STATE UNIVERSITY OF PONTA GROSSA
MASTER DEGREE PROGRAM IN ENVIRONMENTAL AND SANITARY ENGINEERING
DEPARTMENT OF CIVIL ENGINEERING

JOÃO FERNANDES JUNIOR

EVALUATION OF A BRACKISH WATER DESALINATION PILOT SYSTEM USING SOLAR ENERGY

PONTA GROSSA
2019

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Thesis presented to the Master Degree Program in Environmental and Sanitary Engineering of the State University of Ponta Grossa, as a requirement for obtaining the title of Master.

Supervisor: Prof. Dr. Giovana Kátie Wiecheteck

PONTA GROSSA
2019

Fernandes Junior, João
F363 Evaluation of a brackish water desalination pilot system using solar energy/ João Fernandes Junior. Ponta Grossa, 2019.
73 f.

Dissertation (Master Program in Sanitary end Envionmental Engineering – Concentration área of Environmental Sanitation and Water Resources), Ponta Grossa University State.

Advisor: Profa. Dra. Giovana Kátie Wiecheteck

1. Brackish water. 2. Desalination. 3. Ultrafiltration. 4. Softening. 5. Reverse osmosis. I. Wiechetck, Giovana Kátie. II. Ponta Grossa University State - Master Program in Sanitary end Envionmental Engineering. III T.

CDD : 628.1

Ficha catalográfica elaborada por Maria Luzia F. Bertholino dos Santos– CRB9/986

PROGRAMA DE PÓS-GRADUAÇÃO EM
ENGENHARIA SANITÁRIA E AMBIENTAL
UNIVERSIDADE ESTADUAL DE PONTA GROSSA

CERTIFICADO DE APROVAÇÃO

Título da Dissertação: **"Evaluation of a brackish water desalination pilot system using solar energy"**

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Ponta Grossa, 19 de março de 2019.

ACKNOWLEDGEMENTS

I thank my mother Araci Fernandes for the example of humility and honesty, for the support she has always given me during my studies and for prayers, care and understanding.

To Dr. Giovana Kátie Wiecheteck, for the valuable trust and incentive in my work. For the contribution of her knowledge and the orientation of this thesis and her friendship.

To the professors of the Master Degree Program in Environmental and Sanitary Engineering of the State University of Ponta Grossa, for the availability, attention and collaboration of ideas to develop this research.

To Dr. Gabriel Carranza from the University of Louisiana at Lafayette for the friendship and suggestions to improve the project.

To the Water and Sanitation Company of Paraná State (Sanepar), for the provision of equipment and technical support, which were fundamental to develop the experiments of this research.

To the State University of Ponta Grossa and to the Master Degree Program in Environmental and Sanitary Engineering for the opportunity to accomplish the master degree and to support the development of this project.

To the Institute of International Education (IIE) and the British Council through the Global Innovation Initiative (GII) to provide the financial resources to the project and the payment of part of my scholarship.

To the Coordination for the Improvement of Higher Education Personnel (CAPES) for my scholarship.

To my friends and colleagues of the Master Degree Program in Environmental and Sanitary Engineering for the moments of study and relaxation.

To all who participated and contributed directly or indirectly to the achievement of this work.

And above all, to God!

“On ne voit bien qu’avec le cœur.
L’essentiel est invisible pour les yeux.”
(Antoine de Saint-Exupéry)

ABSTRACT

Water desalination systems through membrane filtration are efficient in removing salts and have been widely used in different regions of the world. The main objective of this study was to evaluate the quality of water produced from a desalination pilot system with membrane filtration using solar energy and, its operational conditions. The pilot system was installed next to the Water Treatment Plant (WTP) of *Praia de Leste*, coast of Parana State, Brazil. The feed water for the desalination pilot system was brackish water from the mixture of sea water and fresh water (Pombas river), until total dissolved solids (TDS) concentrations of 3,500 ± 100 mg/L (Experiment 1) and 7,000 ± 100 mg/L (Experiment 2). During the experiments, was evaluated the energy consumption of the pilot system and the production of solar energy by the photovoltaic panels. The brackish water pretreatment using ultrafiltration (UF) was efficient to remove turbidity (95%) and color (100%). The softening system before the reverse osmosis (RO), removed 52.64% of total hardness in the Experiment 1 and 73.36% in the Experiment 2. RO membranes removed 99% of TDS and electrical conductivity, 100% of calcium and 99% of chlorides. The removal efficiency of sulphate from the pilot system was 98%. During the Experiments 1 and 2, the permeation rates presented average values of 22.82 and 22.41 L/h/m. The RO system presented recovery rate of 55.97% (Experiment 1) and 52.65% (Experiment 2). The average osmotic pressure was 10.08 and 13.06 kgf/cm^2 for the Experiments 1 and 2, respectively. The average production of solar energy was 84 kWh and 27 kWh (Experiments 1 and 2) and the energy consumption was 199.17 kWh (Experiment 1) and 189.46 kWh (Experiment 2). The treated water from the desalination pilot system presented suitable quality for the required standards in the Brazilian legislation. However, remineralization is necessary for human consumption.

Keywords: Brackish water. Desalination. Ultrafiltration. Softening. Reverse osmosis.

RESUMO

Sistemas de dessalinização de água por meio de filtração em membranas são eficientes na remoção de sais e têm sido amplamente utilizados em diferentes regiões do mundo. Este trabalho teve como objetivo avaliar a qualidade da água produzida, e as condições operacionais de um sistema piloto de dessalinização implantato na estação de tratamento de água (ETA) da Sanepar, no balneário de Praia de Leste, litoral do estado do Paraná. A água de alimentação do sistema piloto de dessalinização era proveniente da mistura de água do mar e água do rio, até a concentração de 3.500 ± 100 mg/L (Experimento 1) e 7.000 ± 100 mg/L (Experimento 2) de sólidos dissolvidos totais (SDT). Durante os experimentos, foi avaliado também o consumo de energia e a produção de energia por meio de oito painéis fotovoltaícos. A partir dos resultados obtidos, constatou-se que o pré-tratamento com UF foi eficiente na remoção de turbidez (95%) e de cor (100%). No abrandamento obteve-se remoção de 52,64% de dureza total no experimento 1 e de 73,36% de remoção no experimento 2, diferença decorrente das condições operacionais de regeneração do sistema. As membranas de osmose reversa removeram 99% de TDS e de condutividade elétrica, 100% de cálcio, 99% de cloretos. Com relação ao sulfato, a remoção total do sistema foi de 98%. Durante as 2 etapas experimentais, as taxas de filtração apresentaram valores médios de 22,82 e 22,41 L/h/m. A taxa de recuperação do sistema piloto de osmose reversa foi de 55,97% (Experimento 1) e de 52,65% (Experimento 2). A pressão osmótica média foi de 10,08 e 13,06 kgf/cm^2 para o primeiro e segundo Experimento, respectivamente. A produção média de energia solar foi de 84 kWh e 27 kWh (Experimento 1 e 2) e o sistema apresentou consumo de 199,17 kWh no Experimento 1 e 189,46 kWh no Experimento 2. A água tratada no sistema piloto de dessalinização apresentou qualidade adequada aos padrões exigidos pela legislação brasileira. No entanto, a remineralização é necessária para o consumo humano.

Palavras-chave: Água salobra. Dessalinização. Ultrafiltração. Abrandamento. Osmose Reversa.

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ABREVIATIONS

BW	Brackish water
CIP	Clean in Place
COLIT	Territorial Development Council of the Parana State Coast
CONC	Saline Concentrate
EC	Electrical Conductivity
IBGE	Brazilian Institute of Geography and Statistics
MF	Microfiltration
NF	Nanofiltration
NTU	Nephelometric Turbidity Units
RO	Reverse Osmosis.
PAC	Polyaluminum Chloride
pH	Potential of Hydrogen
Sanepar	Water and Sanitation Company of Parana State
SD	Standard Deviation
TDS	Total Dissolved Solids
UEPG	State University of Ponta Grossa
UF	Ultrafiltration
uH	Units Hazen
UV	Ultraviolet
WHO	World Health Organization
WTP	Water Treatment Plant

SUMMARY

INTRODUCTION

The concern regarding to the drinking water production is one of the main reasons that drive the search for water treatment alternatives that are efficient in removing chemical compounds that are not effectively removed in conventional water treatment systems.

According to Giri and Qui (2016) the population growth is the major factor which interferes on the water quality for human consumption, demanding more land for habitation and food growing without the concern with the protection and conservation of water resources. Several of the world's regions present problems related to the high level of water pollution which requires advanced techniques and/or the use of more chemical products in order to treat water (FIRSOFF, 2015).

Problems in coastal regions have been frequents when there is the sea water intrusion into the fresh water rivers, altering the water quality and interfering in the efficiency of the processes in water treatment plants.

Membrane filtration such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) are compact technologies and easy to be automatized. The result of this type of water treatment is good water quality, being an alternative to provide water in regions with water shortage (OLIVEIRA, 2010).

In order to study alternative processes of water treatment to the coastal regions, a brackish water desalination pilot system using UF, softening followed by RO and solar energy to drive the system, was installed in *Praia de Leste*, coast of Parana State, Brazil. The brackish water was prepared from the mixture of sea water and fresh water (from Pombas river) in two TDS concentrations: TDS = 3,500 ± 100 mg/L (Experiment 1) and TDS = 7,000 ± 100 mg/L (Experiment 2).

Aiming to reach the general objective of this work, two articles were elaborated, both of which are presented in the form of chapters. The first chapter refers to the article 1, which had as main objective to present the efficiency of the desalination pilot system using solar energy by the quality parameters of water and operational conditions of the RO system. The second chapter, related to article 2, had as main objective to analyze the parameters for water quality employing a multiple linear regression model and, for parameters which were not significant in the multiple regression, a linear Pearson correlation matrix was elaborated to analyze the correlation among the parameters.

LITERATURE REVIEW

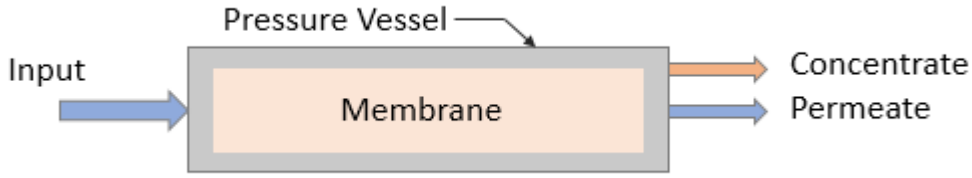
MEMBRANE FILTRATION

The membrane filtration can be defined as a selection barrier between two phases. The efficiency occurs through two mechanisms: selectivity or selective permeability and flow or filtration rate (MARQUES, 2017).

For Rosa (2012) the selectivity is related to the pore diameters and the manufacturing material of the membrane. The membrane filtration rate can be defined as the volume which flows through the section of the membrane per unit of time (Habert et al., 2006).

Figure 1 shows the operational principle of filtration by semipermeable membranes considering the input water, permeate and concentrate. From the input water (feed water), the permeate or product (water which passes through the semipermeable membrane) is separated of the concentrate (water which does not pass through the membrane).

Figure 1 - Operational principle for semipermeable membrane filtration.



Source :The author (2019).

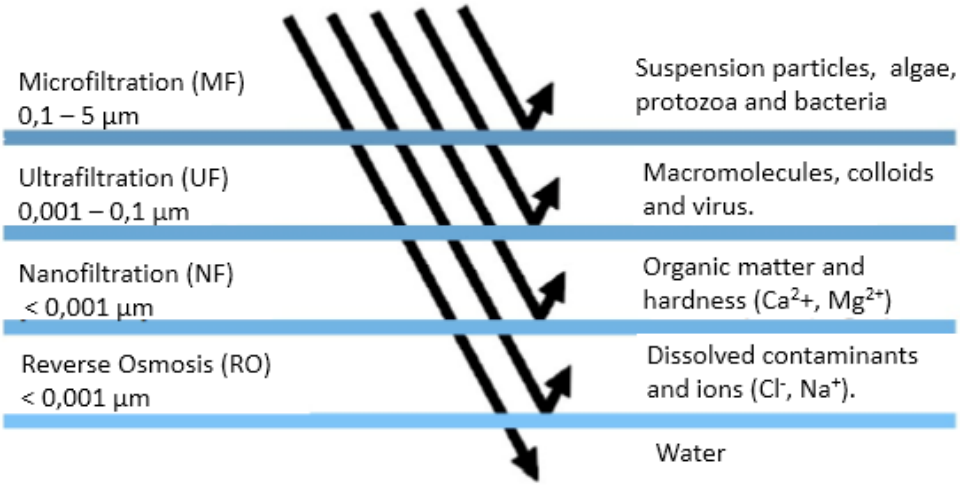
MEMBRANE FILTRATION CLASSIFICATION

The classification of the porous membrane is based on the: pore diameters, applied pressure, membrane material and configuration, mechanism and contaminant separation capacity.

The membranes are differentiated by their pore sizes, which can be divided in low-pressure membranes: microfiltration (MF) and, ultrafiltration (UF); and, high-pressure membranes: nanofiltration (NF) and reverse osmosis (RO) (METCALF & EDDY, 2016).

The removal effectiveness of the main membranes categories is showed in Figure 2. Their selectivity capacities are associated to the pore size and the presence of particles in the solution to be filtered.

Figure 2 - Main membrane separation processes.



Source: Adapted from NRC (2008).

Microfiltration (MF)

In most cases, MF removes colloidal and suspended particles (0,1 to 5 µm). The system operates in low pressure and is suitable to treat water for consumption in some cases (DEL COLLE, 2005).

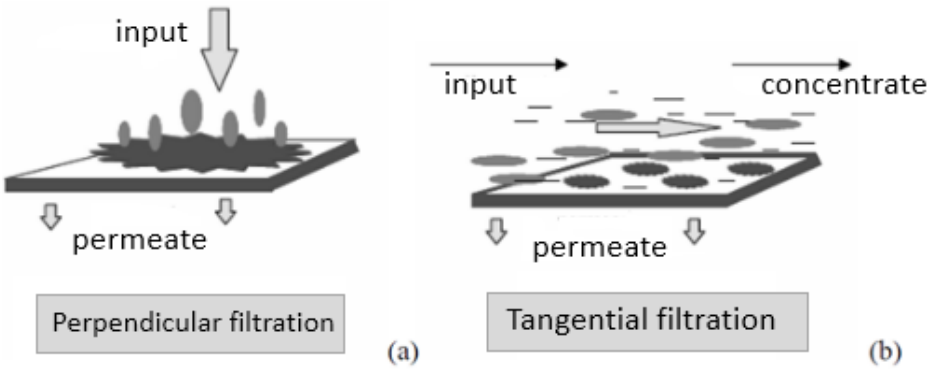
According to Trevisoli (2010), the advantage of MF is the absence of chemicals harmful to the environment and requiring low energy consumption for the pumps. MF has an easier cleaning process and larger life cycle when compared to other membrane filtration processes (Haneda, 2010).

Hinková et al. (2014) demonstrated in their research that MF is not the best performing method. They obtained 50% of impurities removal from the water in a sugar-cane industry. The operation was unfeasible due to the fouling, with the obstruction of the membrane caused by the accumulation of organic matter, bacteria, metals and other solids in the feed water.

MF operation process can be done through the conventional method (perpendicular filtration) or by means the tangential method. In the first one, the solution is pressed against the membrane (Figure 3a). Suspended solids are retained in the surface of the membrane while the permeate flows through it (ALICIEO et al., 2008).

In the tangential method (also known as dynamic filtration method), the solution flows parallel to the section of the membrane (Figure 3b), while the permeate is transported perpendicularly (HABERT, BORGES and NÓBREGA, 2006).

Figure 3 - Standard (a) and tangential (b) microfiltration.



Source: HABERT, BORGES and NÓBREGA (2006).

Ultrafiltration (UF)

UF presents the ability to separate particulate matter, colloids, microorganisms and high molecular weight molecules. Its porous section possesses an average diameter from 0.001 to 0.1 μm (OLIVEIRA, 2010).

Based on pore diameter, UF is situated between MF and NF technologies. Its membrane possesses a denser filtering surface when compared to the MF membrane, presenting a higher dynamic resistance (Mülder, 2006).

Although physical phenomena is predominant in the UF, there is also the chemical phenomena. Dissolved salts go through the membrane, while high molecular weight substances, such as colloids, proteins and carbohydrates are rejected (METCALF & EDDY, 2003).

UF is used to recover proteins and milk serum, in the food industry. It is indicated as pre-treatment to remove suspended solids and organics, improving the effluent quality in the RO treatment processes. In this sense, the size of the water treatment plants can be reduced and, in some cases, there is no need of chemical treatment (KUCERA, 2014).

According to Krüger (2009), UF is the most suitable process for pre-treatment in water desalination systems by RO, providing greater efficiency to remove suspended particles and colloids from sea water.

Nanofiltration (NF)

As an intermediary process between UF and RO, nanofiltration presents average pore diameter in the order of nanometers.

The separation occurs by the effect of the size exclusion, electrostatic interactions between the membrane and loaded species, diffusivity and solubility differences, surface energy differences and dielectric exclusion (Kosutic et al., 2004).

NF systems require lower pressures than the RO, which provides an economic advantage (Mülder, 2006).

According to Schãfer et al. (2005), the main factors which differ NF from other separation systems are: retention of negative multivalent ions (anions) such as SO_4^{-2} e PO_4^{-3}; retention proportion amounting up to 70% of NaCl for systems with complex mixtures; and, particles removal of without charge, dissolved materials and most positive ions, considering size and shape of the species.

Reverse Osmosis (RO)

The RO phenomenon occurs when two solutions, one hypotonic (lesser concentration of solute) and another hypertonic (greater concentration of solute), pass from the lesser concentrated medium to the greater concentrated medium, through a semipermeable membrane (ROSA, 2013).

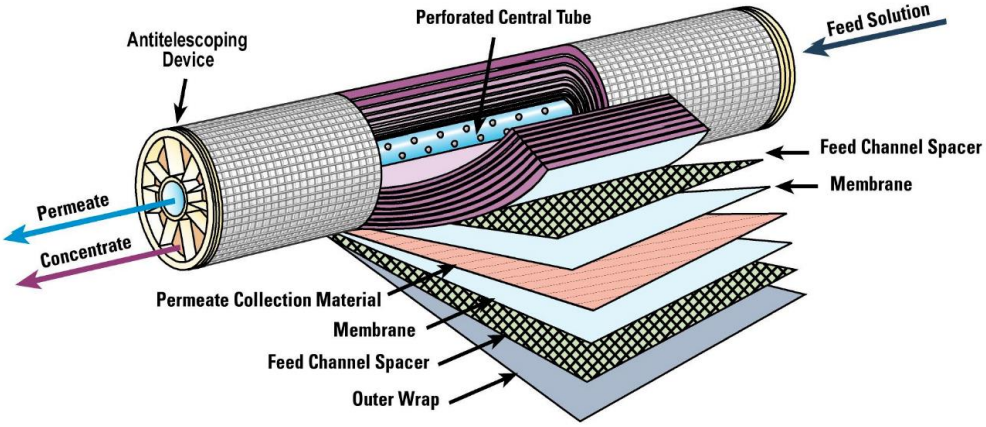
The natural osmotic flow is reversed by applying osmotic pressure from the greater salt concentration to the lesser concentration.

RO is a desalination process which uses hydraulic pressure as a driving force. The solute retention occurs by a semipermeable membrane where the solution with elevated salt levels is forced to pass (Bovaroti, 2018).

The membrane diameter used in RO systems is smaller than 0.001 µm. There is the retention of monovalent ions. The separation mechanism cannot be understood as simple filtration, but as a process of diffuse nature which depends on the affinity of the different species with the membrane material (process of absorption/diffusion) (HABERT et al. 2006).

Figure 4 shows a membrane module wrapped into a spiral, commonly used in RO systems. The feed water flows through the membranes through a spacer and is forced on the membrane’s surface by osmotic pressure, producing the permeate which leaks off through the collecting tube (METCALF; EDDY, 2016).

Figure 4 - Membrane module wrapped into a spiral.



Source: Diniz (2012).

In order to avoid damage to the RO membrane systems, water quality and operational parameters must be constantly monitored in devices installed before and after the membrane (PERMUTION, 2016; PURETEC INDUSTRIAL WATER, 2016).

OPERATIONAL PARAMETERS

Osmotic Pressure

In RO systems, the osmotic pressure which is exerted by a high-pressure hydraulic pump will be greater than the natural osmotic pressure. The pressure application occurs in the solution compartment which presents the greater concentration of TDS, forcing the water to pass by the semipermeable membrane in the reverse direction of the natural osmosis. This process removes the salts and contaminants and produces relatively pure water (PURETEC INDUSTRIAL WATER, 2016).

Permeation Rate

The filtration rate corresponds to the permeate volume treated per unit of time regarding to the available membrane permeation area (PURETEC INDUSTRIAL, 2016). The permeate flow is directly proportional to the temperature and pressure, which are important parameters to monitor the obstruction of the membrane porous by scaling (ALMEIDA, 2017).

Recovery Rate

It is the percentage, by calculating the permeate production in relation to the input water (feed water).

The membrane scaling (salt precipitation), the osmotic pressure and permeate quality are the most important factors to be analyzed when the recovery rate decreases (MOURA, 2008).

SOFTENER SYSTEMS

According to Richter and Azevedo (2002), total hardness from the water can be removed by two processes: chemical process of lime and soda, and ion exchange. In the first one, lime and sodium carbonate are added to the water to react with the compounds which cause hardness, promoting the precipitation of them.

Ion exchange occurs through a cationic resin, denominated filtering medium. Sodium ions (Na^{2+}) are exchanged for calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions (PERMUTION, 2016).

The use of softening systems as pre-treatment in RO systems is to remove total hardness and metals, such as iron and manganese, which degrade the RO membranes (Kucera, 2015).

RENEWABLE ENERGY

The use of renewable energy is growing around the world. Climate changes induced by the use of fossil fuels, associated to the concern to the sustainable development, have attributed relevance to the renewable sources of energy. An analysis of the technological potential of these sources show that, to answer to the world demand for energy in the 21st century, solar, wind and biomass energy can provide great contributions (FREITAS, 2015).

According to Kucera (2014), the solar energy should be used to develop sustainable systems of water desalination.

The ability of some materials (especially crystals) to generate an electrical current when hit by a beam of light, defines the principle and functioning of a photovoltaic cell. Among the semiconductors, silicon is the most used material due to economic advantage and electricity production (RODRIGUES, 2003). Figure 4 shows

the set of photovoltaic panels installed in *Praia de Leste*, used to provide energy to the desalination pilot plant, in conjunction with the conventional power grid.

Figure 5 - Set of photovoltaic panels.

Source: The author (2019).

WATER QUALITY PARAMETERS

Color

Color is an important measure to identify natural organic compounds, denominated humic substances, which derives from degradation of plants and animals. When these substances are in contact with free chlorine in the disinfection process, results in the formation of trihalomethanes and organ halogens which are harmful for human health (DI BERNARDO, DANTAS and CENTURIONE FILHO, 2002).

According to Di Bernardo et al. (2011), apparent color is influenced by turbidity and is measured without the removal of the suspended particles in the water. The real (or true) color is obtained by centrifugation, in which the process will eliminate the suspended solids, thus enabling the analysis of the solution with the dissolved solids (VON SPERLING, 2005).

Turbidity

Suspended particles and colloidal state, which can present a wide range of sizes, are related to water turbidity. Turbidity can be caused by several materials, such as thin sand particles, silt, clay and other microorganisms (DI BERNARDO, DANTAS and VONTAN, 2011).

The water disinfection process will be more effective if the produced water in the WTP presents less turbidity. Suspended solids can shelter pathogen microorganisms (Richter and Azevedo Netto, 2002).

Electrical Conductivity (EC)

Electrical conductivity depends on the amount of mineral and small quantities of dissolved organic matter in water (VON SPERLING, 2005). Its measurement allows to estimate the amount of total dissolved solids (TDS) present in the water.

When values of TDS are higher, the solubility of the aluminum and iron precipitates are higher, interfering in the coagulation kinetics. In this case, pipes can be affected by the formation and precipitation of calcium carbonate, promoting corrosion processes (Di Bernardo et al., 2002)

Potential of Hydrogen (pH)

It is used to express the condition of acidity, neutrality or alkalinity of the water (VON SPERLING, 2005). It is a fundamental parameter for coagulation, filtration, disinfection and corrosion control.

According to Di Bernardo et al. (2002), waters with low pH value tend to be corrosive and aggressive to certain metals and concrete structures, while waters with elevated values for pH tend to form incrustations.

Total dissolved solids (TDS)

TDS contain inorganic salts such as calcium, magnesium, potassium, sodium, bicarbonates, chlorides and sulphates, and small quantities of organic material. They are determined as filtrable solids and their presence in high concentration is considered harmful for the water quality (ORAM, 2012).

Total Hardness

Von Sperling (2005) defines total hardness as the concentration of multi-metal cations in a solution, especially calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions. In high concentrations, it can cause the reduction of foam and incrustation in hot water pipelines. A special attention should be given to boiler pipes when the water must be free of hardness to avoid accident risks.

Chloride

The presence of chloride in water indicates some form of pollution. High chloride concentrations interfere in the coagulation process and gives salty flavor to the water. High chloride concentrations can be harmful for people with heart or kidney diseases (Di Bernardo, 2002).

CHAPTER 1

WATER QUALITY FROM A BRACKISH WATER DESALINATION PILOT PLANT USING SOLAR ENERGY

ABSTRACT

This paper presents the efficiency of a brackish water desalination pilot system installed in the coast of Parana State, Brazil. The brackish water was prepared from the mixture of seawater with fresh water from the *Pombas* river. Two experiments with 10 operations each were done, using brackish water with different Total Dissolved Solids (TDS) concentrations, 3,500 ± 100 mg/L (Experiment 1) and 7,000 ± 100 mg/L (Experiment 2). The pretreatment system was composed by coagulation, ultrafiltration (UF) and, softening, followed by reverse osmosis (RO) membrane filtration. The desalination pilot system was operated for 3 hours per day and, samples were collected in seven collection points, to be analyzed in laboratory. Evaluation of water quality consisted on the monitoring of TDS, electrical conductivity (EC), pH, temperature, apparent color, turbidity, total hardness, calcium, alkalinity, sulphate, chloride, E. Coli and total coliforms. The operating conditions of the RO system were controlled and verified in terms of recovery rate, filtration rate, osmotic pressure and energy consumption. UF pretreatment system presented total removal of apparent color and, average removal of turbidity superior than 95%. The softeners removed 52.64% (Experiment 1) and 73.36% (Experiment 2) of total hardness. RO system presented more than 99% of TDS removal. The solar system provided 42.18% of energy for the desalination pilot system during the Experiment 1 and 26.85% during the Experiment 2.

Keywords: Brackish water. Desalination. Ultrafiltration. Softening. Reverse osmosis. Water quality. Solar energy.

1.1 INTRODUCTION

Water scarcity has been a problem in many regions of the world, especially due to factors such as climate changes and population growth. According to the United Nations (UN, 2016), the world population will be greater than nine billion inhabitants by the end of the 21st century. Food production, industries and the economy are severely affected with the lack of water.

More than a billion people do not have access to quality water for consumption, most of them are concentrated in Asia and Africa (Chen et al., 2015). Furthermore, special attention should be given to the Sub-Saharan Africa, in which every inhabitant manages to survive with less than 20 liter of water per day (WHO, 2015).

In Brazil, the northeastern region presents the greatest water shortages when compared to other regions of the country. The underground water reserves in this region has high ionic concentrations, with high salinity and alkalinity (Dias et al., 2004).

The intrusion of sea water in the freshwater has been a problem in the coastal cities of Brazil, mainly due to the tide variations and drought periods. The water becomes brackish and inappropriate to be treated in conventional water treatment systems which are generally used to treat fresh water. The water desalination systems are more indicated for such cases.

Although the use of RO in water desalination treatment is considered very expensive and consumes a lot of energy, RO technology offers the advantage of smaller infrastructure and the total treated water cost is becoming competitive with traditional thermal processes (KUCERA, 2014). In order to protect the RO membranes and to improve the treatment, pretreatment is recommended, such as coagulation and use of microfiltration, ultrafiltration (UF) or nanofiltration membranes.

Renewable energies to drive desalination systems using RO has been a viable alternative. The production capacity and energy consumption are important factors to be addressed in the project. The photovoltaic power generation provides a significant environmental footprint when compared to other sources of power, offering optimal performance regarding to the electricity generation (ELTAWIL et al., 2008).

The main objective of this work was to evaluate the efficiency of a brackish water desalination pilot plant with ultrafiltration and RO, for two concentrations of total

dissolved solids (TDS) in the feed water, experiments 1 and 2, with use of solar energy.

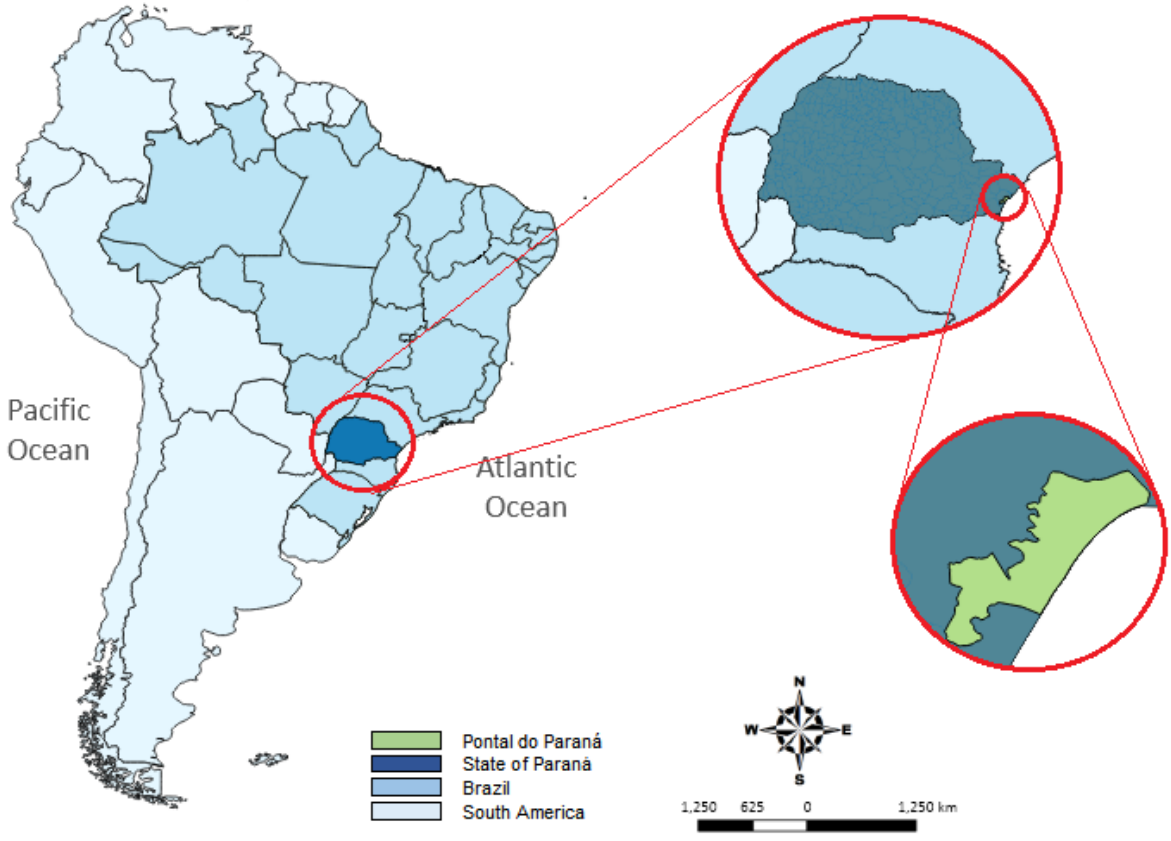
1.2 MATERIAL AND METHODS

1.2.1 Location and description of the brackish water desalination pilot plant

The desalination pilot plant was installed close to the Sanepar's Water Treatment Plant (WTP), located in the city of *Pontal do Paraná*, Brazil (Figure 1.1).

According to Koppen, *Pontal do Paraná* has a subtropical climate with the lowest average monthly temperature ranging 18ºC (mesothermic) and the highest average monthly temperature around 22ºC, with hot summers and rainfall tendency concentrated in the months of December to March (IAPAR, 2018).

Figure 1.1 - Location map of Pontal do Paraná.



Source :The author (2019).

Considering the data from the Institute of Geography and Statistics (IBGE, 2015), *Pontal do Paraná* has 199.85 km² of land and about 20,920 inhabitants. According to the Council of the *Litoral* (COLIT, 2004), there is also a great variation

between residents and tourists, which causes an impact on the quality of sanitation services.

The water supply of *Praia de Leste* comes from *Pombas* river, located in the Watershed of *Guaraguaçu* river. The water from Pombas river has high fulvic and humic acid concentration, originated from the decomposition of organic matter, which gives color to the water. The pumping system to bring the water from the river to the WTP is by piping with extension of 10 km. (GERVASONI, et al. 2016).

1.2.2 Brackish water

The brackish water was prepared from the mixture of fresh water from the *Pombas* river and seawater. Three 10 m³ tanks were used to storage water: two for seawater which was pumped and transported by truck and one for the fresh water which was pumped directly from the piping that arrived in the WTP and, in which the brackish water was prepared with TDS of 3,500 ± 100 mg/L (experiment 1) and 7,000 ± 100 mg/L (experiment 2). A recirculation pump was used during the experiments in order to homogenize the water. The experiment 1 and experiment 2 were done in 20 operation for a time of the 3 hours each.

The variation of the brackish water characteristics in the pilot desalinization system is presented in Table 1.1.

Table 1.1 - Brackish water quality.

Parameters	Mean ± SD	
	Experiment 1	Experiment 2
TDS (mg/L)	3,541.03 ± 23.01	7,028.97 ± 30.36
EC (µS/cm)	4,583.57 ± 41.05	8,558.73 ± 33.66
Turbidity (NTU)	5.54 ± 0.48	5.20 ± 0.62
Color (Pt-Co)	44.27 ± 3.84	34.97 ± 2.40
Alkalinity (mg/L)	15.99 ± 2.01	24.62 ± 1.52
Total Hardness (mg/L)	1,276.58 ± 51.49	3,356.01 ± 190.03
Calcium (mg/L)	241.52 ± 15.63	767.85 ± 24.17
Sulphate (mg/L)	266.62 ± 33.96	495.14 ± 15.76
Chloride (mg/L)	1,307.93 ± 26.54	3,381.89 ± 70.77
pH	6.88 ± 0.09	7.21 ± 0.04
Temperature (ºC)	20.35 ± 2.41	20.27 ± 1.16

Source: The author (2019).
Notes: TDS = total dissolved solids; EC = electrical conductivity.

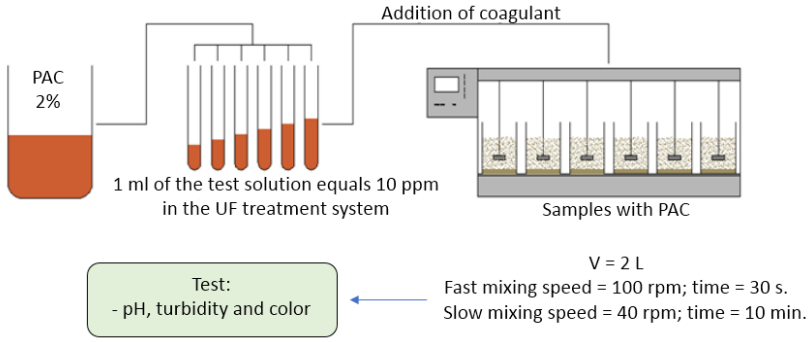
1.2.3 Water treatment steps

1.2.3.1 Coagulation and flocculation

The process of coagulation/flocculation removes the material in suspension and colloidal of the water. Coagulant is added to the water to reduce the forces that tend to keep the suspended particles separated, promoting the agglomeration of these particles through fluid transport (CARDOSO, 2015).

Polyaluminum chloride was the coagulant used to promote the coagulation. The dose of coagulant was determined in tests conducted in Jar test equipment, as shown in Figure 1.2. They were done before the first and fifth day of work of each experiment.

Figure 1.2 - Sequence of Jar test laboratory experiment.



Source :The author (2019).

Brackish water was analyzed in terms of pH, color and turbidity. Two liters of water were added in each of the six jars available.

PAC was added to the jars and after 30 seconds of coagulation and 10 minutes of flocculation, water samples were collected from the jars and analyzed. Results obtained in similar studies by Bovaroti (2018) and Almeida (2017), an average of 14.70 mg/L and 26.50 mg/L of PAC.

1.2.3.2 Ultrafiltration (UF)

After coagulation, the water was pumped to a disk filter in order to retain particles with diameter larger than 300 μm. The water was pre-filtered in a vertical flow hydrophilic membrane of UF, with the following characteristics: Model X-Flow Aquaflex 55 made by Pentair, composed of polyvinylperrolidone and polyethersulfone, pores of 20 nm, asymmetrical and microporous structure, filtration area of 55 m^2 and maximum flowrate of 2.40 m^3/s.

The UF permeate was stored in a stainless-steel tank of 1.5 m^3.

The UF membrane required a hydraulic backwashing manual each 30 minutes of operation (equals to 1 cycle). The backwashing was done by closing and opening of valves using the UF permeate, with a hydraulic pump. Backwash water was discarted in the sludge tank of the WTP.

After 100 cycles of operation (= 50 hours) was required the chemical cleaning, of the membrane with sodium hydroxide 10% and after 200 operation cycles, with hydrochloric acid 10%.

The UF system was controlled and monitored by an electronic panel.

1.2.3.3 Water softening system

The UF permeate was pressurized by a centrifugal pump. The pretreated water passed through a disk filter to remove particles larger than 130 µm. The water softening system was composed of two softeners with ion exchange resin, one of them was always in standby. In the ion exchange process, sodium ions (Na^{2+}) are exchanged for undesirable calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions (PERMUTION, 2016).

The ion exchange resin was regenerated at the end of each system operation day. The regeneration was done in three steps: the softener was backswashed with the UF permeate. After, the resin was regenerated with the sodium chloride solution and the last backwash was done with UF permeate in order to remove the excess of salt.

1.2.3.4 Reverse osmosis (RO)

After the water softening, a dosing pump add of 2 mL/min of sodium metabisulphite with concentration of 10%, in order to preserve the physical integrity of the membranes.

The sodium metabisulphite was mixed in the water through a static mixer and before entering in the membranes, the water passed through a cartridge filter to retain particles larger than 5 µm.

The water was pumped to the five RO membranes of horizontal flow, model Vontron-LP21-4040, composed of spiral shaped polyamide, effective pores of 1 nm

and total filtration area of 42 m². Finally, the RO permeate passed through an ultraviolet disinfection system with wavelength of 185-254 nm.

RO permeate was stored in a 5 m³ tank. Brine generated in the OR was stored in another 5 m³ tank and was treated in wetland systems (ZAIKA, 2018).

The combined softening and reverse osmosis systems were monitored in a control panel, with components for protection and CLP. Data of osmotic pressure, flow rate, conductivity, transmittance and UV dose were verified and controlled for in the touch screen IHM and stored in a data logger.

1.2.4 Production and consumption of energy

The desalination pilot system was connected to a photovoltaic generation system with 8 solar panels model HR 250 P with 2,000 Wp power capacity.

Photovoltaic solar panels generated electricity in direct current (DC) by means of the photoelectric effect. They were connected to an on-grid inverter, which synchronized between the panels and the electrical grid, converting DC to AC and injecting to the grid.

The SF 1600 TL inverter, with an AC output voltage of 220 V, recorded data of energy while sending power to the grid.

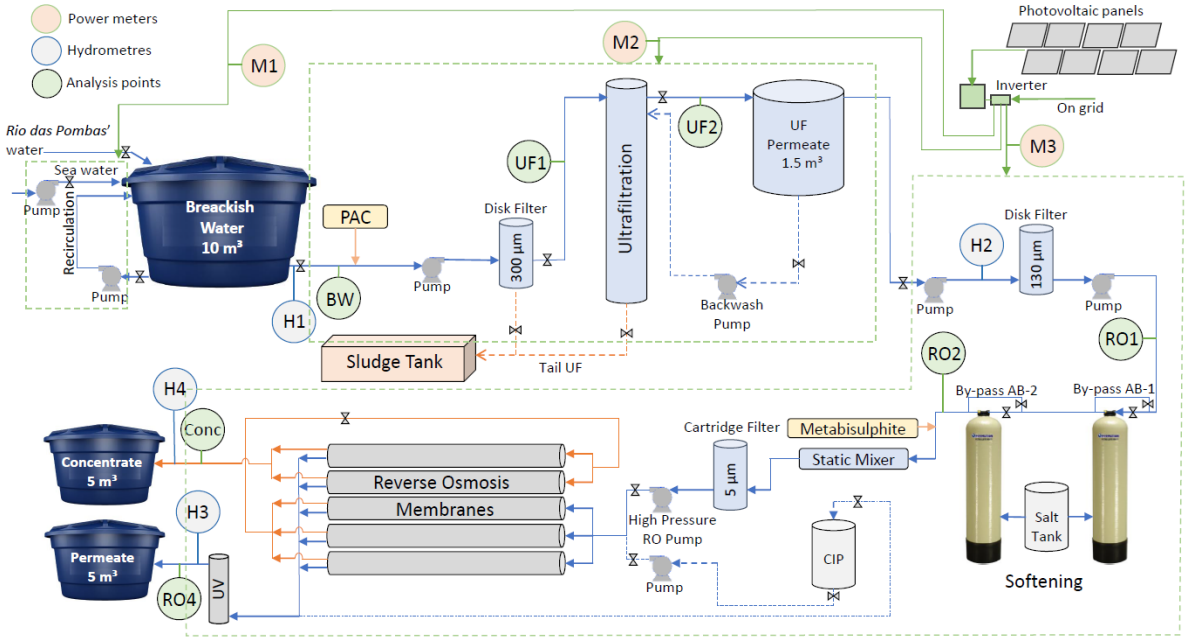
Three energy meters Kron® were installed to measure the energy consumption of pumps used to transfer sea water to the mixing tank of brackish water, to maintain, the UF system and the softening and RO system.

1.2.5 Operational conditions and water quality monitoring

Seven water sample collection points, indicated in Figure 1.3 as BW, UF1, UF2, RO1, RO2, RO4 and CONC, were monitored during the experiments. Hydrometers, represented by H in Figure 1.3 were used to mensure the water volumes of each system, aiming to compare with the flowrates registered in the control panel.

Turbidity, apparent color, temperature, electrical conductivity, TDS, pH and bacteriological tests were monitored on site. Water samples were collected and stored for analysis of alkalinity, total hardness, calcium, sulphite and chloride, which were done at State University of Ponta Grossa (UEPG) laboratories, following the methods recommended by APHA (2012).

Figure 1.3 - Schematic drawing of the desalination pilot plant.



Source :The author (2019).

1.2.6 Statistical analysis

Three water samples were collected in each operationt: the first one after 45 minutes of system operation, the second one after 1 hour and 45 minutes and the last one after 2 hours and 45 minutes from the beginning of the system operation. For both experiments, total of 20 operation days and 360 water samples were collected and analyzed.

In order to evaluate the data empirical distribution and the removal efficiency of the system, Origin software was use to provide boxplot graphics, composed mainly of the first and third quarters, means and medians. The rods indicate the upper and lower boundaries.

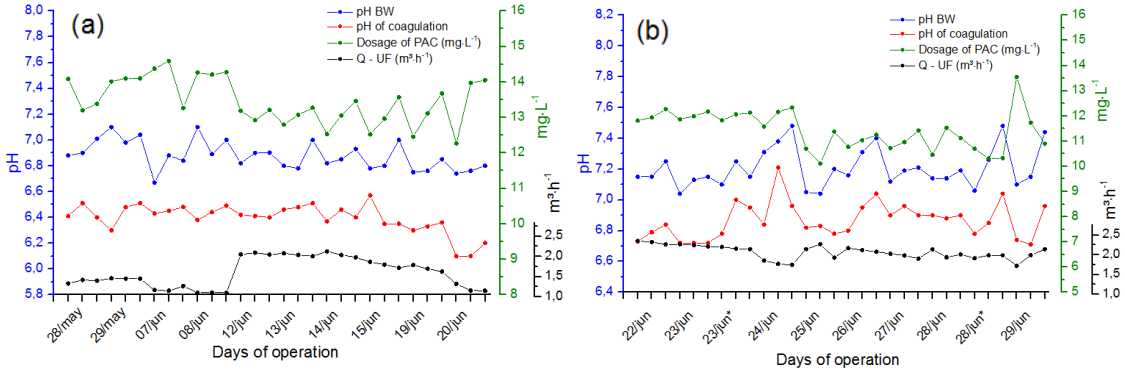
Results regarding to the daily means of each water sample collection point were analyzed according to the 5% significance level, by employing the software R. When performing the t tests, the requirements for normality were observed. When data distribution was normal, Shapiro-Wilk tests were used. When data do not answer to the requirements for normality, Wilcoxon test was used.

1.3 RESULTS AND DISCUSSION

1.3.1 pH and coagulant dosage

Figure 1.4 shows the results obtained from each hour of operation system. The pH decreased after the addition of the coagulant (PAC). The dosage controlled manually through dosing pumps, was in accordance with the flowrate of the UF system.

Figure 1.4 - Coagulation effect: Experiment 1 (a); Coagulation effect: Experiment 2 (b).



Source: The author (2019).

The criteria for the coagulant dosage was based on the turbidity, pH and color analyses of each jar after coagulation, flocculation and sedimentation.

Figure 1.4 (a) shows the results of experiment 1 (TDS = 3,500 ± 100 mg/L). The average dosage of coagulant was 14 mg/L for the first five days and of 13 mg/L for the last five days. The turbidity of the brackish water varied from 4.78 to 6.47 NTU, with average of 5.54, and after PAC addition, from 7.76 to 11.70 NTU with average of 9.30 NTU. pH varied from 6.80 to 7.10, with average of 6.88. Coagulation pH varied from 6.17 to 6.80, with average of 6.48.

For the experiment 2, as showed in Figure 1.4 (b), TDS = 7,000 ± 100 mg/L, the average of coagulant dosage was mean 12 mg/L in the first five days of operation and 11 mg/L in the five final days. Turbidity of brackish water varied from 4.68 to 6.23 NTU, with average of 5.20 NTU and, after coagulant addition varied from 7.58 to 12.00 NTU, with average of 9.47 NTU. Coagulation pH varied from 7.04 to 7.48, with average of 7.21 in the brackish water and 6.71 to 7.21, with average of 6.87, after coagulation.

In similar experiments, Sun et al. (2015) obtained a variation from 3 to 6 mg/L of coagulant dosage to promote the flocculation, with turbidity varying from 1.6 to 3.0

NTU, lower values than those presented in Figure 1.4. This justified the higher coagulant dosage used for the experiments 1 and 2. The higher turbidity, the higher coagulant dosage.

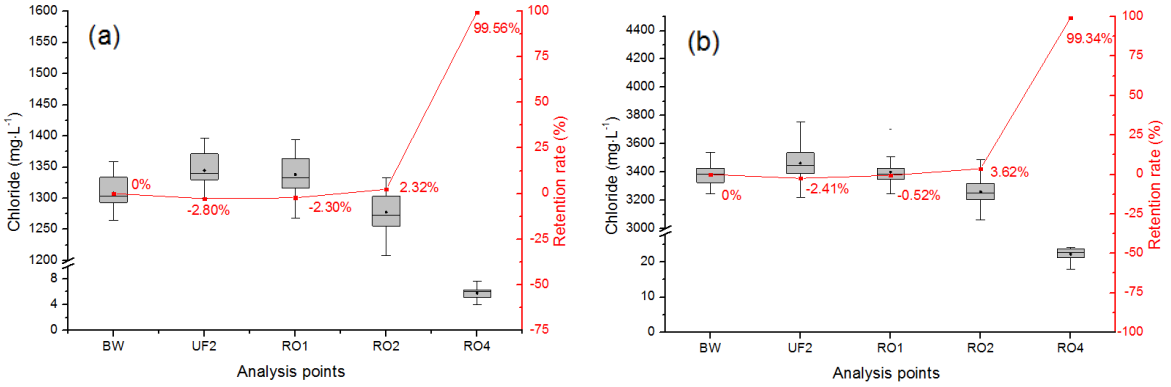
Bovaroti (2018) worked with 13.00 to 18.20 mg/L of PAC dosage in brackish water with 1,500 ± 100 mg/L of TDS. The turbidity varied from 2.13 to 7.98 NTU and, after coagulation, from 3.73 to 10.90 NTU.

1.3.2 Chemical characteristics of the water

1.3.2.1 Choride

Figure 1.5 shows the empirical distribution analyses related to experiments 1 and 2. Table 1.2 presents the statistical analysis for mean comparison among the collection points.

Figure 1.5 - Empirical distribution of chloride (Experiment 1) and accumulated removal (a); Empirical distribution of chloride (Experiment 2) and accumulated removal (b).



Source: The author (2019).
Notes: BW = brackish water; UF2 = UF permeate; RO1 = before the softener; RO2 = after the softener; OR4 = RO permeate.

In Figure 1.5 is observed an increase of 2.80% of chloride in the UF permeate, provided by the coagulant (PAC). Between the points UF2-RO1 there was no removal chloride. There was significant removal (4.62%) between RO1-RO2, after the softener. The greatest removal occurred in the RO permeate, 97.24% of chlorides were removed. The overall removal efficiency of the desalination pilot system, considering all steps of treatment, resulted in 99.56%.

Similar situation can be observed in Figure 1.5 (b), experiment 2. There was significant increase in chlorides (2.41%) after the coagulant addition. The daily means did not differ statistically between UF2-RO1. In RO1-RO2 the chloride

removal by the softeners was of 4.12%. The greatest removal occurred in the RO membranes, (95.72%). The overall efficiency of the system was 99.34%.

Table 1.2 - Mean and statistical analysis (STUDENT pt or WILCOXON pw) of chloride in the different water sample collection points.

Analysis points	Experiment 1			Experiment 2		
	t / w	Mean (mg/L)		*t / w*	Mean (mg/L)	
BW - UF2	pt < 0.05	1,307.93	1,344.60	pt < 0.05	3,381.89	3,463.56
UF2 - RO1	pw ≥ 0.05	1,344.60	1,338.01	pt ≥ 0.05	3,463.56	3,399.52
RO1 - RO2	pt < 0.05	1,338.01	1,277.65	pt < 0.05	3,399.52	3,259.31
RO2 - RO4	pt < 0.05	1,277.65	5.77	pt < 0.05	3,259.31	22.20

Source: The author (2019).
Note: Differences of mean, with *p-value* greater or equal to the level of significance of 5%, do not differ statistically from each other.

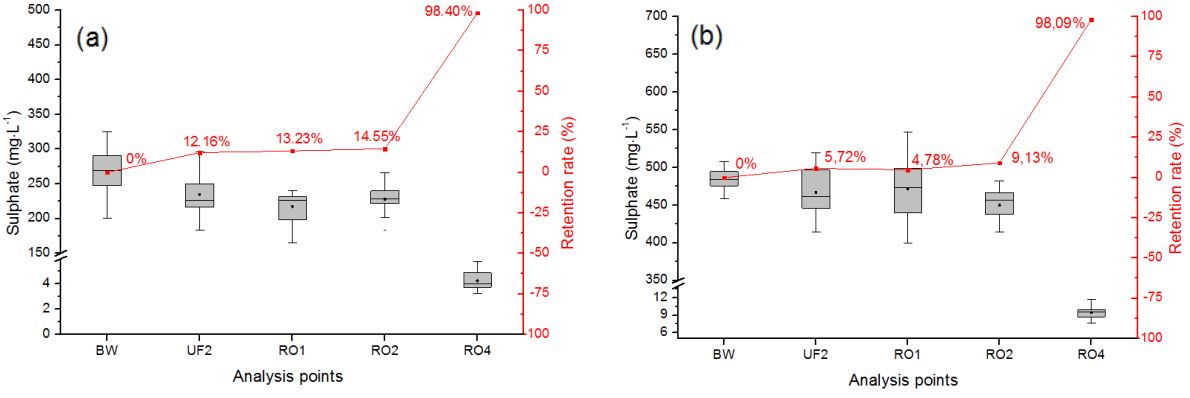
Bovaroti (2018) obtained overall removal efficiency of 97.40%, with 645 mg/L of chloride concentration in the brackish water and TDS of 1,500 ± 100 mg/L. Almeida (2017) obtained average removal efficiency of 99.05%, with chloride concentration of 523.05 mg/L, and TDS = 1,500 ± 100 mg/L in the brackish water.

1.3.2.2 Sulphate

Figure 1.6 presents results of sulphate in each step of the treatment process. A similar behavior can be noted in the removal curves for both experiments. The statistic results regarding to the sulphate concentration are showed in table 1.3.

Figure 1.6 (a) shows significant removal (12.16%) of sulphate in the UF permeate. Between the points UF2-RO1 there was no significant variation. In RO1-RO2 the removal was not significant. Most of the removal occurred in the RO membranes (83.85%). The overall removal efficiency in the system was 98.40%.

Figure 1.6 - Empirical distribution of sulphate (experiment 1) and accumulated removal (a); Empirical distribution of sulphate (experiment 2) and accumulated removal (b).



Source: The author (2019).
Notes: BW = brackish water; UF2 = UF permeate; RO1 = before the softeners; RO2 = after the softeners; RO4 = RO permeate.

Figure 1.6 (b) demonstrates removal of 2.41% in the UF permeate. The daily means variation was not statistically significant between the points UF2-RO1. The sulphate removal after softening was 4.35%.

Most of the sulphate removal (88.95%) occurred after the OR membranes. The overall system efficiency was 98.09%.

Table 1.3 - Mean and statistical analysis (STUDENT pt or WILCOXON pw) of sulphate in the different water sample collection points.

Analysis points	Experiment 1			Experiment 2		
	t / w	Mean (mg/L)		*t / w*	Mean (mg/L)	
BW - UF2	pt < 0.05	266.62	234.51	pt < 0.05	495.14	466.83
UF2 - RO1	pt ≥ 0.05	234.51	231.35	pt ≥ 0.05	466.83	471.47
RO1 - RO2	pt ≥ 0.05	231.35	227.82	pt < 0.05	471.47	449.91
RO2 - RO4	pt < 0.05	227.82	4.26	pt < 0.05	449.91	9.46

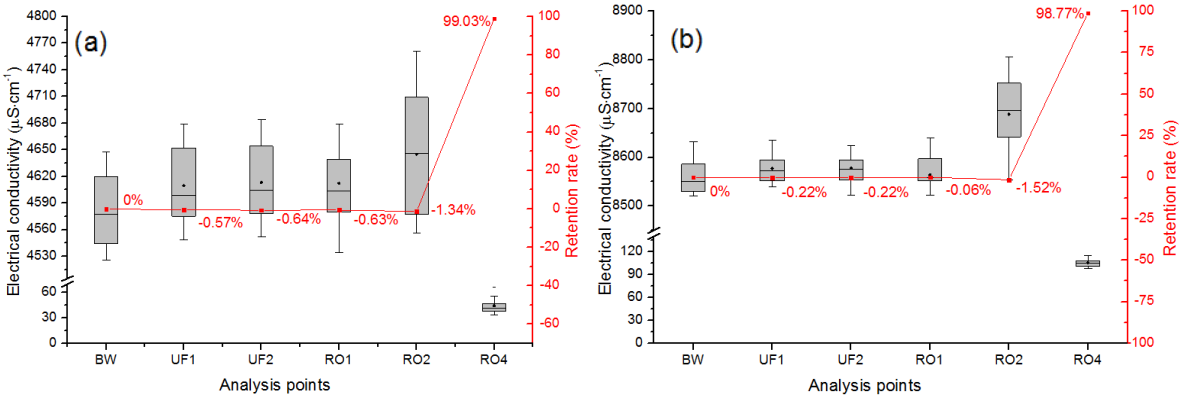
Source: The author (2019).
Note: Differences of mean, with *p-value* greater or equal to the level of significance of 5%, do not differ statistically from each other.

Bovaroti (2018) obtained efficiency removal of 100% with 127.8 mg/L of sulphate concentration in the brackish water. Almeida (2017) got the overall efficiency removal of 99.10%, with mean sulphate concentration of 115.38 mg/L in the brackish water.

1.3.2.3 Electrical conductivity (EC)

Figure 1.7 presents the EC values for each step of treatment process. Table 1.4 demonstrates the statistical results obtained for this parameter.

Figure 1.7 - Empirical distribution of EC (experiment 1) and accumulated removal (a); Empirical distribution of EC (experiment 2) and accumulated removal (b).



Source: The author (2019).
Notes: BW = brackish water; UF2 = UF permeate; RO1 = before the softeners; RO2 = after the softeners; RO4 = RO permeate.

There was positive variation of the daily mean in the order of 0.57% in UF1, although not significant, see Figure 1.7 (a).

Table 1.4 - Mean and statistical analysis (STUDENT ρt or WILCOXON ρw) of EC in the different water sample collection points.

Analysis points	Experiment 1			Experiment 2		
	t / w	Mean (µS/cm)		*t / w*	Mean (µS/cm)	
BW - UF1	ρt ≥ 0.05	4,583.57	4,609.67	ρt ≥ 0.05	8,558.73	8,577.17
UF1 - UF2	ρt ≥ 0.05	4,609.67	4,613.10	ρt ≥ 0.05	8,577.17	8,577.70
UF2 - RO1	ρw ≥ 0.05	4,613.10	4,612.23	ρt ≥ 0.05	8,577.70	8,564.23
RO1 - RO2	ρt < 0.05	4,612.23	4,644.97	ρt < 0.05	8,564.23	8,688.67
RO2 - RO4	ρt < 0.05	4,644.97	44.46	ρt < 0.05	8,688.67	105.22

Source: The author (2019).
Note: Differences of mean, with *ρ-value* greater or equal to the level of significance of 5%, do not differ statistically from each other.

There was no significant variation between UF1-UF2 and UF2-RO1. There was an increase of 0.71% of EC in RO1-RO2, after the softeners, possibly caused by the operational conditions of the softeners.

EC increased 1.34% after the softening, compared to the conductivity at the beginning of operation system. RO membranes presented removal efficiency of 99.03%.

The behavior of the EC removal process was similar for the experiment 1, as shown in Figure 1.7 (b). There was no significant variation of the daily means between BW-UF1, UF1-UF2 and UF2-RO1. The softener performance was evidenced through the increase of EC after the ion exchange resin regeneration. There was increase of 1.45% increase. Overall removal efficiency of 98.77% was obtained in the RO membranes.

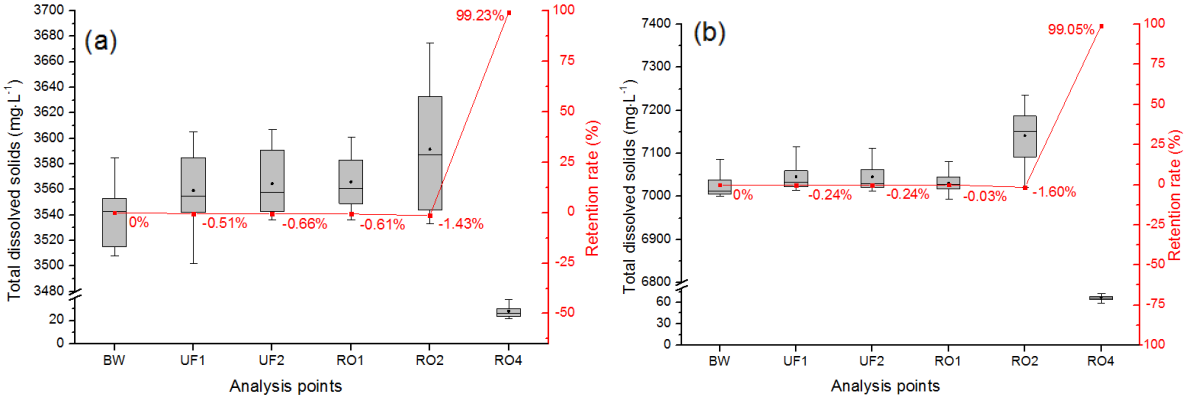
Shen et. al (2016) operated a RO desalination system using brackish water from a well with EC of 4,000 µS/cm. The removal efficiency was 98%.

1.3.2.4 TDS

Figure 1.8 (a) shows significant increase of the TDS (0.51%) in UF1. This increase is due to the addition of PAC, used to promote the coagulation. There was no significant daily mean variation between UF1-UF2 and UF2-RO1.

There was significant increase in TDS (0.81%) after the softening system. The overall efficiency was 99.23%, mainly in the RO system.

Figure 1.8 - Empirical distribution of TDS (experiment 1) and accumulated removal (a); Empirical distribution of TDS (experiment 2) and accumulated removal (b).



Source: The author (2019).
Notes: BW = brackish water; UF2 = UF permeate; RO1 = before the softeners; RO2 = after the softeners; RO4 = RO permeate.

Figure 1.8 (b) shows increase of 0.24% of TDS in UF1 (Experiment 2), mainly caused by the addition of PAC. However, this variation was not significant compared to the average values of the brackish water. There was no significant variation in UF1-UF2 and UF2-RO1. The TDS removal by the RO membranes was 99.05%.

Table 1.5 - Mean and statistical analysis (STUDENT ρt or WILCOXON ρw) of TDS in the different water sample collection points.

Analysis points	Experiment 1			Experiment 2		
	t / w	Mean (mg/L)		*t / w*	Mean (mg/L)	
BW - UF1	ρt < 0.05	3,541.03	3,559.13	ρt ≥ 0.05	7,028.97	7,046.17
UF1 - UF2	ρt ≥ 0.05	3,559.13	3,564.53	ρt ≥ 0.05	7,046.17	7,045.77
UF2 - RO1	ρt ≥ 0.05	3,564.53	3,562.70	ρt ≥ 0.05	7,045.77	7,031.33
RO1 - RO2	ρt < 0.05	3,562.70	3,591.53	ρt < 0.05	7,031.33	7,141.57
RO2 - RO4	ρt < 0.05	3,591.53	27.12	ρt < 0.05	7,141.57	66.89

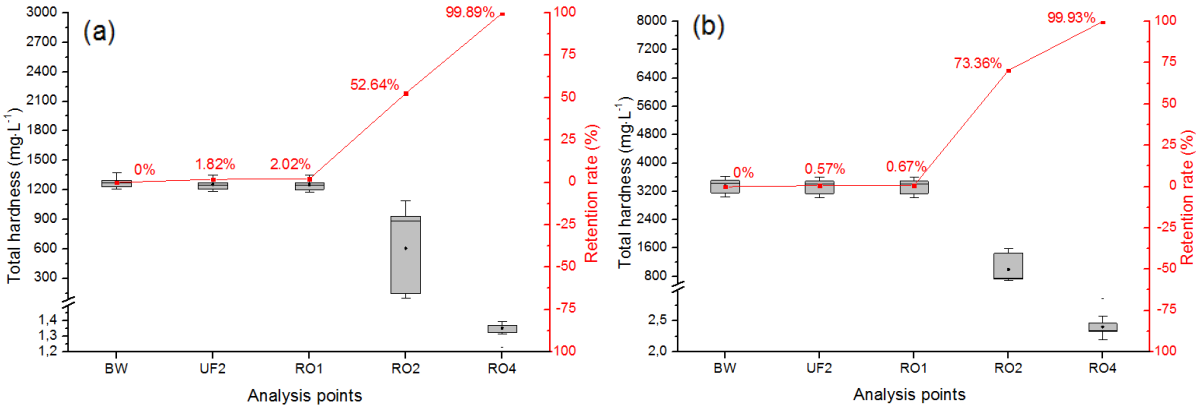
Source: The author (2019).
Note: Differences of mean, with *ρ-value* greater or equal to the level of significance of 5%, do not differ statistically from each other.

Elassad et al. (2015) operated a RO system to treat brackish water from a well with 2,100 mg/L of TDS, with RO permeate production production of 1 m³, and obtained removal results superior to 99%. Almeida (2017) and Bovaroti (2018), worked in the same desalination pilot plant in Praia de Leste, with 1,500 ± 100 mg/L of TDS in the brackish water and obtained TDS removal efficiency of 99%.

1.3.2.5 Total hardness

Figure 1.9 shows empirical data related to the total hardness for each step of the treatment. Table 1.6 demonstrates the statistical results for this parameter.

Figure 1.9 - Empirical distribution of total hardness (experiment 1) and accumulated removal (a); Empirical distribution of total hardness (experiment 2) and accumulated removal (b).



Source: The author (2019).
Notes: BW = brackish water; UF2 = UF permeate; RO1 = before the softeners; RO2 = after the softeners; RO4 = RO permeate.

For both experiments, the average results between BW-UF2 and UF2-RO1 were not statistically different. The softener presented total hardness removal of 50.62% at the first experiment (see Figure 1.9 a), and 72.33% total hardness removal on the second experiment (see Figure 1.9 b). According to the technical manual, the total hardness removal by ion exchange was under dimensioned for concentrations used (PERMUTION, 2016).

Table 1.6 - Mean and statistical analysis (STUDENT ρt or WILCOXON ρw) of total hardness in the different water sample collection points.

Analysis points	Experiment 1			Experiment 2		
	t / w	Mean (mg/L)		*t / w*	Mean (mg/L)	
BW - UF2	ρt ≥ 0.05	1,276.58	1,253.34	ρt ≥ 0.05	3,356.01	3,336.76
UF2 - RO1	ρw ≥ 0.05	1,253.34	1,250.77	ρw ≥ 0.05	3,336.76	3,333.49
RO1 - RO2	ρt < 0.05	1,250.77	604.55	ρt < 0.05	3,333.49	994.71
RO2 - RO4	ρt < 0.05	604.55	1.35	ρt < 0.05	994.71	2.40

Source: The author (2019).
Note: Differences of mean, with *ρ-value* greater or equal to the level of significance of 5%, do not differ statistically from each other.

RO system efficiency to remove total hardness was 47.25% for experiment 1, with the global efficiency was 99.89%, and 26.57% for experiment 2 and 99.93% of global removal efficiency of total hardness.

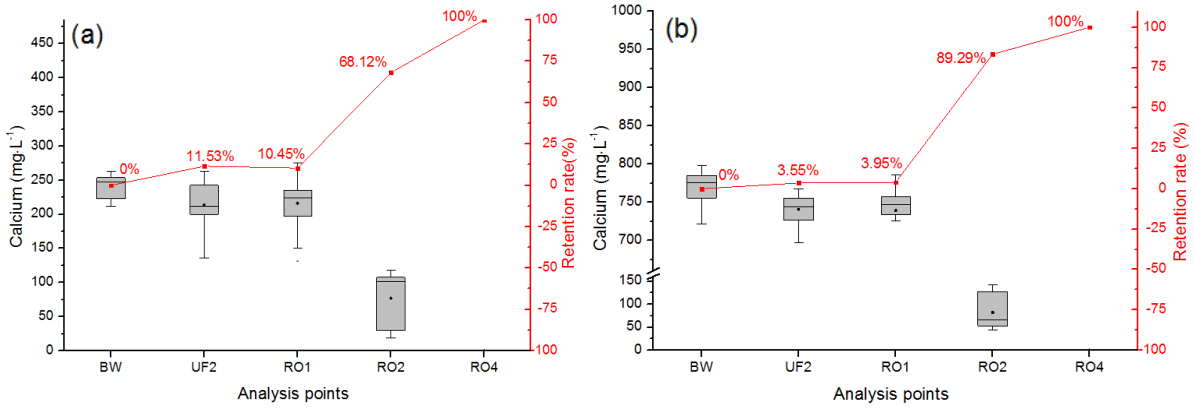
Sarah (2013) evaluated the removal of total hardness in underground brackish water with 300 – 1,000 mg/L using ion exchange, obtaining 97% of removal efficiency.

1.3.2.6 Calcium

Figure 1.10 presents the calcium values for each step of the treatment, and Table 1.7 shows the statistic results for calcium concentration.

Figure 1.10 (a) shows 11.53% of calcium removal present in the experiment 1. There was no significant variation in UF-RO1. The softener system removed 57.67% of calcium and the RO system removed 31.88%. The overall removal efficiency was 100%.

Figure 1.10 - Empirical distribution of calcium (experiment 1) and accumulated removal (a); Empirical distribution of calcium (experiment 2) and accumulated removal (b).



Source: The author (2019).
Notes: BW = brackish water; UF2 = UF permeate; RO1 = before the softeners; RO2 = after the softeners; RO4 = RO permeate.

UF system presented calcium removal rate of 3.55% in the experiment 2, Figure 1.10 (b). The softener system removed 85.34% and the RO system removed 10.71%, with overall removal efficiency of 100%.

Table 1.7 - Mean and statistical analysis (STUDENT ρt or WILCOXON ρw) of calcium in the different water sample collection points.

Analysis points	Experiment 1			Experiment 2		
	t / w	Mean (mg/L)		*t / w*	Mean (mg/L)	
BW - UF2	ρt < 0.05	241.52	213.68	ρt < 0.05	767.85	740.58
UF2 - RO1	ρw ≥ 0.05	213.68	216.29	ρt ≥ 0.05	740.58	737.55
RO1 - RO2	ρt < 0.05	216.29	76.99	ρt < 0.05	737.55	82.27
RO2 - RO4	ρt < 0.05	76.99	0.00	ρt < 0.05	82.27	0.00

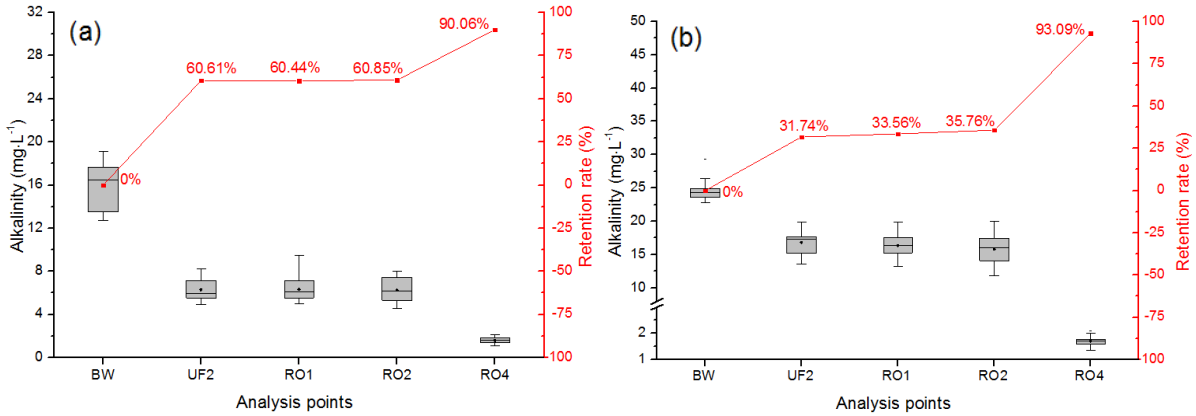
Source: The author (2019).
Note: Differences of mean, with *ρ-value* greater or equal to the level of significance of 5%, do not differ statistically from each other.

Khaled et al. (2013) analyzed calcium removal with initial concentration of 365 mg/L in the brackish water using a RO system. Although they did not use pretreatment, the system presented total calcium removal efficiency of 93.15%.

1.3.2.7 Alkalinity

Figure 1.11 shows the empirical data, and Table 1.8 presents the statistical results for alkalinity.

Figure 1.11 - Empirical distribution of alkalinity (experiment 1) and accumulated removal (a); Empirical distribution of alkalinity (experiment 2) and accumulated removal (b).



Source: The author (2019).
Notes: BW = brackish water; UF2 = UF permeate; RO1 = before the softeners; RO2 = after the softeners; RO4 = RO permeate.

There was a higher removal efficiency in the experiment 2 (93.09%) comparing to the experiment 1 (90.06%). A greater initial removal efficiency (UF permeate) can be observed in the experiment 1 (60.61%) comparing to the experiment 2 (31.74%). According to Figure 1.11 (a), UF pre-treatment presented twice the removal efficiency compared to the experiment 2. The pretreatment was fundamental in the removal of alkalinity, mainly in the experiment 1. Therefore, the RO system was essential to remove alkalinity in the experiment 2.

Table 1.8 - Mean and statistical analysis (STUDENT pt or WILCOXON pw) of alkalinity in the different water sample collection points.

Analysis points	Experiment 1			Experiment 2		
	t / w	Mean (mg/L)		*t / w*	Mean (mg/L)	
BW - UF2	pt < 0.05	15.99	6.30	pt < 0.05	24.62	16.81
UF2 - RO1	pt ≥ 0.05	6.30	6.33	pt ≥ 0.05	16.81	16.36
RO1 - RO2	pt ≥ 0.05	6.33	6.26	pt ≥ 0.05	16.36	15.82
RO2 - RO4	pt < 0.05	6.26	1.59	pt < 0.05	15.82	1.70

Source: The author (2019).
Note: Differences of mean, with *p-value* greater or equal to the level of significance of 5%, do not differ statistically from each other.

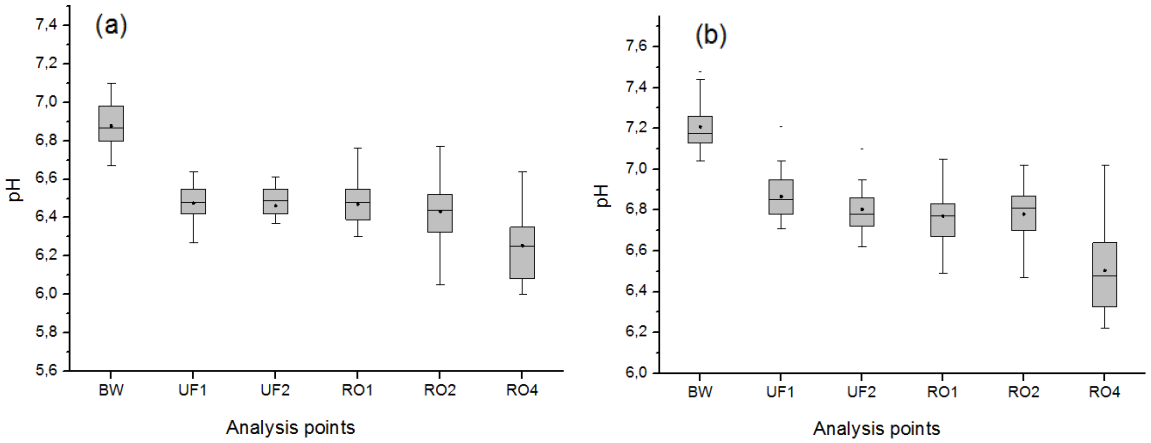
Almeida (2017) and Bovaroti (2018) treated brackish water with average alkalinity of 13.28 mg/L and 11.5 mg/L respectively, in the same pilot plant. Alkalinity

removal efficiency in all steps of the treatment was 88.8% (Almeida, 2017) and 90.6% (Bovaroti, 2018).

1.3.2.8 pH

Figures 1.12 (a) and (b) shows the variation of pH in UF1 (after coagulant addition). The decrease was expected due to the acidity of PAC solution.

Figure 1.12 - Empirical distribution of pH: experiment 1(a); Empirical distribution of pH: experiment 2(b).



Source: The author (2019).
Notes: BW = brackish water; UF2 = UF permeate; RO1 = before the softeners; RO2 = after the softeners; RO4 = RO permeate.

There was no significant variation of the average results in UF1-UF2, UF2-RO1 e RO1-RO2 for both experiments as shown in Table 1.9.

The average pH values for the RO permeate presented significant reduction compared to the results from the previous water sample points (BW-RO4). This is due to the decrease of TDS concentration.

Table 1.9 - Mean and statistical analysis (STUDENT ρt or WILCOXON ρw) of pH in the different water sample collection points.

Analysis points	Experiment 1			Experiment 2		
	t / w	Mean (mg/L)		*t / w*	Mean (mg/L)	
BW - UF1	ρt < 0.05	6.88	6.48	ρt < 0.05	7.21	6.87
UF1 - UF2	ρt < 0.05	6.48	6.46	ρt < 0.05	6.87	6.80
UF2 - RO1	ρw ≥ 0.05	6.46	6.47	ρw < 0.05	6.80	6.77
RO1 - RO2	ρt ≥ 0.05	6.47	6.43	ρt ≥ 0.05	6.77	6.78
RO2 - RO4	ρt ≥ 0.05	6.43	6.25	ρt < 0.05	6.78	6.50

Source: The author (2019).
Note: Differences of mean, with *ρ-value* greater or equal to the level of significance of 5%, do not differ statistically from each other.

Variation pH was similar in both experiments. There was 9.15% of pH decrease in the RO permeate in the experiment 1 compared to the BW pH in experiment 2, the pH decrease was 9.84%.

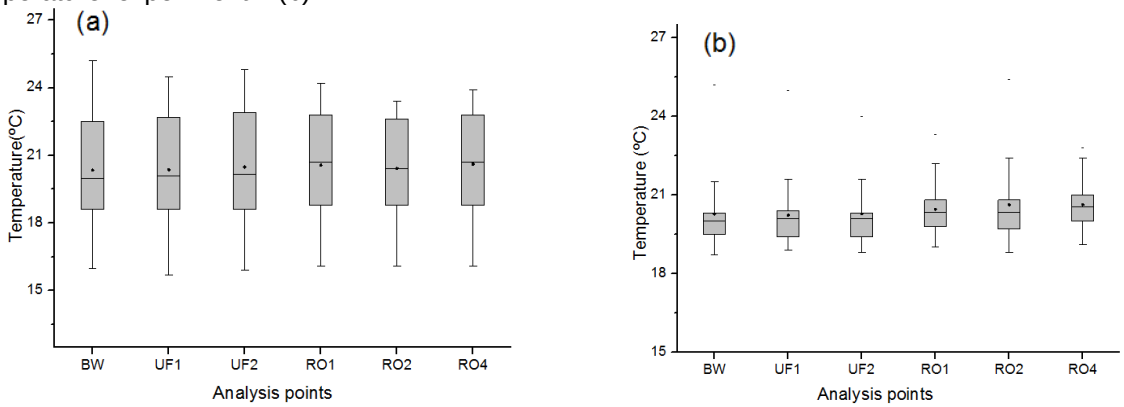
Gedam et. al (2012) obtained 13% of pH decrease, for desalination of underground brackish water with 3,250 mg/L of TDS concentration, using RO membranes.

1.3.3 Physical characteristics of the water

1.3.3.1 Temperature

The average results of temperature varied in both experiments (Figure 1.13). The variation was 15.7 – 25.2 ºC in the experiment 1 and 18.8 – 25.5 ºC in the experiment 2.

Figure 1.13 - Empirical distribution of temperature: experiment 1(a); Empirical distribution of temperature: experiment 2 (b).



Source: The author (2019).
Notes: BW = brackish water; UF2 = UF permeate; RO1 = before the softeners; RO2 = after the softeners; RO4 = RO permeate.

There was no significant difference between the results, according to Table 1.10. The temperatures remained close to the ambient temperature.

Table 1.10 - Mean and statistical analysis (STUDENT ρt or WILCOXON ρw) of temperature in the different water sample collection points.

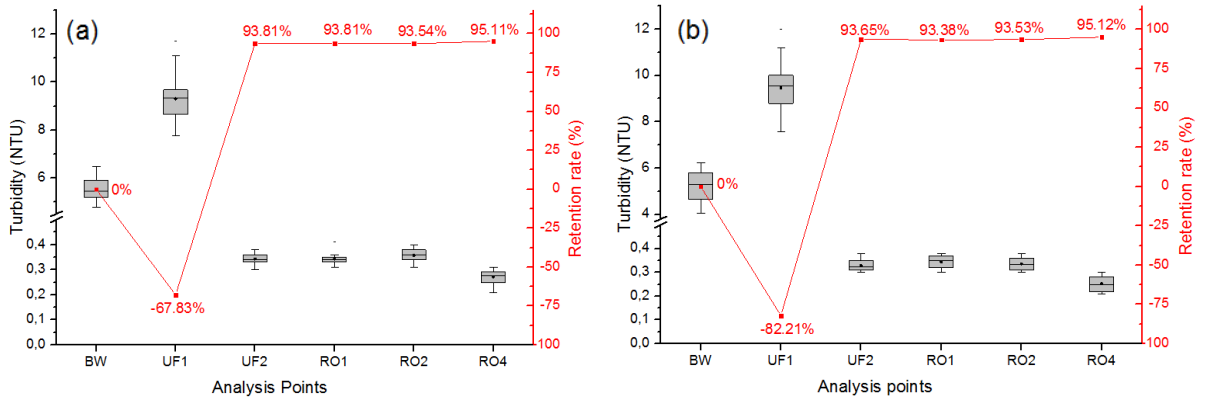
Analysis points	Experiment 1			Experiment 2		
	t / w	Mean (mg/L)		*t / w*	Mean (mg/L)	
BW - UF1	ρt ≥ 0.05	20.35	20.36	ρw ≥ 0.05	20.27	20.22
UF1 - UF2	ρt ≥ 0.05	20.36	20.49	ρw ≥ 0.05	20.22	20.28
RO1 - RO2	ρw ≥ 0.05	20.57	20.42	ρw ≥ 0.05	20.45	20.62
RO2 - RO4	ρt ≥ 0.05	20.42	20.61	ρw ≥ 0.05	20.62	20.63

Source: The author (2019).
Note: Differences of mean, with *ρ-value* greater or equal to the level of significance of 5%, do not differ statistically from each other.

1.3.3.2 Turbidity

Figure 1.14 presents the results of turbidity in all water sample collection points in the system.

Figure 1.14 - Empirical distribution of turbidity (experiment 1) and accumulated removal (a); Empirical distribution of turbidity (experiment 2) and accumulated removal (b).



Source: The author (2019).
Notes: BW = brackish water; UF2 = UF permeate; RO1 = before the softeners; RO2 = after the softeners; RO4 = RO permeate.

Figure 1.14 (a) shows the significant increase of turbidity (67.83%) in the experiment 1, after the PAC addition. The coagulant promoted the destabilization and agglutination of the solid particles presents in the brackish water. A similar situation occurred in the experiment 2 as shown in Figure 1.14 (b), in the UF1 the turbidity increased 82.21% compared to the BW turbidity.

Table 1.11 - Mean and statistical analysis (STUDENT ρt or WILCOXON ρw) of turbidity in the different water sample collection points.

Analysis points	Experiment 1			Experiment 2		
	t / *w*	Mean (mg/L)		*t* / *w*	Mean (mg/L)	
BW - UF1	ρt < 0.05	5.54	9.30	ρt < 0.05	5.20	9.47
UF1 - UF2	ρt < 0.05	9.30	0.34	ρt < 0.05	9.47	0.33
UF2 - RO1	ρt ≥ 0.05	0.34	0.34	ρt ≥ 0.05	0.33	0.34
RO1 - RO2	ρt ≥ 0.05	0.34	0.36	ρt ≥ 0.05	0.34	0.34
RO2 - RO4	ρt < 0.05	0.36	0.27	ρt < 0.05	0.34	0.25

Source: The author (2019).
Note: Differences of mean, with *ρ-value* greater or equal to the level of significance of 5%, do not differ statistically from each other.

There was turbidity removal efficiency of 93.81% in the experiment 1 and 93.65% in the experiment 2, in the UF permeate (UF2). This demonstrates the pretreatment efficiency to remove turbidity removal, as observed by Almeida (2017) and Bovaroti (2018). They obtained turbidity removal efficiency, in the UF system of 96.4% and 95.10%, respectively.

There were no significant variations of turbidity in UF2-RO1 and RO1-RO2.

There was additional turbidity removal efficiency of 1.56% and 1.59% in the RO system, with overall removal efficiency of 95.11% and 95.15% in the experiment 1 and 2, respectively.

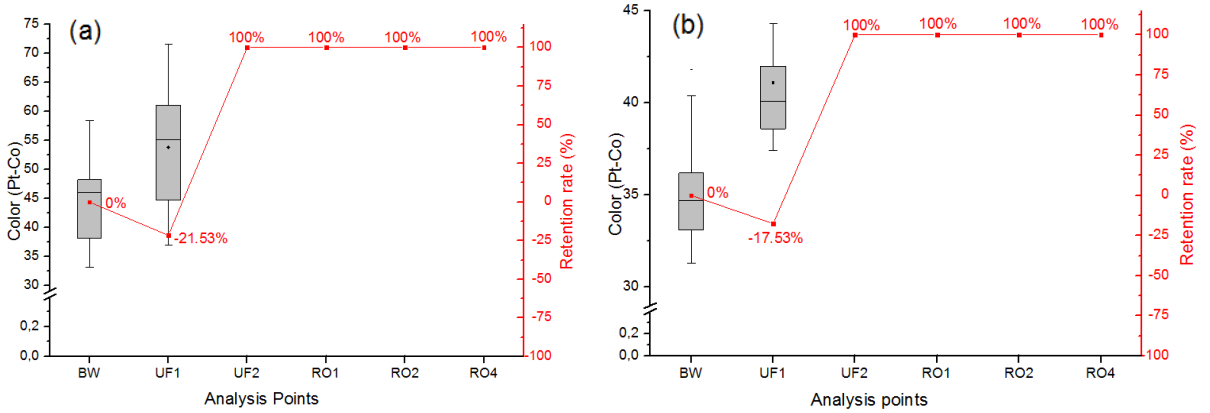
Almeida (2017) obtained total efficiency of 97.8%, for brackish water with 6.70 NTU. Bovaroti (2018) obtained global turbidity removal efficiency of 96.9%, for brackish water with 4.91 NTU of turbidity.

In a similar desalination system, with RO and UF pretreatment, Sun at al. (2015) obtained removal efficiency of turbidity of 90%, for brackish water with 1.6 – 7.0 NTU.

1.3.3.3 Apparent color

Figure 1.15 presents the empirical data of color for every step of treatment, and Table 1.12 shows the statistical results for this parameter.

Figure 1.15 - Empirical distribution of color (experiment 1) and accumulated removal (a); Empirical distribution of color (experiment 2) and accumulated removal (b).



Source: The author (2019).
Notes: BW = brackish water; UF2 = UF permeate; RO1 = before the softeners; RO2 = after the softeners; RO4 = RO permeate.

There was removal efficiency of color in the UF. For both experiments, UF removed 100% of the color from the brackish water.

There was increase of color (21.53%) in the UF1 in experiment 1, and 17.53% in the experiment 2. This increase indicates efficiency coagulation with the particle destabilization.

Table 1.12 - Mean and statistical analysis (STUDENT ρt or WILCOXON ρw) of apparent color in the different water sample collection points.

Analysis points	Experiment 1			Experiment 2		
	t / w	Mean (mg/L)		*t / w*	Mean (mg/L)	
BW - UF1	ρt < 0.05	44.27	53.80	ρt < 0.05	34.97	41.10
UF1 - UF2	ρt < 0.05	53.80	0.00	ρt < 0.05	41.10	0.00

Source: The author (2019).
Note: Differences of mean, with *ρ-value* greater or equal to the level of significance of 5%, do not differ statistically from each other.

Almeida (2017) and Bovaroti (2018) obtained removal efficiency of color of 98% and 98.6%, for brackish water with 20.83 uH and 45.10 uH (average values) of color, respectively.

Arhin et. al (2018) verified the efficiency of an UF system to treat brackish water with 77 uH of color, obtaining removal of 100% with PAC dosage of 18 mg/L in the coagulation.

1.3.4 Bacteriological characteristics

Bacteriological analisis were done in the first, fifth and last days of operation in both experiments.

It was found 2,891 and of 3.438 NMP/100 mL of total coliforms (average values), 38.0 and 48.0 NMP/100 mL of *Echerichia coli (E. coli)* in the brackish water, in the experiment 1 and 2, respectively.

The UF system was able to remove 100% of total coliforms and E. Coli in both experiments. WHO (2018) requires total absence of E. Coli and total coliforms in the treated water for human consumption.

1.3.5 Solar energy production

During the experiment 1, the desalination pilot system consumed 199.17 kWh of energy. 42.18% (84.00 kWh) was supplied by the fotovoltaic panels and 57.82% (115.16 kWh) was complemented by the grid.

Desalination pilot system consumed 189.45 kWh of energy during the experiment 2, while the solar energy system provided 27.0 kWh (14.25%). 85.75% (162.45 kWh) of the consumed energy was provided by the grid.

The difference of energy production by the solar energy system is that the system worked 10 non-consecutive days, during 05/28/18 to 06/18/18, and the total energy production is relative to the same period. During the experiment 2, the total energy

production is relative to the period from 06/21/18 to 06/29/18 (9 days) and the system worked all the time with twice runs in a day.

Table 1.13 shows the consumption of energy by the desalination pilot system.

Table 1.13 - Consumption of energy by the desalination pilot system.

meters	system	Experiment 1		Experiment 2	
		energy consumption (kWh)	(%)	energy consumption (kWh)	(%)
M1	pumps to mix and transfer water from the tanks	75.76	38.04	67.00	35.37
M2	UF	8.64	4.34	14.81	7.82
M3	RO	114.77	57.62	107.65	56.82
Total		199.17	100	189.46	100

Source: The author (2019).

In both experiments the RO system had the highest consumption of 57.62% and 56.81% compared to the total consumption. Pumps for used to transfer sea water and to mix the brackish water consumed 38.04% in the experiment 1 and 35.37% in the experiment 2. The UF system presented a consumption of 4.34% and 7.81% in the experiments 1 and 2, respectively.

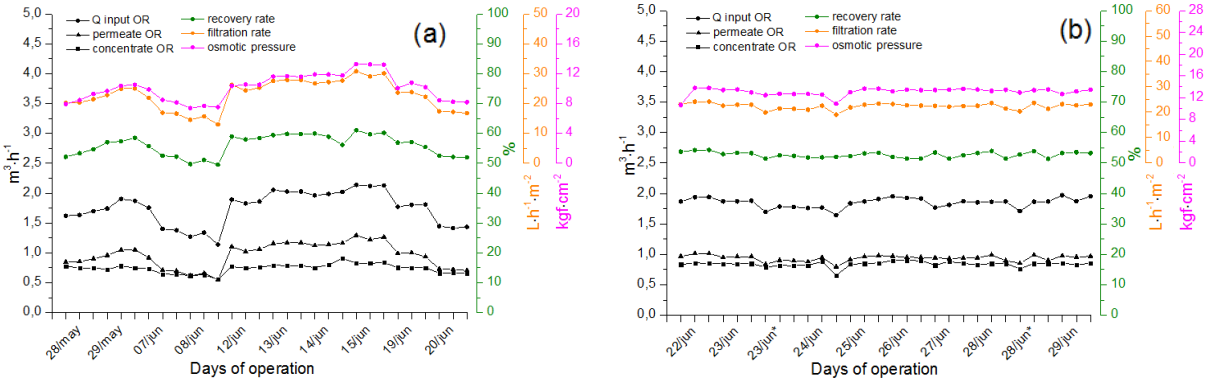
1.3.6 Operational conditions of the RO system

Figures 1.16 (a) and (b) presents the values of osmotic pressures, recovery and filtration rates, which are directly linked to the feeding flowrates of the RO system, permeate and brine production. The values flow rates of the RO system were 1.75 m^3/h and 1.85 m^3/h in the experiment 1 and 2, respectively (see Figure 1.16 (a) and (b)).

During the experiment 1 was produced 0.96 m^3/h of RO permeate and 0.74 m^3/h of brine, representing a recovery rate of 55.97%. In the experiment 2 it was similar, with 0.94 m^3/h of permeate production and 0.85 m3/h of brine, corresponding to 52.65% of recovery rate. There was no statistically significant difference comparing the results of filtration rates in both experiments. The average values obtained were 22.82 L/h/m^2 (experiment 1) and 22.41 L/h/m^2 (experiment 2).

The average osmotic pressures resulted in 10.08 kgf/cm^2 (9.89 bars) in the experiment 1 and 13.06 kgf/cm^2 (12.81 bars) in the experiment 2. There was a significant increase (29.5%) of the osmotic pressure in the experiment 2, due to the higher TDS concentration of the brackish water.

Figure 1.16 - Operational conditions of the RO system in the for experiment 1 (a); Operating parameters of the OR membrane for experiment 2 (b).



Source: The author (2019).

1.4 CONCLUSIONS

It was verified that, for the use of desalination systems by RO, pretreatment units should be included in order to preserve membranes against damage due to fouling and scaling.

In the UF pretreatment there was removal of more than 93% for turbidity and total removal of the apparent color, for the two experiments. The softener system removed 52.64% in the first experiment and 73.36% in the second experiment.

The efficiency of the RO system was analyzed through the removal of TDS. For the two experiments the removal of this parameter was superior to 99%.

Bacteriological tests indicated that the UF system was efficient in the removal of total coliforms and E. coli from brackish water. The solar panels provided, for the first and second experiments, 42.18% e 14.25% of the energy consumed by the desalination pilot system.

The RO system consumed the most part, about 56% of the total energy accounted for, for its operation. The pump to mix the brackish water and pump transfer sea water consumed about 38,04% and 35,37% of the energy disponible, in the two experiments. Finally, the UF system had the lowest energy consumption 4.34% and 7.81%, experiment 1 and 2, respectively.

For the experiment 1 the osmotic pressure had an average of 10,08 bar, a filtration rate of 22.82 L/h/m^2 and a RO recovery rate of 55.97%. In experiment 2 the average osmotic pressure was 13.06 bar, filtration rate 22.41 L/h/m^2 and RO recovery rate 52.65%.

CHAPTER 2

USE OF MULTIPLE LINEAR REGRESSION AND CORRELATION MATRICES TO EVALUATE A BRACKISH WATER DESALINATION PILOT SYSTEM

ABSTRACT

In this paper, Pearson's correlation matrix and multiple linear regression model were used to identify the relationship between the water quality parameters and operational parameters of a brackish water desalination pilot system. The pilot system was installed in the dependencies of the Water Treatment Plant (WTP) of *Praia de Leste* located in the coast of Parana State, Brazil. Two experiments were done varying the total dissolved solids (TDS) concentration of the brackish water, which was the feedwater of the pilot system. In both experiments, the pilot system was operated by 10 days, Experiment 1 using brackish water with TDS = 3.500 ± 100 mg/L and Experiment 2 with TDS = 7,000 ± 100 mg/L. Seawater and fresh water (from the *Pombas* river) were mixed until reaching those TDS concentration to get the brackish water. Water samples were collected each 1 hour of operation time to verify TDS, electrical conductivity (EC), pH, temperature, apparent color, turbidity, total hardness, calcium, alkalinity, sulphate and chloride, totalizing 330 analysis for each experiment. Filtration rate, recovery rate and osmotic pressure were the operational conditions evaluated from the RO system. Water quality from each water sample collection point, BW (brackish water), UF1 (after coagulation), UF2 (UF permeate), RO2 (after the softeners), RO4 (RO permeate) and Conc (RO concentrate), presented relation between independent variables which could explain the variability of the dependent variable. RO operational conditions and water quality analysis did not present significance using multiple linear regression model, then it was developed the Pearson’s correlation matrix.

Key-words: Brackish water. Desalination. Ultrafiltration. Softening. Reverse osmosis. Multiple linear regression model. Pearson correlation matrix.

2.1 INTRODUCTION

Quality of life is directly dependent on access to drinking water. Health benefits are attained when this resource is adequately provided for the population (WHO, 2014).

There are reports of health issues on Eastern Africa related to the groundwater consumption, due to the contaminant concentration being higher than the acceptable amount established by the World Health Organization's (WHO) guidelines (SHEN, 2016).

Reverse osmosis (RO) water treatment is presented as a powerful ally to solve problems such as the aforementioned. According to Bovaroti (2018), several countries have invested resources in the process to treat groundwater to provide drinking water for human consumption.

Almeida (2017) reports that water desalination has been used throughout semiarid, desertic, island and coastal areas such as in the coastal portion of Australia, countries of the Middle East, western United States of America, the Caribbean islands, and in regions of the northeastern semiarid in Brazil and islands such as *Fernando de Noronha.*

There are two water desalination processes currently dominant: thermal distillation and membrane separation (Ida, 2014). Membrane separation process is the dominant water treatment both in Brazil and worldwide. It is currently used in seawater and brackish water desalination, and in systems to treat water for reuse and in the sewage treatment (MOLINA; CASAÑAS, 2010).

Conventional water treatment systems are not efficient to remove salts from brackish water and, in many of Brazil's coastal regions, there are problems related to the seawater intrusion in freshwater. This issue can be observed in Praia de Leste, coast of Parana State.

The present article presents the relation between water quality parameters and operational conditions of the brackish water desalination system pilot using coagulation, ultrafiltration (UF) and softening as pretreatment to the RO system. The brackish water was prepared from the mixture of seawater and fresh water of the Pombas river, in *Praia de Leste*.

It was proposed the development of the multiple regression model to verify the behavior of the parameters analyzed. For the parameters which did not have

significance in this model, the Pearson correlation matrix was developed to verify if there is a simple relation between the parameters.

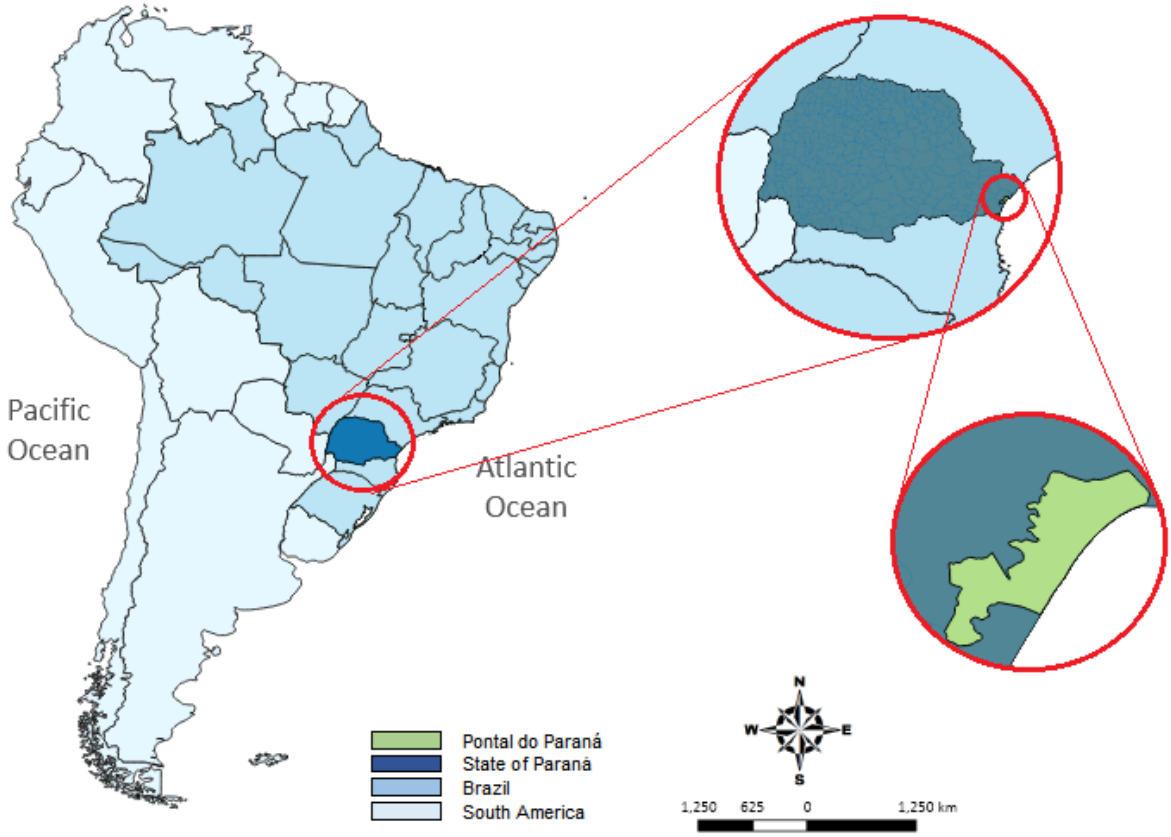
This study is a part of the research done among State University of Ponta Grossa (UEPG), University of North Texas (UNT), University College London (UCL) and the Water and Sanitation Company of Parana State (Sanepar).

2.2 MATERIAL AND METHODS

2.2.1 Description of the region

Praia de Leste, as shown in Figura 2.1 integrates one of the 48 beaches of the *Pontal do Paraná* county, located 104,9 km from Curitiba, capital city of Parana State. It has a smooth and low altitude terrain, often designated as sandbank area (PONTAL DO PARANA, 2015).

Figure 2.1 - Location map of *Pontal do Paraná* county.



Source: The author (2019).

2.2.2 Desalination pilot system

The brackish water desalination pilot system was composed by pretreatment with coagulation and UF, ion exchange system (softeners) followed by RO and ultraviolet disinfection (UV). It was installed next to the water treatment plant (WTP) to supply water for the population of *Praia de Leste,* in the coast of Parana State.

2.2.2.1 Brackish water

The brackish water used in the experiments was prepared in a 10 m³ tank in two distinct experiments with different TDS concentrations: 3,500 ± 100 mg/L (Experiment 1) and 7,000 ± 100 mg/L (Experiment 2). Freshwater from Pombas river from the pipe of the *Praia de Leste* WTP was mixed with seawater pumped and transported by truck to the WTP to obtain the different TDS concentrations.

Both experiments were developed during 10 days, with intermittent operation of three hours per day. Brackish water (feedwater for the desalination pilot system), UF permeate, the product of softening system, RO permeate and RO concentrate samples was collected in each operation hour. Water quality was evaluated from pH, temperature, color, turbidity, alkalinity, total hardness, TDS, electrical conductivity (EC), calcium, sulfate and chloride, totalizing 30 water samples and 330 water analysis per experiment.

2.2.2.2 Pretreatment pilot system

A UF pilot system was used as pretreatment to the RO pilot system. Before the UF membrane, the brackish water was coagulated with diluted to 10% polyaluminium chloride (PAC) in order to destabilize the suspended and colloidal material and promote the flocculation. The coagulant was and added between the brackish water tank and the entrance of the UF pilot system. PAC dosage varied according to the flow rates and jar test laboratory tests.

Coagulated water passed through a disk filter (300 μm) to remove thicker particles. After that, the water was pumped to the UF membrane of ascending and vertical flow. UF permeate was stored in a 1.5 m³ tank. The maximum flow rate in the UF pilot system was 2.4 m^3/h.

The membrane's characteristics are described in Table 2.1.

Table 2.1 - Characteristics of UF membrane.

Model	Pentair - X - Flow Aquaflex55
Useful area	55 m²
Membrane	hydrophilic
Effetive pore	20 nm
Maximum pressure	300 kPa
pH range	2 - 12
Tolerance to free residual chlorine	250 $mg \cdot L^{-1}$
Bacteria removal	99.99%
Virus removal	99.99%
Turbidity	< 0.1 NTU
Recovery rate	90 - 98%
Capacity for treatment	2.40 m³/h

Source: Pentair (2018)

2.2.2.3 Ion exchange and RO pilot system

The water softening was done through the ion exchange system which was projected to remove the total hardness from the water and prevent the deposit of calcium carbonate on the RO membrane's surface (VENKATESAN, 2014).

The pilot system was constituted of two cationic vases which operated in an alternate way. The softeners worked according to the ion exchange principles which occurs when water passes through a filter media where sodium ions (Na^{2+}) are exchanged for undesirable concentrations of calcium (Ca^{2+}) e magnesium (Mg^{2+}) from the water. The characteristics of the softeners are described in Table 2.2.

Table 2.2 - Characteristics of softener.

Model	AB 1465-AT
Cylinder	polyethylene coated in fiberglass
Filter element	Strongly acid cationic resin in sodium cycle
Regeneration tank	capacity for 200 kg of salt
Regeneration material	sodium chloride
Output	2 m³/h

Source: Permution (2016).

The softening pilot system was initially projected to treat water volume of 50 m³ with estimated total hardness of 100 mg/L. When the system reached this volume, the softener automatically regenerated. However, during the operation, the total hardness was not being completely removed, for the sample surpassed the limit established in the initial project. This caused the regeneration, in the experiment 1, to

be undertaken on every 25 m³ of treated water, and in the experiment 2 on every 10 m³ of treated water.

After the softening, sodium metabisulphite was added through a dosing pump to protect the RO membranes. The water passed through a static mixer, a polypropylene cartridge filter to remove particles larger than 5 µm, and was pumped to the five RO membranes system of horizontal flow.

The characteristics of the RO membranes are described in Table 2.3.

Table 2.3 - Characteristics of RO membrane.

Model	Vontron - LP21-4040
Material	spiral wound polyamide
Effetive pore	1 nm
Unit filtration area	8.40 m²
Total filtration area	42 m²

Source: Permution (2016).

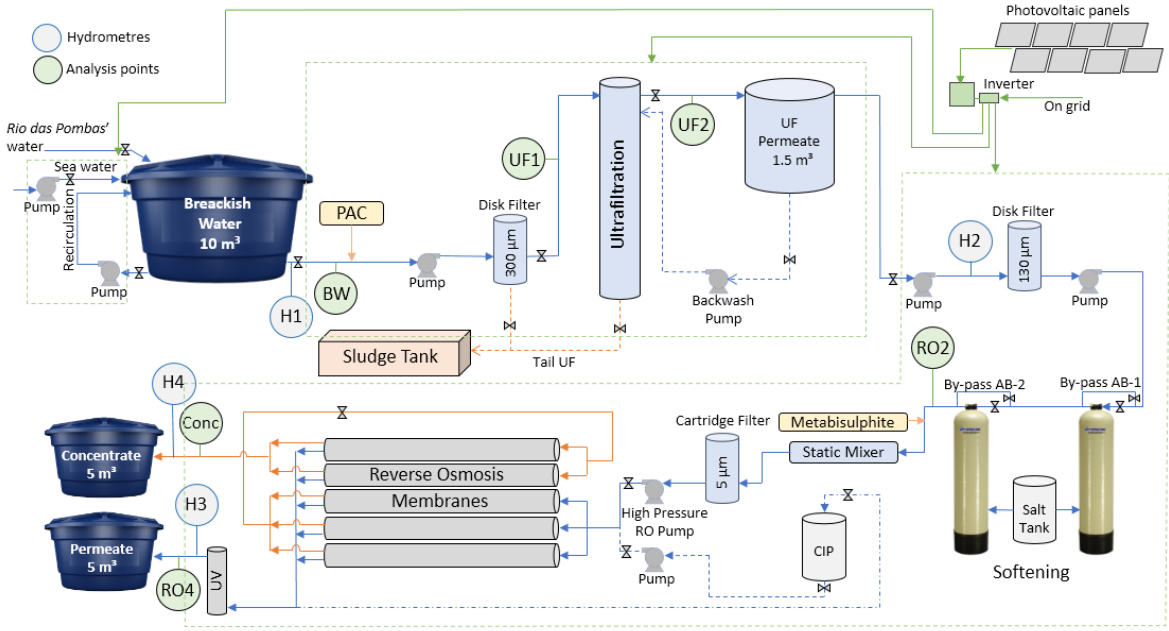
2.2.3 Collection and identification of the parameters for analyses

Samples were collected on seven points of the system (see Figure 2.2). BW = brackish water; UF1 = after the addition of coagulant and the disk filter; UF2= after the UF membrane (UF permeate); RO2 = after the disk filter and the softener; RO4= after the RO membranes (RO permeate) and UV disinfection (final permeate); CONC = after the RO membranes (RO concentrate or brine).

pH, temperature, SDT, conductivity, and turbidity analysis were held on site. Alkalinity, total hardness, calcium, color, sulfate and chloride analysis were done in laboratories of UEPG, according to the recommended methods by APHA et al. (2012).

Operational conditions of the RO pilot system were also analyzed: input RO flow rate, permeate and concentrate production, recovery rate, filtration rate and osmotic pressure.

Figure 2.2 – Schematic drawing of the brackish water desalination pilot system.



Source: The author (2019).

2.2.4 Statistical analysis

2.2.4.1 Correlation matrix

A correlation matrix was used to develop the statistical analysis. It determines the degree of relationship between two variables. The relationship is shown in Pearson's coefficient, also known as correlation coefficient. This coefficient ranges from -1 to 1. Negative or positive signals determine the direction, while the value determines the correlation's scale. That means if a correlation is close to the extremes of -1 or 1, the higher is the association level between the variables. However, there is a low association level or absence of correlation if the value is closer to zero (KRUSCHEWSKY et. al, 2018).

There is direct proportion between the parameters whenever the correlation is positive. Correlation is expressed with a negative signal when the proportionality is indirect (RIBEIRO, et al. 2016).

For this study, the correlation coefficient higher than 0.6 expresses a strong relationship and will be used to evaluate the parameters (RIBEIRO et al., 2016).

2.2.4.2 Multiple linear regression model

The multiple linear regression analysis determines how the "y" variable is related to two or more independent "x" variables. (SUBRAMANIAN, 2013).

R determination coefficient is estimated in the multiple regression equation. It is interpreted as the proportion of the variation of the dependent variable through the regression equation. Was opted to develop the linear regression model in cases where there was significant proportion dependent between variables.

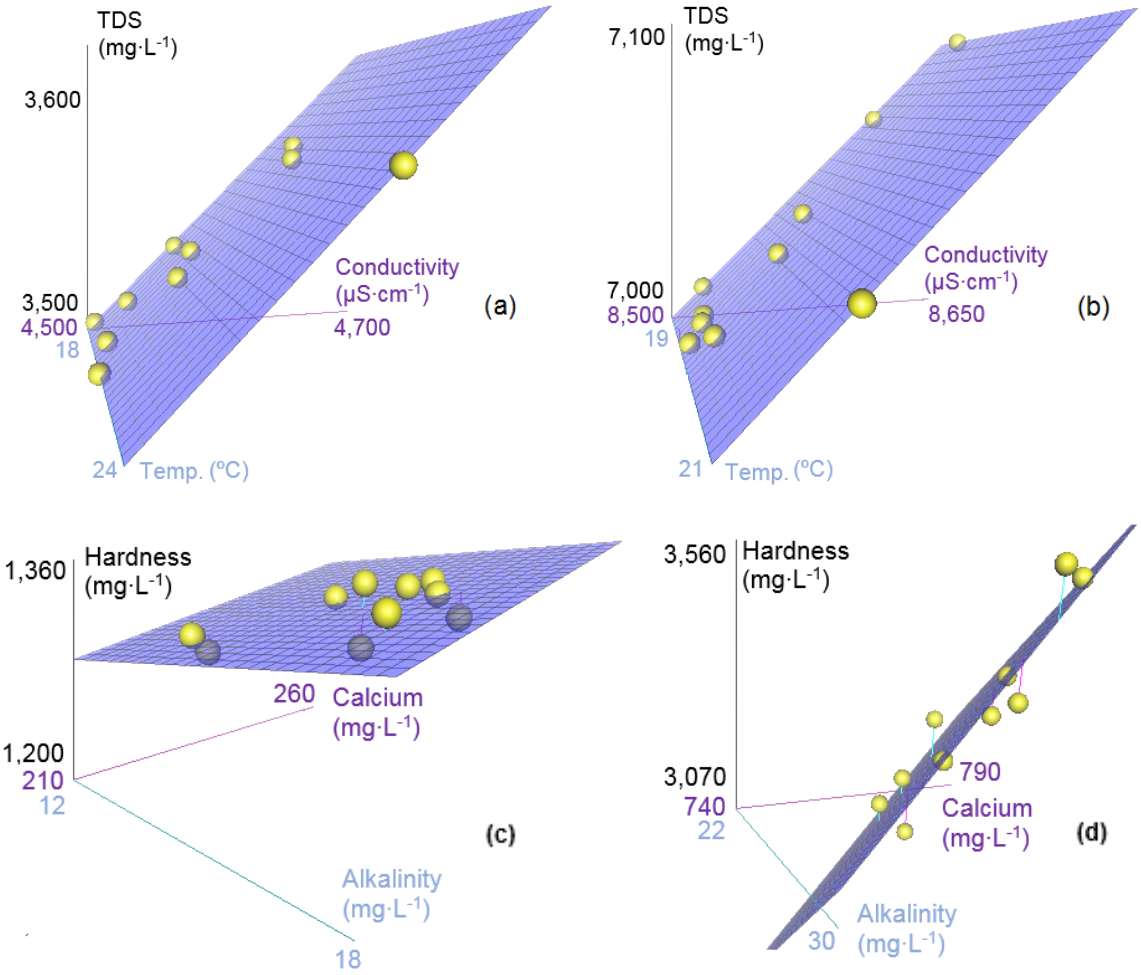
After the choice of the best model for every case, the data normality was tested through Shapiro-Wilk tests to a 5% significance level.

2.3 RESULTS AND DISCUSSION

2.3.1 Brackish water collection point

Figure 2.3 presents the multiple regression surface for the experiments 1 and 2. Two models were found in each experiment, significant to the α = 0.05 level.

Figure 2.3 - Regression surface between TDS, EC and Temperature for BW samples (a) (b); Regression surface between Total hardness, Alkalinity and Calcium for BW samples (c) (d).



Source: The author (2019).
Notes: (a) (b) Results obtained in the experiment 1; (c) (d) Results obtained in the experiment 2.

Table 2.4 presents the equations developed for each model. Estimated values were significant for the confidence level of 95%.

Table 2.4 - Results of multiple linear regression for BW.

Model (a)		*ρ-value*	Model (b)		*ρ-value*
Intercept	-283.81		Intercept	-419.58	
EC	0.86	$1.71 \cdot 10^{-5}$	EC	0.90	$1.33 \cdot 10^{-9}$
Temp.	-6.10	0.004	Temp.	-12.22	$2.58 \cdot 10^{-7}$
TDS = -283.81 + 0.86·EC - 6.10·T			TDS = -419.58 + 0.90·EC - 12.22·T		
Model (c)		***ρ-value***	**Model (d)**		***ρ-value***
Intercept	1000.54		Intercept	-3056.75	
Calcium	0.94	0.034	Calcium	5.30	0.034
Alkalinity	1.02	0.007	Alkalinity	93.34	0.006
TH = 1,000.54 + 0.94·Ca + 1.02·A			TH = -3,056.75 + 5.30·Ca + 93.34·A		

Source: The author (2019).
Notes: (a) (c) regressions related to the experiment 1; (b) (d) regressions related to the experiment 2.

There were statistical evidences (p-value < 0,05) of relationship between the independent variable of EC and temperature and TDS as a dependent variable, for both (a) and (b) models. The models presented R^2 value of 0.9748 and 0.9961, respectively. This indicates that the independent variables explain 97.48% and 99.61% of the TDS variation.

The (c) and (d) models also presented statistically relevant evidences between the independent variables of calcium and alkalinity, and the dependent variable of total hardness. In the (c) model, 74.79% of the variance in the values of total hardness is explained by the independent parameters of calcium and alkalinity. The same occurs with model (d), which presented R value of 0.8817%.

Table 2.5 - Pearson correlation matrix for BW.

(a)	TDS	Conductivity	Turbidity	Color	Alkalinity	Hardness	Calcium	Sulphate	Chloride	pH	Temperature
TDS	1.00										
Conductivity	0.95	1.00									
Turbidity	0.08	-0.11	1.00								
Cor	0.09	0.03	0.75	1.00							
Alkalinity	-0.47	-0.50	0.50	0.48	1.00						
Hardness	-0.26	-0.44	0.53	0.54	0.78	1.00					
Calcium	-0.59	-0.71	0.50	0.53	0.65	0.69	1.00				
Sulphate	-0.38	-0.47	0.47	0.37	0.37	0.44	0.55	1.00			
Chloride	0.08	0.07	0.54	0.22	-0.29	0.54	0.38	0.67	1.00		
pH	0.22	0.25	0.28	-0.20	0.61	-0.42	-0.41	-0.14	0.11	1.00	
Temperature	0.45	0.44	-0.36	-0.17	0.22	-0.21	0.32	0.25	0.24	0.34	1.00

(b)	TDS	Conductivity	Turbidity	Color	Alkalinity	Hardness	Calcium	Sulphate	Chloride	pH	Temperature
TDS	1.00										
Conductivity	0.89	1.00									
Turbidity	0.07	-0.17	1.00								
Cor	0.27	0.12	0.74	1.00							
Alkalinity	-0.44	-0.43	0.55	0.31	1.00						
Hardness	-0.29	-0.29	0.42	0.37	0.81	1.00					
Calcium	-0.23	-0.11	0.22	0.44	0.75	0.77	1.00				
Sulphate	-0.50	-0.38	0.33	0.48	0.22	0.30	0.42	1.00			
Chloride	0.09	0.17	0.33	0.24	-0.30	0.34	0.11	0.79	1.00		
pH	0.60	0.49	0.28	-0.16	0.75	-0.59	-0.49	-0.20	0.14	1.00	
Temperature	0.38	0.23	-0.47	-0.22	0.05	-0.07	0.21	0.22	0.19	0.23	1.00

Source: The author (2019).
Notes: (a) experiment 1; (b) experiment 2.

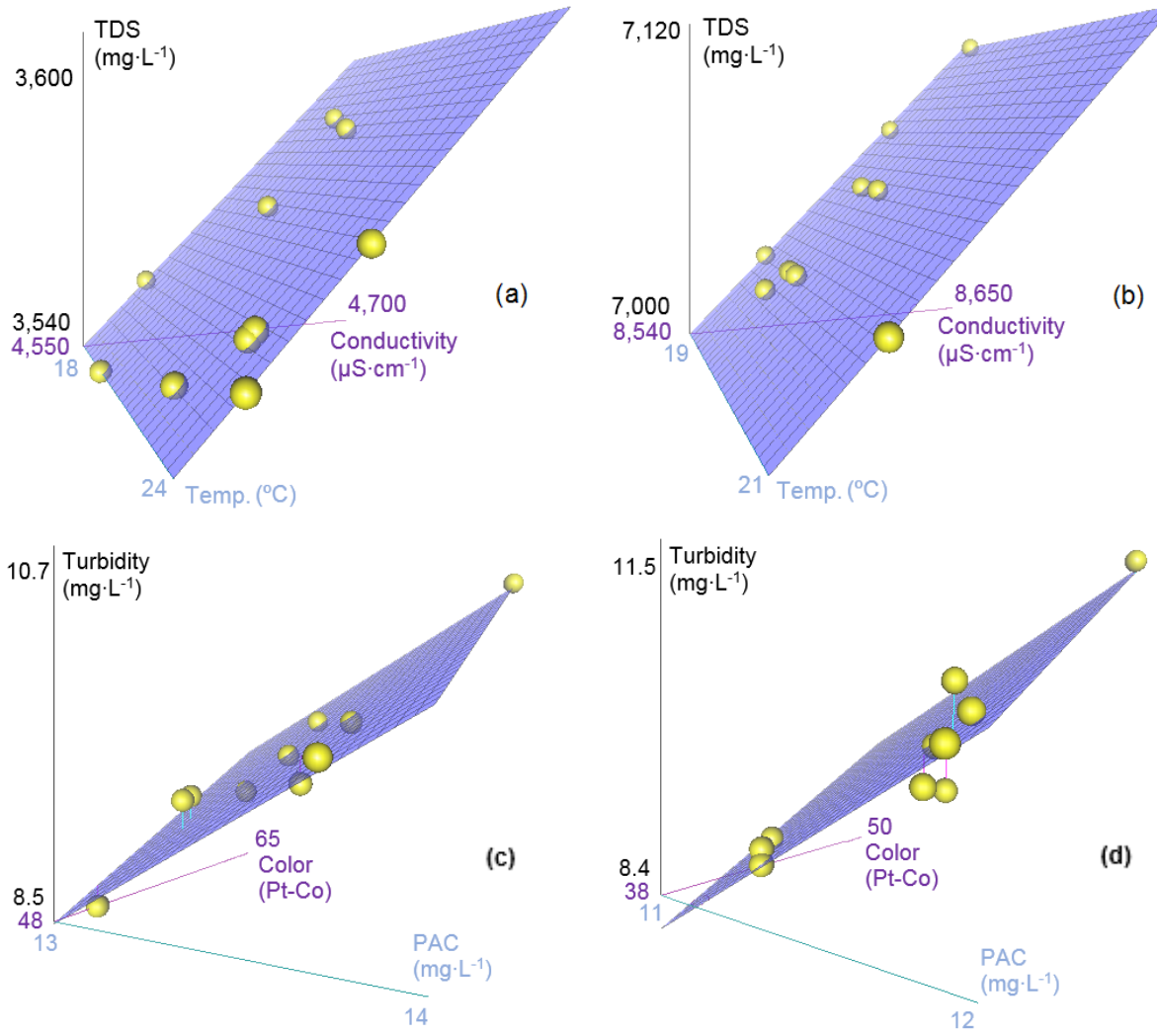
A Pearson correlation matrix was developed, as illustrated in Table 2.5, to determine whether there are simple linear correlations. There was positive correlation of color and turbidity (R =0.75), chloride and sulphate (R ≥ 0.67), and pH and alkalinity (R ≥ 0.61) in both experiments.

2.3.2 Coagulation parameters – UF1

Figure 2.4 presents the multiple regression plans regarding to the values obtained in the UF1 (after PAC addition).

There was increase in the TDS values with the increase of the EC. However, there was decrease in the TDS, once the temperature was raised.

Figure 2.4 - Regression surface between TDS, EC and Temperature for UF1 (a) (b); Regression surface between Turbidity, Color and PAC for UF1 (c) (d).



Source: The author (2019).
Notes: (a) (b) Results obtained in the experiment 1; (c) (d) Results obtained in the experiment 2.

There is evidence, in the models (a) and (b) shown in Table 2.6, that EC and temperature are related to the TDS, both of them presented p-value lower than 0.05. R^2 values of 79.54% for the (a) model and 99.35% for the (b) model explain the variability in the TDS parameter.

A significant relationship could be observed among the independent variables of color and PAC addition, for the turbidity, shown in models (c) and (d). How greater the color, greater is the PAC dosage and greater is the turbidity.

Table 2.6 - Results of multiple linear regression for BW.

Model (a)		*p-value*	Model (b)		*p-value*
Intercept	1159.46		Intercept	-734.23	
EC	0.53	0.024	EC	0.93	$1.19 \cdot 10^{-8}$
Temp.	-1.93	0.046	Temp.	-10.19	$6.71 \cdot 10^{-6}$
TDS = 1159.46 + 0.53·EC - 1.93·T			TDS = -734.23 + 0.93·EC - 10.19·T		
Model (c)		*p-value*	Model (d)		*p-value*
Intercept	-4.16		Intercept	-4.20	
Color	0.07	0.021	Color	0.13	0.001
PAC	0.02	0.005	PAC	0.02	0.001
T = -4.16 + 0.07·Co + 0.02·PAC			T = -4.20 + 0.13·Co + 0.02·PAC		

Source: The author (2019).
Notes: (a) (c) regressions related to the experiment 1; (b) (d) regressions related to the experiment 2.

Di Bernardo (2012) shows in the laboratory tests that there is an optimal range for PAC addition. If PAC dosage is superior to the limit, the turbidity will decrease. This means that the coagulant dosage in the days of the system operation was adequate, contributing to the flakes formation which were removed in the UF membrane. The variability of turbidity was 84.48% and 91.48% for the experiments 1 and 2, respectively.

There were no other strong simple linear correlations found among the remaining parameters.

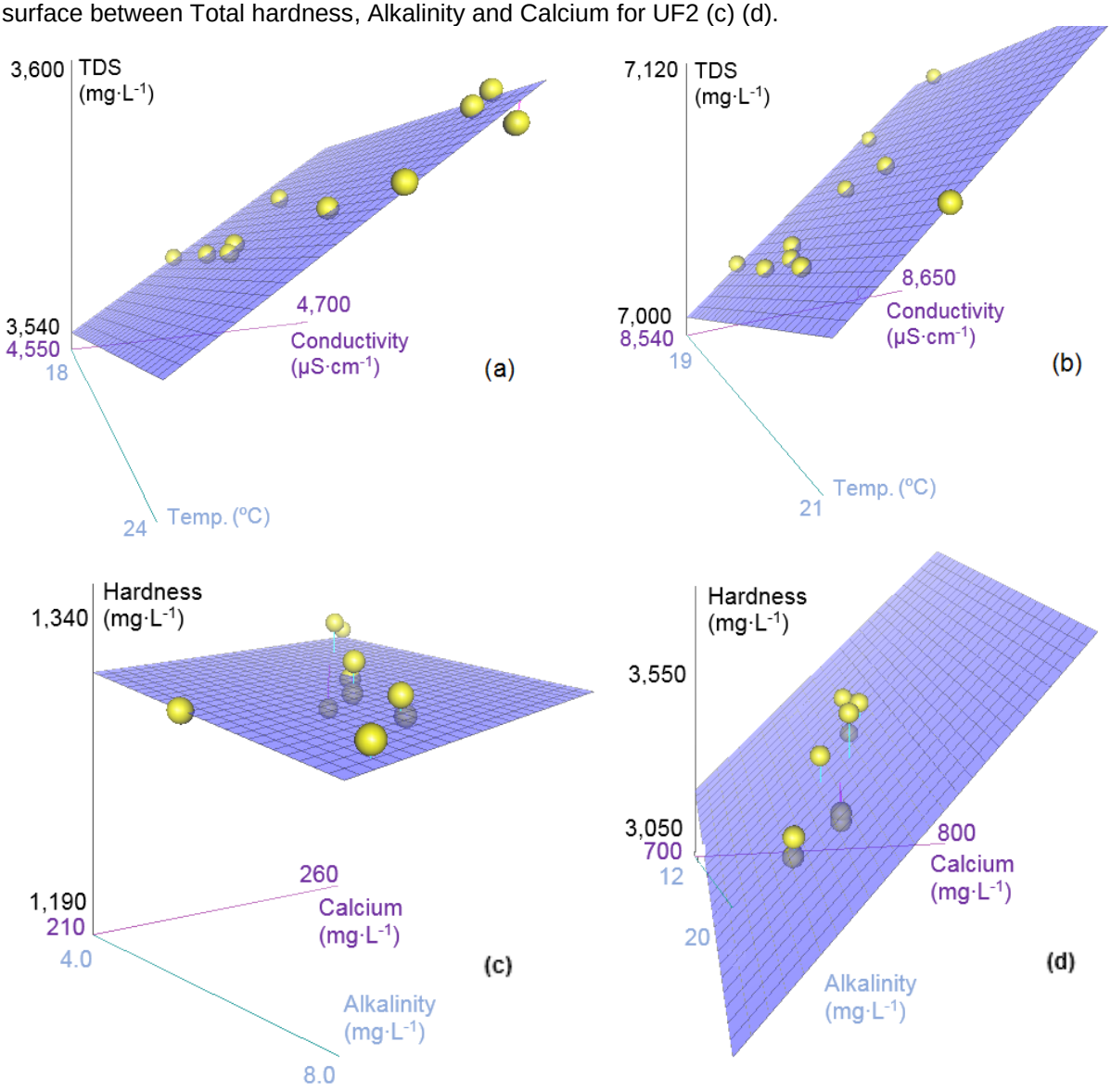
2.3.3 UF2 collect point

Figure 2.5 shows the behavior of the TDS as dependent variable with EC and temperature as independent variables in the (a) and (b) models, as well as total hardness as dependent variable with calcium and alkalinity as independent variables, in the (c) and (d) models.

There was a parameter that contributed to the increase or decrease of the values for the dependent variables, in each of the models.

For the (a) and (b) models, as shown in Table 2.7, a relationship was found between EC and temperature as independent variables and TDS as dependent variable. Both of them presented p-value lower than 5%. The same independent variables explain 98.07% and 99.93% of the TDS variance.

Figure 2.5 - Regression surface between TDS, EC and Temperature for UF2 (a) (b); Regression surface between Total hardness, Alkalinity and Calcium for UF2 (c) (d).



Source: The author (2019).
Notes: (a) (b) Results obtained in the experiment 1;(c) (d) Results obtained in the experiment 2.

The variance of the total hardness average values, 76.56% and 78.93%, for the (c) and (d) models, is explained by the independent variables. Alkalinity is responsible for the decrease of total hardness in the model. This occurred mainly because there was a significant removal of this parameter by the UF membrane –

61.08% in the experiment 1, and 34.63% on the experiment 2 – altering the multiple regression model when compared to the previous collection point.

Table 2.7 - Results of multiple linear regression for UF2.

Model (a)		*ρ-value*	Model (b)		*ρ-value*
Intercept	-182.43		Intercept	-463.00	
EC	0.84	$3.21 \cdot 10^{-6}$	EC	0.91	$3.91 \cdot 10^{-12}$
Temp.	-5.59	0.001	Temp.	-0.13	$1.43 \cdot 10^{-9}$
TDS = -182.43 + 0.84·EC - 5.59·T			TDS = -463.00 + 0.91·EC - 0.13·T		
Model (c)		***ρ-value***	**Model (d)**		***ρ-value***
Intercept	936.94		Intercept	-3,118.54	
Calcium	2.27	0.013	Calcium	9.88	0.015
Alkalinity	-24.77	0.015	Alkalinity	-55.78	0.031
TH = 936.94 + 2.27·Ca - 24.77·A			TH = -3,118.54 + 9.88·Ca - 55.78·A		

Source: The author (2019).
Notes: (a) (c) regressions related to the experiment 1; (b) (d) regressions related to the experiment 2.

Table 2.8 presents the Pearson correlation matrix for the remaining parameters of water quality, in the UF2 collection point (UF permeate).

Table 2.8 - Pearson correlation matrix for UF2.

(a)	TDS	Conductivity	Turbidity	Alkalinity	Hardness	Calcium	Sulphate	Chloride	pH	Temperature
TDS	1.00									
Conductivity	0.95	1.00								
Turbidity	0.01	0.10	1.00							
Alkalinity	-0.33	-0.39	0.28	1.00						
Hardness	-0.23	-0.28	-0.34	-0.61	1.00					
Calcium	-0.13	-0.08	-0.53	-0.55	0.68	1.00				
Sulphate	-0.51	-0.58	0.42	0.48	-0.72	-0.67	1.00			
Chloride	0.40	0.47	0.17	-0.59	0.53	0.20	0.16	1.00		
pH	0.12	0.19	-0.61	0.49	0.35	0.49	-0.56	0.39	1.00	
Temperature	0.35	0.44	-0.20	-0.45	0.60	0.07	-0.40	0.47	-0.15	1.00

(b)	TDS	Conductivity	Turbidity	Alkalinity	Hardness	Calcium	Sulphate	Chloride	pH	Temperature
TDS	1.00									
Conductivity	0.91	1.00								
Turbidity	0.45	0.31	1.00							
Alkalinity	-0.24	-0.12	0.03	1.00						
Hardness	-0.01	-0.06	0.10	-0.64	1.00					
Calcium	-0.22	-0.22	-0.33	-0.59	0.73	1.00				
Sulphate	-0.39	-0.49	0.34	0.15	-0.55	-0.39	1.00			
Chloride	0.60	0.59	0.45	-0.25	0.24	0.14	0.07	1.00		
pH	0.41	-0.18	-0.51	0.54	0.40	0.47	-0.22	0.29	1.00	
Temperature	0.39	0.48	-0.36	-0.27	0.11	0.30	-0.06	0.35	-0.40	1.00

Source: The author (2019).
Notes: (a)experiment 1; (b) experiment 2.

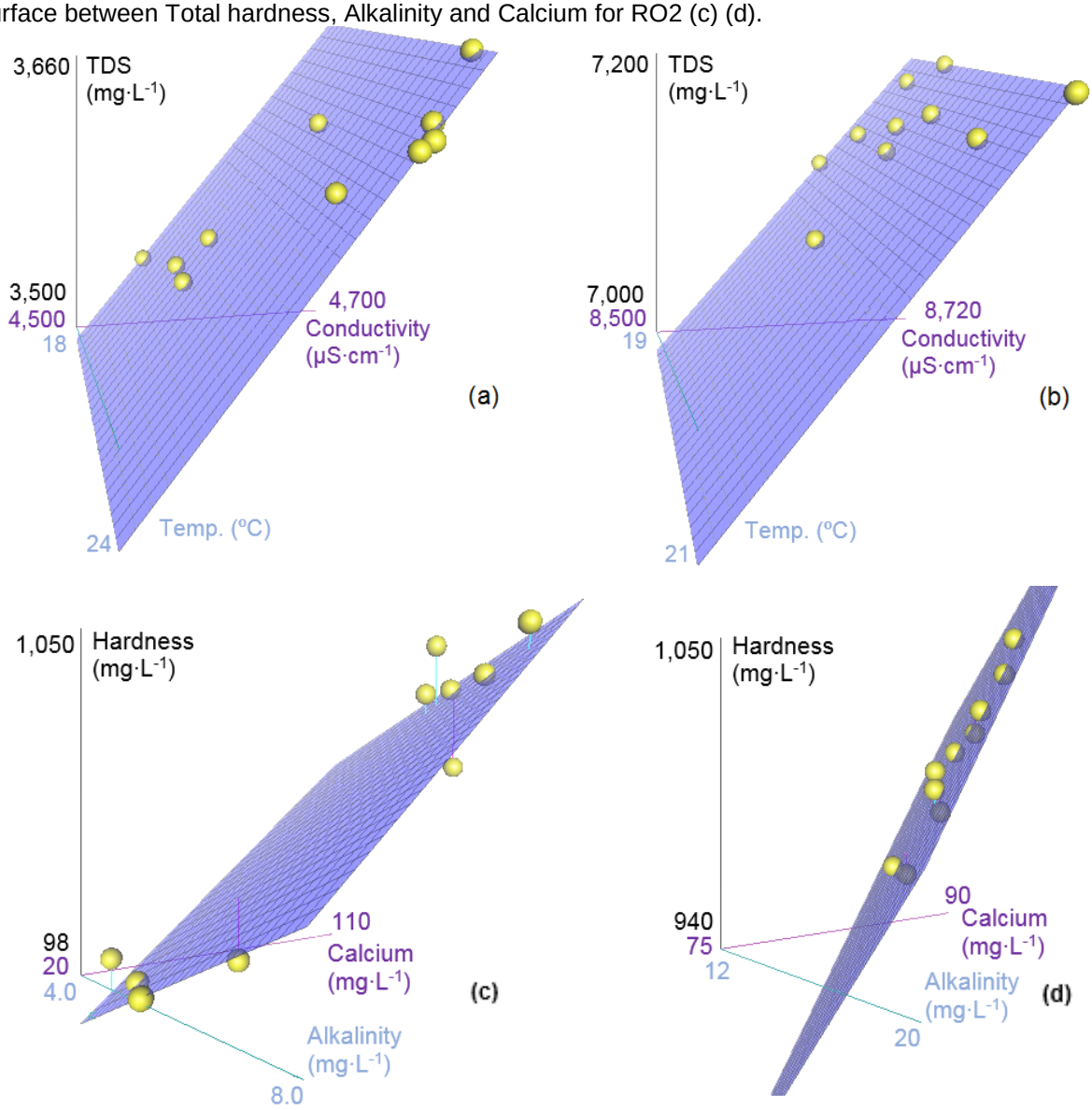
As shown in table 2.8, there was an expressive correlation between TDS and EC ($R \geq 0.95$) in both experiments. This means that the higher the concentration of dissolved salts, the greater the ability of this solution to conduct electricity. Total hardness and calcium presented positive correlation ($R \geq 0.68$). For total hardness and alkalinity the correlation obtained negative value ($R \leq -0.61$), thus indicating an inverse proportion between the parameters.

2.3.4 RO2 collect point

Figure 2.6 shows the regression surface, for the parameters analyzed in order to check the performance of the softeners in the RO2 collection point.

Figure 2.6 (c) shows that the softener performance was not the same for every operation day. This occurred mainly because the regeneration was conducted every 8 operation hours in the experiment 1.

Figure 2.6 - Regression surface between TDS, EC and Temperature for RO2 (a) (b); Regression surface between Total hardness, Alkalinity and Calcium for RO2 (c) (d).



Source: The author (2019).
Notes: (a) (b) Results obtained in the experiment 1; (c) (d) Results obtained in the experiment 2.

The softener system lost removal efficiency after 3 hours of operation from the total hardness values. Only in the experiment 2 the regeneration was conducted after each daily operation.

Table 2.9 shows that the (a) and (b) models are similar when compared to the previous analysis points. The set of independent variables explain 99.86% and 99.82% of the variance for the dependent variable, for the experiments 1 and 2, respectively.

Table 2.9 - Results of multiple linear regression for RO2.

Model (a)		*ρ-value*	Model (b)		*ρ-value*
Intercept	-126.59		Intercept	-550.48	
EC	0.82	$1.16 \cdot 10^{-9}$	EC	0.91	$7.36 \cdot 10^{-11}$
Temp.	-5.33	$2.93 \cdot 10^{-5}$	Temp.	-12.38	$4.25 \cdot 10^{-8}$
TDS = -126.59 + 0.82·EC - 5.33·T			TDS = -550.48 + 0.91·EC - 12.38·T		
Model (c)		*ρ-value*	Model (d)		*ρ-value*
Intercept	-768.38		Intercept	-1341.37	
Calcium	7.80	0.004	Calcium	24.09	0.001
Alkalinity	121.95	0.002	Alkalinity	18.67	0.001
TH = -768.38 + 7.80·Ca + 121.95·A			TH = -1341.37 + 24.09·Ca + 18.67·A		

Source: The author (2019).
Notes: (a) (c) regressions related to the experiment 1; (b) (d) regressions related to the experiment 2.

The softener's behavior can be seen in the (c) and (d) models. Although not all the necessary regenerations were executed in the experiment 1, the behavior of the models was similar for both cases.

Table 2.10 - Pearson correlation matrix for OR2.

(a)	TDS	Conductivity	Turbidity	Alkalinity	Hardness	Calcium	Sulphate	Chloride	pH	Temperature
TDS	1.00									
Conductivity	0.99	1.00								
Turbidity	0.39	0.42	1.00							
Alkalinity	-0.47	-0.42	0.38	1.00						
Hardness	-0.42	-0.31	-0.16	0.74	1.00					
Calcium	-0.36	-0.33	-0.22	0.79	0.74	1.00				
Sulphate	-0.38	-0.35	-0.37	0.80	0.75	0.96	1.00			
Chloride	0.35	0.36	0.30	-0.17	-0.14	0.25	-0.29	1.00		
pH	0.08	0.03	-0.41	0.05	-0.35	0.20	-0.30	0.07	1.00	
Temperature	0.43	0.55	0.41	-0.78	-0.58	-0.45	-0.48	0.31	-0.10	1.00

(b)	TDS	Conductivity	Turbidity	Alkalinity	Hardness	Calcium	Sulphate	Chloride	pH	Temperature
TDS	1.00									
Conductivity	0.92	1.00								
Turbidity	0.19	0.22	1.00							
Alkalinity	-0.28	-0.31	0.40	1.00						
Hardness	-0.33	-0.40	0.01	0.76	1.00					
Calcium	-0.27	-0.24	-0.30	0.61	0.78	1.00				
Sulphate	-0.23	-0.25	-0.15	0.60	0.74	0.93	1.00			
Chloride	0.32	0.25	0.51	0.43	-0.28	0.20	0.46	1.00		
pH	-0.05	-0.27	0.29	0.68	-0.45	0.48	0.52	0.61	1.00	
Temperature	-0.04	0.36	0.16	-0.25	-0.31	-0.29	-0.14	0.05	-0.48	1.00

Source: The author (2019).
Notes: (a)experiment 1; (b) experiment 2.

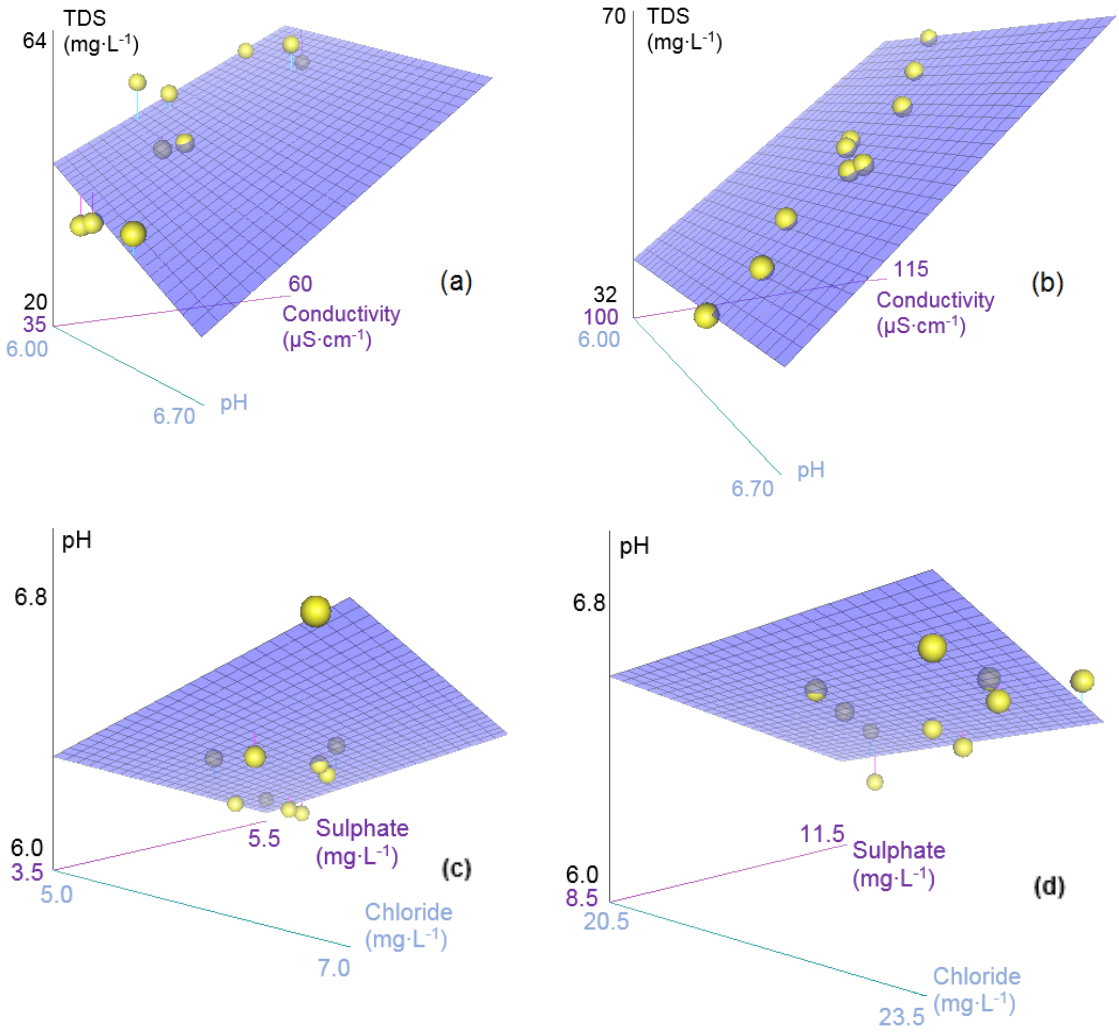
The independent parameters alkalinity and calcium explain 91.41% and 95.51% of the total hardness variance. The correlation matrix presented in Table 2.10 shows that the sulfate had positive correlations with alkalinity (R ≥ 0.60), total hardness (R ≥ 0.74) and calcium (R ≥ 0.93).

2.3.5 RO4 collect point

Figure 2.7 shows the multiple regression parameters analyzed in the collection point located after the RO.

There was decrease in the TDS whenever there was positive variation of pH, for the (a) and (b) models, as shown in Table 2.11.

Figure 2.7 - Regression surface between TDS, EC and pH for RO4 (a) (b); Regression surface between pH, Sulphate and Chloride for RO4 (c) (d).



Source: The author (2019).
Notes: (a) (b) Results obtained in the experiment 1; (c) (d) Results obtained in the experiment 2.

The opposite was observed regarding to the EC. How the greater is EC values, the greater will be the TDS values. The variability, 89.30% and 99.99%, of the TDS can be explained by the EC and pH.

When the sulphate concentration rises, the pH values decrease, to a 5% significance level, for (c) and (d) models; and when chloride increases, pH also increases. The variance, 91.44% and 75.88% for pH is explained by the independent variables, sulphate and chloride.

Table 2.11 - Results of multiple linear regression for RO4.

Model (a)		*ρ-value*	Model (b)		*ρ-value*
Intercept	34.07		Intercept	1.93	
EC	0.47	0.001	EC	0.63	$1.13 \cdot 10^{-9}$
pH	-4.32	0.009	pH	-0.05	0.043
TDS = 34.07 + 0.47·EC - 4.32·pH			TDS = -1.93 + 0.63·EC - 0.05·pH		
Model (c)		*ρ-value*	Model (d)		*ρ-value*
Intercept	6.74		Intercept	6.81	
Sulphate	-3.35	0.019	Sulphate	-0.13	0.027
Chloride	0.17	0.017	Chloride	0.05	0.032
pH = 6.74 - 3.35·S + 0.17·Ch			pH = 6.81 - 0.13·S + 0.05·Ch		

Source: The author (2019).
Notes: (a) (c) regressions related to the experiment 1; (b) (d) regressions related to the experiment 2.

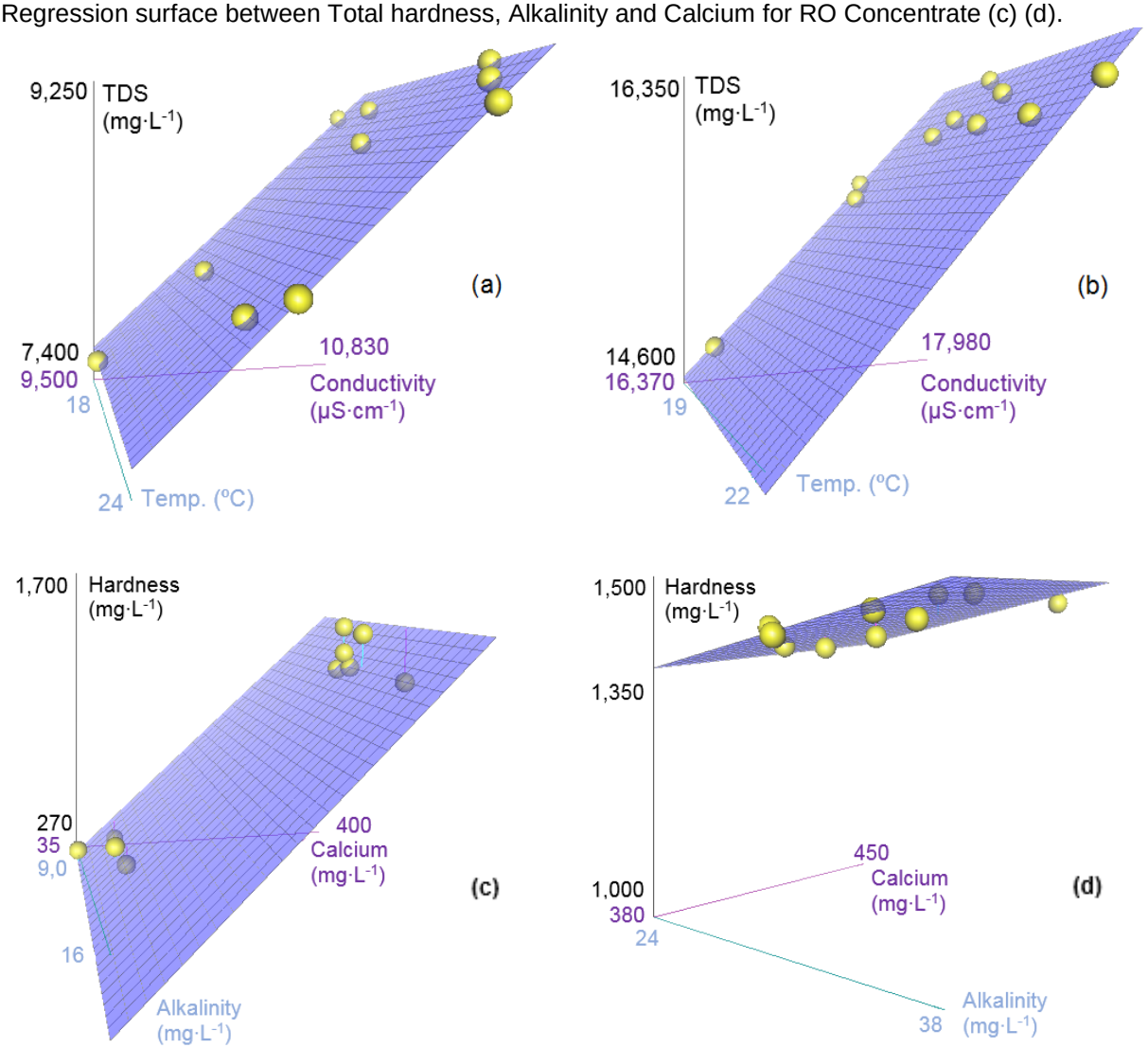
Only the TDS and EC parameters presented significant Pearson correlation at this collection point ($R \geq 0.86$).

2.3.6 Saline concentrate point of analysis

Figure 2.8 shows the multiple regression for the parameters of RO concentrate.

The increase of the independent variable EC results in the increase of the TDS, as shown in table 2.12, (a) and (b) models. With increase in the temperature, there was decrease in the dependent variable, TDS. The multiple correlation coefficient indicates strong relationship between the dependent variable and independent variables. These models explain the variance of TDS values (99.99%).

Figure 2.8 - Regression surface between TDS, EC and Temperature for RO Concentrate (a) (b); Regression surface between Total hardness, Alkalinity and Calcium for RO Concentrate (c) (d).



Source: The author (2019).
Notes: (a) (b) Results obtained in the experiment 1; (c) (d) Results obtained in the experiment 2.

Table 2.12 - Results of multiple linear regression for RO Concentrate.

Model (a)		*ρ-value*	Model (b)		*ρ-value*
Intercept	-669.90		Intercept	-2728.00	
EC	0.93	$3.76 \cdot 10^{-15}$	EC	1.10	$3.55 \cdot 10^{-9}$
Temp.	-13.54	$3.32 \cdot 10^{-6}$	Temp.	-36.24	$1.01 \cdot 10^{-14}$
TDS = -669.90 + 0.93·EC - 13.54·T			TDS = -2728.00 + 1.10·EC - 36.24·T		
Model (c)		*ρ-value*	Model (d)		*ρ-value*
Intercept	588.87		Intercept	224.81	
Calcium	-47.66	0.005	Calcium	0.21	0.010
Alkalinity	4.44	0.034	Alkalinity	0.01	0.021
TH = 588.87 - 47.66·Ca + 4.44·A			TH = 224.81 + 0.21·Ca + 0.15·A		

Source: The author (2019).
Notes: (a) (c) regressions related to the experiment 1; (b) (d) regressions related to the experiment 2.

For the (c) and (d) models, the behavior of the regression surface was different because the independent variable (calcium) influences inversely in the dependent variable (total hardness), in the (c) model and directly in the (d) model. Correlation coefficients of 89.54% and 80.47% explain the total hardness variability, in the experiment 1 and 2, respectively.

Table 2.13 shows that there was a Pearson correlation, in both experiments, between TDS and EC (R = 1.00). The parameters alkalinity, total hardness and calcium also had expressive correlation.

Table 2.13 - Pearson correlation matrix for RO Concentrate.

(a)	TDS	Conductivity	Turbidity	Alkalinity	Hardness	Calcium	Sulphate	Chloride	pH	Temperature
TDS	1.00									
Conductivity	1.00	1.00								
Turbidity	0.42	0.53	1.00							
Alkalinity	-0.03	-0.06	-0.31	1.00						
Hardness	-0.18	-0.21	-0.34	0.74	1.00					
Calcium	-0.17	-0.19	-0.37	0.79	0.77	1.00				
Sulphate	0.56	0.55	0.31	0.49	0.37	0.09	1.00			
Chloride	0.60	0.58	-0.06	0.36	0.30	0.26	0.56	1.00		
pH	0.60	0.59	0.42	0.08	0.28	0.21	0.47	0.30	1.00	
Temperature	0.04	0.09	0.19	-0.49	-0.62	-0.54	0.52	-0.33	0.11	1.00

(b)	TDS	Conductivity	Turbidity	Alkalinity	Hardness	Calcium	Sulphate	Chloride	pH	Temperature
TDS	1.00									
Conductivity	1.00	1.00								
Turbidity	0.29	0.33	1.00							
Alkalinity	-0.07	-0.11	-0.27	1.00						
Hardness	-0.12	-0.15	-0.16	0.69	1.00					
Calcium	-0.30	-0.33	-0.14	0.58	0.67	1.00				
Sulphate	0.55	0.56	0.09	0.56	0.45	0.17	1.00			
Chloride	0.41	0.40	-0.57	0.22	0.01	0.18	0.43	1.00		
pH	-0.27	-0.30	0.45	0.44	0.31	0.45	0.47	0.15	1.00	
Temperature	0.23	0.26	0.17	-0.19	-0.29	-0.49	0.50	0.12	0.42	1.00

Source: The author (2019).
Notes: (a) experiment 1; (b) experiment 2.

2.3.7 Operational conditions

Table 2.14 shows the Pearson correlations for both experiments. There was positive correlation between all operational parameters, in the experiment 1 and 2.

The osmotic pressure presented positive correlation with the inflow (R ≥ 0.85), RO permeate (R ≥ 0.88), RO concentrate (R ≥ 0.80), recovery rate (R ≥ 0.85) and filtration rate (R ≥ 0.88).

The RO inflow presented correlation with the RO permeate (R ≥ 0.92), RO concentrate (R ≥ 0.83), recovery rate (R ≥ 0.91) and filtration rate (R ≥ 0.92).

Table 2.14 - Pearson correlation matrix for RO operational conditions.

(a)	Inflow	Permeate	Concentrate	Recovery rate	Filtration rate	Pressure
Inflow	1.00					
Permeate	1.00	1.00				
Concentrate	0.98	0.96	1.00			
Recovery rate	0.97	0.98	0.91	1.00		
Filtration rate	1.00	1.00	0.96	0.98	1.00	
Pressure	0.96	0.97	0.90	0.95	0.97	1.00

(b)	Inflow	Permeate	Concentrate	Recovery rate	Filtration rate	Pressure
Inflow	1.00					
Permeate	0.92	1.00				
Concentrate	0.83	0.86	1.00			
Recovery rate	0.91	0.96	0.88	1.00		
Filtration rate	0.92	1.00	0.93	0.94	1.00	
Pressure	0.85	0.88	0.80	0.85	0.88	1.00

Source: The author (2019).
Notes: (a)experiment 1; (b) experiment 2.

2.4 CONCLUSIONS

In the models, where the TDS dependent variable was related to the independent variables EC and temperature, similar behaviors were found in the points BW (R^2 = 97.48%; 99.61%), UF1 (R^2 = 79.54%; 99.35%), UF2 (R^2 = 98.07%; 99.93%), RO2 (R^2 = 99.86%; 99.82%) and, Conc. (R^2 >99.99%).

This shows that these variables were directly related until the treatment by the RO membranes, where it was verified that the pH and EC presented more significant values to explain the TDS – RO4 variability (R^2 = 89.30%; 99.99%).

When total hardness, dependent variable, was related to the alkalinity and calcium independent variables, there was relation in the points: BW (R^2 = 74.79%; 88.17%), UF2 (R^2 = 76.56%; 78.93%), RO2 (R^2 = 91.41%; 95.51%) and Conc. (R^2 = 89.54%; 80.47%). This indicates the relation during the pretreatment and in the RO concentrate.

There was positive correlation between turbidity and color (R = 75%) in the BW point. However, in the UF1 point, the turbidity variability is explained by the color values and PAC dosage (R^2 = 84.48%; 91.48%). There was influence of the coagulant addition in the pretreatment process. It was verified positive correlation of Pearson among all operational parameters in the experiment 1 and 2, with respect to the parameters of the RO system. This means that when there is increase in a certain parameter, there will necessarily be increase the other operating parameters.

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APPENDIX – RESULTS OBTAINED IN THE EXPERIMENTS 1 AND 2

Table A.1 - Average results of the quality and operating parameters of the system.

(continue).

Points	Parameters	Mean ± SD Experiment 1	Experiment 2
Operation	RO permeate (m^3/h)	0.96 ± 0.21	0.94 ± 0.03
	RO concentrate (m^3/h)	0.75 ± 0.07	0.85 ± 0.02
	Recovery rate (%)	55.97 ± 3.48	52.65 ± 0.77
	Filtration rate ($L/h/m^2$)	22.82 ± 5.06	22.41 ± 0.79
	Osmotic pressure (kgf/cm^2)	10.08 ± 1.81	13.06 ± 0.25
BW	TDS (mg/L)	3,541.03 ± 23.01	7,028.97 ± 30.36
	EC (µS/cm)	4,583.57 ± 41.05	8,558.73 ± 33.66
	Turbidity (NTU)	5.54 ± 0.48	5.20 ± 0.62
	Color (Pt-Co)	44.27 ± 3.84	34.97 ± 2.40
	Alkalinity (mg/L)	15.99 ± 2.01	24.62 ± 1.52
	T. Hardness (mg/L)	1,276.58 ± 51.49	3,356.01 ± 190.03
	Calcium (mg/L)	241.52 ± 15.63	767.85 ± 24.17
	Sulphate (mg/L)	266.62 ± 33.96	495.14 ± 15.76
	Chloride (mg/L)	1,307.93 ± 26.54	3,381.89 ± 70.77
	pH	6.88 ± 0.09	7.21 ± 0.04
	Temperature (ºC)	20.35 ± 2.41	20.27 ± 1.16
UF1	TDS (mg/L)	3,559.13 ± 20.32	7,046.17 ± 30.71
	EC (µS/cm)	4,609.67 ± 41.97	8,577.17 ± 30.11
	Turbidity (NTU)	9.33 ± 0.70	9.47 ± 0.88
	Color (Pt-Co)	53.80 ± 3.91	41.10 ± 3.08
	pH	6.48 ± 0.11	6.87 ± 0.08
	Temperature (ºC)	20.36 ± 2.44	20.22 ± 1.09

Source: The author (2019).

Table A.1 - Average results of the quality and operating parameters of the system.

(continuation).

Points	Parameters	Mean ± SD Experiment 1	Experiment 2
UF2	TDS (mg/L)	3,564.53 ± 24.96	7,045.77 ± 30.69
	EC (µS/cm)	4,613.10 ± 42.53	8,577.70 ± 32.53
	Turbidity (NTU)	0.34 ± 0.01	0.33 ± 0.02
	Color (Pt-Co)	0.01 ± 0.00	0.01 ± 0.00
	Alkalinity (mg/L)	6.30 ± 0.96	18.81 ± 1.28
	T. Hardness (mg/L)	1,253.34 ± 48.32	3,336.76 ± 192.26
	Calcium (mg/L)	213.68 ± 9.56	740.58 ± 10.65
	Sulphate (mg/L)	234.21 ± 24.27	466.83 ± 19.29
	Chloride (mg/L)	1,344.60 ± 16.15	3,463.56 ± 110.08
	pH	6.46 ± 0.16	6.80 ± 0.09
	Temperature (ºC)	20.49 ± 2.42	20.28 ± 1.01
RO2	TDS (mg/L)	3,591.53 ± 42.49	7,141.57 ± 33.25
	EC (µS/cm)	4,644.97 ± 63.83	8,688.67 ± 38.93
	Turbidity (NTU)	0.36 ± 0.02	0.34 ± 0.02
	Color (Pt-Co)	0.01 ± 0.00	0.01 ± 0.00
	Alkalinity (mg/L)	6.26 ± 0.89	15.82 ± 0.97
	T. Hardness (mg/L)	604.55 ± 423.32	994.71 ± 36.05
	Calcium (mg/L)	76.99 ± 40.18	82.27 ± 0.88
	Sulphate (mg/L)	227.82 ± 9.80	449.91 ± 3.79
	Chloride (mg/L)	1,227.65 ± 21.47	3,259.31 ± 66.67
	pH	6.43 ± 0.19	6.78 ± 0.14
	Temperature (ºC)	20.42 ± 2.25	20.62 ± 1.15
RO4	TDS (mg/L)	27.12 ± 2.90	66.89 ± 2.73
	EC (µS/cm)	42.26 ± 4.78	105.22 ± 4.37
	Turbidity (NTU)	0.27 ± 0.02	0.25 ± 0.03
	Color (Pt-Co)	0.01 ± 0.00	0.01 ± 0.00
	Alkalinity (mg/L)	1.59 ± 0.24	1.70 ± 0.10
	T. Hardness (mg/L)	1.35 ± 0.06	2.40 ± 0.15
	Calcium (mg/L)	0.01 ± 0.00	0.01 ± 0.00
	Sulphate (mg/L)	4.26 ± 0.26	9.45 ± 0.53
	Chloride (mg/L)	5.78 ± 0.54	22.20 ± 1.21
	pH	6.25 ± 0.18	6.51 ± 0.12
	Temperature (ºC)	20.61 ± 2.45	20.63 ± 0.86

Source: The author (2019).

Table A.1 - Average results of the quality and operating parameters of the system.

(conclusion).

Points	Parameters	Mean ± SD	
		Experiment 1	Experiment 2
Conc.	TDS (mg/L)	8,558.97 ± 668.28	15,825.00 ± 477.79
	EC (µS/cm)	10,219.37 ± 720.85	17,501.67 ± 451.50
	Turbidity (NTU)	0.34 ± 0.03	0.39 ± 0.02
	Color (Pt-Co)	0.23 ± 0.09	0.20 ± 0.05
	Alkalinity (mg/L)	12.76 ± 1.89	30.93 ± 3.88
	T. Hardness (mg/L)	1,011.47 ± 607.71	1,424.89 ± 38.91
	Calcium (mg/L)	241.64 ± 147.15	407.32 ± 9.96
	Sulphate (mg/L)	518.51 ± 43.68	1,012.54 ± 42.16
	Chloride (mg/L)	3,776.80 ± 494.07	7,290.43 ± 217.24
	pH	6.50 ± 0.20	6.96 ± 0.12
	Temperature (ºC)	20.46 ± 2.57	20.66 ± 1.04

Source: The author (2019).