventional treatment but needs to adopt new ways if it is efficient and economical, hence we plan to adopt membrane technology for this WTP".

The application of membranes in public water works in Malaysia can be regarded as being at the early stage, despite the fact the first membrane used was in the 1980s in isolated areas. Less than 2% of the water treated from both public and industrial water works in the whole country use membrane technology. A study by Kasim et al. [4] found that membrane has the potential for removing iron and manganese from groundwater sources. However, the study shows that an increase in pressure leads to a significant increase in permeate flux with decrease in Fe rejection. This may be due to an increase of solvent permeability compared with the solute permeability at higher pressure. However, the opposite happened in the case of Mn.

Contrary to the practices in Malaysia, the Duesseldorf Waterworks in Germany, for example, which is located next to the Rhine River, did not abstract surface water directly from the river. Raw water abstracted for the waterworks is estimated to be 70% from the bank filtrate and 30% from groundwater [1]. Jokela et al. [5] highlighted the practice in Finland where managed aquifer recharge (MAR) is applied for the removal of natural organic matter from surface waters. MAR consists of the infiltration of surface water with subsequent withdrawal of the MAR-treated water from wells that are a few hundred metres deep. The infiltrated water should have a residence time of at least approximately 1 month before withdrawal to provide sufficient time for the subsurface processes needed to break down or remove humic substances. However, the MAR plants in Finland do not have pre-treatment and raw water is infiltrated directly into the soil. This procedure is quite similar to that practised by Dunea Water in the Netherlands where MAR was constructed in an area of dunes to give a residence time of about 28 d [6]. However, in the case of Dunea Water, the raw water used for MAR is pre-treated to ensure no contamination of the aquifer. Hence, it is evident that high-quality raw water source is a prerequisite for abstraction to produce drinking water in Europe.

It should also be noted that the Department of Environmental Quality of Oklahoma [7] observed that pre-treatment for nanofiltration and reverse osmosis (NF/RO) depends on the quality of the raw water. If the feed water has a turbidity of less than 1 nephelometric turbidity unit (NTU) or silt density index (SDI) of less than 5, then cartridge filters with a pore size range of less than 20 μm will suffice prior to the NF/RO treatment. If the feed water turbidity is 1 NTU or greater or the SDI is 5 or greater, then a more rigorous method of particulate removal, such as conventional treatment (including media filtration) or MF/UF membranes for particle removal is required. The use of MF/UF for pre-treatment is more commonly known as an integrated membrane system (IMS). The IMS is a method which allows for the removal of particulate matter and microorganisms as well as some dissolved contaminants such as hardness, iron and manganese or disinfection by-product (DBP) precursors.

3. Methodology

The following methodology has been adopted for three cases, that is, 20 $m^3\,d^{-1}$ brackish water desalination plant, 3,000 $m^3\,d^{-1}$ fibre membrane treatment unit and 3,000 $m^3\,d^{-1}$ hybrid membrane treatment plant:

- Assess the current performance of existing membrane system in treatment plants
- Determine the remedy of past events related to membrane system
- Evaluate and benchmark other facilities
- Determine enabling factors for using membrane in water treatment
- Planning the way forward

However, the study of the 3,000 $m^3\,d^{-1}$ hybrid membrane treatment plant was further extended where several parameters were assessed, and laboratory tests were carried out to evaluate the treatability of raw water to minimise problems related to the operations of the membrane system. Jar tests were conducted to evaluate the effectiveness of chemical coagulation by using stirring device with six paddles which were operated at varying speed between 0 and 200 rpm. The speed and duration of stirring were adjusted to simulate the coagulation, flocculation, sedimentation and filtration processes of the treatment works using different chemical combinations as follows:

- Polyaluminium chloride (PAC), lime and polymer
- PAC and lime
- Alum, lime and polymer

The concentrations of the chemicals are shown in Table 1.

4. Findings and discussion

4.1. Brackish water desalination plant

Membrane modules were chosen for this study to treat brackish water on an island with limited raw water sources. The membrane system has the capacity of producing 20 m^3 d^{-1} using RO modules. The capital cost of the basic components of this plant is about RM20 (USD5) per litre d^{-1} which is comparatively high due to poor site conditions. The installation was completed within 6 months with the layout as shown in Fig. 1.

However, it was then modified to reduce the components by minimising the pre-treatment units to simplify the process. This minimisation initiative had reduced the ability of the pre-treatment units to handle raw water with turbidity ranging from 30 to 100 NTU. The pre-commissioning results showed that the turbidity of pre-treated water had increased above 5 NTU. This subsequently increased fouling and reduced flux substantially.

Prior to the minimisation of the pre-treatment units, the turbidity of pre-treated water was less than 1 NTU and salinity above 10 g L^{-1} of chloride. The treated water had turbidity of less than 0.1 NTU.

4.2. Hollow fibre membrane treatment unit

The second WTP was designed as an emergency and pilot project to bridge water demand in a small town and has a capacity of producing potable water at 3,000 m^3 d^{-1}. It used hollow fibre membranes, aimed to be completed within 3 months. The speed of project completion was the main criteria for selecting membrane technology. However, it was commissioned later than the initial commissioned date due to errors of the programmable logic controller.

Fig. 1. View of treatment plant.

It is important to mention the importance of resilience in treatment facilities provided even for a pilot project. This window of opportunity was not fully utilised by the membrane supplier to convince water operators that membrane technology is suitable for the intended purpose. Equipment failures and delay in commissioning of this membrane unit had given a bad impression of the performance of membrane WTP. There is no doubt of the ability of this membrane plant to treat the river water directly into this system as the raw water had a turbidity of less than 40 NTU most of the time. However, the lack of expertise in its implementation was detrimental to the acceptance of the technology by the client. The tests carried out on the final product quality showed that the turbidity achieved was less than 1 NTU with traces of Fe and Mn within allowable limits.

4.3. Hybrid membrane treatment plant

This is another noble attempt to use membrane in public WTP. The treatment plant with a capacity of 3,000 m^3 d^{-1} was built using hybrid technology where RO membrane was used together with conventional pre-treatment plus second stage pre-filtration (cartridge filter) to treat intermittent saline, odourous and coloured raw water. The plant was completed and commissioned within 1 year. However, the operation was terminated to make way for upgrading works. Fig. 2 shows the arrangement of the hybrid treatment plant:

In the upgrading works, additional treatment using granulated activated carbon was incorporated to enhance the removal of odour and colour as both have been major problems to the plant operations. Extensive analysis on data from laboratory jar testing results was conducted to evaluate the performance of the water treatment with the current set up of the WTP. However, the laboratory testing was limited to assess the ability of removing impurities in the pre-treatment process which consists of aeration, coagulation, flocculation, sedimentation and filtration.

Results from jar tests show that pre-treatment water would not clog filter cartridges as fast as what was previously experienced at the WTP. Colour and salinity were two major issues that need to be resolved at this plant and had been the main reason for choosing hybrid system. At times the salinity level increased to more than 20 g L^{-1} due to sea water intrusion at the raw water intake point. The water level fluctuation at the intake point varied drastically and had affected the operations of the WTP as shown in Fig. 3:

In principle, the RO membrane should be able to remove salinity. However, the pre-treatment installed was not able to reduce SDI to less than 5. SDI higher than the value 5 will not be sufficient to ensure RO membrane performane and reliability.

Series of jar tests were carried out to determine the effectiveness of chemical coagulation and the results are shown in Table 1.

It is important to effectively remove turbidity, iron and colour at the pre-treatment stage, followed by RO for salt removal. This will avoid the problems of frequent fouling of membrane modules. The main operational issue at this plant was the inefficiency of pre-treatment to produce pre-treated

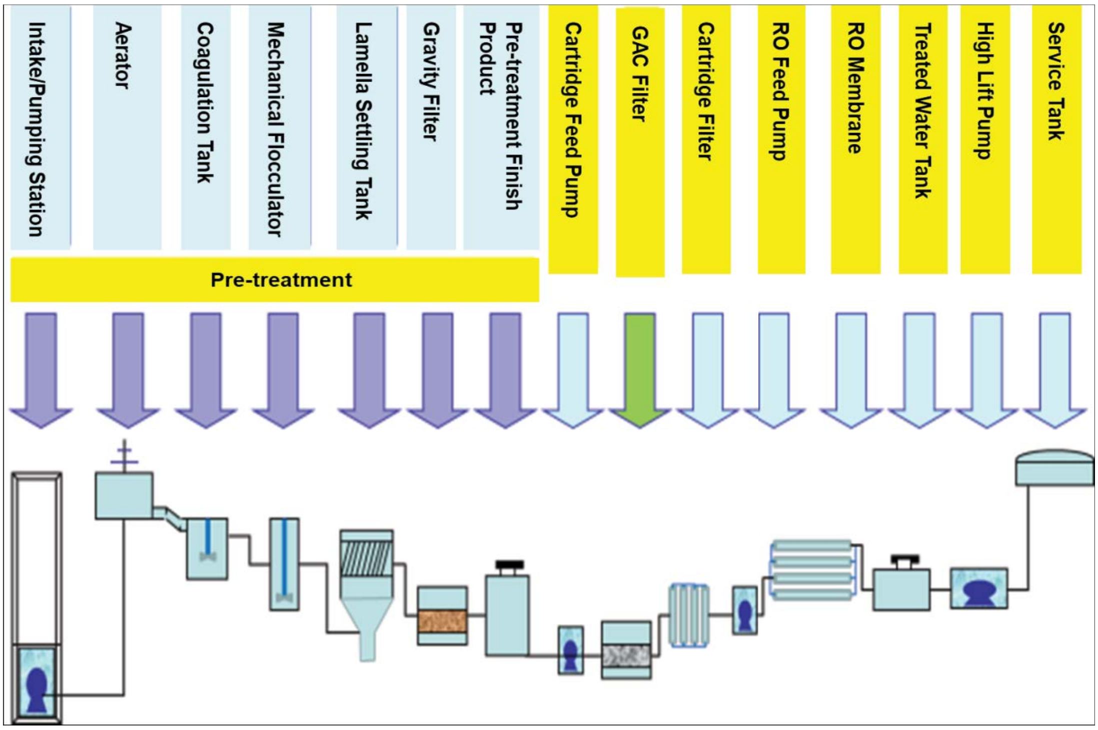

Fig. 2. Treatment plant arrangement.

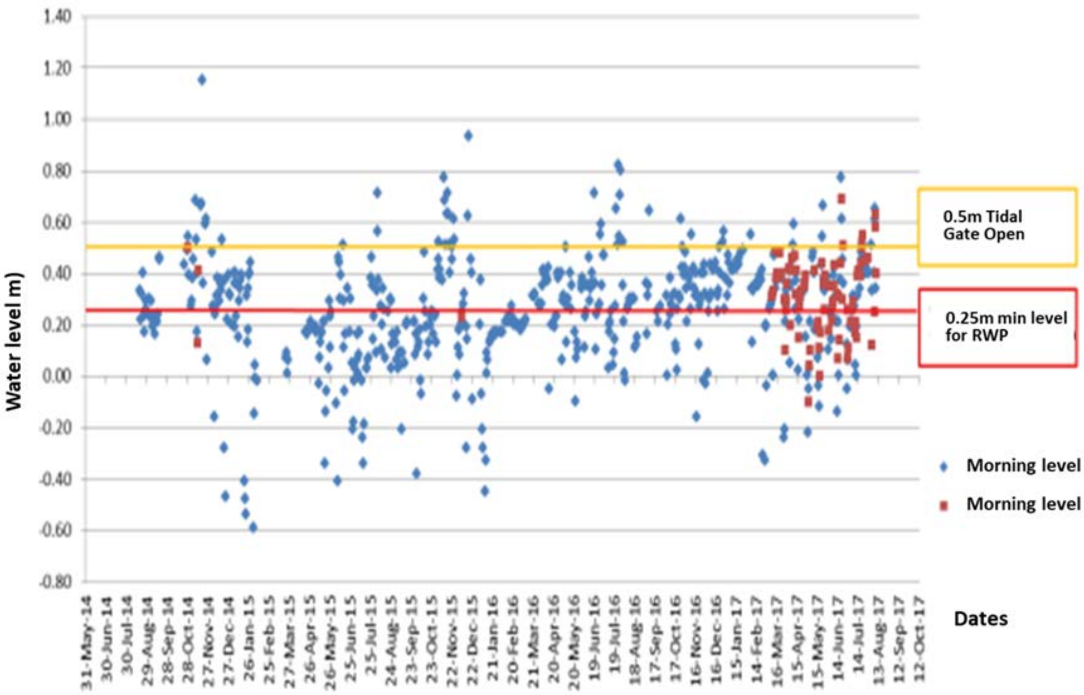

Fig. 3. Raw water levels at the intake point.

water of SDI lower than 5 or turbidity less than 1 NTU. It was shown through jar tests that turbidity values of less than 1 NTU for unfiltered samples could be achieved. The filtered samples turbidity was done selectively and had shown turbidity of less than 0.1 NTU.

It was also reported by the Water Supply Department Malaysia [8] that the operating cost of the hybrid membrane

Table 1
Jar test results using PAC and lime.

PAC, lime + polymer	No	1	2	3	4	5	6
Dos PAC	mg/l	100	120	140	160	180	200
Dos lime	mg/l	10	10	10	10	10	10
Dos polymer	mg/l	1	1	1	1	1	1
RW Turbidity	NTU	47.7	47.7	47.7	47.7	47.7	47.7
RW Colour	Pt.Co	550	550	550	550	550	550
RW iron	mg/l	3.3	3.3	3.3	3.3	3.3	3.3
RW pH	-	6.58	6.58	6.58	6.58	6.58	6.58
SW Turbidity	NTU	0.9	0.82	0.47	0.43	0.32	0.7
SW Colour	Pt.Co	12	29	18	21	7	16
SW iron	mg/l	2.74	2.13	2.93	2.83	3.08	3.08
Turbidity removal		98%	98%	99%	99%	99%	99%
Colour removal		98%	95%	97%	96%	99%	97%
Iron removal		17%	35%	11%	14%	7%	7%

27/11/2014 PAC & w/o polymer	No	1	2	3	4	5	6
PAC	mg/l	20	40	60	80	100	120
Dos lime	mg/l	10	10	10	10	10	10
Dos polymer	mg/l	0	0	0	0	0	0
RW Turbidity	NTU	19.6	19.6	19.6	19.6	19.6	19.6
RW Colour	Pt.Co	340	340	340	340	340	340
RW iron	mg/l	2.63	2.63	2.63	2.63	2.63	2.63
RW pH	-	6.40	6.40	6.40	6.40	6.40	6.40
SW Turbidity	NTU	19.6	1.5	0.83	0.73	0.71	0.95
SW Colour	Pt.Co	340	46	7	12	8	20
SW iron	mg/l	2.46	0.13	0.05	0.07	0.04	0.02
Turbidity removal		0%	92%	96%	96%	96%	95%
Colour removal		0%	86%	98%	96%	98%	94%
Iron removal		6%	95%	98%	97%	98%	99%

Alum & lime w/o Polymer	No	1	2	3	4	5	6
Dos Alum	mg/l	20	40	60	80	100	120
Dos lime	mg/l	10	10	10	10	10	10
Dos polymer	mg/l	0	0	0	0	0	0
RW Turbidity	NTU	19.6	19.6	19.6	19.6	19.6	19.6
RW Colour	Pt.Co	340	340	340	340	340	340
RW iron	mg/l	2.63	2.63	2.63	2.63	2.63	2.63
RW pH	-	6.40	6.40	6.40	6.40	6.40	6.40
SW Turbidity	NTU	19.1	10.9	0.84	0.62	1.39	1.54
SW Colour	Pt.Co	340	194	25	10	4	25
SW iron	mg/l	2.17	1.13	0.06	0.05	0.07	0.09
Turbidity removal		3%	44%	96%	97%	93%	92%
Colour removal		0%	43%	93%	97%	99%	93%
Iron removal		17%	57%	98%	98%	97%	97%

From the results:

- High dosing of coagulant is required especially to overcome high colour
- Optimum pH is essence and hence lime dose is imperative
- Alum can perform as coagulant but sensitive to coagulant content.
- Proper pre-treatment can overcome current problems related to high SDI,

WTP was RM 1.07 m^{-3} (USD 0.26 m^{-3}) as compared with RM 0.46 m^{-3} (USD 0.11 m^{-3}) for conventional WTP. The power consumption of a 3,000 m^3 d^{-1} hybrid membrane WTP in Labuan was 1.5 kWh m^{-3} as compared with 0.43 kWh m^{-3} for a conventional system in the same district. In another project, the energy consumption of a membrane WTP was 3.0 kWh m^{-3}. The second stage pre-treatment filters in the hybrid membrane plant were changed on a weekly basis as compared with conventional filter media which usually last more than 5 years depending on the quality of the settled water.

It is evident from the three projects discussed that membrane application for public water treatment works require extensive feasibility studies, particularly on the raw water quality variation, and operation and maintenance issues. The feasibility studies should also address the financial aspects of the whole scheme.

The main problem at the WTPs that has applied membrane technology was poor raw water quality which mainly contained high TSS. It was widely recommended by consulting engineers to perform pre-treatment with polymers. However, the use of polymers may invite faster membrane fouling as experienced during the early hours of the commissioning of the 20 m^3 d^{-1} RO plant. Similarly the 3,000 m^3 d^{-1} hybrid plant also faced frequent change of cartridge and unsatisfactory pre-treatment water due to the use of polymer. Wang et al. [9] highlighted the risk of membrane fouling when using organic polymers as the polymers have high molecular weight. The study showed severe fouling of microfiltration membranes at very low polymer concentrations, suggesting that residual polymers carried over from the coagulation/flocculation basin can contribute significantly to membrane fouling. In comparison, WTP operators in the EU region, in particular Germany and the Netherlands, always ensure high raw water quality used at their treatment plants.

Hence, as a multi-pronged solution, it is imperative that the raw water quality standards prior to membrane treatment be improved either through natural process or forced, physically or chemically. This will have the spill over effect of good water quality for any treatment process and hence reduce chemical costs and sludge produced.

5. Recommendations

Studies show that the main issue with the membrane performance in tropical countries such as Malaysia was the variation of raw water quality. There have been attempts made by designers to adopt a more simplified pre-treatment to reduce high turbidity and SDI.

From the findings, it is inevitable that a new entry point needs to be explored for membrane application in public water treatment facilities. Several approaches elaborated below would improve raw water quality without extensive pre-treatment and subsequently enable membrane technology applications at public water treatment facilities.

5.1. Downstream reservoir

Conventionally, reservoirs are constructed at the upper reaches of the river to collect pristine water from the hills and mountains where the river originated. However, the water harvested at the upper reaches, which is stored in reservoirs, is usually released to rivers where the dam regulates the river to meet its required demand during low flows. After the release to the river, it may be exposed to pollution and becomes contaminated along the river stretch. In general, the typical turbidity of Malaysian rivers could be more that 1,000 NTU during rainy season. During dry season, the typical turbidity could be less than 100 NTU. Therefore, storing in the clean area with pristine quality does not benefit the cause as it gets eventually polluted before reaching the WTP.

Downstream reservoir has been widely acceptable in Malaysia as it can harvest more water, has higher flexibility in operations and encourages citizens not to pollute the rivers supplying the downstream reservoir. Off-river storage, bunded storage, coastal reservoir and pond can be part of the downstream reservoirs. Having storages near to WTP can encourage lean management of water resources.

5.2. River bank filtration

River bank filtration (RBF) well can be constructed as a radial well system or merely a vertical well. Using radial well will reduce the load of abstracting water from the centre well and is capable of improving the quality of raw water as it has travelled a distance from its original source which could be the river or the infiltration of rainfall to the ground. Lee et al. [10] mentioned that many RBF wells have been used in riparian zones, including both vertical and horizontal (radial collector type) wells. Radial collector wells consist of a vertical caisson, to which a number of horizontal arms are connected. However, there must be some control on RBF abstraction as it may be detrimental to the environment as Lee et al. [10] warned of the possibility of serious stream water depletion.

5.3. Infiltration pond

Infiltration ponds are similar to dunes where they serve as a natural purification process and can act as an artificial recharge to the groundwater as shown in Fig. 4. TSS will be significantly reduced in the infiltration ponds. The quality of water abstracted from vertical well from this area is of high quality with turbidity less than 1 NTU.

5.4. Off-river storage

Off-river storage is a storage built to store water for immediate use or during crisis period due to drought or contamination of an existing source. The size of the storage will be dependent on the purpose of the storage and its replenishment rate. The construction can be fully lined, partially lined or unlined. However, the slope stability of the storage needs to be properly constructed to avoid piping or other embankment failures.

The hybrid off-river storage (HORAS) built in Selangor is a significant breakthrough as it harvests groundwater, surface water and water from the sky. It is unlined, uncovered and built below the normal river level to allow gravity flow into the storage. It was constructed with low level bund in

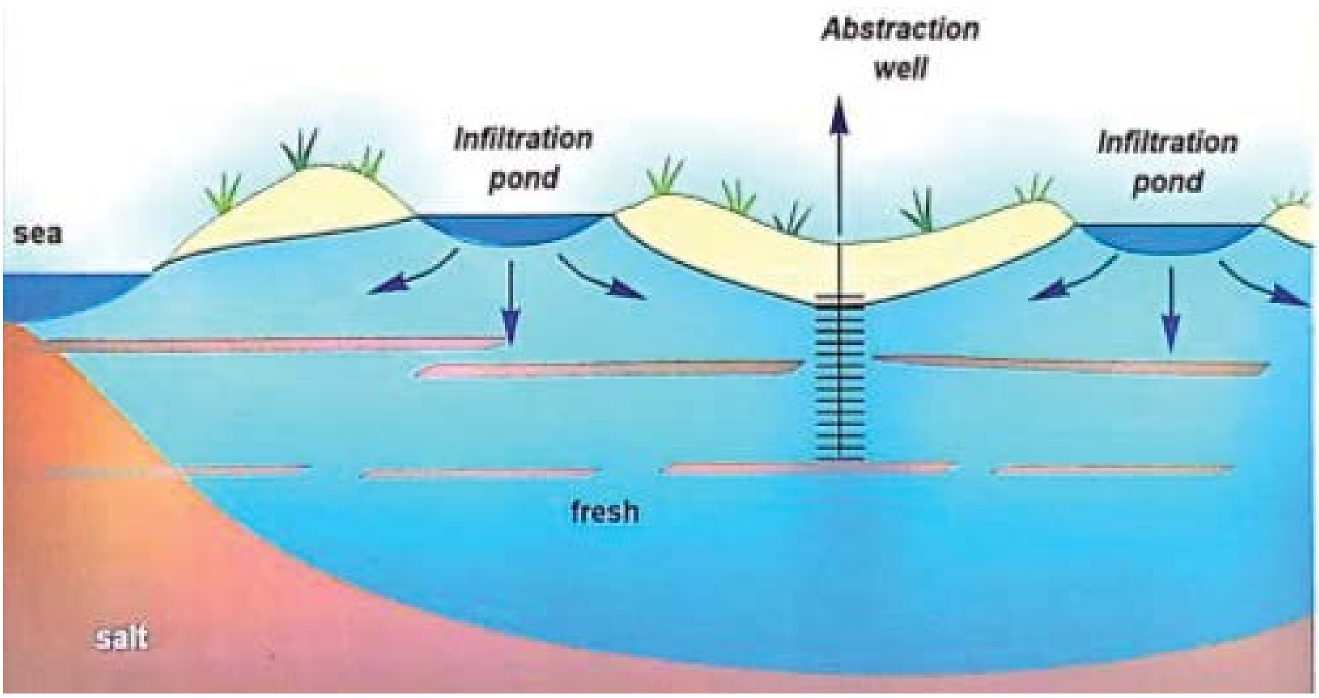

Fig. 4. Infiltration pond.

the middle to enable isolation for maintenance as shown in Fig. 5. However, the first phase of this HORAS did not provide direct pumping to WTP which impeded the advantage of low turbidity accomplished in the 3-month retention in HORAS.

5.5. Environmental challenges against entrance

5.5.1. Economy

Cost is an important consideration for technology selection. Although things of low cost are always associated with low quality and poor performance, membrane suppliers need to promote the technology so that it becomes competitive and affordable.

5.5.2. Technology

Resilience, speed and quality are imperatives for membrane acceptance by industry players in Malaysia. It was observed that inappropriate installation had resulted in cessation of operation. Hence, application of membrane in WTP should be more resilient and holistic in nature.

5.5.3. Politics

Politics plays an important role for things to happen. In a developing nation such as Malaysia, the top-down approach is most common in many organisations despite their apparent embrace of total quality management which encourages bottom-up approach. Conflict may happen if the management goes against the will of political masters.

5.5.4. Sociology

People at large dictate the demand for the product they want. That is the reason countries have different sets of water quality standards. As the awareness of people on quality increase, a more superior treatment process such as membrane will be attaining high demand.

5.6. Porter's five forces

It is interesting to evaluate, assess and highlight the industrial challenges. Porter's Five Forces [11] are relevant in assessing these challenges.

5.6.1. Suppliers power

Suppliers of membrane systems should not aim for excessive profits since they need to compete with conventional systems which is widely acceptable and user friendly. As noted by Han et al. [12], a supplier's power may be reduced if the supplier is competing in a diverse portfolio of suppliers. Hence Williamson et al. [13] suggested that operators need to synergise to stay in a competitive market.

5.6.2. Buyers power

Membrane systems are new to many water operators in Malaysia. The water operators have very strong bargaining

Fig. 5. Hybrid Off-River Storage (HORAS) Under Construction.

power and keen in keeping to the status quo and this has always been the case. Hence, price would be another attractive motivation to water operators to go for membrane.

5.6.3. Substitutes

Membranes have great potential to substitute current systems as the raw water quality keeps deteriorating and new emerging pollutants need to be removed. This is a strong plus point for membrane technology. Slack and Lewis [14] suggested that trade promotion is good to attract buyers to choose goods or items they have not used before. These promotions should offer special prices which may motivate the water operators to change to membranes.

5.6.4. New entrant

There has been a lot of innovation in the conventional method to reduce carbon footprint. Dissolved air flotation systems and tube settlers are going for a low detention time of about 40 min as compared with 2 h in the traditional design.

5.6.5. Rivalry among competitors

Intensity of rivalry will be determined by the market growth, fixed costs, switching costs, product differentiation level and exit barriers. Technology superiority should be the pre-requisite of application of membrane systems. There is a need to look at the resilience of systems provided to customers.

6. Conclusion

Membrane technology suppliers should understand the background and experience of previous applications of membrane in water treatment in Malaysia before embarking into it. The existing entry points identified above such as ability to treat salinity and salt water, speed of project completion and mobility of treatment units were not adequate for membrane technology to be sustainable and become the choice for future endeavours.

The emphasis on providing high quality raw water should be given priority and not taken for granted. The opportunities are available but new motivation and assertion of quality and practicality are required. As awareness of water quality improves, the demand for higher water quality will increase. Coupled with improvements on previous shortcomings, these changes are the key enablers that will open a new entry point for membrane technology in Malaysia.

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