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# Designing an advanced electrodialysis water treatment system to produce drinking water.

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***Abstract- The semi-arid climate conditions in the Chanduy community, province of Santa Elena (Ecuador), coupled with a significant deficit in drinking water coverage, are leading to severe water shortages. New approaches are needed to reduce the high natural water salinity, thus increasing the overall water availability in this area. This research aims to evaluate an advanced water treatment technology named "Electrodialysis" for desalination to meet the population's basic needs and promote the community's economic development. Surface and groundwater samples were collected to characterize the in-situ physicochemical parameters and major ions. The electrodialysis technology has decreased the total dissolved solids (TDS) concentration to the threshold values of 500- 600 mg/L, recommended by the World Health Organization (WHO) for consumption purposes. The system presented a low energy consumption (0.72 kWh/m³), resulting in a low treatmentcost of USD 0.07 per m³. The optimal operational condition of the electrodialysis system was 6 V arranged in a stack of 6 cell pairs to desalinate 500 mL of synthetic water in 30 minutes. Thiswork contributes to achieving the Sustainable Development Goals N° 6 "Clean Water and Sanitation" and N° 11 "Sustainable Cities and Communities" in semi-arid water scarcity areas.***

***Keywords- Desalination, electrodialysis, advanced water treatment, energy consumption.***

## I. INTRODUCTION

Water constitutes 71% of the earth's surface, including 97.5% seawater and 2.5% freshwater, from which 0.8% is used for consumption [1]. Population growth increases the worldwide need for more water resources. Many rural communities in arid and semi-arid climates rely on high salinity water and overall brackish conditions. This fact challenges the development of advanced treatments for water desalination [2]. Desalination is currently a boosting alternative for producing drinking water from non-polluting solar energy, especially in coastal cities, as a cost-effective and sustainable source [3]. Most current desalination treatment methods include evaporation-condensation, multi-stage distillation, membrane separation, reverse osmosis, electrocoagulation, and electrodialysis, each with advantages and disadvantages concerning the location and type of water to be treated [4]. The advanced treatment processes are reverse osmosis to desalinate high salt-containing water and electrodialysis to desalinate brackish water. For example, reverse osmosis technology is more efficient for treating water with electrical conductivity (EC) greater than 15000 µS/cm. The recovery rate of water treated with reverse osmosis technology is around 15 to 18% without optimization, and this treatment system operates at high pressures exceeding 10 bar [5].

The electrodialysis process efficiently treats water with low EC, below 4000 µS/cm. Its technology uses anion and cation exchange membranes that generate a permeate (treated water) and a concentrate (rejection) flowchannel. Voltages are applied as saline water flows throughthe flow channels; thus, an electric field is generated internally, causing the ions in the media to migrate toward the oppositely charged electrode. Thereby desalinating the effluent known as "permeate" or "treated water".

The largest plants used for desalination worldwide are found in countries with scarce water. This is caused by a shortage of rainfall, often due to climate change. Another factor is population growth. Israel, Libya, Kuwait, Qatar, Japan, Spain, and the United States are countries where a desalination plant consumes 4 out of every 5 liters of water. The largest is in Sorek, Israel, andwas inaugurated in 2013. This plant operates by reverse osmosis using IDE membrane desalination technology. It can produce 624,000 m³/day [6].

In recent years, electrodialysis has been used to desalinate brackish water and as a metal recovery method in several European countries. For example, the recovery of Zn in the steel galvanizing industry is essential and depends on primary extraction to obtain it. The recovery ofZn with two pairs of membranes was studied by applying 10 V, achieving 97% within 25 minutes of treatment [7].

One of the pilot plants implemented in the world was developed by the company Hangzhou Lanran Technology in China. The device had a stack of 40x20 cm and an effective area of 518.5 cm². It had 40 pairs of anion exchange membranes and 41 cation exchange membranes, where the volume of the concentrate, dilute, and electrolyte tank was 10 L [8].

The first application of an advanced water treatment system in Ecuador was in 2020 on Puná Island, Guayas province, to produce drinking water from the seawater via the osmosis system [9]. This solution was deployed to alleviate the shortage and quality of water unsuitable for human consumption extracted from shallow wells. Despite implementing advanced water treatment systems for desalination purposes, these technologies are very limited in other ruralcommunities without drinking water.

One of the best alternatives for desalination in isolated areas with brackish water is the electrodialysis technique because the low voltage consumption allows the implementation of photovoltaic solar panels, representing a sustainable and economical technology that is easy to maintain [10].

The Chanduy, Santa Elena province community hasa limited number of intermittent surface water bodies; therefore, precipitation is often used as a water source [11]. Since this community is on the outskirts of Santa Elena province, only 24.4% of the population is connected to the drinking water distribution network. In contrast, tankers supply 28.4%, and 47.2% obtain water fromgroundwater sources [12]. These groundwater sources present high salinity levels, with TDS concentrations ranging from 1500-12000 mg/L, while the World Health Organization established that drinking water should not exceed 600 mg/L of TDS [13]. This work aims to produce drinking water in terms of TDS by designing an advanced electrodialysis water treatment system to obtain drinking water for the Chanduy community.

## II. METHODOLOGY

### A. Field sampling

The study was conducted in the Zapotal River watershed, part of the community of Chanduy. Thefield visit to the Zapotal River basin was conducted during the dry season in September 2022. Physicochemical indicators of water quality, such as pH, temperature, electrical conductivity (EC), and TDS, were monitored in situ at the 9 points using the HACH HQ40D portable multiparameter calibrated against pH and EC standards. Samples were transported and refrigerated following the guidelines of the Ecuadorian technical document INEN 2169 [14].

### B. Hydrochemical analyses

Analyses of major ions were carried out to identify the water quality and classify the hydrochemical facies at each water sampling point. The measurements of major ions $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $Cl^{-}$, $SO^{2-}$, $HCO^{3-}$, $NO^{-}$, were carried out at the ESPOL Polytechnic University laboratory through titration and UV-Vis spectrophotometric methods (HACH DR 3900). Standards were used to adjust the spectrophotometric measurements before each test.

### C. Electrodialysis system

The electrodialysis technology comprised a stack through which an external voltage was applied under potentiostatic conditions. The electrical field is coupled with the anion and cation exchange membrane and formed inside the system; it thus allows the ions to migrate to the opposite side of the electrode, separating two flows, the concentrate and permeate. The flow was recirculated to reach the targeted TDS concentration. Fig. 1 shows the principal components of the bench-lab electrodialysis set-up, the synthetic solution with different EC concentrations, the peristaltic pump (dosing pump), the stack with cathode and anode electrodes (64 $cm^2$ of area), and the D.C. power supply.

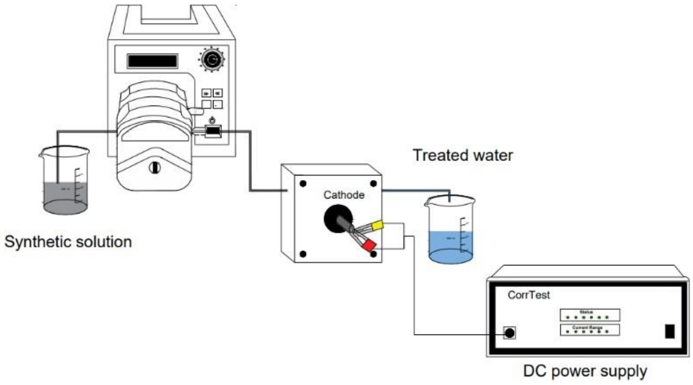


Fig. 1 Schematic of the advanced electrodialysis water treatment system used to produce drinking water.

Six cell pairs and spacers were used to configure the electrodialysis stack. One cell pair consisted of a cation exchange membrane (CEM), followed by a spacer and an anion exchange membrane (AEM). Fig. 2 depicts the set-up of the electrodialysis stack. The gaskets were placed next to the electrode plates to not mix the electrolyte solution with the synthetic water sample. The gaskets served to seal the stack. Bolts with their respective nuts were used to prevent water leaks.

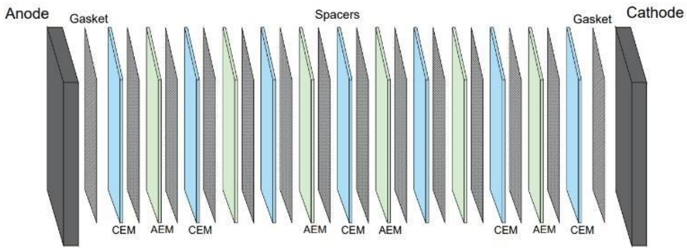


Fig. 2 Internal arrangement of the anionic and cationic exchange membranes (six pairs) within the electrodialysis water treatment system

### D. Synthetic sample preparation and electrodialysis procedure

Synthetic water samples (raw water) were prepared according to the TDS concentration of the water in the sector under study using table salt (NaCl). The EC value reported in situ was 3000 µS/cm. The $Na_2SO_4$ electrolyte solution was prepared to reach an EC value of 1500 µS/cm.

Before each experiment, bubbles were removed from the pipes (diameter of 0.17 cm), where synthetic water was recirculated. The electrolyte solution was pumped using a submersible pump. The raw water was pumped using a calibrated peristaltic pump (Landto Tech, BT600F) to ensure the dose of a constant flow rate.

The calibration of the peristaltic pump consists of choosing a constant flow rate of 100 mL/min, to check this, the flow rate at the outlets is measured, reaching 100 mL/min, achieving the calibration of the equipment.

The experiments were performed with 500 mL of synthetic water, applying different voltages of 10, 8, 6, and 4 V, with a 100 mL/min flow rate.

# III. RESULTS

Fig. 3 presents the EC results measured at the points sampled in the study area. The EC varied between 109 to 3250 µS/cm, and the TDS between 49.4 to 1709 mg/L. The size of the symbology of the sampled points refers to the amount of electrical conductivity present in the study site, that is, the larger the symbol, the sector has a higher EC concentration. Both rivers and groundwater have similar EC concentrations with a range of 2000-3500 µS/cm. Nevertheless, the highest EC values corresponded to groundwater, which is affected by water-rock interaction. In addition, river water is often stagnant and exposed to evaporation, increasing the salinity in water. Other researchers have proven that a high salinity content in groundwater is not always expected, Patni et al. [15] reported very low EC values ranging between 200 and 500 µS/cm from groundwater in cold climate regions, while Prakash et al. [16], the measured electrical conductivities ranged between from excellent quality with a 765 µS/cm and unsuitable quality with 4896 µS/cm. Lower ECs measured in the study area corresponded to superficial water conveyed from the Daule River through the Chongón San Vicente irrigation canal. The area presented high TDS and EC; therefore, the use of advanced treatment systems is required to desalinize the water to meet the salinity thresholds established by the World Health Organization (WHO) for drinking water (600 mg/L TDS and 800 µS/cm EC, respectively) [13].

Is important to consider a pre-treatment stage before deploying the electrodialysis process. Pre-treatment mechanisms such as coagulation-flocculation of the organic and colloidal matter, granular filtration with sand and activated carbon, and even ultrafiltration can be applied to improve the performance of the electrodialysis and promote a longer life span of the selective membranes.

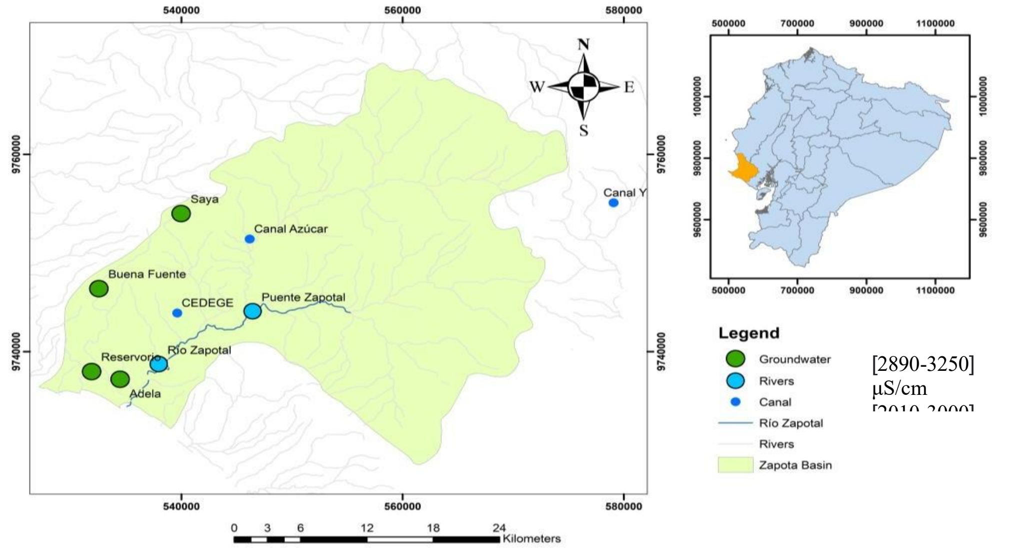


Fig. 3 Map of the sampling points from the study area showing electrical conductivities measured in situ in surface and underground water bodies.

Fig. 4 presents the Stiff diagram of the surface water samples collected in canals. Similar behavior can be observed in the Y, CEDEGE, and Azúcar canals. It reveals that the surface water of the irrigation canal has approximately 2 mEq/L of bicarbonate and 1 mEq/L of calcium. Due to the low concentrations of ions, it can be concluded that these waters are fresh and of the calcium bicarbonate type.

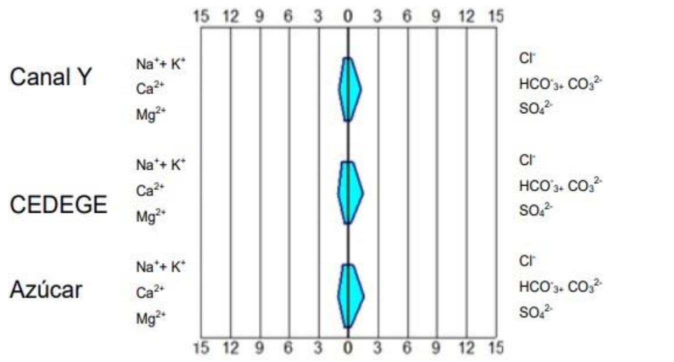


Fig 4. The Stiff diagram of the samples from the irrigation canal water. The hydrochemical composition is presented.

The Stiff diagram of streamwater and groundwater samples is shown in Fig. 5. The streamwater point Rio Zapotal point presents similarity with a groundwater source, Adela, in concentrations of $Na^+$ ions of about 45 mEq/L, in addition to the content of $SO_4^{2-}$ classifying them as chloride, sulfate-sodium water. Buena Fuente, a groundwater point in addition to high concentrations of $Cl^-$ (29 mEq/L), presents similar concentrations of $Na^+$ and $Mg^{2+}$ (approximately 24 mEq/L); thus, this source of water presented a chloride-sulfate-sodium-magnesium hydrochemical facies. Finally, water samples from points such as Reservorio, Puente Zapotal, and Saya are of the sodium chloride type. Reservorio presented concentrations of approximately 18 and 20 mEq/L in $Cl^-$ and $Na^+$, respectively. At the same time, Puente Zapotal and Saya have $Cl^-$ concentrations ranging from 24 to 27 mEq/L and approximately 25 mEq/L of $Na^+$.

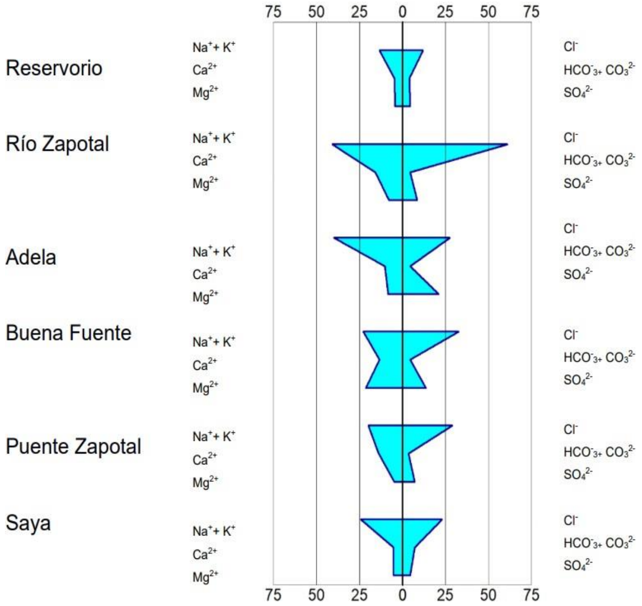


Fig. 5 Hydrochemical facies of sampled surface and groundwater from Zapotal Basin.

Fig. 6 shows the variation of EC versus desalination time for treating 500 mL of water at a flow rate (Q) of 100 mL/min and 50% recovery. To establish the adequate flow rate that circulates over the stack, it was analyzed that increasing the flow rate improves the mass transfer. However, the elimination of salts is decreased, for which a Q of 100 mL/min was established, which allowed a comparison between the velocity of the passage of the fluid and the residence time in the stack. The desalination rates were 126.96 and 119.82 µS/cm/min when applying 10 and 8 V, respectively. No significant difference in desalination rateswas observed despite the increase of the voltage from 8 to 10 V. In both cases, a concentration of 800 µS/cm or 500 mg/L was reached in approximately 20 min of electrodialysis. The application of6 V to the electrodialysis system produced a desalination rate of 73.11 µS/cm/min in an experimental time of 30 min.Application of 4 V to the electrodialysis system increased the desalting time approximately twofold, e.g., 75 min, resulting from the low desalting rate of 28.42 µS/cm/min.

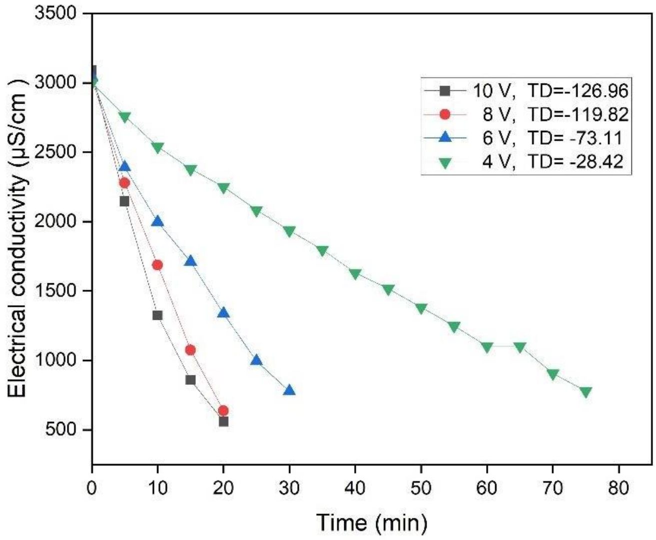


Fig. 6 Electrical conductivity versus time during the electrodialysis process under various voltages. The volume of treated water was 500 mL.

Other authors have reported similar trends, where the concentration of electrical conductivity reduced as the voltage increased [17]. Banasiak et al. [18] demonstrated that the electrodialysis system decreased the initial salt concentration from the feedwater from 5000 mg/L to around 10 mg/L when applying 18 V for 50 min. The system efficiency improved from 80% to 99% when increasing the voltage from 9 to 18 V, at a given time.

Fig. 7 demonstrates the decrease in TDS concentration concerning time and voltage variation. The TDS values present a proportional trend concerning the EC It is observed that the application of 10 and 8 V for 15 min produces treated water, meeting concentrations of 500 mg/L of TDS recommended by the WHO and established in INEN 1108. However, when decreasing the voltage between 6 and 4 V, the electrodialysis time increased to 25 and 75 minutes, respectively, to reach 500 mg/L of TDS.

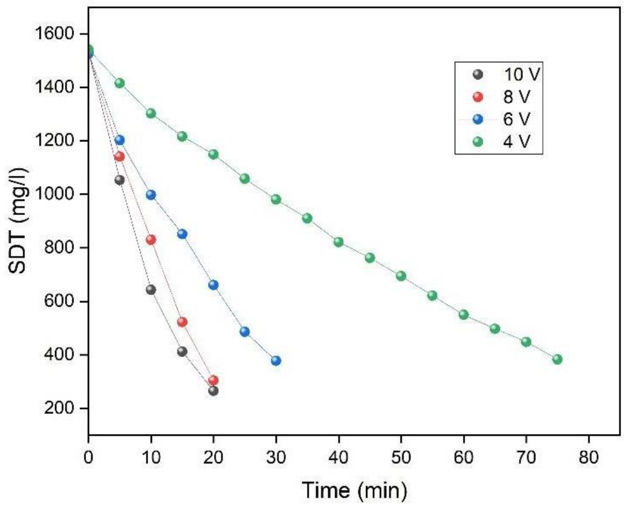


Fig. 7 Total dissolved solids versus electrodialysis time. The system was operated under different voltages.The volume of treated water in the electrodialysis system was 500 mL.

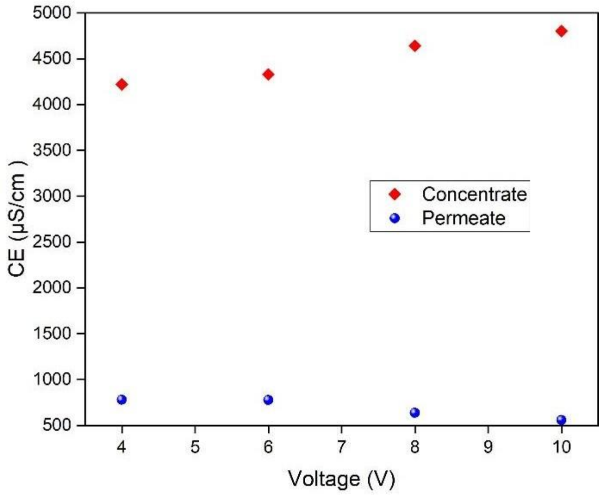

Fig. 8 Electrical conductivity variation in the permeate and concentrate with increasing applied voltages. The volume of treated water in the electrodialysis system was 500 mL.

Fig. 8 illustrates the decrease in EC in the treated water and the increase in EC in the concentrate when applying voltages of 4, 6, 8, and 10 V. Applying 10 V produces a permeate with EC of 560 µS/cm and a concentrate with EC of 4800 µS/cm. Applying 8 V makes water with a 637 µS/cm concentration and an EC concentration of 4640 µS/cm. Using 6 V to the electrodialysis system yielded permeate with an EC concentration of 778 µS/cm and concentrate with an EC of 4330 µS/cm.

The current was monitored during the experiments to calculate the energy consumption. Fig. 9 shows the current generated with voltage variation. The current developed for 6 V was estimated as 0.09 A; when 4 V was applied, the current was 0.05 A.

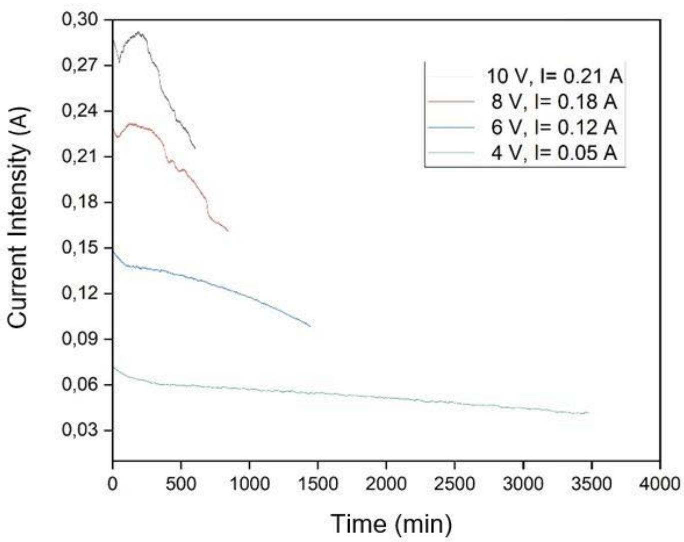

Fig. 9 Behaviour of the current intensity to the applied voltage during each experiment.

According to the result found by Moura et al. [19], the curves behave similarly, in the first two hours, the current tends to increase and then decrease, this decrease in current is due to the depletion of ions in the dilute compartment that leads to an increase in its electrical resistance.

The energy consumption for the different voltages andthe cost to treat 1 $m^3$ of water in Ecuador were estimated, using the current results and the treated water volume of 500 mL, Table I shows the energy consumption results andthe costs associated with the treatment. The highest energyconsumption was 1.39 kWh/$m^3$ under the application of 10 V to the system, which generated costs of USD 0.13/$m^3$ of water to treat. The energy consumption decreased to 0.95 kWh/$m^3$ with respective parameters 8 V and USD 0.09/$m^3$.Application of 6 V led to energy consumption of 0.72 kWh/$m^3$ with a price of USD 0.07. The lowest energy consumption was 0.50 kWh/$m^3$ with 4 V for USD 0.05 per $m^3$ of treated water.

The selection for the optimal voltage was the consideration of a low energy cost but an average desalination time because a greater amount of water can be desalinated in an optimal time.

TABLE I

SPECIFIC ENERGY WAS OBTAINED BY THE DIFFERENTVOLTAGES APPLIED TO TREAT 500 ML OF WATER.

| Voltage (V) | Current (A) | Time (h) | Specific energy (kWh/m³) | Cost (USD) |
|---|---|---|---|---|
| 10 | 0,21 | 0,33 | 1,39 | 0,13 |
| 8 | 0,18 | 0,33 | 0,95 | 0,09 |
| 6 | 0,12 | 0,50 | 0,72 | 0,07 |
| 4 | 0,05 | 1,25 | 0,50 | 0,05 |

## IV. CONCLUSIONS

The study reveals that an advanced electrodialysis system is an efficient, sustainable, and economical approach to improving the quality of brackish water in a rural semi-arid area of Ecuador. Water in the target area shows an elevated ion content of $Cl^-$, $SO_4^{2-}$, and $Na^+$, and overall high EC values between 3000 and 3250 µS/cm.

The research determined that the electrodialysis system is advantageous due to its low energy consumption, the salt concentrate that is generated is not harmful (brine) and the by-products in the concentrate effluent can be used for marketing purposes. The water treated with the electrodialysis process reaches the EC and TDS concentrations recommended by the WHO for human consumption.

It can be concluded that the most promising configuration among the investigated electrodialysis procedures is electrodialysis with a voltage lower than 8 V and a recovery rate of 80% because it maintains the behavior with 10 V despite entering a greater amount of energy in the system. This does not result in a faster desalination time, in addition to recovering a higher percentage of treated water and generating less volume of concentrate but with more nutrients, that is, a greater amountof $Cl^-$ and $Na^+$.

The overall setup demonstrates a high potential for water treatment in rural areas with the presence of highly saline natural waters.

Coastal communities possess salty water bodies primarily due to their proximity to the sea. Therefore, the application of advanced electrodialysis technology for the use of brackish water will allow obtaining drinking and domestic water at a lower cost and low energy consumption, which will benefit rural communities and improve the living conditions of the population.

## ACKNOWLEDGEMENTS

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