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Estimation of maximum water recovery in RO desalination for different feedwater inorganic compositions

A. Ruiz-García[a,*], J. Feo-García[b]

[a]*Department of Mechanical Engineering, University of Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Spain, Tel. +34 928 451888; Fax +34 928 451879; email: alejandro.ruiz@ulpgc.es*
[b]*Department of Electronic and Automatic Engineering, University of Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Spain, Tel. +34 928 451963; email: jose.feo@ulpgc.es*

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ABSTRACT

Groundwater is essential for agriculture in the Canary Islands. For example, in Gran Canaria 47.7% of water demand for agricultural purposes is taken from groundwater and in Tenerife 162.7 hm^3/year are also taken from wells. In water desalination processes, water recovery is one of the most important indexes for reverse osmosis (RO) system design. This article aims to estimate the maximum recovery levels for RO systems, based on the scaling potential of the sparingly soluble salts shown in the chemical analysis. The required input data are the chemical composition of the feedwater, its pH and temperature range. Both islands were divided in different areas as the water composition can vary considerably. More than one hundred groundwater wells were analyzed to know the inorganic composition. This composition of the feedwater plays an important role in the operation of a brackish water reverse osmosis system since it may be responsible of extra cost due to scaling. The silica, calcium carbonate and calcium sulphate are the most commonly found salts in the groundwater of Gran Canaria and Tenerife. In most cases, silica had the highest effect on recovery limits. The results showed some cases where the maximum flux recovery was barely around 60% even using specific silica anti-scalant. This has a considerable impact on the viability of the process. The calcium carbonate was also an important limiting factor in most of wells.

Keywords: Brackish water; Reverse osmosis; Desalination plants; Recovery; Scaling

1. Introduction

The aim of this paper was to propose a simple algorithm to estimate the maximum water recovery in different regions of Gran Canaria and Tenerife Islands (Spain) using a simple algorithm. Maximum water recoveries were calculated considering the scaling potential of feedwater. In this region, brackish water sources are usually groundwater; these groundwaters can be naturally saline aquifers or groundwater that has become brackish due to seawater intrusion or other factors like overuse or irrigation. Brackish waters can have a wide range of total dissolved solids (TDS) (1,000–10,000 mg/L) and are typically characterized by low organic carbon content and low particulate or colloidal contaminants. Brackish waters can vary widely from source to source; an important factor in the reverse osmosis (RO) system optimization is the inorganic composition of the feedwater.

In the Canary Islands, groundwater is considered a water source for agricultural purposes. Fig. 1 shows the well distribution in the Gran Canaria Island but there is no map of groundwater wells available in Tenerife Island. Public administration of both island established groundwater bodies taking into account qualitative criteria (Figs. 2 and 3).

Each groundwater body has been studied by analysing the inorganic composition of different wells. With increased

* Corresponding author.

Fig. 1. Groundwater wells in Gran Canaria [1].

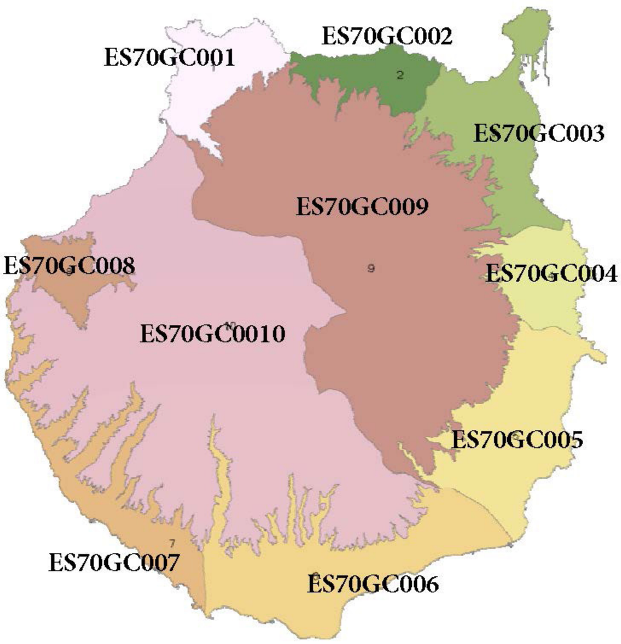

Fig. 2. Groundwater bodies in Gran Canaria [1].

product water recovery, the concentration of inorganic species near the membrane surface rises and, beyond a critical recovery level, can exceed the solubility of sparingly soluble mineral salts (e.g., silica (SiO_2), calcium carbonate ($CaCO_3$), calcium sulphate dihydrate (denoted simply as $CaSO_4$), barium sulphate ($BaSO_4$), strontium sulphate ($SrSO_4$) and calcium fluoride (CaF_2)).

The scaling potential of these salts will depend on their concentration in the feedwater (chemical analysis), on the pH value, the temperature, the RO system's recovery and

Fig. 3. Groundwater bodies in Tenerife [2].

on the solubility limits of the respective salts. As one of the main limiting factors in RO despite the advancements in antiscalant chemistry [3–11], scaling has been studied by many authors [12–22], even working on new scaling potential index for a single salt [19,20]. Marwan et al. [22] worked on a simple code for the estimation of scaling potential of sparingly soluble mineral salts. This code was tested with experimental data. Al-Shammiri et al. [21] proposed a simple code to estimate the scaling potential showing to be more accurate than Marwan's equations. The Al-Shammiri's equations for the $CaSO_4$, $BaSO_4$, $SrSO_4$ and CaF_2 solubility product (K_{sp}) were used in this work. Al-Shammiri used the Stiff and Davis Saturation Index (S&DSI) to estimate the calcium carbonate scaling. But for brackish water the Langelier Saturation Index (LSI) should be used instead of S&DSI, which is usually used for seawater. In the proposed algorithm both saturation indexes were implemented.

The determination of the silica scaling is very complex. Semiat et al. [23] reported minor inhibitory effects by four antiscalant tested. Hater et al. [24] checked the effectiveness of 13 antiscalants for silica was measured at different pH values between 7.6 and 9.0 and with silica concentrations from 120 to 275 mg/L. Two of the antiscalants investigated in that paper had a significant antiscaling effect for silica. Other authors [25,26] have studied pretreatments to prevent silica scaling increasing the water recovery. The specific price increase due to this sort of pretreatments should be evaluated and compared with the antiscalant prices to check the viability.

Usually the maximum water recovery is a boundary condition that should be calculated before the RO system design. The designer has to use antiscalant manufacturer software to estimate this limiting factor to be taken into account in the membrane manufacturer software. This work proposes an algorithm, which can be implemented in an RO system design software, to estimate the maximum water recovery considering the theoretical inhibitory potential of products of different antiscalant manufacturers. The user can set margins of safety in terms of saturation limits allowing more flexibility. This software was used considering more than one hundred inorganic composition of groundwater wells in the islands of Gran Canaria and Tenerife. It gives relevant information about the maximum water recovery capacity in different areas of each island.

2. Material and methods

2.1. Groundwater inorganic composition

It was possible to get a water analysis from different groundwater wells in Gran Canaria, but in Tenerife just ranges per groundwater body. All information about groundwater inorganic composition was given by public administration ("Consejo Insular de Aguas de Gran Canaria" and "Consejo Insular de Aguas de Tenerife").

The inorganic composition of groundwater in both islands is shown in Table 1 (wells located in different groundwater bodies) and Table 2 (ranges per groundwater body). The samples were collected and analyzed in 2009 (Gran Canaria) and 2006 (Tenerife). The inorganic composition of groundwater in both islands can vary considerably due to location. The TDS are in a range of 79.1–16,933 mg/L and 68.6–4,935 mg/L in Gran Canaria and Tenerife, respectively. Some chemical analyses in Gran Canaria Island were not taken into account due to no silica concentration determination or inconsistent values. The fluorine concentration was not collected in Gran Canaria but it was collected in Tenerife where it is a serious problem [27]. A temperature between 20°C and 24°C was considered due to the unavailability of the data.

2.2. Procedure and equations

The following considerations were made in this work:

- Use of scale inhibitor's parameters (Genesys™ LF and SI, Vitec™ 3000 and 4000, Chemtəx™ PC191, HS40 and AS80, Pure Aqua™ PA0100) (Table 3). Note that for the Genesys™ products the ranges for the power of inhibition of silica are 180–240 ppm for LF and 350–400 ppm for SI. Averages values were considered, 210 ppm and 375 ppm, respectively.
- Temperature range between 20°C and 24°C was considered.
- Ideal membrane performance in terms of salt rejection. This is equivalent to considering a CO_2 rejection rate of 0%, and the rest of the compounds in the feedwater a rejection rate of 100%.
- RO systems without using acid in the pretreatment.

The selection of antiscalant products was focus on SiO_2 and $CaCO_3$ inhibition as it is the main concern in this region. In some cases, the power of inhibition for other compounds was not available and it was supposed the same as it is not relevant for the inorganic compositions studied. The third 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 the reality if it is taken into account that, as a result of the effect of concentration polarization on the membrane surface, there is a higher concentration of salts than for the reject flow.

Scaling potential of SiO_2 [28], $CaCO_3$ [29,30], $CaSO_4$, $BaSO_4$, $SrSO_4$ [31] and CaF_2 [21] were taken into account to calculate the maximum water recovery in RO using different scale inhibitor:

- calculation of the maximum water recovery for there to be no silica scaling;
- calculation of the maximum water recovery for there to be, along with no silica scaling and no calcium carbonate scaling;
- calculation of the maximum water recovery for there to be, along with no silica scaling, no calcium carbonate scaling and no calcium sulphate scaling;
- calculation of the maximum water recovery for there to be, along with no silica scaling, no calcium carbonate scaling, no calcium sulphate scaling and no barium sulphate scaling;
- calculation of the maximum water recovery for there to be, along with no silica scaling, no calcium carbonate scaling, no calcium sulphate scaling, no barium sulphate and no strontium sulphate scaling; and
- calculation of the maximum water recovery for there to be, along with no silica scaling, no calcium carbonate scaling, no calcium sulphate scaling, no barium sulphate, no strontium sulphate scaling and no calcium fluoride scaling.

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

- cations in mg/L: calcium $[Ca]_f$, magnesium $[Mg]_f$, sodium $[Na]_f$, potassium $[K]_f$, barium $[Ba]_f$ and strontium $[Sr]_f$;
- anions in mg/L: carbonates (0 mg/L), bicarbonates $[HCO_3]_f$, sulphates $[SO_4]_f$, nitrates $[NO_3]_f$, chlorides $[Cl]_f$ and fluorides $[F]_f$;
- others: silica $[SiO_2]_f$ (mg/L) and pH_f; and
- temperatures in °C: minimum (T_{min}), mean (T_{med}) and maximum (T_{max}).

2.2.1. Silica

Carbon dioxide $[CO_2]$ content estimation in the feed:

$$\left[CO_2\right]_f = \frac{\left[HCO_3^-\right]_f}{10^{(pH_f - 6.3)}} \tag{1}$$

Maximum soluble silica concentration for the minimum temperature ($[SiO_2]_{r-max}$) and pH ranging between 7 and 7.8 [28,32]:

$$\left[SiO_2\right]_{r\text{-}max} = 2.1 \cdot T_{min} + 75 \tag{2}$$

It is calculated the maximum concentration factor (CF_{max}) for silica concentration in the reject water to be $[SiO_2]_{r-max}$:

$$CF_{max} = \frac{2.1 \cdot T_{min} + 75}{\left[SiO_2\right]_f} \tag{3}$$

It is calculated in mg/L as $CaCO_3$ the expected concentration of bicarbonates in the reject water ($[HCO_3^-]_{r-CaCO3}$), for the above concentration factor:

$$\left[HCO_3^-\right]_{r\text{-}CaCO_3} = \left[HCO_3^-\right]_{f\text{-}CaCO_3} \cdot CF_{max} \tag{4}$$

Table 1
Inorganic composition of groundwater in Gran Canaria [1]

Groundwater body (sampling points)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^-	NO_3^-	Cl^-	SiO_2	Fe	Mn	TDS	pH
ES70GC001 (16)	83.00	107.00	760.00	22.00	885.00	342.00	171.00	819.00	56.00	–	–	2,894.50	7.4
	407.00	449.00	1,200.00	40.00	711.00	564.00	67.00	3,021.00	71.00	–	–	6,459.00	6.9
	75.00	107.00	555.00	20.00	1,129.00	247.00	163.00	430.00	71.00	–	–	2,725.00	6.9
	175.00	168.00	652.00	25.00	1,293.00	325.00	169.00	792.00	71.00	–	–	3,598.00	7.2
	65.00	90.00	365.00	17.00	635.00	281.00	204.00	255.00	85.00	–	–	1,911.00	6.8
	556.00	556.00	1,085.00	44.00	602.00	750.00	195.00	3,322.00	64.00	–	–	7,434.00	7.3
	217.00	118.00	144.00	26.00	1,098.00	97.00	–	281.00	107.00	–	0.90	1,671.60	6.8
	175.00	150.00	365.00	20.00	1,342.00	134.00	67.00	439.00	112.00	–	0.54	2,317.00	6.4
ES70GC002 (11)	388.00	499.00	1,461.00	58.00	509.00	650.00	60.00	3,662.00	86.00	–	0.01	7,287.00	6.2
	186.00	141.00	437.00	25.00	246.00	517.00	201.00	833.00	53.00	–	–	2,587.00	7.8
	99.00	59.00	371.00	31.00	376.00	164.00	–	600.00	57.00	–	0.65	1,699.00	7.8
	67.00	72.00	338.00	43.00	455.00	248.00	168.00	370.00	73.00	0.02	–	1,747.20	6.8
ES70GC003 (18)	162.00	186.00	862.00	37.00	1,045.00	325.00	36.00	1,397.00	108.00	–	0.09	3,969.70	6.5
	127.00	102.00	543.00	44.00	383.00	384.00	198.00	818.00	47.00	–	–	2,779.00	7.7
	93.00	77.00	177.00	48.00	221.00	338.00	172.00	229.00	49.00	–	–	1,332.10	7.5
	33.00	19.00	574.00	39.00	756.00	351.00	77.00	334.00	67.00	–	0.28	2,023.70	6.5
	213.00	271.00	474.00	26.00	1,427.00	359.00	15.00	857.00	126.00	–	0.31	3,642.00	6.7
	107.00	85.00	138.00	13.00	610.00	163.00	12.00	199.00	130.00	–	0.16	1,262.10	6.2
	51.00	72.00	475.00	20.00	732.00	210.00	62.00	471.00	73.00	–	–	2,336.00	6.9
	151.00	150.00	863.00	49.00	762.00	344.00	54.00	1,429.00	103.00	–	–	4,109.00	7.4
	47.00	87.00	941.00	34.00	637.00	294.00	50.00	1,255.00	64.00	–	0.01	3,433.50	7.4
ES70GC004 (11)	83.00	77.00	378.00	20.00	481.00	436.00	107.00	336.00	84.00	–	–	1,780.80	7.2
	37.00	27.00	139.00	16.00	183.00	157.00	118.00	79.00	84.00	–	–	756.00	7.6
	942.00	920.00	1,389.00	83.00	359.00	728.00	127.00	5,665.00	64.00	0.02	0.01	11,683.00	6.8
	32.00	38.00	306.00	19.00	370.00	139.00	72.00	324.00	71.00	–	–	1,365.70	7.3
	28.00	30.00	257.00	14.00	342.00	79.00	26.00	281.00	89.00	–	–	1,057.00	7.4
	87.00	91.00	169.00	18.00	976.00	43.00	18.00	92.00	86.00	–	–	1,493.00	6.5
	70.00	70.00	360.00	22.00	390.00	218.00	125.00	451.00	73.00	–	–	1,801.80	7.4
ES70GC005 (16)	1,616.00	1,718.00	2,257.00	75.00	133.00	1,071.00	21.00	10,042.00	69.00	–	–	16,933.00	7.2
	829.00	763.00	509.00	36.00	183.00	412.00	16.00	4,064.00	86.00	–	–	8,288.00	7.5
	31.00	26.00	102.00	9.40	298.00	24.00	6.80	101.00	100.00	–	–	598.00	8.2
	510.00	401.00	330.00	27.00	187.00	201.00	8.40	2,258.00	94.00	–	–	3,922.00	7.6
	227.00	145.00	214.00	21.00	196.00	126.00	84.00	900.00	55.00	–	–	1,913.00	7.9
	563.00	477.00	757.00	32.00	1,051.00	706.00	18.00	2,480.00	77.00	–	0.22	6,084.00	7.4
	39.00	26.00	93.00	8.90	266.00	52.00	6.10	89.00	65.00	–	–	579.00	8.1
	113.00	181.00	859.00	33.00	439.00	634.00	152.00	1,362.00	43.00	–	–	3,772.00	8.1
ES70GC006 (29)	228.00	97.00	1,462.00	36.00	112.00	331.00	6.90	2,623.00	40.00	–	0.02	4,896.00	7.6

(Continued)

Table 1 (*Continued*)

Groundwater body (sampling points)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^-	NO_3^-	Cl^-	SiO_2	Fe	Mn	TDS	pH
	88.00	59.00	168.00	11.00	366.00	38.00	1.50	363.00	4.60	–	–	1,095.00	7.3
	46.00	20.00	621.00	13.00	87.00	151.00	5.00	973.00	48.00	–	0.03	1,915.00	7.3
	14.00	11.00	320.00	4.80	497.00	109.00	7.10	194.00	41.00	–	–	1,157.00	8.5
	76.00	47.00	233.00	9.80	304.00	167.00	85.00	310.00	52.00	–	–	1,299.20	8.0
	142.00	114.00	319.00	24.00	553.00	54.00	–	749.00	147.00	–	0.16	1,955.00	7.3
	54.00	53.00	277.00	17.00	176.00	87.00	7.60	514.00	63.00	0.03	–	1,442.00	8.0
	65.00	36.00	280.00	9.60	201.00	103.00	9.00	467.00	53.00	–	–	1,171.00	7.8
	60.00	52.00	482.00	21.00	289.00	194.00	11.00	738.00	48.00	–	–	1,847.00	7.7
	89.00	119.00	534.00	22.00	336.00	341.00	73.00	861.00	110.00	–	–	2,375.00	7.6
	26.00	16.00	161.00	5.60	165.00	64.00	19.00	204.00	44.00	–	–	660.00	7.9
	105.00	98.00	634.00	21.00	304.00	445.00	93.00	923.00	40.00	–	–	2,623.00	8.1
	88.00	65.00	218.00	13.00	394.00	57.00	2.60	418.00	98.00	–	0.01	1,254.00	7.4
	59.00	39.00	226.00	13.00	129.00	83.00	3.60	446.00	57.00	–	0.01	997.00	7.8
	16.00	15.00	306.00	12.00	337.00	64.00	1.40	320.00	63.00	–	–	1,070.00	8.1
	55.00	36.00	236.00	12.00	126.00	80.00	4.30	441.00	63.00	–	–	992.00	7.4
	20.00	16.00	272.00	12.00	241.00	60.00	2.10	339.00	61.00	–	–	962.00	8.1
	252.00	121.00	1,141.00	28.00	118.00	305.00	6.30	2,203.00	40.00	–	–	4,173.00	7.5
ES70GC007 (17)	80.00	60.00	664.00	16.00	171.00	234.00	32.00	1,049.00	51.00	–	–	2,777.60	7.8
	70.00	58.00	197.00	6.60	196.00	61.00	2.50	445.00	66.00	–	–	1,262.80	7.3
	65.00	44.00	411.00	18.00	173.00	125.00	13.00	690.00	55.00	–	–	1,896.30	7.8
	106.00	96.00	251.00	13.00	253.00	213.00	65.00	529.00	67.00	–	–	1,750.00	7.8
	33.00	43.00	166.00	23.00	170.00	104.00	31.00	276.00	47.00	–	–	985.60	8.1
	83.00	65.00	464.00	17.00	150.00	156.00	14.00	868.00	59.00	–	–	2,215.50	7.5
	36.00	40.00	106.00	3.30	245.00	65.00	32.00	125.00	83.00	–	–	652.00	8.0
	124.00	161.00	212.00	6.80	275.00	365.00	247.00	420.00	81.00	–	–	1,812.00	8.0
	104.00	118.00	206.00	5.70	448.00	203.00	107.00	358.00	76.00	–	–	1,549.00	8.0
	55.00	39.00	318.00	18.00	157.00	104.00	7.00	568.00	62.00	–	–	1,444.10	7.9
ES70GC008 (9)	224.00	146.00	349.00	15.00	241.00	642.00	231.00	654.00	46.00	–	–	2,502.00	7.4
	113.00	101.00	447.00	14.00	290.00	265.00	25.00	836.00	36.00	–	–	2,090.00	7.8
	232.00	254.00	461.00	9.20	403.00	670.00	304.00	959.00	63.00	–	–	3,293.00	7.8
ES70GC009 (78)	216.00	175.00	153.00	16.00	1,164.00	367.00	4.80	250.00	137.00	–	6.00	2,345.00	6.4
	29.00	31.00	253.00	14.00	537.00	114.00	21.00	134.00	89.00	–	–	1,133.00	7.3
	51.00	62.00	289.00	12.00	354.00	193.00	40.00	342.00	35.00	–	–	1,343.00	7.8
	17.00	8.70	39.00	6.60	112.00	19.00	28.00	28.00	57.00	–	–	258.00	7.6
	18.00	10.00	30.00	8.30	95.00	13.00	31.00	34.00	71.00	–	–	238.00	7.8
	70.00	34.00	68.00	11.00	515.00	32.00	3.60	22.00	40.00	–	0.01	755.00	7.8
	14.00	12.00	13.00	2.50	96.00	6.40	5.10	16.00	69.00	–	–	166.00	7.9
	20.00	9.70	28.00	9.00	127.00	12.00	16.00	25.00	49.00	–	–	246.00	8.0
	11.00	8.20	41.00	7.80	120.00	35.00	1.90	21.00	40.00	–	–	245.00	8.1
	25.00	19.00	27.00	6.80	204.00	12.00	7.10	19.00	92.00	–	0.10	320.00	7.1

(Continued)

Table 1 (*Continued*)

Groundwater body (sampling points)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^-	NO_3^-	Cl^-	SiO_2	Fe	Mn	TDS	pH
	55.00	52.00	96.00	11.00	580.00	23.00	12.00	64.00	98.00	–	–	79.10	6.0
	15.00	10.00	15.00	3.80	98.00	5.80	13.00	19.00	70.00	–	–	171.50	7.5
	13.00	7.80	28.00	6.20	92.00	14.00	17.00	24.00	75.00	–	–	199.50	7.7
	6.00	2.80	37.00	4.70	98.00	5.90	8.40	17.00	33.00	–	–	179.00	8.1
	52.00	34.00	82.00	13.00	354.00	44.00	13.00	87.00	103.00	–	–	623.70	6.2
	4.70	8.90	12.00	32.00	1.20	25.00	52.00	91.00	50.00	0.06	–	187.00	8.2
	8.30	9.10	49.00	5.10	110.00	11.00	20.00	43.00	55.00	–	–	255.00	7.8
	58.00	30.00	40.00	9.50	397.00	8.30	17.00	25.00	142.00	–	0.28	494.90	6.1
	112.00	46.00	108.00	19.00	774.00	51.00	11.00	44.00	92.00	–	2.00	1,165.00	6.6
	23.00	15.00	61.00	7.00	177.00	21.00	27.00	51.00	74.00	–	–	382.00	8.0
	95.00	47.00	44.00	11.00	610.00	7.30	–	28.00	121.00	–	0.59	683.90	6.4
	15.00	11.00	15.00	3.20	95.00	4.00	12.00	17.00	82.00	–	–	172.00	7.8
	31.00	21.00	42.00	10.00	202.00	26.00	31.00	36.00	82.00	–	0.04	399.00	7.5
	9.10	5.00	19.00	3.30	50.00	4.00	14.00	23.00	56.00	–	–	127.00	8.1
	17.00	10.00	27.00	6.30	79.00	15.00	32.00	34.00	74.00	–	–	231.00	7.5
	60.00	45.00	110.00	13.00	445.00	28.00	9.00	137.00	101.00	–	0.01	847.00	7.3
	11.00	6.80	22.00	4.50	67.00	5.00	23.00	24.00	66.00	0.02	–	163.10	7.6
	76.00	44.00	48.00	14.00	549.00	6.80	7.60	27.00	95.00	–	2.00	630.00	6.0
	22.00	16.00	37.00	6.30	82.00	40.00	46.00	45.00	82.00	–	–	310.80	7.6
	67.00	69.00	53.00	6.60	640.00	12.00	12.00	35.00	80.00	–	0.01	895.00	7.2
	19.00	8.00	41.00	18.00	218.00	5.70	4.00	11.00	83.00	–	–	325.00	7.7
	22.00	9.80	47.00	8.20	144.00	22.00	24.00	36.00	53.00	–	–	312.00	7.5
	143.00	68.00	65.00	24.00	976.00	12.00	–	19.00	99.00	–	0.87	1,307.00	6.4
	38.00	20.00	76.00	13.00	409.00	6.30	4.80	20.00	72.00	–	0.02	441.70	8.2
	8.50	7.90	12.00	4.00	78.00	4.00	5.10	12.00	53.00	–	–	131.00	7.7
	85.00	53.00	558.00	62.00	1,790.00	189.00	–	137.00	72.00	–	1.00	2,873.00	6.6
	67.00	37.00	35.00	9.40	476.00	5.70	–	23.00	107.00	–	0.29	534.80	6.2
	50.00	30.00	73.00	5.90	315.00	82.00	7.80	56.00	56.00	–	0.16	618.00	7.3
ES70GC0010 (5)	36.00	21.00	166.00	9.50	245.00	118.00	90.00	112.00	52.00	–	–	784.70	7.7
	15.00	6.50	204.00	5.30	311.00	36.00	2.00	168.00	74.00	–	0.23	748.00	7.7

Table 2
Inorganic composition (ranges) of groundwater in Tenerife [2]

Groundwater body (sampling points)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^-	NO_3^-	Cl^-	SiO_2	F^-	TDS	pH
ES70TF001 (31)	0–87	0–93	15–230	2–58	50–1,175	1.5–105.0	0.1–49.0	3–354	19–106	0.1–1.2	68.6–1,127	6–8
ES70TF002 (8)	12–166	29–85	209–432	44–109	611–1,711	39.0–325.0	2.2–8.3	22–54	42–73	0.7–7	611–1,711	6–8
ES70TF003 (15)	10–186	10–237	61–1,582	10–71	136–867	12.0–372.0	8.3–110.4	21–1,775	21–94	0.2–10.7	136–867	6–8
ES70TF004 (5)	11–47	11–35	46–182	17–37	116–274	28.0–116.0	37.2–116.7	29–129	21–30	0.2–1.4	116–274	6–8

Table 3
Antiscalant characteristics

Salt	Theoretical power of inhibition							
	Genesys LF	Genesys SI	Vitec 3000	Vitec 4000	PC191	HS40	AS80	PA0100
$CaCO_3$	LSI ≤ 2.6	LSI ≤ 2.4	LSI ≤ 3	LSI ≤ 2.5	LSI ≤ 2.6	LSI ≤ 2.5	LSI ≤ 2.7	LSI ≤ 2.8
$CaSO_4$	$3.5·K_{sp}$	$3.5·K_{sp}$	$3.5·K_{sp}$	$3.5·K_{sp}$	$3.5·K_{sp}$	$3.5·K_{sp}$	$3.5·K_{sp}$	$3.5·K_{sp}$
$BaSO_4$	$105·K_{sp}$	$105·K_{sp}$	$105·K_{sp}$	$105·K_{sp}$	$105·K_{sp}$	$105·K_{sp}$	$105·K_{sp}$	$105·K_{sp}$
$SrSO_4$	$20·K_{sp}$	$20·K_{sp}$	$20·K_{sp}$	$20·K_{sp}$	$20·K_{sp}$	$20·K_{sp}$	$20·K_{sp}$	$20·K_{sp}$
CaF_2	$1,000·K_{sp}$	$1,000·K_{sp}$	$1,000·K_{sp}$	$1,000·K_{sp}$	$1,000·K_{sp}$	$1,000·K_{sp}$	$1,000·K_{sp}$	$1,000·K_{sp}$
SiO_2	210 ppm	375 ppm	120 ppm	Two· saturation	217 ppm	325 ppm	175 ppm	120 ppm

Expected pH value in the reject water for the above concentration factor:

$$pH_r = 6.3 + \log\left(\frac{\left[HCO_3^-\right]_{r\text{-}CaCO_3}}{\left[CO_2\right]_f}\right) \quad (5)$$

The pH coefficient (C_{pH}) for estimation of the maximum silica concentration level in the reject water:

$$\text{If } 7 \le pH_{r\text{-min-}SiO_2} \le 7.8 : C_{pH} = 1 \quad (6)$$

$$\text{If } pH_r < 7 : C_{pH} = 1.819 - \left(0.117 \cdot pH_r\right) \quad (7)$$

$$\text{If } pH_r > 7.8 : C_{pH} = 0.47 \cdot 0.0006 \cdot e^{(0.87 \cdot pH_r)} \quad (8)$$

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

$$CF_{max} = \frac{2.1 \cdot T_{min} + 75}{\left[SiO_2\right]_f} \cdot C_{pH} \quad (9)$$

Required conversion in % to obtain the above concentration factor:

$$R_{max} = 100 \times \frac{CF_{max} - 1}{CF_{max}} \quad (10)$$

2.2.2. Calcium carbonate

To evaluate the saturation of $CaCO_3$, two saturation indexes were used, LSI [29] and S&DSI [30]. For the LSI ($TDS_r \le 10,000$):

$$LSI = pH_r - pHs_r \quad (11)$$

where pHs_r is the reject water saturation pH value:

$$pHs_r = p-\left[Ca^{2+}\right]_r + p-\left[HCO_3^-\right]_r + C \quad (12)$$

where

$$p\text{-}\left[Ca^{2+}\right]_r = \log\left(\frac{10^5}{\left[Ca^{2+}\right]_{r\text{-}CaCO_3}}\right) \quad (13)$$

$$p\text{-}\left[HCO_3^-\right]_r = \log\left(\frac{5 \cdot 10^4}{\left[HCO_3^-\right]_{r\text{-}CaCO_3}}\right) \quad (14)$$

If $TDS_r \le 6,000$:

$$C = \frac{\log\left(TDS_r\right) - 1}{10} - 13.12 \times \log\left(T_{max} + 273.15\right) + 34.46 \quad (15)$$

If $6,000 < TDS_r \le 10,000$:

$$C = 0.2778 - 13.12 \times \log\left(T_{max} + 273.15\right) + 34.46 \quad (16)$$

If $TDS_r > 10,000$, S&DSI is calculated:

$$S\&DSI = pH_r - pHs_r \quad (17)$$

where

$$pHs_r = p-\left[Ca^{2+}\right]_r + p-\left[HCO_3^-\right]_r + K \quad (18)$$

The parameter K depends on the temperature and ionic strength (IS):

$$IS_f = \frac{1}{2}\sum m_{if} \cdot z_i^2 \quad (19)$$

where m_{if} is the molal concentration of the ion I in the feedwater and z_i is the charge of the ion i.

$$IS_r = IS_f \cdot CF_{max} \quad (20)$$

The parameter K was fitted by the following third-degree polynomials [33]:

$$K_{10^\circ} = 1.3944 \cdot (IS_r)^3 - 4.8733 \cdot (IS_r)^2 + 4.8189 \cdot (IS_r) + 2.28 \quad (21)$$

$$K_{20^\circ} = 1.4389 \cdot (IS_r)^3 - 5.0767 \cdot (IS_r)^2 + 5.0578 \cdot (IS_r) + 2.06 \quad (22)$$

$$K_{25^\circ} = 1.5861 \cdot (IS_r)^3 - 5.4283 \cdot (IS_r)^2 + 5.2222 \cdot (IS_r) + 1.96 \quad (23)$$

$$K_{30^\circ} = 1.3417 \cdot (IS_r)^3 - 4.7350 \cdot (IS_r)^2 + 4.7933 \cdot (IS_r) + 1.87 \quad (24)$$

The antiscalant manufacturer did not establish a limit for the S&DSI, so the LSI was also used for $TDS_r > 10{,}000$.

2.2.3. Calcium sulphate, barium sulphate, strontium sulphate and calcium fluoride

The calcium sulphate scaling tendency level is verified for the R_{max}:

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

$$IP_{r\text{-}CaSO_4} = \left[\left(SO_4\right)_f \cdot \frac{CF_{max}}{96{,}000} \right] \cdot \left[\left(Ca\right)_f \cdot \frac{CF_{max}}{40{,}080} \right] \quad (25)$$

The solubility product of the calcium sulphate in the reject water ($K_{r\text{–}CaSO4}$) [21,31]:

$$K_{r\text{-}CaSO_4} = 0.0016 \left(IS_r\right)^{(0.6742)} \quad (26)$$

- If $IP_{r\text{–}CaSO4} \le 0.8 \cdot K_{r\text{–}CaSO4}$. The addition of scaling inhibitor is not necessary.
- If $0.8 \cdot K_{r\text{–}CaSO4} < IP_{r\text{–}CaSO4} \le$ (manufacturer data)$\cdot K_{r\text{–}CaSO4}$. The addition of scaling inhibitor is necessary.
- If (manufacturer data)$\cdot K_{r\text{–}CaSO4} < IP_{r\text{-}CaSO4}$. The R_{max} is reduced.

Similarly, for $BaSO_4$:

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

$$IP_{r\text{-}BaSO_4} = \left[\left(SO_4\right)_f \cdot \frac{CF_{max}}{96{,}000} \right] \cdot \left[\left(Ba\right)_f \cdot \frac{CF_{max}}{137{,}340} \right] \quad (27)$$

The solubility product of the barium sulphate in the reject water ($K_{r\text{–}BaSO4}$) [21,31]:

$$K_{r\text{-}BaSO_4} = 7 \cdot 10^{-9} \left(IS_r\right)^{(0.835)} \quad (28)$$

- If $IP_{r\text{–}BaSO4} \le 0.8 \cdot K_{r\text{–}BaSO4}$. The addition of scaling inhibitor is not necessary.
- If $0.8 \cdot K_{r\text{–}BaSO4} < IP_{r\text{–}BaSO4} \le$ (manufacturer data)$\cdot K_{r\text{–}BaSO4}$. The addition of scaling inhibitor is necessary.
- If (manufacturer data)$\cdot K_{r\text{–}BaSO4} < IP_{r\text{–}BaSO4}$. The R_{max} is reduced.

Similarly, for $SrSO_4$:

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

$$IP_{r\text{-}SrSO_4} = \left[\left(SO_4\right)_f \cdot \frac{CF_{max}}{96{,}000} \right] \cdot \left[\left(Sr\right)_f \cdot \frac{CF_{max}}{87{,}620} \right] \quad (29)$$

The solubility product of the calcium sulphate in the reject water ($K_{r\text{–}SrSO4}$) [21,31]:

$$K_{r\text{-}SrSO_4} = 1 \cdot 10^{-5} \left(IS_r\right)^{(0.6916)} \quad (30)$$

- If $IP_{r\text{–}SrSO4} \le 0.8 \cdot K_{r\text{–}SrSO4}$. The addition of scaling inhibitor is not necessary.
- If $0.8 \cdot K_{r\text{–}SrSO4} < IP_{r\text{–}SrSO4} \le$ (manufacturer data)$\cdot K_{r\text{–}SrSO4}$. The addition of scaling inhibitor is necessary.
- If (manufacturer data)$\cdot K_{r\text{–}SrSO4} < IP_{r\text{–}SrSO4}$. The R_{max} is reduced.

Similarly, for CaF_2 [21]:

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

$$IP_{r\text{-}CaF_2} = \left[\left(F\right)_f \cdot \frac{CF_{max}}{19{,}000} \right] \cdot \left[\left(Ca\right)_f \cdot \frac{CF_{max}}{40{,}080} \right] \quad (31)$$

- If $IP_{r\text{–}CaF2} \le 4 \times 10^{-11}$. The addition of scaling inhibitor is not necessary.
- If $4 \times 10^{-11} < IP_{r\text{–}CaF2} \le$ (manufacturer data)$\cdot K_{r\text{–}CaF2}$. The addition of scaling inhibitor is necessary.
- If (manufacturer data)$\cdot K_{r\text{–}CaF2} < IP_{r\text{–}CaF2}$. The R_{max} is reduced.

3. Results and discussion

The maximum water recoveries for Gran Canaria and Tenerife Islands using different antiscalant products are shown in Tables 4 and 5, respectively. In Gran Canaria and Tenerife the main limiting compound of the maximum water recovery is silica, followed by calcium carbonate. In general, the most appropriate scale inhibitor was the Genesys™ SI since most of maximum recovery flows (~60% in Gran Canaria) were obtained with this product. The values obtained with this product are very close to those achieved by Chemtɘx™ HS40, since they are products with similar characteristics (Table 3). For the groundwater bodies in Tenerife, Genesys™ SI would be the most appropriate product for the lowest concentrations margin and Chemtɘx™ HS40 for the highest concentrations margin. But with both products similar water flux recoveries were achieved as the power of inhibition for silica is very high and the LSI is quite acceptable for the studied water inorganic compositions. When the concentration of the calcium carbonate is very high not having concern about silica, products like Vitec™ 3000, Chemtɘx™ AS80 or Pure Aqua™ PA0100 showed to be quite appropriate considering the economic point of view as these kinds of products are often cheaper than specific silica inhibitors. In some cases theses maximum water recoveries are not achievable due to capability of the groundwater intakes which involve RO system (arrangement) restrictions [34]. The recoveries calculated in this works are an estimation, usually it is used as a safety margin due to the operating conditions or experience with this sort of products since the main drawback of antiscalant products is the degree of uncertainty in terms of solubility limits and dosing. Some authors [35,36] use an LSI ≤ 2.5 for Vitec™ 3000 instead of 3, the power of inhibition of Genesys™ SI was reported for concentrations of silica higher than 300 mg/L [37].

4. Conclusions

Maximum water recoveries of different groundwater bodies in Gran Canaria and Tenerife Islands were calculated using a simple algorithm and taking into account the scaling potential of SiO_2, $CaCO_3$, $CaSO_4$, $BaSO_4$, $SrSO_4$ and CaF_2 using different kind of antiscalant products. The algorithm also allows the user to fix the solubility limits below those established by the different manufacturers

Table 4
Maximum water recovery in Gran Canaria

Groundwater body	Maximum water recovery (%)							
	Genesys LF	Genesys SI	Vitec 3000	Vitec 4000	PC191	HS40	AS80	PA0100
ES70GC001	73	75	53	77	74	77	68	53
	66	73	41	70	67	75	59	41
	66	81	41	70	67	78	59	41
	66	69	41	70	67	71	59	41
	60	77	29	64	61	74	51	29
	67	62	47	65	67	65	63	47
	49	71	11	54	51	67	39	11
	47	70	7	54	48	66	36	7
ES70GC002	59	77	28	65	60	74	51	28
	75	71	56	73	75	73	70	56
	73	73	53	75	74	75	67	53
	65	81	39	69	66	78	58	39
ES70GC003	49	71	10	55	50	67	38	10
	77	73	61	75	77	75	73	61
	77	82	59	83	77	84	72	59
	68	82	44	71	69	79	62	44
	40	66	–	46	42	61	28	–
	38	65	–	48	40	60	26	–
	65	81	39	69	66	78	58	39
	51	71	14	56	53	68	41	14
	70	82	47	75	71	80	63	47
ES70GC004	60	78	30	64	61	74	52	30
	60	78	30	68	61	74	52	30
	70	74	47	73	71	76	63	47
	66	81	41	70	67	78	59	41
	58	76	26	62	59	73	49	26
	59	77	28	64	60	74	51	28
	65	81	39	70	66	78	58	39
ES70GC005	67	70	43	71	68	72	61	43
	59	66	28	66	60	68	51	28
	52	73	17	72	54	69	43	17
	55	68	22	63	57	71	46	22
	74	69	54	71	73	71	69	54
	57	50	36	54	57	54	56	36
	69	77	46	79	70	79	63	46
	68	63	64	65	68	65	70	64
ES70GC006	81	80	67	81	82	81	77	67
	85	82	89	84	85	84	86	87
	77	87	60	81	78	85	73	60
	77	73	66	75	77	75	77	66
	75	73	57	75	76	75	70	57
	30	61	–	37	32	55	16	–
	70	80	48	82	71	81	64	48
	75	81	56	82	76	82	70	56
	77	81	60	82	78	82	73	60

(Continued)

Table 4 (*Continued*)

Groundwater body	Maximum water recovery (%)							
	Genesys LF	Genesys SI	Vitec 3000	Vitec 4000	PC191	HS40	AS80	PA0100
	48	71	8	56	49	66	37	8
	79	86	63	87	80	86	75	63
	72	68	67	70	72	70	74	67
	53	74	18	58	55	70	44	18
	73	84	53	82	74	82	67	53
	70	82	48	83	71	81	64	48
	70	83	48	75	71	81	64	48
	71	83	49	84	72	81	65	49
	81	80	67	82	82	82	77	67
ES70GC007	76	81	58	82	76	82	71	58
	69	82	45	72	70	80	62	45
	74	82	54	83	75	83	69	54
	68	76	44	78	69	78	62	44
	78	82	61	83	78	83	73	61
	72	84	51	78	73	82	66	51
	60	78	31	75	62	74	53	31
	61	70	33	72	63	72	54	33
	64	66	37	68	65	69	57	37
	70	82	48	81	71	81	65	48
ES70GC008	78	78	62	79	79	79	74	62
	78	74	70	76	78	76	79	70
	69	63	48	66	69	66	64	48
ES70GC009	35	63	–	44	37	58	22	–
	58	76	26	62	59	73	49	26
	82	79	71	80	82	80	80	71
	73	85	53	80	74	82	67	53
	66	81	41	77	67	78	59	41
	77	73	67	75	77	75	77	67
	67	82	43	79	68	79	61	43
	77	87	59	87	77	85	72	59
	81	89	67	89	82	88	77	67
	56	75	23	61	58	72	47	23
	53	74	18	61	55	70	44	18
	67	81	42	73	68	78	60	42
	64	80	38	74	65	77	57	38
	84	91	73	92	85	90	81	73
	51	73	14	58	53	68	41	14
	76	87	58	88	77	85	71	58
	74	85	54	83	75	83	69	54
	32	62	–	44	35	56	19	–
	56	75	23	61	58	72	47	23
	65	80	38	78	66	77	58	38
	42	68	–	50	44	63	31	–
	61	78	32	72	62	75	53	32
	61	78	32	67	62	75	53	32
	73	85	53	86	74	83	68	53

(Continued)

Table 4 (*Continued*)

Groundwater body	Maximum water recovery (%)							
	Genesys LF	Genesys SI	Vitec 3000	Vitec 4000	PC191	HS40	AS80	PA0100
	65	80	38	71	66	77	58	38
	52	73	16	57	53	69	42	16
	69	82	45	76	70	80	62	45
	55	75	21	62	56	71	46	21
	61	78	32	69	62	75	53	32
	62	79	33	66	63	75	54	33
	60	78	31	70	62	74	53	31
	75	86	56	81	76	84	70	56
	53	74	18	59	54	70	43	18
	66	72	40	74	67	74	59	40
	75	86	56	83	76	84	70	56
	66	81	40	69	67	78	59	40
	49	71	11	57	51	67	39	11
	73	85	53	77	74	83	68	53
ES70GC0010	75	85	57	83	76	84	70	57
	65	80	38	74	66	77	58	38

Table 5
Maximum water recovery range in Tenerife

Groundwater body	Maximum water recovery (%)							
	Genesys LF	Genesys SI	Vitec 3000	Vitec 4000	PC191	HS40	AS80	PA0100
ES70TF001	91	95	84	92	91	94	89	84
	50	56	12	59	51	59	39	12
ES70TF002	80	89	65	83	81	87	76	65
	47	38	39	42	47	42	51	39
ES70TF003	90	94	83	91	90	94	88	83
	55	49	22	53	56	53	46	22
ES70TF004	90	94	83	91	90	94	88	83
	81	78	75	79	81	79	82	75

since the experience is key to set the mentioned limits and dosage. Because silica was the most limiting compound in the studied feedwaters, the Genesys™ SI and Chemtəx™ HS40 were the most appropriate antiscalant products to be used from the scaling potential point of view. The specific silica antiscalant are more expensive than others. To choose a proper antiscalant other factors than maximum water recovery such as antiscalant cost, dosing and water needs should be taken into account. The water flux recovery has a tremendous impact in the efficiency of brackish water reverse osmosis desalination. In RO system design, it is important to consider the maximum recovery as it plays a relevant role in the possible arrangements, operating conditions and efficiency of these systems.

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