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Estimation of the maximum conversion level in reverse osmosis brackish water desalination plants

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ABSTRACT

This paper proposes a simple calculation method to estimate the maximum conversion level in reverse osmosis (RO) brackish water desalination plants. The method is based on the scaling potential of different compounds found in the water to be treated. These compounds include silica, calcium carbonate, calcium sulphate, barium sulphate, strontium sulphate and calcium fluoride. 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 and its pH and temperature. The programmed method then determines the maximum conversion level of the RO system without the risk of scaling of any of the solutes present in the water. The method can be used as an aid in design optimization of RO brackish water desalination plants with acid-free pre-treatment processes and only the use of scale inhibitors.

Keywords: Brackish water; Reverse osmosis; Desalination plants; Recovery; Conversion level

1. Introduction

The main salts that can be most expected to precipitate in reverse osmosis (RO) systems [1–3] are silica (SiO_2), calcium carbonate ($CaCO_3$), calcium sulphate ($CaSO_4$), barium sulphate ($BaSO_4$), strontium sulphate ($SrSO_4$) and calcium fluoride (CaF_2). The first three of these, namely silica, calcium carbonate and calcium sulphate, are the most commonly found salts in the subterranean brackish waters of the Canary Island region. Of these three, silica has the highest effect on conversion limits, followed by calcium carbonate and finally calcium sulphate.

The scaling potential of these salts will depend on their concentration in the feed water (chemical analysis), on the pH value, the temperature, the RO system's conversion level and on the solubility limits of the respective salts.

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Table 1
Feed water chemical analysis

Sample	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^{2-}	NO_3^-	Cl^-	SiO_2	Fe	TDS	pH	T_{min}	T_{max}
1	96.10	139.70	958.27	32.30	668.70	695.20	382.50	963.00	35.00	0.10	3,970.77	7.80	22.0	22.0
2	282.00	275.90	682.80	18.00	248.90	482.20	12.00	1,864.69	48.00	0.00	3,914.49	7.10	23.0	24.0
3	681.50	489.10	413.34	26.30	74.30	573.50	115.10	2,760.50	22.50	0.10	5,156.14	6.90	22.0	24.0
4	58.60	89.10	2,920.43	45.20	475.30	1,063.40	21.50	3,832.20	22.20	0.10	8,530.93	7.70	24.0	26.0
5	163.70	220.70	1,066.76	31.20	998.10	1,159.00	51.20	1,140.5	27.80	0.00	4,858.96	7.78	23.0	24.0

2. Initial considerations

The following considerations were made in the preparation of this paper:

(1) Use of specific scale inhibitors for $CaCO_3$, $CaSO_4$, $BaSO_4$, $SrSO_4$ 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 brackish water 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 8, and on the other to considering total alkalinity ($[HCO_2^-]+2[CO_3^{2-}]+[OH^-]$) to be practically all due to bicarbonate ions [4].
(5) Ideal membrane performance—in terms of salt rejection. This is equivalent to considering a CO_2 rejection rate of 0%, and for the rest of the compounds in the feed water a rejection rate of 100%.

This fifth consideration assumes a theoretical membrane performance which might appear unreal in its conservatism but which, in practice and from the perspective of the analysis of possible scaling, is not so far from reality if it is taken into consideration that, as a result of the effect of polarization of the concentration on the membrane surface of the module operating in the worst conditions, there is a higher concentration of salts than for the reject flow.

3. Procedure

The following sequential order was observed:

(1) Input data.

Comprising the chemical analysis of the water to be treated, as well as its temperature and pH.

(2) Calculation methodology.

(2.1) Calculation of the maximum RO system recovery level for there to be no silica scaling ($R_1 = R_{\text{max-SiO}_2}$).

(2.2) Calculation of the maximum RO system recovery level to be adopted ($R_{\text{max-adopt}}$).

(2.2.1) Calculation of the maximum RO system recovery level for there to be, along with no silica scaling, no calcium carbonate scaling ($R_2 = R_{\text{max-SiO}_2\text{-CaCO}_3}$).

(2.2.2) Calculation of the maximum RO system recovery level for there to be, along with no silica scaling and no calcium carbonate scaling, no calcium sulphate scaling ($R_3 = R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}$).

(2.2.3) Calculation of the maximum RO system recovery level for there to be, along with no silica or calcium carbonate or calcium sulphate scaling, no barium sulphate scaling ($R_4 = R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4}$).

(2.2.4) Calculation of the maximum RO system recovery level for there to be, along with no silica or calcium carbonate or calcium sulphate or barium sulphate scaling, no strontium sulphate scaling ($R_5 = R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4\text{-SrSO}_4}$).

(2.2.5) Calculation of the maximum RO system recovery level for there to be, along with no silica or calcium carbonate or calcium sulphate or barium sulphate or strontium sulphate scaling, no calcium fluoride scaling ($R_{\text{max-adopt}} = R_6 = R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4\text{-SrSO}_4\text{-CaF}_2}$).

(3) Practical application.

(3.1) Input data.

(3.2) Results.

(4) Conclusions.

(1) Input data.

Before proceeding with the actual calculations, the concentrations in the feed water must be known of the following:

- Cations in mg/l: calcium $(Ca)_f$, magnesium $(Mg)_f$, sodium $(Na)_f$, potassium $(K)_f$, barium $(Ba)_f$, strontium $(Sr)_f$.
- Anions in mg/l: carbonates (0 mg/l), bicarbonates $(HCO_3)_f$, sulphates $(SO_4)_f$, nitrates $(NO_3)_f$, chlorides $(Cl)_f$, fluorides $(F)_f$.

- Others: silica $(SiO_2)_f$ (mg/l), pH_f.
- Temperatures in ℃: minimum ($T_{\min}$), mean (T_{med}) and maximum ($T_{\max}$).

(2) Calculation methodology.

(2.1) Calculation of the maximum RO system recovery level for there to be no silica scaling ($R_1 = R_{\text{max-SiO}_2}$).

Estimate carbon dioxide (CO_2) content:

$$(CO_2)_f = [HCO_3^-]_f/10^{(pH_f-6,3)} \tag{1}$$

Calculate the maximum soluble silica concentration level for the minimum temperature $(SiO2)_{T\min}$ and pH ranging between 7 and 7.8 [1,5,6]:

$$(SiO_2)_{T\min} = 4T_{\min} \tag{2}$$

Calculate the concentration factor required for silica concentration in the reject water to be $(SiO2)_{T\min}$:

$$CF_{\text{min-SiO}_2} = (4T_{\min})/(SiO_2)_f \tag{3}$$

Calculate in mg/l as $CaCO_3$ the expected concentration of bicarbonates in the reject water, for the above concentration factor:

$$[HCO_3^-]_{\text{r-max-SiO}_2} = [HCO_3^-]_f \times CF_{\text{min-SiO}_2} \tag{4}$$

Calculate the expected pH value in the reject water for the above concentration factor:

$$pH_{\text{r-max-SiO}_2} = 6.3 + \log(([HCO_3^-]_{\text{r-max-SiO}_2})/(CO_2)_f) \tag{5}$$

Calculate the pH coefficient for estimation of the maximum silica concentration level in the reject water:

$$\text{If } 7 \leq pH_{\text{r-max-SiO}_2} \leq 7.8 : C_{pH} = 1 \tag{6}$$

$$\text{If } pH_{\text{r-max-SiO}_2} < 7 : C_{pH} = 1.819 - (0.117 \times pH_{\text{r-max-SiO}_2}) \tag{7}$$

$$\text{If } pH_{\text{rmin}} > 7.8 : C_{pH} = 0.47 + 0.0006 \times (e)^{0.87\text{pHr-max-SiO}_2} \tag{8}$$

Calculate the concentration factor required to obtain the maximum silica concentration level in the reject water:

$$CF_{\text{max-SiO}_2} = (4T_{\min}) \times C_{pH}/(SiO_2)_f \tag{9}$$

Calculate the required conversion in % to obtain the above concentration factor:

$$R_1 = R_{\text{max-SiO}_2} = 100 \times (CF_{\text{max-SiO}_2} - 1)/CF_{\text{max-SiO}_2} \tag{10}$$

(2.2) Calculation of the maximum RO system recovery level to be adopted ($R_{\text{max\{\textbackslash hyphen\}adopt}}$).

(2.2.1) Calculation of the maximum RO system recovery level for there to be, along with no silica scaling, no calcium carbonate scaling ($R_2 = R_{\text{max-SiO}_2\text{-CaCO}_3}$).

The calcium carbonate scaling trend level was verified for the conversion $R_1 = R_{\text{max-SiO}_2}$ [7,8]:

$$\text{Calculate } [Ca^{2+}]_{\text{r-max-SiO}_2} = [Ca^{2+}]_F \times CF_{\text{max-SiO}_2} \tag{11}$$

$$\text{Calculate } [HCO_3^-]_{\text{r-max-SiO}_2} = [HCO_3^-]_f \times CF_{\text{max-SiO}_2} \tag{12}$$

$$\text{Calculate } pH_{\text{r-max-SiO}_2} = 6.3 + \log(([HCO_3^-]_{\text{r-max-SiO}_2})/(CO_2)_f) \tag{13}$$

$$\text{Calculate } p\text{-}[Ca^{2+}]_{\text{r-max-SiO}_2} = \log(10^5/[Ca^{2+}]_{\text{r-max-SiO}_2}) \tag{14}$$

$$\text{Calculate } p\text{-}[HCO_3^-]_{\text{r-max-SiO}_2} = \log(5 \times 10^4/([HCO_3^-]_{\text{r-max-SiO}_2})) \tag{15}$$

$$\text{Calculate } (TDS)_{\text{r-max-SiO}_2} = (TDS)_f \times CF_{\text{max-SiO}_2} \tag{16}$$

*If $(TDS)_{\text{r-max-SiO}_2} \leq 10,000$. Calculate the Langelier Saturation Index (LSI) [9]:

If $(TDS)_{\text{r-max-SiO}_2} \leq 6,000$:

$$\text{Calculate } C_{\text{r-max-SiO}_2} = (([\log(TDS)_{\text{r-max-SiO}_2}] - 1)/10) - (13.12 \times \log[T_{\max} + 273.15]) + 34.46 \tag{17}$$

If $6,000 < (TDS)_r \leq 10.000$:

$$\text{Calculate } C_{\text{r-max-SiO}_2} = 0.2778 - (13.12 \times \log[T_{\max} + 273.15]) + 34.46 \tag{18}$$

$$\text{Calculate pHs}_{\text{r-max-SiO}_2} = p\text{-}[\text{Ca}^{2+}]_{\text{r-max-SiO}_2} + p\text{-}[\text{HCO}_3^-]_{\text{r-max-SiO}_2} + C_{\text{r-max-SiO}_2} \tag{19}$$

$$\text{Calculate LSI}_{\text{r-max-SiO}_2} = \text{pH}_{\text{r-max-SiO}_2} - \text{pHs}_{\text{r-max-SiO}_2} \tag{20}$$

From the value obtained in (20), the following considerations were made:

If $\text{LSI}_{\text{r-max-SiO}_2} < 0$. The addition of scaling inhibitor is not necessary. $R_2(R_{\text{max-SiO}_2\text{-CaCO}_3}) = R_1(R_{\text{max-SiO}_2})$ is adopted and the calcium sulphate scaling trend level is verified for this conversion.

If $0 \leq \text{LSI}_{\text{r-max-SiO}_2} \leq 2.5$. The addition of scaling inhibitor is necessary. $R_2(R_{\text{max-SiO}_2\text{-CaCO}_3}) = R_1(R_{\text{max-SiO}_2})$ is adopted and the calcium sulphate scaling trend level is verified for this conversion.

If $\text{LSI}_{\text{r-max-SiO}_2 > 2.5}$. The conversion level $R_2(R_{\text{max-SiO}_2\text{-CaCO}_3}) < R_1(R_{\text{max-SiO}_2})$ is reduced until the new $\text{LSI}_{\text{r-max-SiO}_2\text{-CaCO}_3} \leq 2.5$.

*If $(\text{STD})_{\text{r-max-SiO}_2} > 10,000$. Calculate the Stiff & Davis Stability or Saturation Index (S&DSI) [10]:

Calculate the ionic strength of the feed water from the molal concentrations of all the ions present in it:

$$\text{IS}_\text{f} = 0,5 \times [4(m_\text{Ca})_\text{f} + 4(m_\text{Mg})_\text{f} + (m_\text{Na})_\text{f} + (m_\text{K})_\text{f} + 4(m_\text{Ba})_\text{f} + 4(m_\text{Sr})_\text{f} + (m_{\text{HCO}_3})_\text{f} + 4(m_{\text{SO}_4})_\text{f} + (m_{\text{NO}_3})_\text{f} + (m_\text{Cl})_\text{f} + (m_\text{F})_\text{f}] \tag{21}$$

Calculate the ionic strength of the reject water:

$$\text{IS}_{\text{r-max-SiO}_2} = \text{IS}_\text{f} \times \text{CF}_{\text{max-SiO}_2} = A \tag{22}$$

Calculate the coefficient $K_{T_{\text{max}}}(A)$ from:

$$K_{10^\circ}(A) = 1.3944(A)^3 - 4.8733(A)^2 + 4.8189(A) + 2.28 \tag{23}$$

$$K_{20^\circ}(A) = 1.4389(A)^3 - 5.0767(A)^2 + 5.0578(A) + 2.06 \tag{24}$$

$$K_{25^\circ}(A) = 1.5861(A)^3 - 5.4283(A)^2 + 5.2222(A) + 1.96 \tag{25}$$

$$K_{30^\circ}(A) = 1.3417(A)^3 - 4.7350(A)^2 + 4.7933(A) + 1.87 \tag{26}$$

If the value of T_{max} is different from the previous values (10°, 20°, 25° and 30°C), $K_{T_{\text{max}}}$ (A) is obtained by interpolating between the values immediately above and below.

$$\text{Calculate pHs}_{\text{r-max-SiO}_2} = p\text{-}[\text{Ca}^{2+}]_{\text{r-max-SiO}_2} + p\text{-}[\text{HCO}_3^-]_{\text{r-max-SiO}_2} + K_{T_{\text{max}}}(A) \tag{27}$$

$$\text{Calculate S\&DSI}_{\text{r-max-SiO}_2} = \text{pH}_{\text{r-max-SiO}_2} - \text{pHs}_{\text{r-max-SiO}_2} \tag{28}$$

The following considerations are made based on the value obtained in (28):

If $\text{S\&DSI}_{\text{r-max-SiO}_2} < 0$. The addition of scaling inhibitor is not necessary. $R_2(R_{\text{max-SiO}_2\text{-CaCO}_3}) = R_1(R_{\text{max-SiO}_2})$ is adopted and the calcium sulphate scaling trend level is verified for this conversion.

If $0 \leq \text{S\&DSI}_{\text{r-max-SiO}_2} \leq 2$. The addition of scaling inhibitor is necessary. $R_2(R_{\text{max-SiO}_2\text{-CaCO}_3}) = R_1(R_{\text{max-SiO}_2})$ is adopted and the calcium sulphate scaling trend level is verified for this conversion.

If $\text{S\&DSI}_{\text{r-max-SiO}_2} > 2$. The conversion level $R_2(R_{\text{max-SiO}_2\text{-CaCO}_3}) < R_1(R_{\text{max-SiO}_2})$ is reduced until the new $\text{S\&DSI}_{\text{r-max-SiO}_2\text{-CaCO}_3} \leq 2$.

(2.2.2) Calculation of the maximum RO system recovery level for there to be, along with no silica scaling and no calcium carbonate scaling, no calcium sulphate scaling ($R_3 = R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}$).

The calcium sulphate scaling tendency level is verified for the conversion $R_2 = R_{\text{max-SiO}_2\text{-CaCO}_3}$ [11]:

$$\text{Calculate CF}_{\text{max-SiO}_2\text{-CaCO}_3} = 100/(100 - R_{\text{max-SiO}_2\text{-CaCO}_3}) \tag{29}$$

Calculate the ionic product of the calcium sulphate in the reject water:

$$\text{IP}_{\text{CaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3} = [(\text{SO}_4)_\text{f} \times \text{CF}_{\text{max-SiO}_2\text{-CaCO}_3}/96,000] \times [(Ca)_\text{f} \times \text{CF}_{\text{max-SiO}_2\text{-CaCO}_3}/40,080] \tag{30}$$

Calculate the ionic strength of the reject water:

$$IS_{\text{r-max-SiO}_2\text{-CaCO}_3} = IS_f \times CF_{\text{max-SiO}_2\text{-CaCO}_3} \tag{31}$$

Calculate the solubility product of the calcium sulphate in the reject water [12]:

$$K_{\text{CaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3} = 0.0016(IS_{\text{r-max-SiO}_2\text{-CaCO}_3})^{(0.6742)} \tag{32}$$

The following considerations are made based on the values obtained in (30) and (32):

If $IP_{\text{CaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3} \leq 0.8\ K_{\text{CaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3}$. The addition of scaling inhibitor is not necessary. $R_3(R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}) = R_2(R_{\text{max-SiO}_2\text{-CaCO}_3})$ is adopted and the barium sulphate scaling trend level is verified for this conversion.

If $0.8K_{\text{CaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3} < IP_{\text{CaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3} \leq 2.5K_{\text{CaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3}$. The addition of scaling inhibitor is necessary. $R_3(R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}) = R_2(R_{\text{max-SiO}_2\text{-CaCO3}})$ is adopted and the barium sulphate scaling trend level is verified for this conversion.

If $2.5K_{\text{CaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3} < IP_{\text{CaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3}$. The conversion level $R_3(R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}) < R_2(R_{\text{max-SiO}_2\text{-CaCO}_3})$ is reduced until for the new conversión $IP_{\text{CaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4} \leq 2.5\ K_{\text{CaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}$.

(2.2.3) Calculation of the maximum RO system recovery level for there to be, along with no silica or calcium carbonate or calcium sulphate scaling, no barium sulphate scaling ($R_4 = R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4}$).

The barium sulphate scaling tendency level is verified for the conversion $R_3 = R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}$ [11]:

$$\text{Calculate } CF_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4} = 100/(100 - R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}) \tag{33}$$

Calculate the ionic product of the barium sulphate in the reject water:

$$IP_{\text{BaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4} = [(SO_4)_f \times CF_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}/96,000] \times [(Ba)_f \times CF_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}/137,340] \tag{34}$$

Calculate the ionic strength of the reject water:

$$IS_{\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4} = IS_f \times CF_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4} \tag{35}$$

Calculate the solubility product of the barium sulphate in the reject water [12]:

$$K_{\text{BaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4} = 0.000000007 \times (IS_{\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4})^{0.835} \tag{36}$$

The following considerations are made based on the values obtained in Eqs. (34) and (36):

If $IP_{\text{BaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4} \leq 0.8K_{\text{BaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}$.

The addition of scaling inhibitor is not necessary. $R_4(R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4}) = R_3(R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4})$ is adopted and the strontium sulphate scaling trend level is verified for this conversion.

If $0.8K_{\text{BaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3} < IP_{\text{BaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4} \leq 40K_{\text{BaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}$.

The addition of scaling inhibitor is necessary. $R_4(R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4}) = R_3(R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4})$ is adopted and the strontium sulphate scaling trend level is verified for this conversion.

If $40K_{\text{BaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4} < IP_{\text{BaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4}$.

The conversion level $R_4(R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4}) < R_3(R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4})$ is reduced until for the new conversion $IP_{\text{BaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4} \leq 40K_{\text{BaSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4}$.

(2.2.4) Calculation of the maximum RO system recovery level for there to be, along with no silica or calcium carbonate or calcium sulphate or barium sulphate scaling, no strontium sulphate scaling ($R_5 = R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4\text{-SrSO}_4}$).

The strontium sulphate scaling tendency level is verified for the conversion $R_4 = R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4}$ [11]:

$$\text{Calculate } CF_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4} = 100/(100 - R_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4}) \tag{37}$$

Calculate the ionic product of the strontium sulphate in the reject water:

$$IP_{\text{SrSO}_4\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4} = [(SO_4)_f \times CF_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{BaSO}_4}/96,000] \times [(Sr)_f \times CF_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4}/87,620] \tag{38}$$

Calculate the ionic strength of the reject water:

$$IS_{\text{r-max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4} = IS_f \times CF_{\text{max-SiO}_2\text{-CaCO}_3\text{-CaSO}_4\text{-BaSO}_4} \tag{39}$$

Calculate the solubility product of the strontium sulphate in the reject water [12]:

$$K_{\mathrm{SrSO_4r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4}} = 0.00001(\mathrm{IS}_{\mathrm{r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4}})^{(0.6916)} \tag{40}$$

The following considerations are made based on the values obtained in (38) and (40):

If $\mathrm{IP}_{\mathrm{SrSO_4r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4}} \leq 0.8K_{\mathrm{SrSO_4r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO4}}$. The addition of scaling inhibitor is not necessary. $R_5(R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}}) = R_4(R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4}})$ is adopted and the calcium fluoride scaling trend level is verified for this conversion.

If $0.8K_{\mathrm{SrSO_4r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}BaSO_4}} < \mathrm{IP}_{\mathrm{SrSO_4r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4}} \leq 40K_{\mathrm{SrSO_4r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4}}$. The addition of scaling inhibitor is necessary. $R_5(R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}}) = R_4(R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4}})$ is adopted and the calcium fluoride scaling trend level is verified for this conversion.

If $40K_{\mathrm{SrSO_4r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}}\mathit{BaSO_4}} < \mathrm{IP}_{\mathrm{SrSO_4r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4}}$. The conversion level $R_5(R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}}) < R_4(R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4}})$ is reduced until for the new conversion $\mathrm{IP}_{\mathrm{SrSO_4r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}} \leq 40KB_{\mathrm{SrSO_4r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}}$.

(2.2.5) Calculation of the maximum RO system recovery level for there to be, along with no silica or calcium carbonate or calcium sulphate or barium sulphate or strontium sulphate scaling, no calcium fluoride scaling ($R_{\mathrm{max\text{-}adopt}} = R_6 = R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4\text{-}CaF_2}}$).

The calcium fluoride scaling tendency level is verified for the conversion $R_5 = R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}}$ [1,2,12]:

$$\text{Calculate } \mathrm{CF}_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}} = 100/(100 - R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}}) \tag{41}$$

Calculate the ionic product of the calcium fluoride in the reject water:

$$\begin{aligned}\mathrm{IP}_{\mathrm{CaF_2r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}} &= [(F)_{\mathrm{f}} \times \mathrm{CF}_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}}/19,000] \\ &\quad \times [(\mathrm{Ca})_{\mathrm{f}} \times \mathrm{CF}_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}}/40,080]\end{aligned} \tag{42}$$

The following considerations are made based on the value obtained in (42):

If $\mathrm{IP}_{\mathrm{CaF_2r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}} \leq 4\times10^{(-11)}$. The addition of scaling inhibitor is not necessary. $R_6(R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4\text{-}CaF_2}}) = R_5(R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}})$ is adopted.

If $4\times10^{(-11)} < \mathrm{IP}_{\mathrm{CaF_2r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}} \leq 4\times10^{(-9)}$. The addition of scaling inhibitor is necessary. $R_6(R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4\text{-}CaF_2}}) = R_5(R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}})$ is adopted.

If $4\times10^{(-9)} < \mathrm{IP}_{\mathrm{CaF_2r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}}$. The conversion level $R_6(R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4\text{-}CaF_2}}) < R_5(R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4}})$ is reduced until for the new conversion $\mathrm{IP}_{\mathrm{CaF_2r\text{-}max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4\text{-}CaF_2}} \leq 4\times10^{(-9)}$.

The maximum RO system recovery level to be adopted will be:

$$R_{\mathrm{max\text{-}adopt}} = R_6 = R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3\text{-}CaSO_4\text{-}BaSO_4\text{-}SrSO_4\text{-}CaF_2}}$$

Other types of scaling, as might occur if the presence of trace metals, metal oxides or metal hydroxides is detected in the feed water, were not considered.

(3) Practical application.

(3.1) Input data.

Five samples of brackish water from wells in the Canary Island region were used for this study. The chemical analysis of the samples, used as feed water for RO desalination plants, was as follows (concentrations in mg/l as ion, temperatures in ℃) (Table 1).

(3.2) Results.

The results of the calculations as described above were shown in Table 2:

4. Conclusions

It is deduced from the results obtained (Table 2) that the limiting compound of the maximum conversion level for the first four samples is silica ($R_{\mathrm{max\text{-}adopt}} = R_{\mathrm{max\text{-}SiO_2}}$), with the limitation for the fifth sample being imposed by calcium carbonate ($R_{\mathrm{max\text{-}adopt}} = R_{\mathrm{max\text{-}SiO_2\text{-}CaCO_3}}$).

Since, for the third sample, $0.8K_{\mathrm{CaSO_4r}} < \mathrm{IP}_{\mathrm{CaSO_4r}} \leq 2.5K_{\mathrm{CaSO_4r}}$, the addition of a specific scaling inhibitor to the feed water is required to avoid this type of scaling.

In all the samples, the S&DSIr or, failing that, the $\mathrm{LSI_r}$ (sample 2), is positive. Therefore, the addition to the feed water in all cases of specific scaling inhibitor is required to avoid calcium carbonate scaling.

The RO system design of a brackish water desalination plant employing this system, will need to consider, in addition to the maximum conversion as determined by the calculations previously described,

Table 2
Results of the calculations

Sample	$R_{\text{max-SiO}_2}$	$R_{\text{max-adopt}}$	IS_f	IS_r	$(TDS)_r$	LSI_r	$S\&DSI_f$	IP_{CaSO_4}	K_{CaSO_4r}
1	67.47	67.47	0.0745	0.2289	12,206.00	–	1.75	0.000164	0.000592
2	47.83	47.83	0.0907	0.1738	7,502.80	1.11	–	0.000130	0.000492
3	74.43	74.43	0.1367	0.5346	20,166.00	–	0.53	0.001600	0.001000
4	79.45	79.45	0.1559	0.7586	41,506.00	–	1.35	0.000383	0.001300
5	76.56	69.59	0.0992	0.3262	15,976.00	–	2.00	0.000533	0.000752

other limiting factors including the plant production, the feed water SDI value, the type of RO element to be employed, the desired water quality, the maximum operating pressure, etc.

The proposed Eqs. (1)–(42) enable the use of a simple calculation software programme which can be integrated into the definitive calculation programme used for the RO system design. In this way, later simulations can be easily applied with a high degree of confidence.

List of symbols

Cj_f	_	concentration of the j ion/component in the feed water
$(Cj)_f$	_	idem (expressed in mg/l)
$[Cj]_f$	_	idem (expressed in ppm as $CaCO_3$)
Cj_r	_	concentration of the j ion/component in the reject water
$(Cj)_r$	_	idem (expressed in mg/l)
$[Cj]_r$	_	idem (expressed in ppm as $CaCO_3$)
C_{pH}	_	SiO_2 saturation pH coefficient
CF	_	concentration factor
CF_{max}	_	maximum concentration factor
CF_{min}	_	minimum concentration factor
IP	_	ionic product
IP_{BaSO_4r}	_	ionic product of the barium sulphate of the reject water
IP_{CaF_2r}	_	ionic product of the calcium fluoride of the reject water
IP_{CaSO_4r}	_	ionic product of the calcium sulphate of the reject water
IP_{SrSO_4r}	_	ionic product of the strontium sulphate of the reject water
IS	_	ionic strength
IS_f	_	ionic strength of the feed water
IS_r	_	ionic strength of the reject water
K_{BaSO_4r}	_	reject water barium sulphate solubility product
K_{CaSO_4r}	_	reject water calcium sulphate solubility product
K_{SrSO_4r}	_	reject water strontium sulphate solubility product
K_T	_	temperature and ionic strength parameter of the S&DSI
LSI	_	Langelier saturation index.
$(m_i)_f$	_	molal concentration of the i ion in the feed water
$(m_i)_r$	_	molal concentration of the i ion in the reject water
$p\text{-}[Ca^{2+}]$	_	parameter of the LSI
$p\text{-}[Ca^{2+}]_r$	_	parameter of the LSI of the reject water
pH_f	_	feed water pH value
pH_r	_	reject water pH value
pH_{rmax}	_	reject water maximum pH value
pH_{rmin}	_	reject water minimum pH value
pH_s	_	saturation pH value
pHs_r	_	reject water saturation pH value
$p\text{-}[HCO_3^-]$	_	parameter of the LSI
$p\text{-}[HCO_3^-]_r$	_	parameter of the LSI of the reject water
$R_{\text{max-adopt}}$	_	maximum recovery adopted
$R_{\text{max-BaSO}_4}$	_	maximum recovery for barium sulphate
$R_{\text{max-CaCO}_3}$	_	maximum recovery for calcium carbonate
$R_{\text{max-CaF}_2}$	_	maximum recovery for calcium fluoride
$R_{\text{max-CaSO}_4}$	_	maximum recovery for calcium sulphate
$R_{\text{max-SiO}_2}$	_	maximum recovery for silica
$R_{\text{max-SrSO}_4}$	_	maximum recovery for strontium sulphate
RO	_	reverse osmosis
SDI	_	silt density index
S&DSI	_	Stiff and Davis saturation or stability index
TDS	_	total dissolved salts
T	_	feed water temperature (°C)
T_{max}	_	maximum feed water temperature (°C)
T_{min}	_	minimum feed water temperature (°C)

Subscripts

f	_	feed
r	_	reject
i,j	_	ion/component

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