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Analysis of recovery by desalination systems in the west of Rio Grande do Norte, Brazil

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ABSTRACT

In the Brazilian semiarid region, groundwater usually have high concentration of salts. In order to make these waters suitable for consumption, desalinators have been installed in communities and rural settlements to meet the water demand. However, regardless of the efficiency of the membrane and the installed structure of the desalinators, the reverse osmosis system will produce the drinking water and also the residue with salt concentration higher than the previous water salinity. The sampling of water of wells, purified water, and saline reject was carried out in four expeditions, between October 2013 and November 2014, in seven water treatment facilities of communities and/or rural settlements in the west of Rio Grande do Norte State, Brazil. Determinations included the efficiency of reverse osmosis in water purification and parameters of quality: electrical conductivity, pH, cations and anions, sodium adsorption ratio, calcium/magnesium ratio and the influence of the Langelier saturation index and the Ryznar stability index on the recovery rate of reverse osmosis desalination systems. The results indicate that the average recovery rate for desalination systems was 32.11% in October/November of 2013; 52.42% in February/March of 2014; 41.41% in June/July of 2014, and 33.60% in October/November of 2014.

Keywords: Semiarid region; Salinity; Reverse osmosis

1. Introduction

The lack of water resources in the semi-arid region of the Brazilian Northeast affects a large part of the population, especially those living in the rural area, and is due mainly to the spatial and temporal variability of rainfall [1], as well as to the geological characteristics.

The scarcity of surface water resources makes the use of groundwater an alternative for the survival of communities in order to guarantee, for example, the production and supply of food [2,3].

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However, a problem to be faced in relation to the use of waters from underground aquifers is the high concentration of salts resulting from their long contact time with crystalline rocks [4]. In this context, the installation of desalination systems aims to make water with high concentrations of salts suitable for human consumption.

Although the use of the desalination process presents itself as a potential alternative for the use of water in the regions that coexist with water deficit, its implementation should be evaluated, considering that a residue is generated that is more concentrated than the brackish water itself and presents greater environmental contamination capacity.

According to Monteiro et al. [5], among the variables considered in the design of a desalinator system, those that measure its efficiency are the capacity of system recovery (r), salt rejection (SR) and salt passage (SP), which are established in the preliminary design of the system. The higher the level of recovery of a system, the greater the volume of permeate and, consequently, the smaller the volume of reject produced. This increases the concentration of dissolved salt in the reject stream as well as the possibility of its precipitation on the membrane surface.

The recovery of the desalinator system depends on several factors, such as the formation of crust on the surface of the membranes, the osmotic pressure, and the quality of the water entering the system. In view of the above, this work had as objectives (i) to calculate the rate of recovery of the reverse osmosis system by means of salt balance considering the brackish waters, salt reject and purified water; (ii) to relate the interference of the Langelier saturation index and the Ryznar stability index in the recovery rate of the desalination systems.

2. Materials and methods

2.1. Area covered by the study

Water samples were collected from seven communities in the west region of the state of Rio Grande do Norte, Brazil, from October 2013 to November 2014.

The entire area covered by the study, ranging from the municipality of Mossoró until José da Penha, in the extreme south of the state, presents similar characteristics and has approximately 70 desalination stations. The dominant vegetation is the hyperxerophilic caatinga [6].

2.2. Climate of the region

According to Diniz and Pereira [6], the climate of the region is the tropical of equatorial zone with three subclimates (mild semiarid, average semiarid and strong semiarid). The meteorological data regarding the rainfall on the region and period are covered by the study (Fig. 1).

In the state of Rio Grande do Norte, the large-scale atmospheric system responsible for most of the precipitation (mainly in the first semester) is the intertropical convergence zone [6]. This system generates rainfall data over the equatorial region of the Atlantic, Pacific and Indian Ocean and adjacent continental areas [7] as in the case of the state of Rio Grande do Norte.

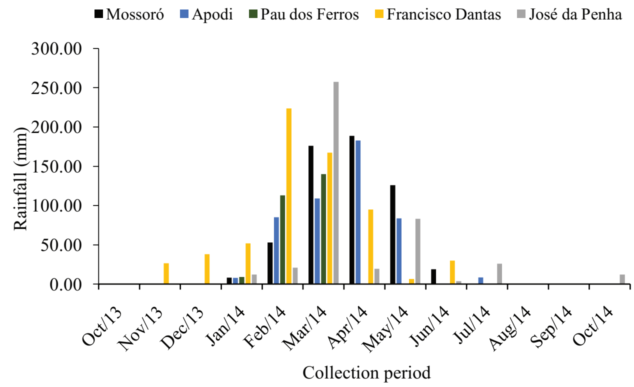

Fig. 1. Rainfall on the region and period covered by the study.

Other atmospheric systems that operate in the state of Rio Grande do Norte at the mesoscale level are as follows:

– Wave disturbances in the field of tradewinds: occur thanks to the deep penetration of frontal systems of the Northern Hemisphere, in equatorial latitudes.
– Convective complexes: they produce isolated rains and are formed due to favorable local conditions (temperature, relief, pressure, etc).
– Upper level cyclonic vortices can produce rainfall in any part of the state, depending on its position, which is variable. These phenomena are formed in the Atlantic Ocean, but they advance throughout the interior of the Northeast of Brazil, producing rain clouds in its periphery and subsidizing dry air at its center, forming areas of high pressure locally and temporarily.
– Sea breezes: carry moisture from the ocean to the interior of the continent up to distances of about 300 km, causing precipitation, mainly in the night period.

2.3. Methods

The cadastral survey of the communities was carried out by consulting the Rio Grande do Norte State Water Resources Secretariat (SEMARH), followed by the selection of a representative number of communities in order to proceed with water collection for the sequence of the research.

Exploratory visits were made to the communities for a participatory diagnosis of the reverse osmosis treatment plants, identifying characteristics that allowed the monitoring of the waters, namely: effective use of the desalinator, and maintenance history (referring to the time for repair in situations of failure).

After diagnosis, the samples were collected at the desalination stations of seven communities: Boa Fé at the municipality of Mossoró; Alagoinha at Mossoró; Lagoa Rasa at the municipality of Apodi; Juazeiro at Apodi; Alagoinhas at the municipality of Pau dos Ferros; Jacu at the municipality of Francisco Dantas, and Ema at the municipality of José da Penha (Fig. 2).

The samples were collected in four periods in each community, with interval of 3 months, in order to portray all the seasons of the year, verifying the behavior of the water changes: S_1 = October/November 2013 – dry period, practically without rainfall; S_2 = February/March 2014, beginning of the

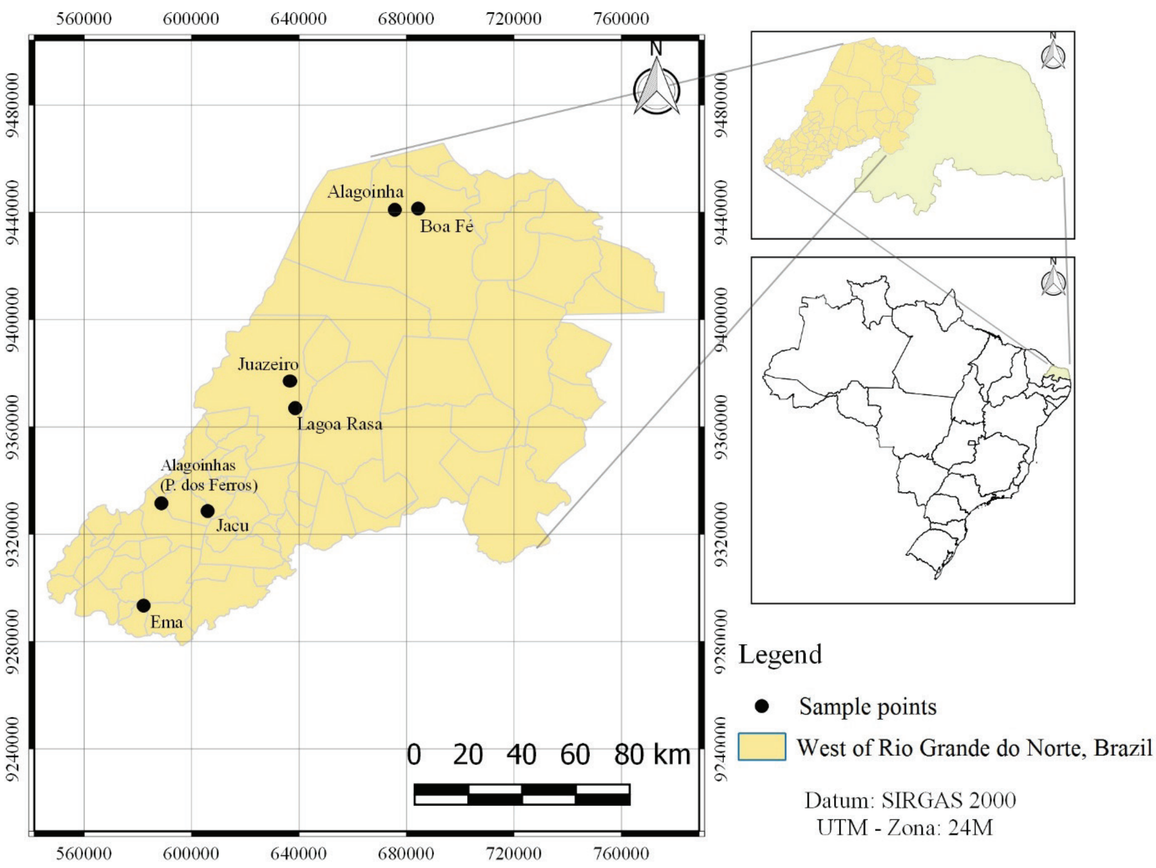

Fig. 2. Location map of sample points.

rainy season; S_3 = June/July 2014, end of the rainy season and S_4 = October/November 2014, closing the cycle of 12 months, again in the dry season.

Water was collected from three sources: brackish water from wells – without any treatment; purified water and the salt reject water.

The collection procedure was done after the operation of the desalination unit for 5 min. The samples were stored in 500 mL opaque plastic bottles, hermetically sealed, conditioned in icebox and then conducted for laboratory analysis.

Analysis of water included the concentrations of sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), chloride (Cl^-), carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) [8].

The system recovery was calculated according to Eq. (1).

$$r(\%) = \frac{Q_p}{Q_f} \times 100 = \frac{Q_p}{Q_p + Q_c} \times 100 \quad (1)$$

where r – system recovery (%); Q_p – permeate flow (m^3 h^{-1}); Q_f – feed flow (m^3 h^{-1}) and Q_c concentrate flow (m^3 h^{-1}).

Due to the fact that data were not collected regarding the flow of the wells, it was calculated from the equation deduced from the mass balance of the system, according to the following procedure:

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

The principle of conservation of matter is given by the following equation:

$$Q_f = Q_p + Q_c \quad (3)$$

Therefore,

$$Q_c = Q_f - Q_p \quad (4)$$

Substituting Eq. (4) into Eq. (2), we will have:

$$Q_f C_f = Q_p C_p + (Q_f - Q_p) C_c$$

$$Q_f C_f = Q_p C_p + Q_f C_c - Q_p C_c$$

$$Q_f C_f - Q_f C_c = Q_p C_p - Q_p C_c$$

$$Q_p (C_p - C_c) = Q_f (C_f - C_c)$$

$$\frac{Q_p}{Q_f} = \frac{C_f - C_c}{C_p - C_c} \quad (5)$$

Substituting Eq. (5) into Eq. (1), we will have:

$$r(\%) = \frac{C_f - C_c}{C_p - C_c} \times 100 \tag{6}$$

Rejection of salts (RS) provides the membrane's ability to reject dissolved salts during water permeation [9] and can be defined as:

$$\mathrm{RS}(\%) = \frac{C_f - C_p}{C_f} \times 100 = \left(1 - \frac{C_p}{C_f}\right) \times 100 \tag{7}$$

where RS is the rejection of salts (%), C_f is the feed concentration (mg L^{-1}) and C_p is the concentration of the permeate (mg L^{-1}).

3. Results and discussion

3.1. Systems recovery

The desalination systems of the west communities of the state of Rio Grande do Norte showed a recovery rate of 39% for reverse osmosis system. The maximum recorded recovery value of the system occurred in Juazeiro at S_3 (88%), while the minimum (13%) occurred at Pau dos Ferros at S_1 (Fig. 3). This parameter reflects the ratio between the amounts of brackish water from wells and of the permeate. It is also observed that the highest recovery average of the system, calculated from the four periods, was verified in the Jacu and Juazeiro communities, with 59% and 53%, respectively. These values contradict what was estimated by Dias et al. [2] who, although did not verify the efficiency of the system, estimated that reverse osmosis would produce waste water (waste, brine or concentrate) estimated in approximately 60% of treated raw water, with salt concentration higher than the salinity of the original water.

Analyzing the Langelier saturation index (LSI) (Table 1), it is observed that, according to the classification suggested by Tchobanoglous et al. [10], for most of the time, and for most communities, there is a tendency of incrustation through the precipitation of $CaCO_3$, (LSI > 0). For S_3, in the localities of Jacu and Juazeiro, tendency to corrosion (LSI < 0) was noticed. In the locality of Jacu, for the period S_2, a chemical equilibrium was observed.

The values were altered according to the collections, with the highest values being observed in S_2, during which the highest precipitations occurred (Table 1). In addition, the $CaCO_3$ presents a greater interatomic distance, which gives it a covalent character, making it difficult to form the solvation layer and, consequently, its solubilization [11].

In the region near the membrane, due to the zone of polarization, ionic concentrations are accentuated, increasing the solubility product (K_{PS}), supersaturating the solution and causing partial and temporary obstruction of the membrane pores fouling. After the use of the desalinator, part of this $CaCO_3$ still remains in the solid state, forming the permanent obstruction (incrustation) that gradually decreases the efficiency of the system.

According to the classification of the APHA – American Public Health Association [12], the Ryznar stability index (RSI) for most locations and periods presented characteristics slightly fouling (RSI from 5.0 to 6.0) (Table 2). This stability index is based on the possibility of $CaCO_3$ precipitation because, among salts, it has the lowest solubility product ($K_{PS} = 3.0 \times 10^{-9}$ mol^2 L^{-2}) [13].

For the locations of Jacu and Juazeiro, in period S_3, the RSI was classified as intolerably corrosive (RSI > 9). As the S_3 corresponds to the end of the rainy season in the region, the recharge of the aquifers may have occurred, with consequent acidity. Pontes et al. [14] and Piratoba et al. [15] observed in their studies that most of the locations monitored presented more acidic water also in the rainy season, which may be associated with aquifer recharge due to the increase in organic acid content.

It was also observed that, for the LSI and RSI indices, the communities that presented the best chemical balance were Lagoa Rosa and Boa Fé, with the lowest recovery means of the systems, possibly related to the high saline concentrations. The same was verified by Oliveira et al. [16] when analyzing the electrical conductivity of wells in this region.

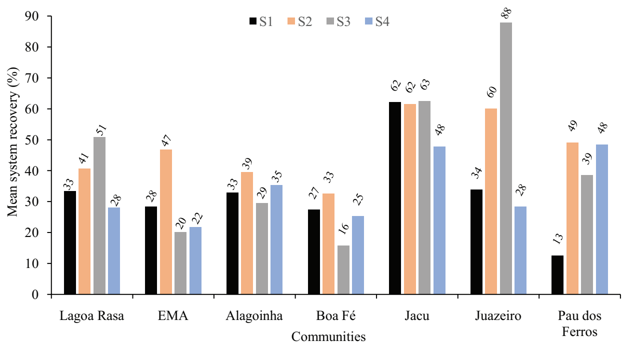

Fig. 3. Index of recovery of reverse osmosis desalination systems in the seven rural communities of the west region of the state of Rio Grande do Norte, Brazil, in dry and rainy seasons, in the years 2013 and 2014. S_1 = Season 1 (October/November – 2013); S_2 = Season 2 (February/March – 2014); S_3 = Season 3 (June/July – 2014) and S_4 = Season 4 (October/November – 2014).

Table 1
Langelier saturation indices (LSI), in the seven rural communities of the region of the state of Rio Grande do Norte, Brazil, during dry and rainy seasons, in the years 2013 and 2014

Locality	LSI			
	S_1	S_2	S_3	S_4
Lagoa Rasa	0.47	0.89	0.74	0.81
Ema	1.13	1.21	0.75	1.02
Alagoinha	1.16	1.37	0.84	0.54
Boa Fé	1.26	1.25	1.11	1.18
Jacu	1.25	0.00	1.33	0.72
Juazeiro	0.26	0.26	1.09	0.55
Pau dos Ferros	0.87	1.71	0.51	0.42

S_1 = Season 1 (October/November – 2013); S_2 = Season 2 (February/March – 2014); S_3 = Season 3 (June/July – 2014) and S_4 = Season 4 (October/November – 2014).

Table 2
Ryznar stability index (RSI) for the rural communities of the west region of the state of Rio Grande do Norte, Brazil, during dry and rainy seasons, in the years 2013 and 2014

Locality	RSI			
	S_1	S_2	S_3	S_4
Lagoa Rasa	6.23	5.69	5.91	5.89
Ema	5.23	4.96	5.80	5.46
Alagoinha	5.39	5.00	5.71	6.06
Boa Fé	4.75	4.65	5.07	4.80
Jacu	5.03	6.13	9.67	5.67
Juazeiro	6.68	6.39	9.17	5.98
Pau dos Ferros	5.64	3.82	7.18	6.63

S_1 = Season 1 (October/November – 2013); S_2 = Season 2 (February/March – 2014); S_3 = Season 3 (June/July – 2014) and S_4 = Season 4 (October/November – 2014).

While analyzing the dissolution characteristics of the water that presented LSI and RSI with solvent tendencies instead of fouling (Tables 1 and 2), the intrinsic dependence between system recovery and stability indices was observed (Figs. 4 and 5). The more negative the LSI value and the higher the RSI value, the lower the fouling tendency and, consequently, the greater the corrosive characteristic of the water. Studies conducted by Cavazzana et al. [3] observed a relationship between LSI and RSI with crusting and corrosion in irrigation equipment.

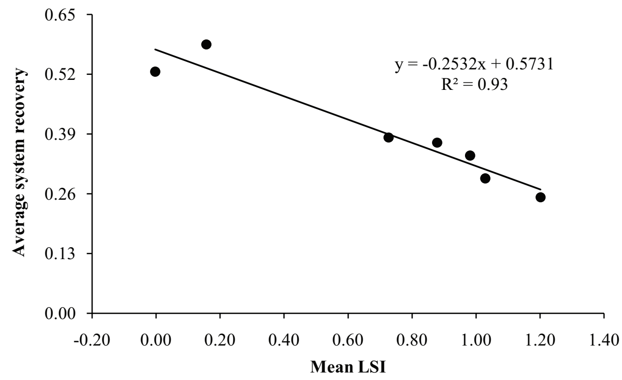

Fig. 4. Relationship between Langelier saturation index (LSI) and mean recovery of reverse osmosis water treatment system.

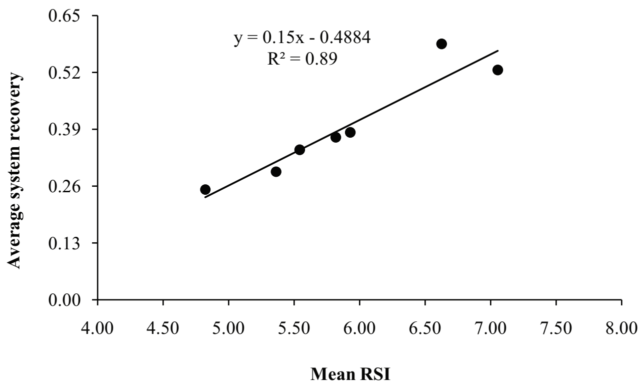

Fig. 5. Relationship between Ryznar stability index (RSI) and mean recovery of reverse osmosis water treatment system.

3.2. Rejection of salts

It can be observed from Table 3 that in all the communities in which there was carbonate (CO_3^{2-}) detection in the water, 100% rejection of this ion by the membrane occurred. This fact, coupled with a high calcium rejection, can cause the formation of fouling and incrustations, reducing the efficiency of the system.

Rejection of salts in a reverse osmosis system varies between 90% and 99.8% for most of the existing ions in solution, with nominal values of 95% – fluoride, chloride; 94% – sodium, potassium; 97% – calcium, magnesium and 98% – heavy metals [17–19].

It is also worth mentioning the presence of null values for potassium rejection in samples from Alagoinha communities in S_2 and Jacu in S_3, as well as bicarbonate in Jacu and Pau dos Ferros in S_3. This fact can be related to the low rejection of these ions by the membrane and that they are monovalent and, therefore, have greater permeability [20]. Instead of decreasing, there was an increase in the concentration of these ions in the permeate. Queiroz et al. [21] found similar data for nitrate rejection in an evaluation of reverse osmosis system.

Considering the parameter proposed by Hydranautics [18], 57% of the samples are within the acceptable range, that is, with salt rejection above 90%, estimated by the decrease in electrical conductivity (EC). This can be generalized, even if each ion has a different osmotic behavior, because just as the EC of the water corresponds to the sum of the individual conductivities, the osmotic pressure of the solution corresponds to the sum of the pressures of each ion. This was observed by Silveira and França [20] who used water from a well and a sodium chloride solution, both with the same EC, and verified that rejection and recovery rates of a desalinator system via reverse osmosis did not differ significantly despite the differences between solution components.

Regarding the individual rejection of ions, there was a satisfactory rate as a percentage of analyzed water samples for chloride (50%), for bicarbonate, sodium, potassium and calcium (54%), and for magnesium in 60%. Taking as reference, the nominal values cited by Scapini [19], specific rejections decreased to 42.9% for chloride, 35.71% for potassium, 21.4% for sodium, 42.9% for calcium and 35.71% for magnesium. This fact is due to the comparison parameters being higher, nominal and, consequently, not taking into account the evolution of the system changes due to its use. In 78.57% of the samples, calcium rejection was higher than that of sodium, corroborating the assertion that bivalent cations suffer greater rejection than monovalents as reported by Silveira and França [20].

4. Conclusions

The desalination systems showed acceptable yield. The lower the saline concentration of feed water, the higher the amount of purified water.

Table 3
Values of the salt rejection rate for the rural communities of the west region of the state of Rio Grande do Norte, Brazil, during dry and rainy seasons, in the years 2013 and 2014

Season	Locality	EC	K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	CO_3^{2-}	HCO_3^-
		Rejection (%)							
S_1	Lagoa Rasa	98.99	100.00	97.22	98.57	97.93	82.35	100.00	97.62
	Ema	95.37	100.00	96.46	98.15	94.29	96.05	100.00	95.89
	Alagoinha	84.40	89.47	74.91	95.00	77.78	87.10	100.00	86.00
	Boa Fé	94.68	81.82	94.19	98.78	94.95	96.89	100.00	90.91
	Jacu	88.58	93.10	91.76	98.25	66.90	95.69	100.00	91.89
	Juazeiro	93.03	95.00	93.59	99.00	97.99	95.88	–	80.00
	Pau dos Ferros	92.38	91.67	92.20	98.06	100.00	94.34	100.00	96.88
S_2	Lagoa Rasa	92.73	0.00	97.95	98.65	93.48	95.24	100.00	94.81
	Ema	38.46	18.47	97.36	94.92	97.73	95.45	100.00	93.08
	Alagoinha	92.00	0.00	76.09	91.78	92.59	88.89	100.00	86.15
	Boa Fé	93.75	53.20	92.49	97.88	97.78	96.56	100.00	80.00
	Jacu	88.85	93.75	91.65	96.15	76.92	91.53	100.00	92.11
	Juazeiro	26.09	84.34	96.34	98.47	93.10	96.12	–	56.52
	Pau dos Ferros	82.61	80.70	91.27	96.57	97.22	85.92	100.00	92.50
S_3	Lagoa Rasa	94.83	19.23	94.85	96.77	93.75	84.21	100.00	98.68
	Ema	96.37	95.08	99.07	92.86	75.86	90.16	–	96.63
	Alagoinha	89.91	85.71	88.16	91.67	5.56	83.87	100.00	88.00
	Boa Fé	95.16	94.20	91.44	98.63	97.09	94.12	–	94.12
	Jacu	93.91	0.00	84.51	25.00	92.31	33.33	–	0.00
	Juazeiro	96.41	91.67	73.10	83.33	40.00	60.00	–	20.00
	Pau dos Ferros	80.70	86.49	99.21	63.64	63.64	80.00	100.00	0.00
S_4	Lagoa Rasa	96.84	100.00	98.66	96.88	81.82	81.82	100.00	94.74
	Ema	95.96	97.01	98.66	93.48	82.46	89.06	100.00	94.62
	Alagoinha	85.44	85.71	85.44	93.22	88.24	73.77	100.00	86.00
	Boa Fé	94.76	96.30	96.22	99.45	98.78	95.15	–	93.02
	Jacu	92.17	95.71	95.61	94.00	95.38	88.18	–	86.49
	Juazeiro	96.92	96.77	96.60	97.86	97.65	95.33	–	89.29
	Pau dos Ferros	82.65	91.53	99.49	62.50	97.67	73.91	100.00	80.43

S_1 = Season 1 (October/November – 2013); S_2 = Season 2 (February/March – 2014); S_3 = Season 3 (June/July – 2014) and; S_4 = Season 4 (October/November – 2014).
EC = electrical conductivity; K^+ = potassium; Na^+ = sodium; Ca^{2+} = calcium; Cl^- = chloride; CO_3^{2-} = carbonate; HCO_3^- = bicarbonate.

The lower the value of the saturation index of Langelier and the higher the value of the stability index of Ryznar the higher the rate of recovery of the system.

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