



Research Paper

Pilot Study of Brackish Water Treatment using Dual Stage Nanofiltration for Domestic Use in Thu Bon Basin, Vietnam

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Highlights

- Salinity of Thu Bon river varies significantly with seasons
- Brackish water with salinity less than 6‰ can be treated well by the single-stage nanofiltration process
- During the season transition from rainy season to dry season with salinity increasing up to 17.5‰, dual-stage nanofiltration process is highly recommended.
- During the dry season with salinity greater than 17.5‰, another solution such as NF-RO must be applied to be able to control the salinity the acceptable level.

Abstract

Due to the impact of climate change, the process of salinity intrusion occurs frequently in coastal areas of Vietnam. The main objective of this study is therefore to try different nanofiltration (NF) processes (such as single-stage and dual-stage NF) to treat brackish water for residential areas in Thu Bon river basin, where the salinity varies significant with seasons. Results have shown that during the rainy season, the salinity was less than 8.5‰, so the single stage NF worked perfectly. When season changes from rainy season to dry season, the river's salinity increases up to 17.5‰, application of dual NF is most appropriate. This dual NF process not only guarantees the effluent quality to meet National Technical Regulation, but also offers reasonable energy cost and finally can prolong the membrane lifespan.

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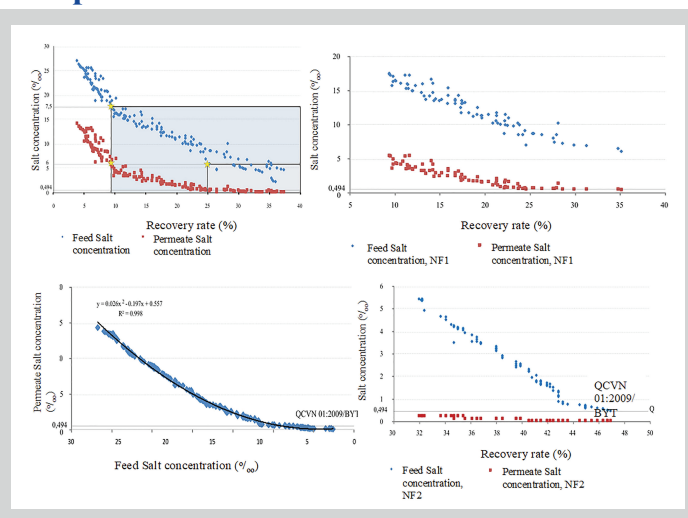
1. Introduction

Desalination is a process of removing dissolved ions in the seawater, brackish water or underground water. According to the International Desalination Association, there were 18,426 desalination plants operated worldwide as of June 2015, producing 86.8 million m³/d, providing water for 300 million people [1]. Desalination can be conducted via ion exchange, solar energy, distillation or membrane processes.

The last two methods, which are distillation and membrane processes,

have been applied the most due to the high efficiency and more reliability [2, 3]. Distillation often requires large footprint, large equipment and mostly relies on the weather. Membrane technologies such as Reverse Osmosis-RO, Nanofiltration-NF, Ultrafiltration-UF, Microfiltration-MF, etc. (see Figure 1), therefore, have been used tremendously in the past two decades because of many advantages. Among the above membrane processes, RO and NF are considered most favorable for desalination. RO can remove up to 99% of

Graphical abstract



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dissolved ions, however, the capital cost and operation cost are substantial due to material, pump energy, electricity and fouling [4]. With those constraints, the application of RO in desalination for drinking water purpose seems to be a big challenge [4, 5].

NF membrane has been proved to be quite effectiveness in controlling divalent ions, turbidity, residual bacteria, hardness ions, and seawater TDS. The main advantage of NF process is its lower energy consumption and lower capital cost compared with RO process [6-8].

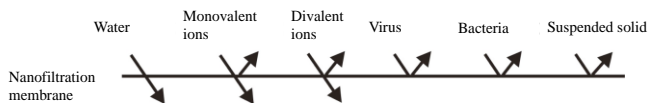


Fig. 1. Rejection mechanism of Nanofiltration.

The application of NF for desalination worldwide goes back to the early of 2000 [9, 10]. A single stage NF was proved not so high removal efficiency. To maximize this outcome, using an integrated membrane process (NF-NF or NF-RO) has been getting more of interest [11]. Al-Tae and Sharif [7] concluded that the energy consumption of NF-NF was 0.38 kWh/m³ lower than that of NF-RO, however TDS in the permeate of NF-NF was 1030 mg/L while TDS in the permeate of NF-RO was only 125 mg/L. Nevertheless, NF has high potential for application in desalination in some circumstances. According to Wilf [2], NF is comparable with RO in treatment of low salt concentration seawater. At high salt concentration or wide concentration variable water, NF can not meet the requirement.

In Vietnam, there have been some studies on desalination but mostly at low and stable salinity and small-scale systems [12]. In fact, the salinity varies quite substantial with seasons in this region. Thus, the main objective of this study is to seek for a proper solution for a wide range of salinity water via piloting at Thu Bon river site. The results obtained from this research would probably apply for other areas with similar conditions.

2. Materials and methods

2.1. Feed water

Brackish water from Thu Bon River estuary was used as the feed water. This water is strongly influenced by natural conditions and human activities, so the tidal regime and water quality changes seasonally. The water transportation and fishing activities occur frequently in the region which generate huge amount of organic matter content in the water including suspended solids, solids, trash, etc. In particular, the salinity of this river varies considerably with seasons. The range of salinity at Cua Dai ward (Hoi An city, Quang Nam province) where the pilot was installed (from August 1, 2012 – October 30, 2013) was 2.3-27.5‰, while it was mainly 20‰ higher than from June to August. With this condition, it is believed that it would be impossible to apply a single process (whether it is conventional or advanced one) for treatment of this river for drinking water purpose.

2.2. Experimental procedure

In this study, we treated the brackish water using dual-stage NF filtration in two phases. Phase 1 involved testing with single-stage NF from 1/8/2012 to 13/11/2012. The feed water had a wide range of salinity, ranging from 2.3‰ to 27.5 ‰. The purpose of this step was to find the favorable salinity level that a single-stage NF could handle, as well as find the appropriate salinity range for the next step. Sand filter followed by UF pre-treatment units were employed in order to remove residuals, viruses and bacteria. This pretreatment step also helped to reduce membrane fouling during the subsequent desalination stage. After that, the water would undergo NF1. The implementation and equipment installed for this step are shown in Figure 2.

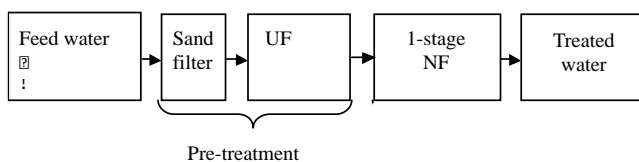


Fig. 2. Diagram of a single-stage NF process.

In Phase 2, the dual – stage NF was tried from 4/2/2013 to 12/6/2013. Based on the results of Phase 1, the appropriate input salinity concentration was found to proceed to Phase 2, where the minimum salinity of the input water $NF_{2,feed}$ would be equal to the maximum salinity of the permeate ($NF_{1,permeate}$) at which it still obtains the $NF_{2,permeate} < 0.495‰$ [13]. The implementation plan and equipment installed for this step are shown in Figure 3. Both phase 1 and phase 2 experiments were set up at site (see Figure 4 for details).

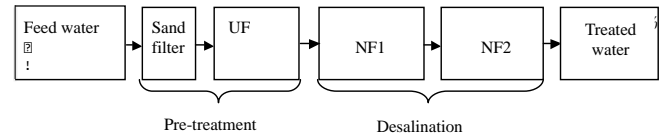


Fig. 3. Diagram of dual stage NF process.

The pilot was designed with capacity of 5 m³/d, operating 16 h/d, including a composite filter with sand (D = 600 mm, height = 2000 mm); UF membranes NTU3360-K4R provided by Nitto Denko company, Q = 7m³/h, N = 2 modules and Polyvinylidene fluoride (PVDF) NF membranes (ESPA1-LF- 4040) were supplied by Nitto Denko company. This kind of membrane was reported to have high corrosion resistant. The ceramic housing was stable and durable.

The operating pressure of NF system was set at 11±0.2 bar for both phases. The pressure and flowrate were recorded everyday so as to be able to determine the recovery rate and the salt rejection at different cases.

Recovery rate was estimated based on the following formula:

$$\% \text{ Recovery rate} = (Q_p/Q_f) * 100 \quad (1)$$

$$Q_f = Q_p + Q_c \quad (2)$$

where: Q_f , Q_p , Q_c are flowrate of the feed, permeate and concentrate. Salt rejection was also determined as follow:

$$\% \text{ Salt Rejection} = (TDS_f - TDS_p) / (TDS_f) * 100 \quad (3)$$

In addition, the energy cost was also determined for treatment of 1 m³ brackish water at different salinity concentrations (for Q = 5 m³/d, operating time = 16 h/d):

$$E = N * U \quad (\$/m^3) \quad (4)$$

$$N = \frac{Q * H * \psi}{102 * \eta_{dc} * \eta_b} * K \quad (\text{kW/h}) \quad (5)$$

In which N: pump power (kW/h); ψ : density of fluid, 1000 kg/m³; Q: pump flowrate (m³/s); H: pump head (m); η_{dc} : engine efficiency; η_b : total pump efficiency ($\eta_{dc} * \eta_b = 0.85$); K: power reserve coefficient.

The current unit electricity cost U (\$/kW) was based on national electricity norm which was about 0.91 \$/kW. The energy cost for treatment of 1 m³ brackish water was evaluated for dual NF and NF-RO processes. Data for NF-RO was referred elsewhere [14].

2.3. Sampling and Analytical method

Samples were collected twice per day from the feed, after sand filter and, after NF1 and NF2. Each sample was analyzed in terms of salt concentration, TDS, conductivity, COD, SO₄²⁻, Cl⁻ and Coliform. The sampling technique (including sampling points, sampling container decontamination, sample preservation) was followed strictly Vietnam Standard TCVN 5992:1995 Water Quality – Sampling – Part 2: Guidance on Sampling Technique. Besides, other parameters were analyzed in accordance with other Vietnamese Analytical Method Standards, including TCVN 6492:2011 for pH, TCVN 6184:2008 for Turbidity, TCVN 6186:1996 for COD_{KMnO4}, TCVN 6200 - 1996 for SO₄²⁻, TCVN 6194:1996 for Cl⁻ and TCVN 6187-2:1996 for Coliform. Salinity was measured by SA287 Digital 1-Click Simple Salinity Meter Tester (Hangzhou Sinomeasure, China). TDS was measured by TDS Tester (Hanna HI98302, Bedfordshire UK).

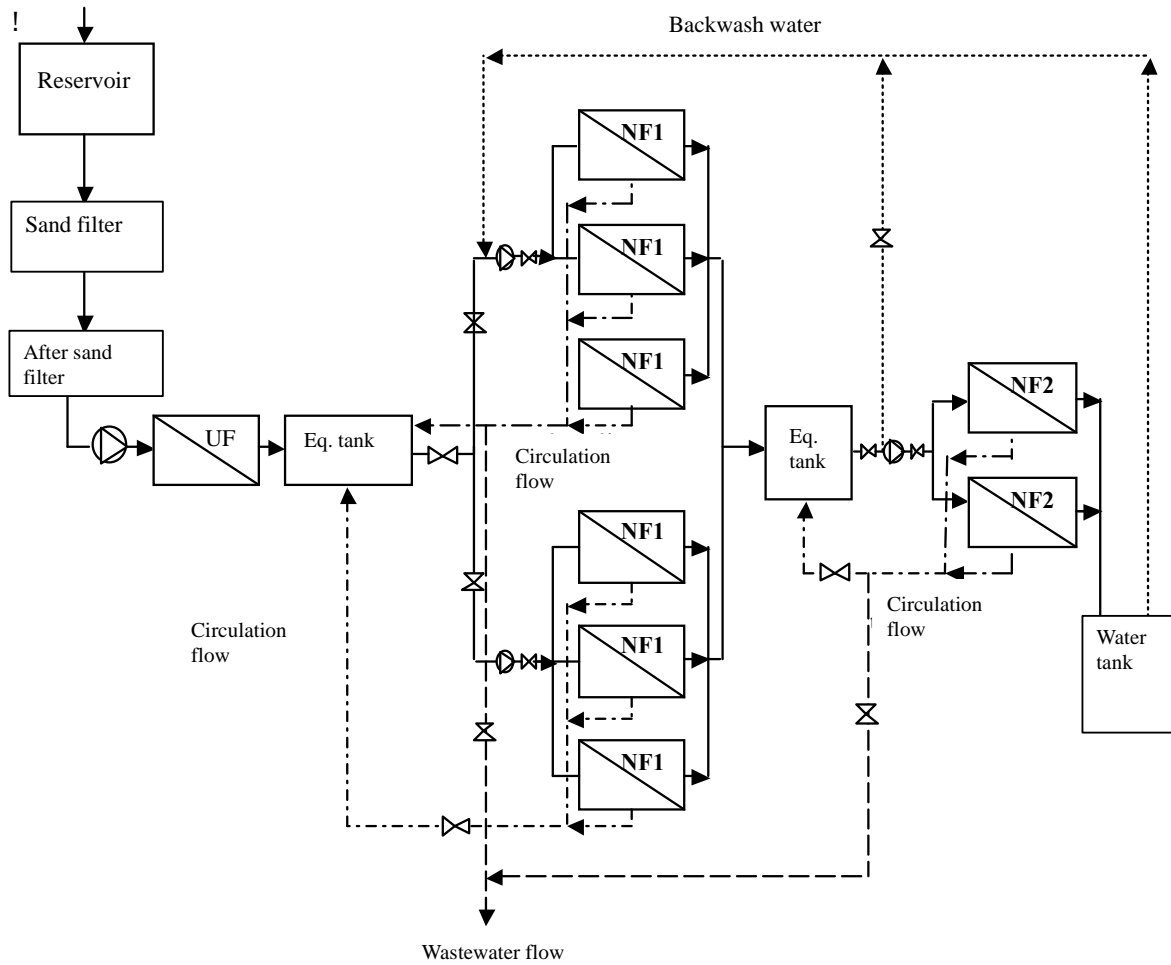


Fig. 4. Pilot testing at site (Q= 5 m³/d).

3. Results and discussion

3.1. Characteristics of feed water

As the composition of brackish water from Thu Bon river varied quite considerably with seasons, the test was conducted from autumn (phase 1), and continued in spring and summer (phase 2) to reflect the wide change of salinity of the river. The temperature was relatively stable (from 25-28 °C). The average value of feed water used in this study is described in Table 1.

Table 1 Analytical result of feed water.

No	Parameters	Rainy season	Dry season
1	pH	7.1-7.8	7.2-7.8
2	Turbidity, NTU	20-45	14-31
3	Salinity, ‰	1-8.5	7.5-27.5
4	TDS, mg/L	1,150-9,600	8000-29,000
5	COD _{KMnO4} , mg/L	2.5-8.3	2.6-5.6
6	SO ₄ ²⁻ , mg/L	110-1850	750-2450
7	Cl ⁻ , mg/L	600-5900	4500-16800
8	Coliform, MPN/100mL	10 ³ -10 ⁵	10 ³ -10 ⁶

It can be seen from Table 1 that the season change had great impacts on the salinity, TDS, Cl⁻ concentration, but not on the turbidity or pH.

3.2. Recovery rate and salt rejection of single stage NF- Phase 1

The results of Phase 1 showed that with salt concentration in the range of 2.3‰-6‰, the permeate salt concentration after NF process ranged from

0.2‰-0.5‰ which met the QCVN 01:2009 requirements (National Technical Regulations on Drinking water quality issued by Ministry of Health, i.e. less than 0.5‰). Salt rejection was about 88%-94% and recovery rate is 25%-37.5%, depending on the salt concentration (see Figure 6). As it can be seen in Figure 7, the permeate salt concentration was a function of the square root of the feed salt concentration. High R² value (R² = 0.998) proves high reliability of this correlation. The trans-membrane pressure of this phase was relatively stable (10.5±0.5 bar).

It should be noted that for this study, relatively constant operating pressure was maintained to compare the membrane performance as a function of salt concentration. Normally, under the same salt concentration, increasing operating pressure increases the ion rejection efficiency because the water flux increase linearly with increase of operating pressure while ion permeation is only a function of feed concentration and is independent of the operating pressure [15].

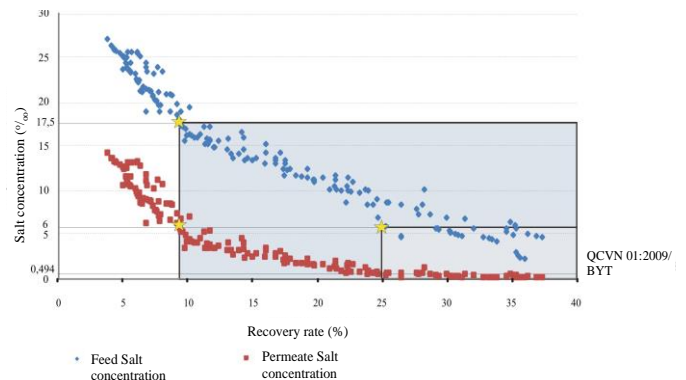


Fig. 5. Recovery rate of the single-stage NF process with wide range of salt concentration.

With the feed salinity of 6‰ - 27.5‰, the permeate salinity ranged from 0.52‰ to 14.3‰ (see Figure 5), which did not meet QCVN 01: 2009/BYT (<0.5‰). The salt rejection reached 47.4% - 91.5% and the recovery rate was low, ranging from 4%-35%, depending on the salinity of the input.

So from Phase 1's results, it was found that when the input water had a maximum salinity of 17.5‰, the output was approximately 6‰ - equals the highest possible input salinity value to obtain accepted water quality, in accordance with Vietnam National Technical Regulations (QCVN 01: 2009/BYT). This means that for a dual-stage NF process, the input salt concentration could not exceed 17.5‰. Besides, the minimum limit would be 6‰ because if salt concentration is lower than 6‰, single-stage NF is sufficient and is recommended to apply.

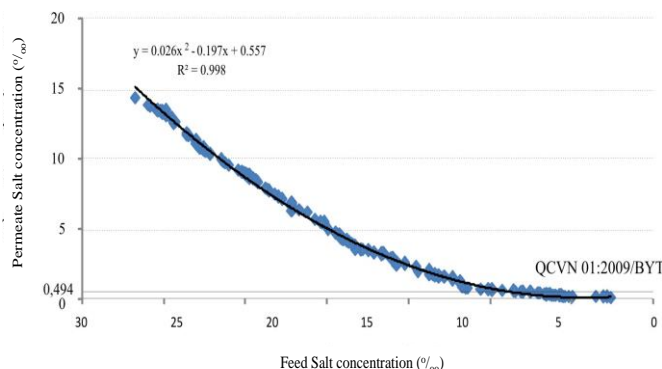


Fig. 6. Correlation between Feed and Permeate salt concentrations of the single-stage NF process.

3.3. Recovery rate and salt rejection of dual -stage NF (Phase 2)

Figure 7 showed clearly the recovery rate of NF1 process was from 10% - 35% for a range of salinity of 6‰-17.5‰. The permeate concentration of NF1 was 0.5‰ - 5.5‰. The trans-membrane pressure was kept constant at 10.5±0.5 bar. Membrane flowrate was from 13.2 - 20.6 L/min. After NF2, the permeate salt concentration was 0.1‰-0.3‰. The overall salt rejection of the dual stage NF system was from 66.5% to 89.7% and the recovery rate was 32%-47% (see Figure 8). It is obvious that with additional NF stage, the salt removal increases to some extent and so does the recovery rate. The permeate after dual-stage NF process all met the requirement of Vietnam National Technical regulations for Drinking water purpose - QCVN 01:2009/BYT issued by Ministry of Health (see Table 2). Azhar et al. [16] observed the recovery rate of their dual-stage NF was 18.9% at input salt concentration of 35‰ and decreased with the increasing salinity.

As in this study, the input salinity was max 17.5‰ for dual-stage NF testing, the recovery rate was more than 30% which was quite reasonable. Al-Tae and Sharif [7] also observed high permeate TDS of 1.3‰ after a dual-stage NF process at the feed salinity of 43‰. Normally, the diffusion mechanism is limited at high concentration, leading lower recovery rate. In other words, at high salinity (i.e. > 20‰), the dual NF system will not be suitable for desalination to meet drinking water quality.

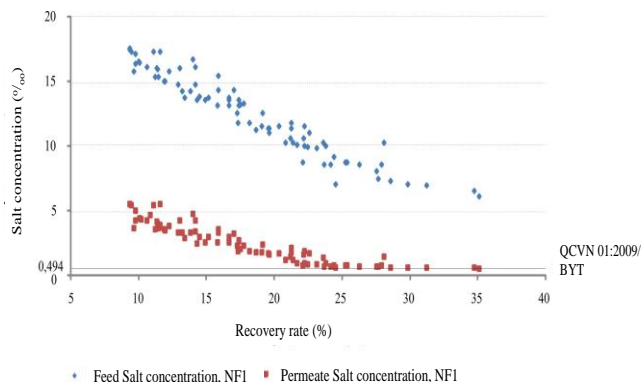


Fig. 7. Recovery rate of NF1 with input salt concentration of 6-17.5‰.

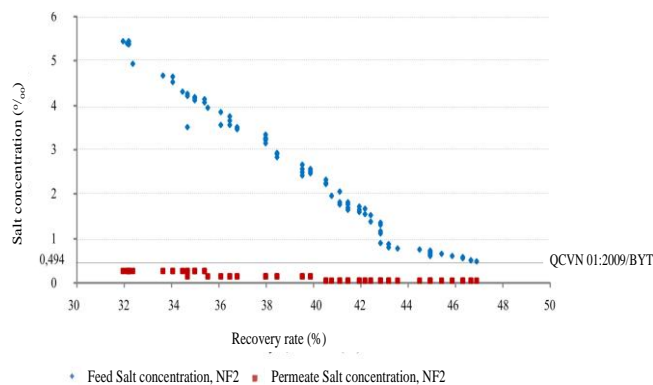


Fig. 8. Overall recovery rate of two-stage NF with input salt concentration of 6-17.5‰.

Through the test, the trans-membrane pressure was relatively stable, the desiccation efficiency (salt rejection) of dual NF process was inversely proportional to the input salt concentration. Increasing the salt concentration would decrease the salt rejection efficiency (see Figure 6). Similarly, the water recovery rates after dual NF process were also inversely proportional to the input salt concentrations (see Figures 5, 7 and 8). At maximum salt concentration (27.5‰), the desalination efficiency was only 47.5% and the recovery rate was very low, only 4% (see Figure 5). The possible explanation may lie in that when a large number of salt ions exists in the feed water, and then in the membrane pores, the layer of the adsorbed water on the pore walls will be thinner due to "salting-out" effect, thus, the salt concentration in the permeate as well as the permeate water will be limited [17].

Table 2

Effluent quality.

No	Parameters	Average Value	QCVN 01:2009/BYT*
1	pH	6.5-7.5	6.5-8.5
2	Turbidity, NTU	< 1	2
3	Salinity, ‰	<0.2	< 0.5
4	COD _{KMnO4} , mg/L	1.3	-
5	SO ₄ ²⁻ , mg/L	≤20	250
6	Cl, mg/L	≤150	250 - 300
7	Coliform, MPN/100mL	0	0

* National Technical Regulations on water quality for drinking purposes.

Compared to the artificial seawater desalination test conducted at lab-scale in our previous research [12], the desalination efficiency at pilot scale was higher, and so was the recovery rate. The main reason for this difference was that these experiments performed at 10.5±0.5 bar trans-membrane pressure, which was 8-10 bar higher than those in the previous experiment [12]. Basically, if the difference in membrane pressure was eliminated, the results of this experiment would probably be similar to those of previous tests. This confirms the consistency of the results at both lab scale and pilot scale.

3.4. Energy consumption

In addition to the membrane performance, the energy consumption and cost was also discussed in this section. The estimated energy cost for treatment of 1 m³ brackish water treated using the dual NF process was present in Table 3, when influent salinity was from 12.5 - 17.5‰.

Similar estimation for energy consumption and cost was implemented at lower salt concentration. It was found that energy costs were 8.28 and 33.4 \$/m³ at (1-6‰) and (6-12.5‰) salt concentrations, respectively. When replacing the two-stage NF process by NF-RO process, which had been described in details about the experimental system and testing procedure in previous study [14], the energy cost of NF-RO was a bit lower at salt concentration of about 22.5‰, however, it was much higher (about 110 \$/m³) when the salinity was higher than that of 22.5‰ (see Figure 9).

Table 3
Energy cost for treatment of brackish water with salinity of 12.5 – 17.5‰

Treatment unit	Q_p (m ³ /h)	P (bar)	Rec. rate (%)	Q_r (m ³ /h)	Q_{pump} (m ³ /h)	Pump head H (m)	Power reserve coef.	Density of fluid (T/m ³)	Total Pump efficiency η_p	Engine efficiency η_{dc}	Pump power (kWh)
NF2	0.45	11	35.78	0.87	0.87	110	1.5	1	0.85	1	0.460
NF1	0.11	11	11.65	7.50	7.50	110	1.25	1	0.85	1	3.304
Sand filter + UF	7.50	3.3	100	7.50	7.50	33	1.25	1	0.85	1	0.991
Feed	7.50	1.5		7.50	7.50	15	1.25	1	0.85	1	0.451
Energy use per day (16 hrs), kW/day											83.291
Unit price of electricity, \$/kW											0.91
Energy cost for 1m ³ treated water, \$											75.70

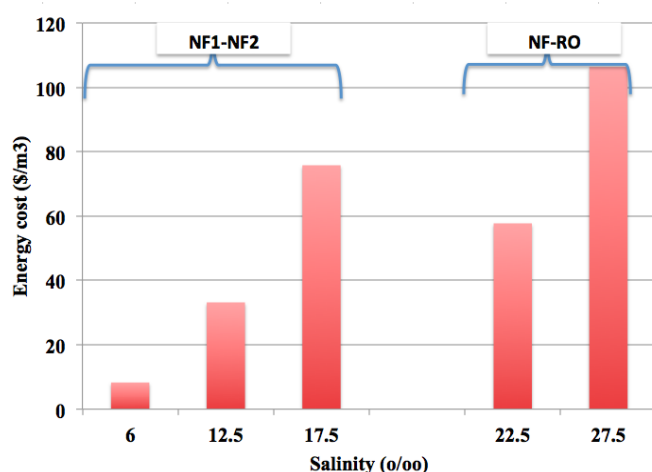


Fig. 9. Comparison of energy cost for different processes (dual NF and with NF-RO).

Conclusions

A seven-month test with NF processes for brackish water treatment has revealed that the nanofiltration process is a promising solution, providing drinking water for the lower Thu Bon River, where the salinity fluctuates significantly with seasons. In rainy season, when the input salinity is less than 6‰, the one-stage NF can completely meet the water quality's standard. When the input water has a salinity of more than 17.5‰, the two-stage NF filtration is the appropriate choice. However, during the dry season peaks, when the salinity was greater than 17.5 ‰, the two-stage NF filtration method was not effective.

The experiment showed that the salt concentration was inversely proportional to the desalination efficiency (i.e., salt rejection) and the recovery rate of the NF membrane. At the same time, the operation cost of the two-stage NF process is more reasonable at lower concentrations. In order to be able to treat the proposed water sample during high salt concentration period, further research will be required.

Acknowledgement

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