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A design method of the RO system in reverse osmosis brackish water desalination plants (procedure)

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ABSTRACT

This study proposes a simple design method of the Reverse osmosis (RO) system in RO brackish water desalination plants. This method is based on the application of maximum available recovery without scaling of any of the compounds present in the water as silica, calcium carbonate, calcium sulfate, barium sulfate, strontium sulfate, and calcium fluoride, and membrane manufacturer design guidelines, and the plant production. Although the method was originally conceived for application to subterranean brackish waters in the Canary Islands, Spain (principally Gran Canaria, Fuerteventura and Tenerife), it can be extrapolated to other types of region and water treatable with RO systems. The required input data are the chemical composition of the feed water, pH, temperature, silt density index membrane manufacturer design guidelines, and the plant production. The programmed method then determines the design of the RO system. The method whose procedure is described graphically and analytically can be used as an aid in design optimization of RO brackish water desalination plants with acid-free pretreatment processes and only the use of scale inhibitor using spiral wound membranes. Practical applications are presented. The final results for different types of feed water and capacities are showed.

Keywords: Brackish water; Reverse osmosis; Desalination plants; RO system design

1. Procedure

The programmed method determines the design of the Reverse osmosis (RO) system according to Fig. 1. One part of this work is based over operational experience in Brackish water (BW) RO desalination plants in Canary Islands.

Although this method use Fimltec FT30 spiral wound membranes [1] it can be extended to others sim-

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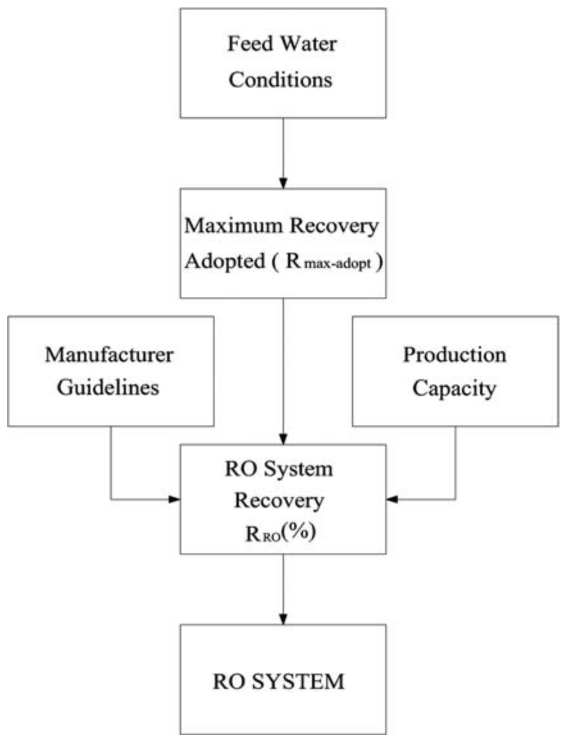


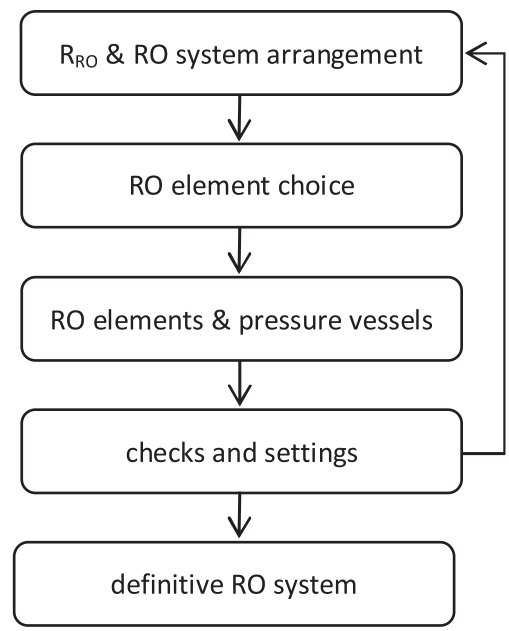
Fig. 1. Procedure.

ilar spiral wound membranes types. The following considerations were made in the preparation of this study:

(1) Use of specific scale inhibitors for $CaCO_3$, $CaSO_4$, $BaSO_4$, SrSO4, and CaF_2.
(2) For economic reasons, namely their high cost, the authors did not consider the use of specific silica scale inhibitors.
(3) The temperature of the reject water is the same as that of the feed water, namely between 10 and 30°C (natural BW temperature range in the Canary Islands region).
(4) The reject water pH value is lower than 8.3. On the one hand, this is equivalent to considering the feed water pH to be lower than eight and on the other to considering total alkalinity ($[HCO_3^-] + 2[CO_3^{2-}] + [OH^-]$) to be practically all due to bicarbonate ions [2].
(5) Use of spiral wound membranes (Filmtec FT30 or similar) of 4´´ length and 4´´ and 8´´ diameter.
(6) RO elements per pressure vessel from 1 to 6.
(7) Range of RO system recovery from 10 (minimum) to 87% (maximum).
(8) Production capacities lower than $2.5\,m^3/day$ are not considered.

From the chemical analysis of the water to be treated, as well as its temperature and pH we calculate the maximum recovery to be adopted ($R_{max\text{-}adopt}$) for there to be, along with no silica or calcium carbonate or calcium sulfate or barium sulfate or strontium sulfate, no calcium fluoride scaling [3–9].

With the $R_{max\text{-}adopt}$ value and with the production capacity (m^3/day) and using the manufacturer guidelines we have designed the RO system [10–12]. The next diagram shows the procedure we have used.



This procedure can be observed along the Figs. 2–7.

2. RO system recovery

According to the adopted maximum recovery in the previous paragraph in% ($R_{max\text{-}adopt}$) to prevent scaling and considering the maximum salinity of the feed water (brackish), it has been considered that the limit was 15,000 mg/l. It means that we can consider that the reject water salts concentration has a maximum value of 18,000 mg/l. In order to prevent, there is a RO system element operating with feed water salinity higher than 15,000 mg/l.

It was considered the RO system recovery (R_{RO}) is the integer value of $R_{max\text{-}adopt}$. According to the condition of the previous section:

$$R_{RO} \le \min\left\{R_{max\text{-}adopt,}\left[100\cdot\left(1-\left(\frac{TDS_f}{18000}\right)\right)\right]\right\}$$

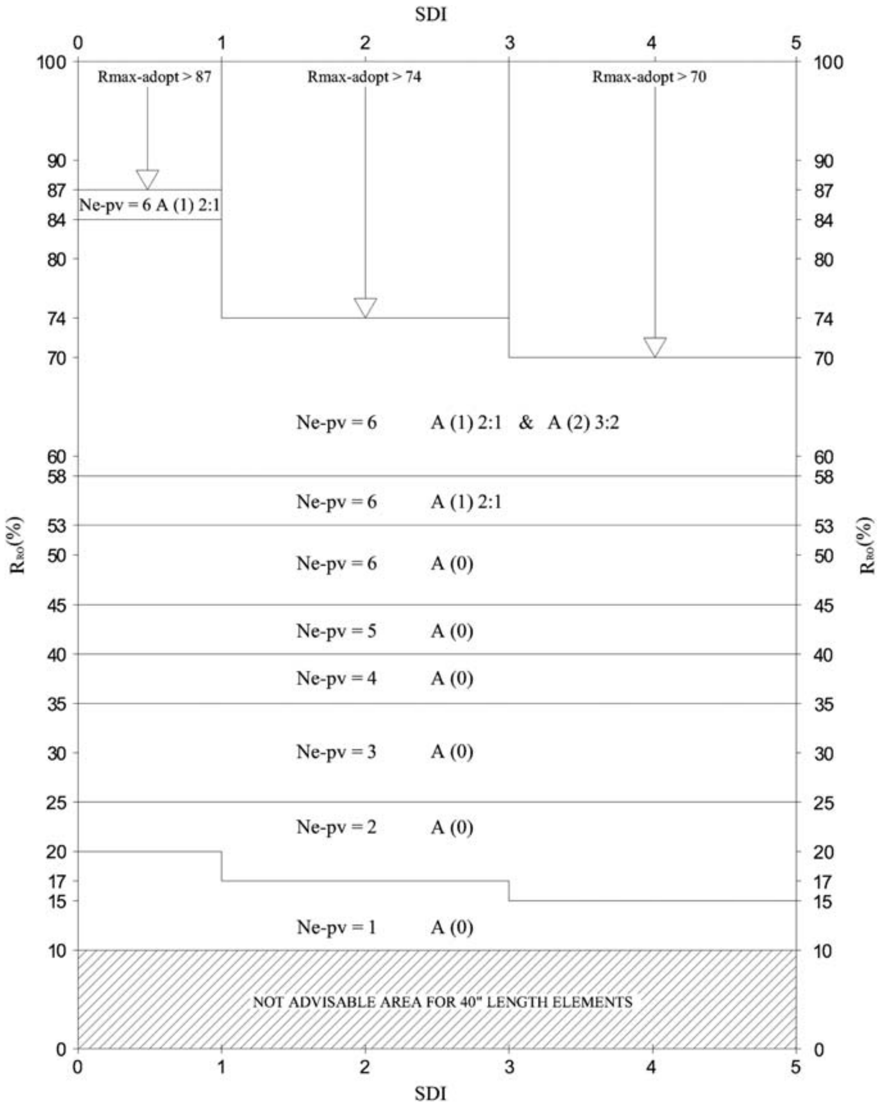


Fig. 2. RO elements per pressure vessel.

Besides their values are bounded between 10 and 87%: $R_{RO} \geqslant 10\%$. According to the feed water, silt density index (SDI) the maximum values are: If $3 \leqslant SDI < 5$ and $R_{max\text{-}adopt} > 70$. Then $R_{RO} = 70$. If $1 \leqslant SDI < 3$ and $R_{max\text{-}adopt} > 74$. Then $R_{RO} = 74$. If $SDI < 1$ and $R_{max\text{-}adopt} > 87$. Then $R_{RO} = 87$.

3. RO elements per pressure vessel. Basic arrangement

The number of elements per pressure vessel and the basic arrangement of the RO system depend on the recovery and it can be deduced from Figs. 2 and 3. The distribution of the production capacity is shown in Fig. 3.

4. Element choice for the RO system

Initially, the RO element type to choose will be the 40´´ in length and 4´´ diameter (4´´ × 40´´), and from these the element with the less active membrane area (cheaper), for example, the Filmtec BW30–4040 [1], which corresponds to an active area $S_{e\text{-}4} = 6.5\,m^2$.

If the capacity of the plant and the number of RO elements of 4´´ is high enough and taking into account that the production of 8´´ element is approximately the same as four 4´´ elements and considering one 8´´ element approximately cost 2.5 times the 4´´ element. The system will be also designed with 8´´ × 40 elements and initially using the element with the less active area, for example, the Filmtec BW30–330 [1], which corresponds

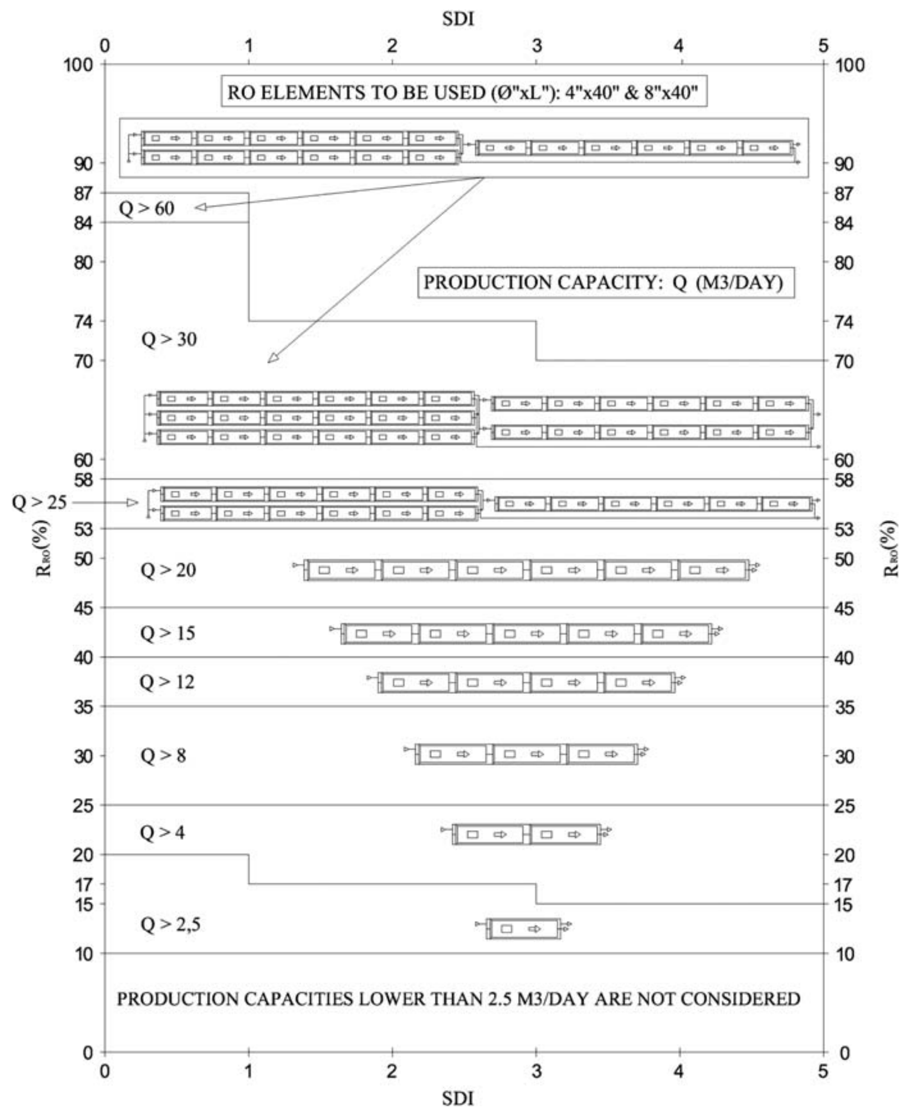


Fig. 3. Basic arrangement and production capacity distribution.

to an active area $S_{e-8} = 31\ m^2$. In this case, the RO system arrangement will be changed.

5. Maximum product flow and minimum reject flow per RO element

According to the manufacturer guidelines [10], the maximum product flow ($Q_{pe\text{-}max}$) and the minimum reject flow ($Q_{re\text{-}min}$) per RO element depend on the active membrane area and feed water SDI. These parameters have been written for 4´´ and 8´´ elements in Fig. 4.

6. Average product flow per RO element

The average product flow per RO element depends on the number of elements per pressure vessel and the R_{RO} value. We have considered the approximated values shown in Fig. 5.

7. Number of elements and pressure vessels in the RO system

The number of 4´´ RO elements ($N_{e\text{-}4}$) will be:

$$\frac{Q}{Q_{pe-med-4}}$$

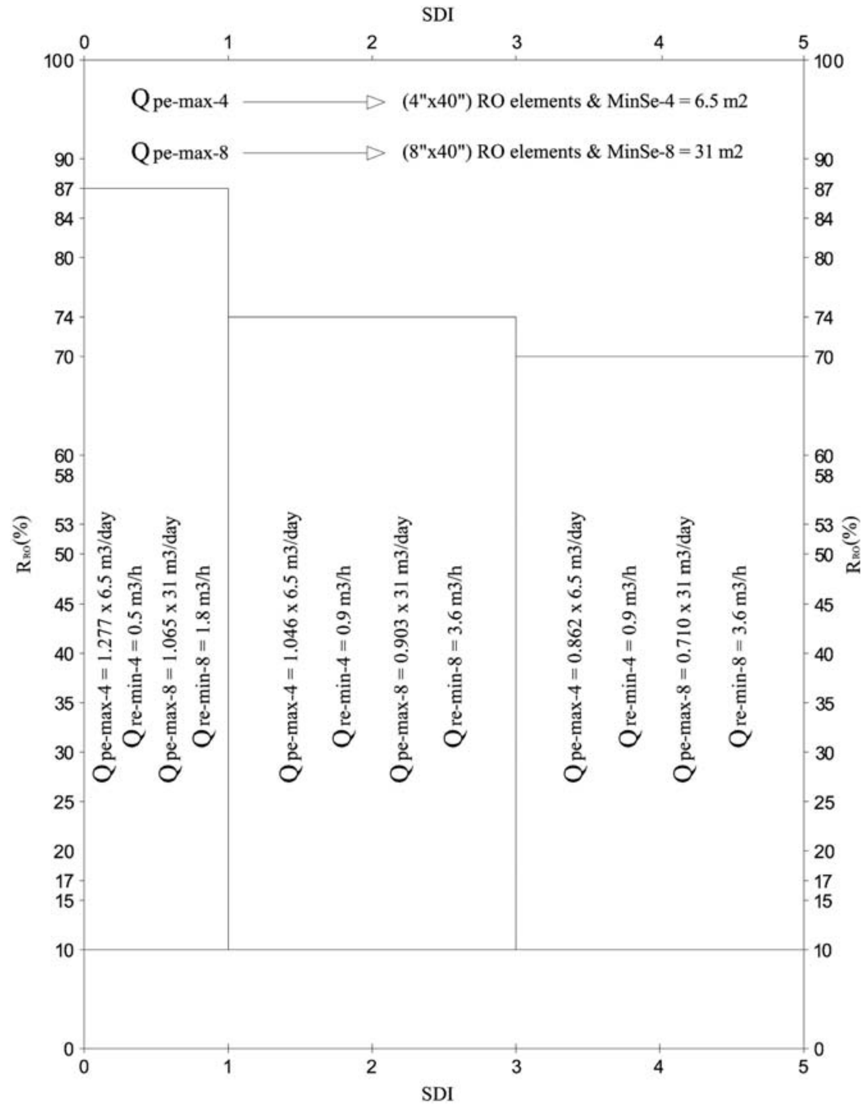


Fig. 4. Maximum product flow and minimum reject flow per RO element.

The number of 4´´ pressure vessels ($N_{pv\text{-}4}$) will be:

$$\frac{\left(\frac{Q}{Q_{pe}-\text{med}-4}\right)}{N_e-\text{pv}-4}$$

Taking $N_{pv\text{-}4}$ as the higher rounded value from the previous formula, the $N_{e\text{-}4}$ value can be deduced:

$$N_{e-4} = N_{pv-4} \cdot N_{e-pv-4}$$

The followed procedure for 4´´ y 8´´ elements is shown in Figs. 6 and 7.

8. RO system checks and settings

The checks and adjustments of the RO system according with the R_{RO} values and SDI are shown in Figs. 6 and 7.

If it is necessary the adjustments will be carried out reducing the system recovery till the reject flows are higher than the minimum recommended, recalculating the RO system to get the final R_{RO} value.

9. Practical application

Three samples of BW from wells in the Canary Islands were used for this work. The feed water chemical analysis for RO desalination plants are presented

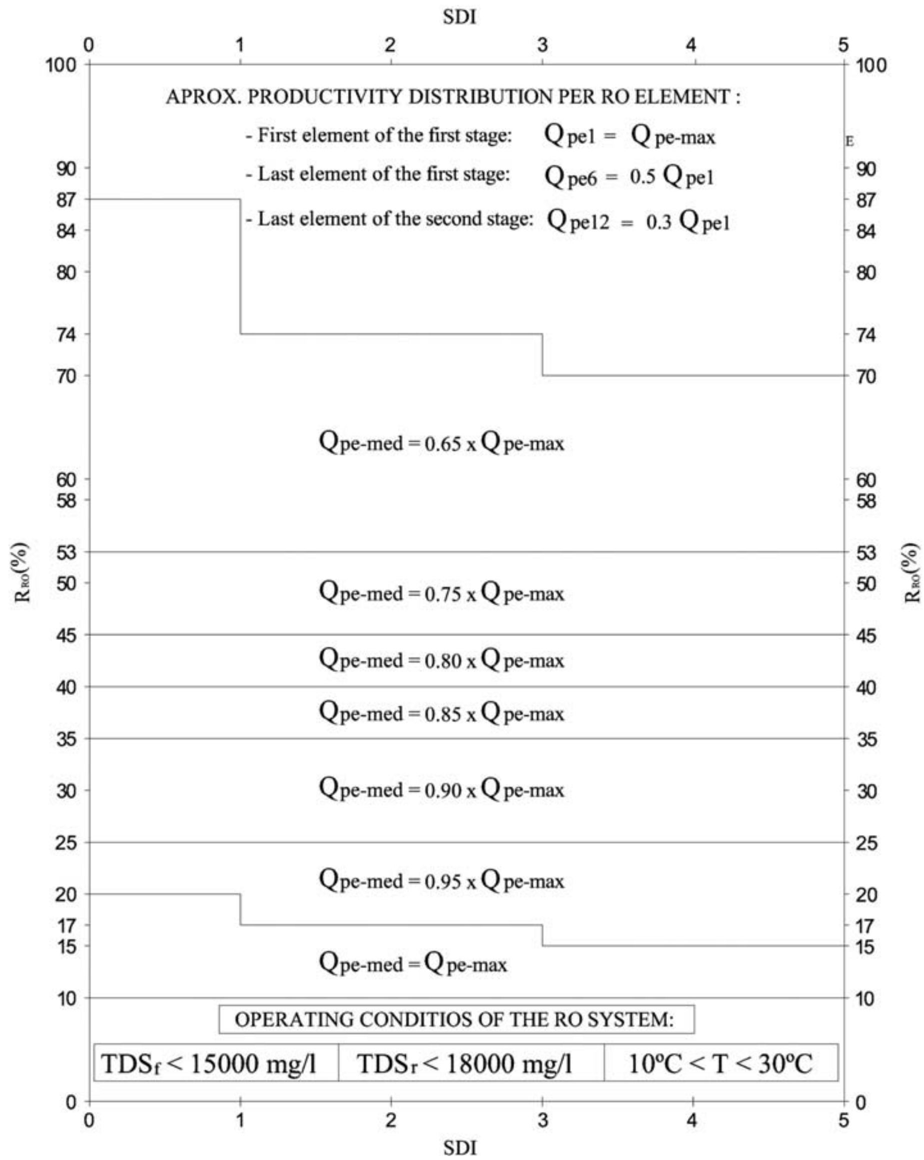


Fig. 5. Average product flow per RO element.

in Table 1 (concentrations in mg/l as ion, temperatures in ℃).

The calculation results are presented in Table 2.

10. Conclusions

From the obtained results (Table 2), it can be deduced that the limiting parameter of the maximum recovery of the RO systems 2 and 3 is $(TDS)_r$ (>18,000 mg/l). Because of that it was necessary to decrease the R_{RO} value to 71% (2) and 52% (3).

The 4´´ RO systems 1 and 2 have two possible arrangements in two stages: 2:1 and 3:2. The 8´´ RO systems 1 and 2 have only one possible arrangement in two stages: 2:1 for RO system 1 and 3:2 for RO system 2. The 4´´ and 8´´ RO system 3 have only one possible arrangement. It is in one stage.

The RO system design of a BW desalination plant employing this procedure, will need to consider, in addition to the results previously described, other limiting factors including economics, the type of RO element to be employed, the maximum operating pressure, the desired product water quality, etc.

The proposed method enables the use of a simple calculation software program that can be integrated

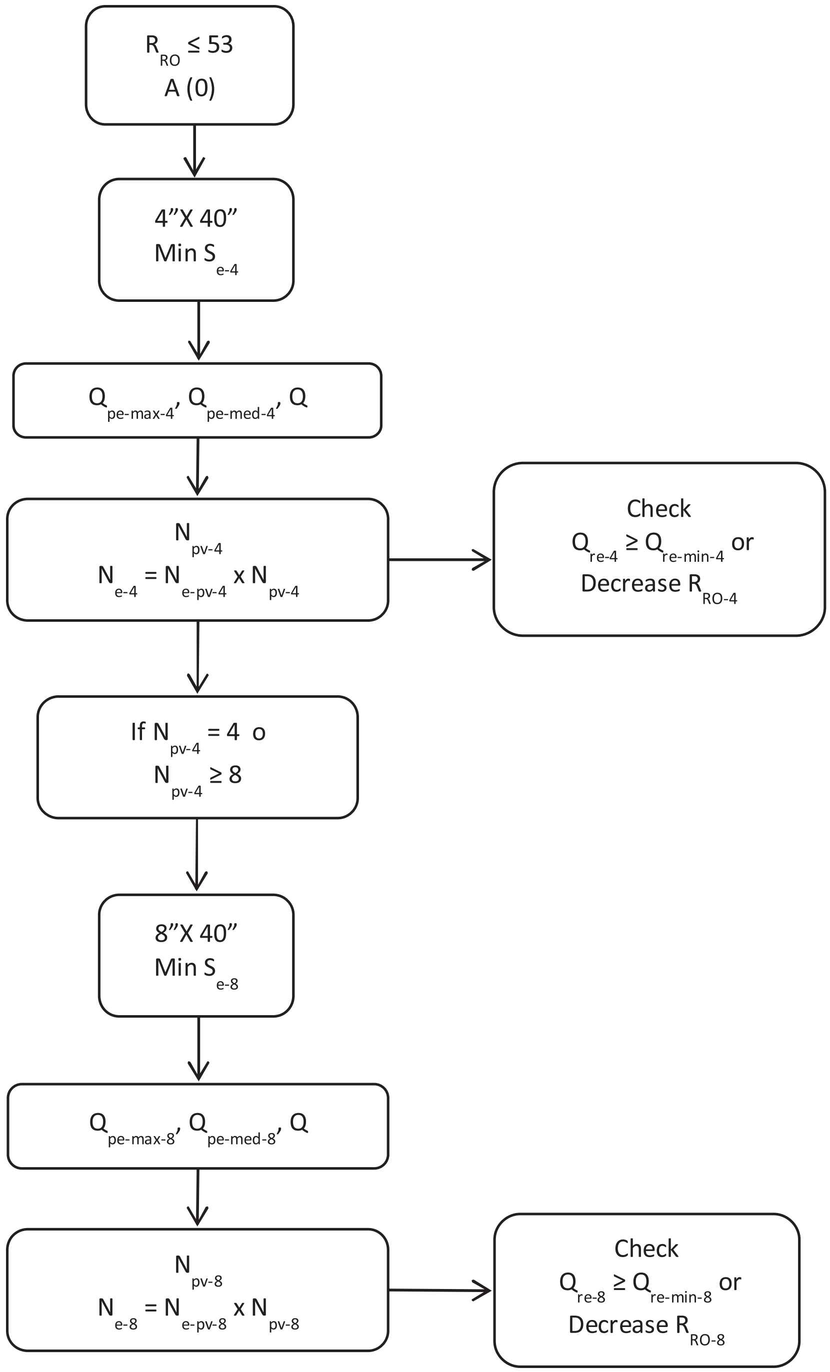


Fig. 6. RO system checks and settings ($R_{RO} \leqslant 53\%$).

into the definitive calculation program used for the BW RO plant design. In this way, later simulations can be easily applied with a high degree of confidence.

Although the RO system have been designed with the less active membrane area of 4´´ × 40 and 8´´ × 40 elements. These elements can be changed for larger active area of 4´´ × 40 and 8´´ × 40 elements, e.g. BW30LP-4040 ($S_{E-4} = 7.25\,m^2$) and BW30–365 ($S_{E-8} = 34\,m^2$) and BW30–400 ($S_{E-8} = 37\,m^2$) and BW30–440 ($S_{E-8} = 41\,m^2$) Filmtec elements [1] keeping the same RO system arrangement. In order to reduce the operating pressure of the plant.

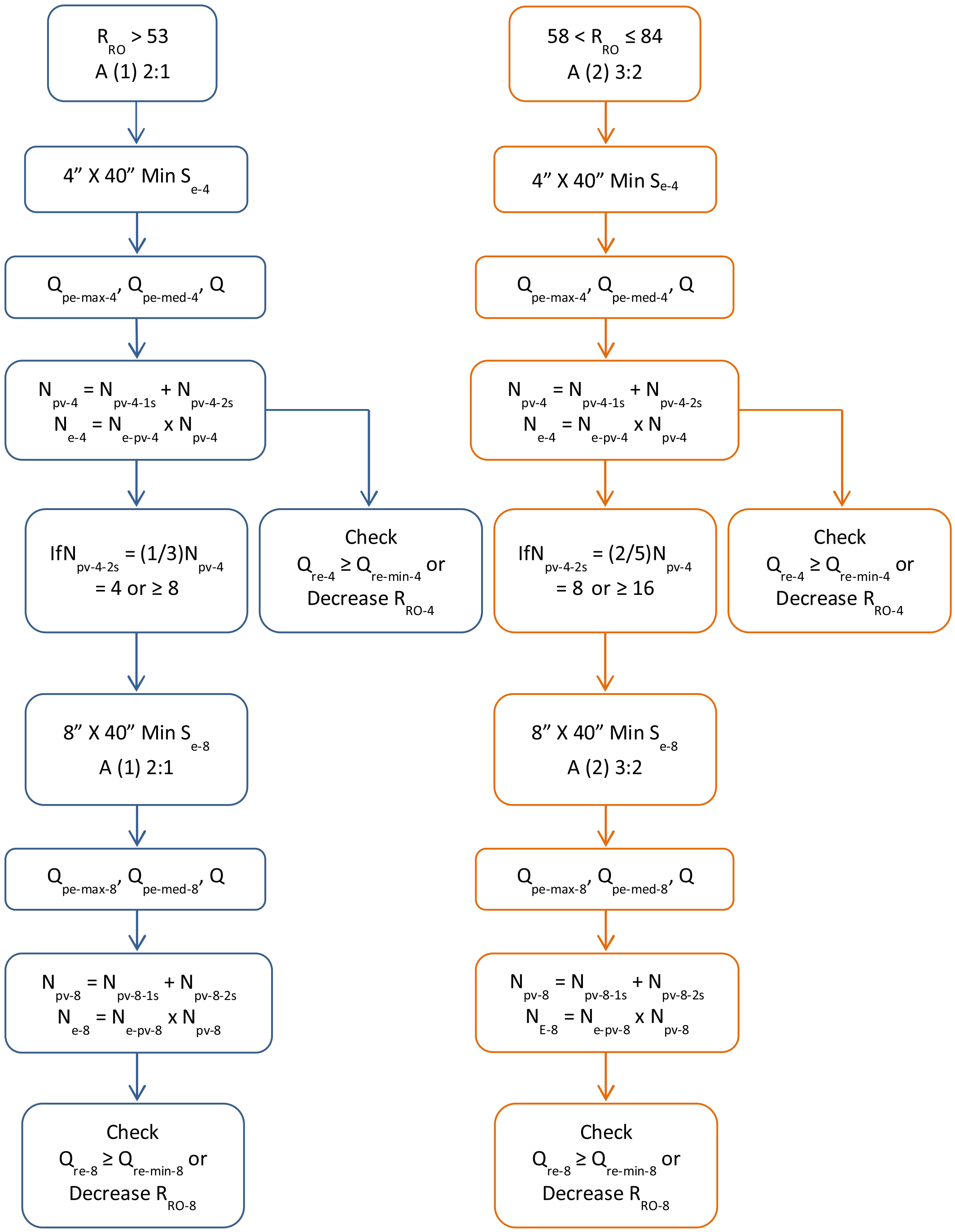


Fig. 7. RO system checks and settings ($R_{RO} > 53\%$).

Table 1
Feed water chemical analysis

Sample	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{-}	NO_3^{-}	Cl^{-}	SiO_2	Fe	TDS	pH	T_{min}	T_{max}	SDI
1	96.10	139.70	958.27	32.30	668.70	695.20	382.50	963.00	35.00	0.10	3970.77	7.80	22.0	22.0	2.70
2	681.50	489.10	413.34	26.30	74.30	573.50	115.10	2760.50	22.50	0.10	5156.14	6.90	22.0	24.0	2.50
3	58.60	89.10	2920.43	45.20	475.30	1063.40	21.50	3832.20	25.20	0.10	8530.93	7.70	24.0	26.0	2.60

Table 2
Results

RO system	1	2	3
Capacity (m^3/day)	600	500	300
TDS (mg/l)	3,970.77	5,156.14	8,530.93
$R_{max\text{-}adopt}$ (%)	67.47	74.43	79.45
$(TDS)_r$ for $R_{max\text{-}adopt}$	12,206	20,166	41,506
R_{RO} (%)	67	71	52
$N_{e\text{-}pv}$	6	6	6
Stages	2	2	1
$N_{pv\text{-}4}$ (A 0)	0	0	10
$N_{pv\text{-}8}$ (A 0)	0	0	3
$N_{pv\text{-}4}$ (A 1)	24	21	0
$N_{pv\text{-}4}$ (A 2)	25	20	0
$N_{pv\text{-}8}$ (A 1)	6	0	0
$N_{pv\text{-}8}$ (A 2)	0	5	0
4´´ arrangement (A 1)	6 + 8	14 + 7	0
4´´ arrangement (A 2)	15 + 10	12 + 8	0
8´´ arrangement (A 1)	4 + 2	0	0
8´´ arrangement (A 2)	0	3 + 2	0
$N_{e\text{-}4}$ (A 0)	0	0	60
$N_{e\text{-}8}$ (A 0)	0	0	18
$N_{e\text{-}4}$ (A 1)	144	126	0
$N_{e\text{-}4}$ (A 2)	150	120	0
$N_{e\text{-}8}$ (A 1)	36	0	0
$N_{e\text{-}8}$ (A 2)	0	30	0

Symbols

A	—	arrangement
BW, bw	—	brackish water
FT 30	—	Filmtec spiral wound membrane
L	—	length
LSI	—	Langelier saturation index
Min $S_{e\text{-}4}$	—	minimum membrane surface per 4´´ RO element
Min $S_{e\text{-}8}$	—	minimum membrane surface per 8´´ RO element
$N_{e\text{-}4}$	—	total 4´´ RO elements
$N_{e\text{-}8}$	—	total 8´´ RO elements
$N_{e\text{-}pv}$	—	RO elements per pressure vessel
$N_{e\text{-}pv\text{-}4}$	—	4´´ RO elements per pressure vessel
$N_{e\text{-}pv\text{-}8}$	—	8´´ RO elements per pressure vessel
$N_{e\text{-}pv\text{-}4\text{-}1s}$	—	first stage 4´´ RO elements per pressure vessel
$N_{e\text{-}pv\text{-}8\text{-}1s}$	—	first stage 8´´ RO elements per pressure vessel
$N_{e\text{-}pv\text{-}4\text{-}2s}$	—	second stage 4" RO elements per pressure vessel
$N_{e\text{-}pv\text{-}8\text{-}2s}$	—	second stage 8´´ RO elements per pressure vessel
$N_{pv\text{-}4}$	—	total 4´´ pressure vessels
$N_{pv\text{-}8}$	—	total 8´´ pressure vessels
$N_{pv\text{-}4\text{-}1s}$	—	first stage 4´´ pressure vessels
$N_{pv-8-1s}$	—	first stage 8´´ pressure vessels
$N_{pv\text{-}4\text{-}2s}$	—	second stage 4´´ pressure vessels
$N_{pv\text{-}8\text{-}2s}$	—	second stage 8´´ pressure vessels
PV, pv	—	pressure vessel
Q	—	production capacity (m3/day)
$Q_{pe\text{-}max}$	—	maximum product flow per RO element
$Q_{pe\text{-}max\text{-}4}$	—	maximum product flow per 4´´ RO element
$Q_{pe\text{-}max\text{-}8}$	—	maximum product flow per 8´´ RO element
$Q_{pe\text{-}med}$	—	average product flow per RO element
$Q_{pe\text{-}med\text{-}4}$	—	average product flow per 4´´ RO element
$Q_{pe\text{-}med\text{-}8}$	—	average product flow per 8´´ RO element
$Q_{re\text{-}4}$	—	4´´ RO element reject flow
$Q_{re\text{-}8}$	—	8´´ RO element reject flow
$Q_{re\text{-}min}$	—	minimum reject flow per RO element
$Q_{re\text{-}min\text{-}4}$	—	minimum reject flow per 4´´ RO element
$Q_{re\text{-}min\text{-}8}$	—	minimum reject flow per 8´´ RO element
$R_{max\text{-}adopt}$	—	maximum recovery adopted
R_{RO}	—	RO system recovery (%)
$R_{RO\text{-}4}$	—	4´´ RO system recovery (%)
$R_{RO\text{-}8}$	—	8´´ RO system recovery (%)
RO, ro	—	reverse osmosis
SDI	—	silt density index
T	—	feed water temperature
TDS	—	total dissolved salt
Ø	—	diameter

Subscripts

e	—	element
f	—	feed
p	—	product, permeate
r	—	reject

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