

NM WRI Student Water Research Grant Progress Report Form
Final Report due May 31, 2020

1. Student Researcher: Juliano Penteado de Almeida
Faculty Advisor: Dr. Pei Xu

2. Project title:

Enhanced Water Recovery and Membrane Scaling Mitigation for Desalination Using Innovative Electromagnetic Field (EMF) and 3D Printed Open Flow Channel Membranes

3. Description of research problem and research objectives.

The growing population requires increasing amounts of fresh water. Hence, there is a pressing need for more effective and less expensive desalination methods. Reverse osmosis (RO) and nanofiltration (NF) membranes are principal methods for treating brackish water, wastewater and seawater. Despite advances in membrane technologies, membrane fouling and scaling remains as a key impediment for successful implementation of desalination technologies. Colloidal particles, microbes, and sparingly soluble salts (e.g., CaCO_3 , CaSO_4 , SiO_2 , and BaSO_4) in feed water can attach and precipitate within membrane polymer matrix or on membrane surface leading to membrane fouling and scaling. Expenditures derived from membrane fouling and scaling consist of direct costs associated with feed water pretreatment, periodic chemical cleaning, increased energy demand, and shortened membrane life as well as indirect costs resulted from reduced water production.

Therefore, the objective of this project is to develop an innovative High Recovery Reverse Osmosis (HRRO) process to reduce membrane fouling and scaling, and to enhance desalination efficiency. To address the intensive chemical demands (e.g., antiscalants, acids, and chemicals for softening) for conventional HRRO, the proposed technology uses non-chemical pretreatment with EMF for 3D printed open flow channel membranes. The HRRO is expected to significantly reduce chemical demands, operational costs, energy, and negative environmental impacts of desalination technologies. In this project, we are using the HRRO to treat brackish groundwater which is a critical water source and provides a reliable, drought-resistant alternative water supply to address the water shortage and conflicts in arid and semiarid Southwestern regions.

4. Description of methodology employed.

EMF treatment is a simple non-chemical technology that can be used to control membrane scaling. EMF can be applied by magnetic fields using ferrite magnets, or by using wires wrapped around or positioned near a metal pipe through which water flows or directly around membrane vessels. Different mechanisms could be involved in the EMF for scaling prevention. EMF was reported to activate colloidal silica present in water to adsorb Ca^{2+} , Mn^{2+} or other metal ions, and

then precipitate from the solution through enhanced particle coagulation processes. Our proof-of-concept study demonstrated that EMF (Figure 1) boosted bulk precipitation of crystals rather than adhesion to membrane surface. However, the precipitates were captured and accumulated in the traditional RO spacer mesh, clogged the feedwater flow channel, caused the drop in water recovery. Therefore, we hypothesize that *the EMF pretreatment could be combined with innovative open channel spacers in RO elements to further improve water recovery and reduce membrane fouling.*

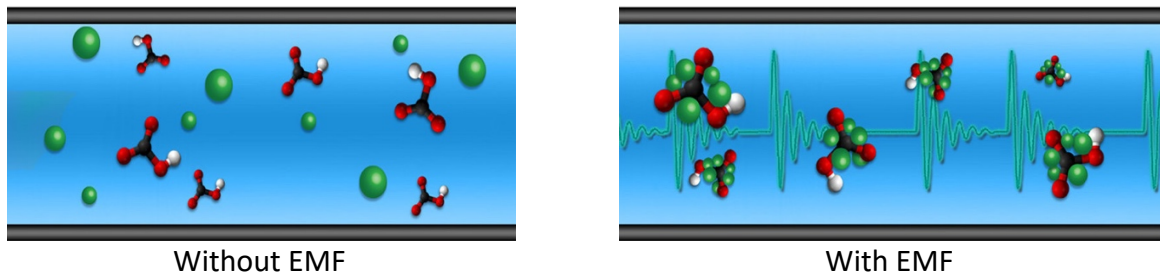


Figure 1. Comparison of water molecule arrangement in a pipe without EMF (left) and with EMF (right). Source: Hydroflow-usa.com

3D printed spacers (Figure 2) are a new approach to provide structural support to keep feed channel open and also allow turbulent flow to mitigate solute concentration build-up at the vicinity of membrane surface. In this project, we are using RO membranes with 3D printed open flow channel spacers, manufactured by Aqua Membranes LLC in Albuquerque, NM. The feed spacer has been replaced by printing materials directly on the membrane surface. The printing process does not damage the membrane, and salt rejection is not compromised.

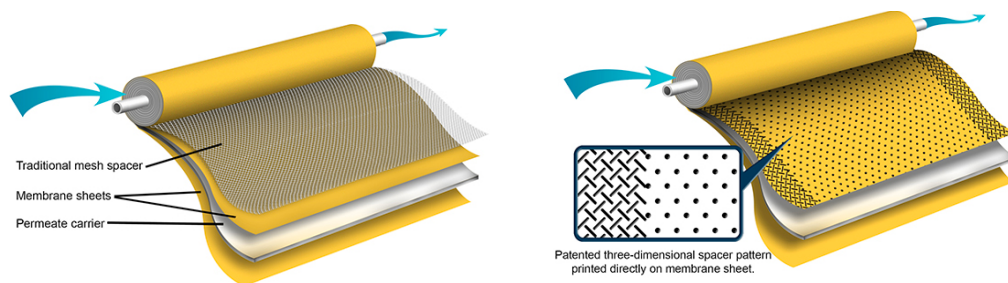


Figure 2. Comparison of RO membranes with conventional feed spacer (left) and 3D printed spacer technology (right). Source: Aquamembranes.com

The EMF inducer used is a HydroFLOW Model S38 that has a specialized transducer connected to a ring of ferrites that performs the electric signal to the contact water pipeline.

The project started with bench-scale membrane experiments to (i) compare desalination performance and water production of RO membranes with conventional mesh spacer, and 3D printed spacers with open flow channels (dotted and striped 3D printed spacers); (ii) evaluate the impact of EMF on the performance of different types of feed spacers during desalination of challenging brackish groundwater with different salt compositions. The schematic diagram of the bench scale system is shown in Figure 3.

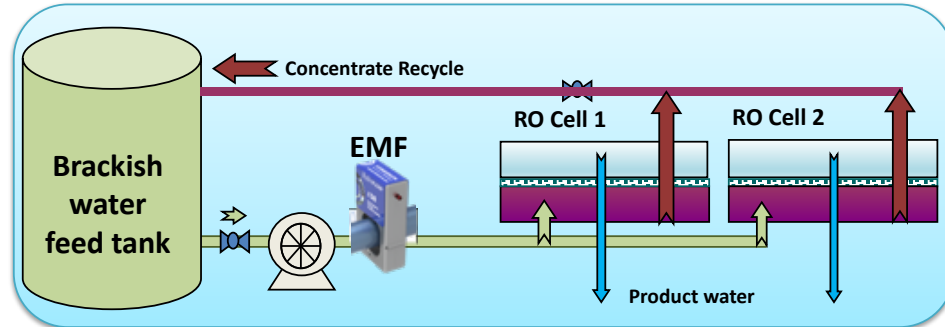


Figure 3. Schematic diagram of the high recovery RO system.

The bench-scale system was built and designed to closely simulate the full-scale RO desalination process, in a semi-batch process. Two cross-flow flat-sheet membrane units were employed in this study. The test units consisted of two rectangular plate-and-frame cells having dimensions of 14.6 cm × 9.5 cm × 0.86 mm (34 mil) for channel length, width, and height, respectively. These channel dimensions provide an effective membrane area of 139 cm² per unit and cross-sectional flow area of 0.82 cm². The test cell and tubing for rejection tests were made of stainless steel for the proper induction of EMF.

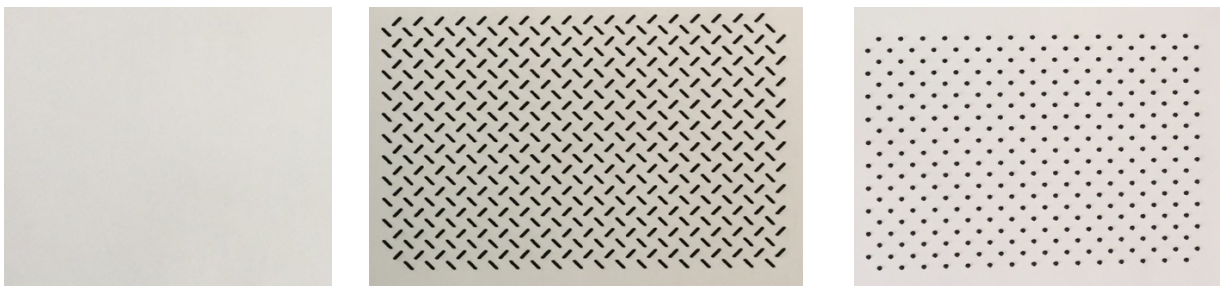


Figure 4. Regular flat-sheet membrane (left), 3D printed membrane in stripped pattern (middle) and 3D printed membrane in dotted pattern (right)

Hydranautics RO membrane ESPA-DHR was tested in three different configurations. Commercial ESPA-DHR flat sheet membranes with conventional mesh spacer were tested to desalinate synthetic water and brackish groundwater (Figure 4 left). Then, ESPA-DHR flat sheet

membranes were tested with two types of with 3D printed spacers, dotted and striped ones. The studied spacers are shown in Figure 4 middle and right.

The impacts of EMF on mesh spacer and 3D printed spacers were tested with brackish groundwater. Different types of feed water were tested, including deionized (DI) water to measure the pure water permeability of the membranes; 1,500 mg/L of NaCl solution to verify the salt rejection and membrane water permeability in comparison with membrane manufacturer data; and a brackish groundwater collected from Well 2 in Brackish Groundwater National Desalination Research Facility (BGNDRF), Alamogordo, NM, for membrane scaling experiments.

A 25 L plastic feed tank was constructed to store the feed solution. The RO system was operated at a recirculation mode and the permeate was discharged so that the water recovery of the system was continuously increased (Figure 5) over time. The feed water flow rate was controlled at 1 L/min (cross-flow velocity 0.21 m/s) using a Hydra-cell pump (M03EKSGSFSHA, Wanner Engineering, Inc., MN). The flow rate was controlled by a Dayton motor (1F798, Grainger, IL). Feed pressure was set from 50 to 300 psi and measured by a Cole Parmer 0-1000 psi pressure transducer and controlled using a manual Swagelok pressure valve and an automated Hass pressure valve. A 0.5 L tank was used to gather permeate. Permeate conductivity was measured using an Oakton 1K conductivity probe and an Oakton Cond6+ Meter. Permeate pressure was measured using a Megadyne 0-1 psi pressure transducer and the volume change was used to calculate the permeate produced. The RO system was monitored and controlled using a Labview (Version 2016, National Instruments, TX) data acquisition system. Throughout the testing, pressure, flow rate, conductivity, pH, temperature, and turbidity were monitored on all the streams of the RO system. Turbidity measured by a LaMotte 2020t Turbidity Meter was used as an indicator of the crystallization formation of the concentrate in the RO system.



Figure 5. Bench scale RO system (left) and EMF inducer (right)

The EMF device powered by the Hydropath Technology was calibrated using an Owon HDS handheld digital storage oscilloscope and digital multimeter (Model HDS1021M-N, Canada) before installation (Figure5). The voltage of the Hydropath sine wave signal was measured to be 17.2 volts. The S38 was installed in the inlet of the RO units to control membrane scaling.

5. Description of results; include findings, conclusions, and recommendations for further research.

RESULTS

5.1.Pure Water Permeability of the Membranes

Firstly, the performance of different types of membranes was evaluated in terms of member permeability using DI water, i.e., Pure Water Permeability (PWP), under operating conditions of 50, 100, 150, 200 and 250 psi (Figure 6).

Equation (1)

$$PWP, \frac{L}{m^2h} = \frac{\text{permeate flow rate, L/h}}{\text{Membrane effective area, } m^2}$$

The PWP of all the three membranes increased linearly with increasing pressure. The regular membrane showed the highest PWP of 0.53 L/m²-h-psi (calculate from the slope of the trendline), while the striped and dotted membranes exhibited similar PWPs of 0.32 and 0.34 L/m²-h-psi.

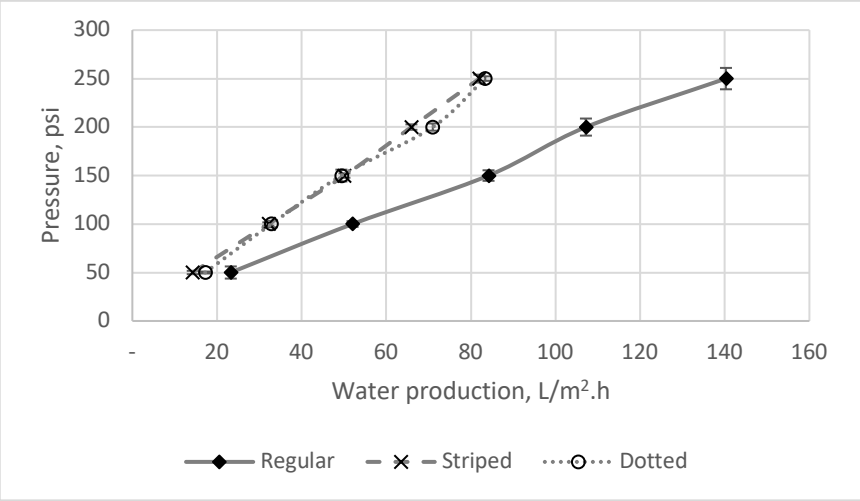


Figure 6. PWP of different membranes. Error bars represent the standard deviation of duplicate membranes

5.2. Salt Rejection Testing

To compare with the membrane manufacturer's datasheet, the salt rejection of the membranes was verified based on manufacturer's standard testing conditions using 1,500 mg/L NaCl solution and at 150 psi. Salt rejection is defined as:

Equation (2)

$$\text{Salt rejection, \%} = 100 \times \left(\frac{\text{Feed water conductivity} - \text{Permeate water conductivity}}{\text{Feed water conductivity}} \right)$$

The differences of salt rejection were not significant for all the three membranes (Figure 7). The values varied from 95.3% to 97.8%, with an average between 96.7% to 97.0%, slightly lower than the Hydranautics manufacturer data that the regular spiral-wound membrane should achieve a minimum salt rejection of 99%. Our previous experiments demonstrated that the salt rejection in spiral-wound elements was typically higher than the flat-sheet testing results. Therefore, the salt rejection of the membranes was demonstrated normal and considered meeting membrane manufacturer's standards.

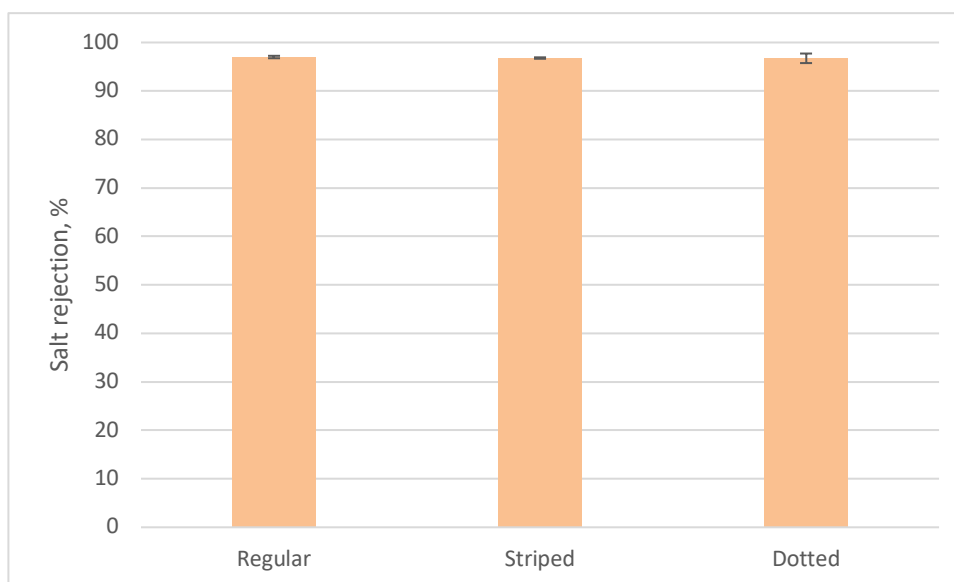


Figure 7. Salt rejection of the membranes with 1,500 mg/L NaCl solution at 150 psi

5.3. Scaling Testing

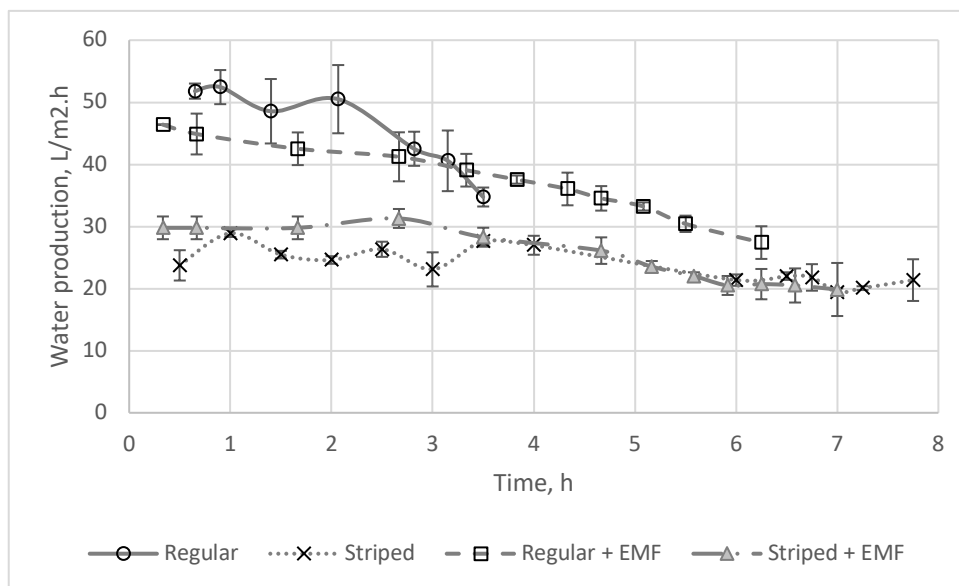
Membrane scaling experiments were conducted at 150 psi using the brackish groundwater collected from Well 2 in the BGNDRF. The groundwater has a total dissolved solids (TDS) concentration of 5,850 mg/L, a hardness of 2,550 mg/L, primarily CaSO₄ type of water (Table 1).

Table 1. Water quality of Well 2 brackish groundwater

Parameter	Value	Parameter	Value
Temperature, °C	27	Mg ²⁺ , mg/L	316
pH	7.17	K ⁺ , mg/L	2.1
Conductivity, µS/cm	6,400	SiO ₂ , mg/L	20.8
TDS, mg/L	5,850	Na ⁺ , mg/L	650
Total Alkalinity, mg/L as CaCO ₃	244	Sr ²⁺ , mg/L	8.1
Total hardness, mg/L as CaCO ₃	2,550	Cl ⁻ , mg/L	521
Ca ²⁺ , mg/L	501	SO ₄ ²⁻ , mg/L	3,200

For the initial membrane scaling tests, we decided to work only with regular membrane and striped membrane, because PWP and salt rejection tests did not show significant difference between striped and dotted membranes.

Laboratory tests showed that the water production decreased with the increasing water recovery due to membrane scaling (Figures 8 and 9), and the water flux decline increased over time (Figures 10 and 11). The permeate flux decline was considered as an indication of scale growth on the membrane surface.

Figure 8. Water production *versus* time during desalination of brackish groundwater

The regular mesh spacer had initial higher water production, but faster permeation flux decline, as shown in Figure 8 and 9. Its time of operation was short due to severe membrane scaling. Mesh spacer with EMF showed an initial lower water production than the regular one, but its flux decline was also lower and for this reason, we can treat brackish water for longer.

Running the system using EMF permitted to reach a higher recovery of 70% than 50% without EMF. Regular spacer with EMF took more time to present the same flux decline as regular membrane without EMF, however the EMF did not show significant impact on the striped membranes, due to a higher standard deviation obtained in the experiments. In both tests using

EMF, the same flux decline was reached with higher water recovery, being the best result for regular membrane with EMF. When the water recovery was about 45%, the flux decline was 34% for regular membrane and 19% for regular membrane with EMF (56.5% lower). The flux declined for regular membrane with EMF reached 35% of flux decline when the water recovery was 61% (35.4% higher).

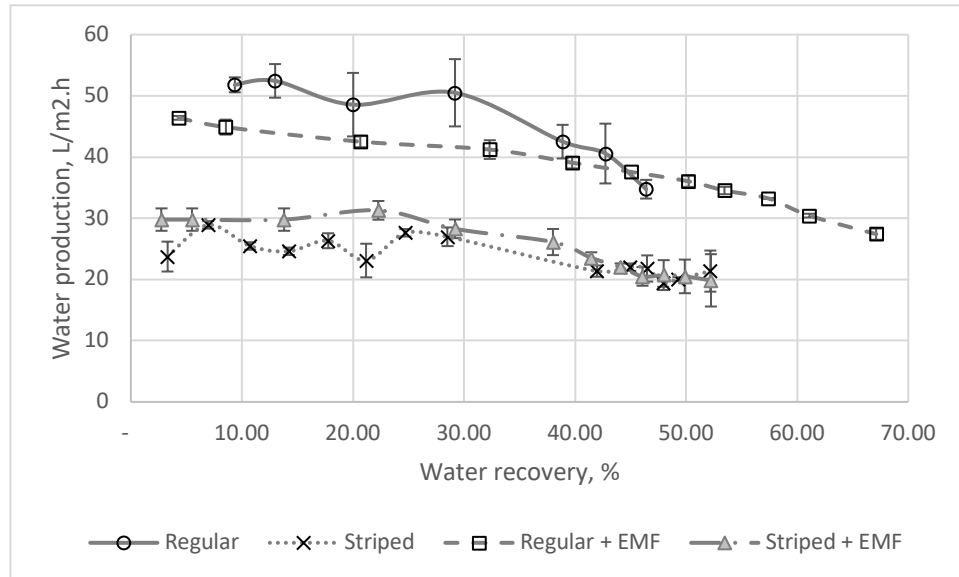


Figure 9. Water production *versus* water recovery during desalination of brackish groundwater

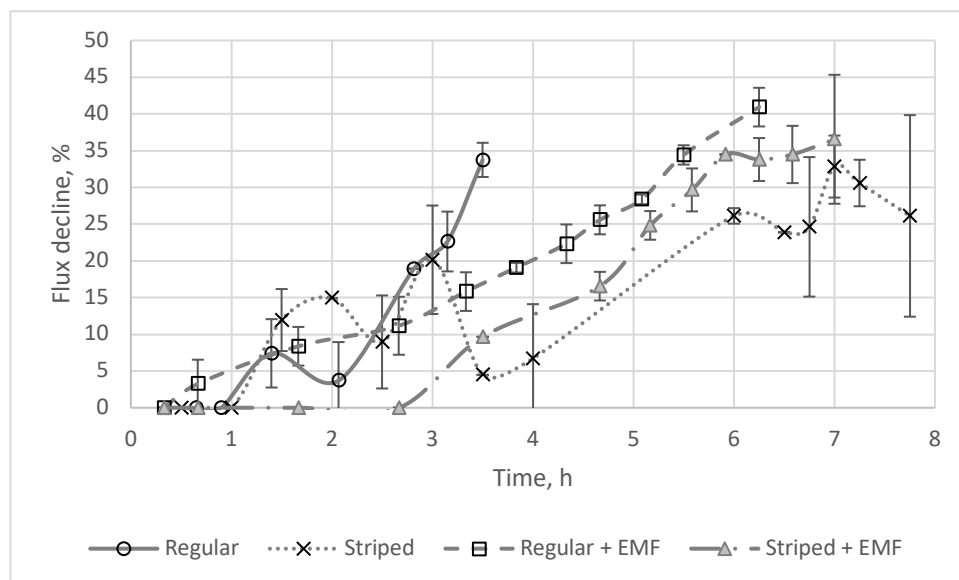


Figure 10. Flux decline *versus* time during desalination of brackish groundwater

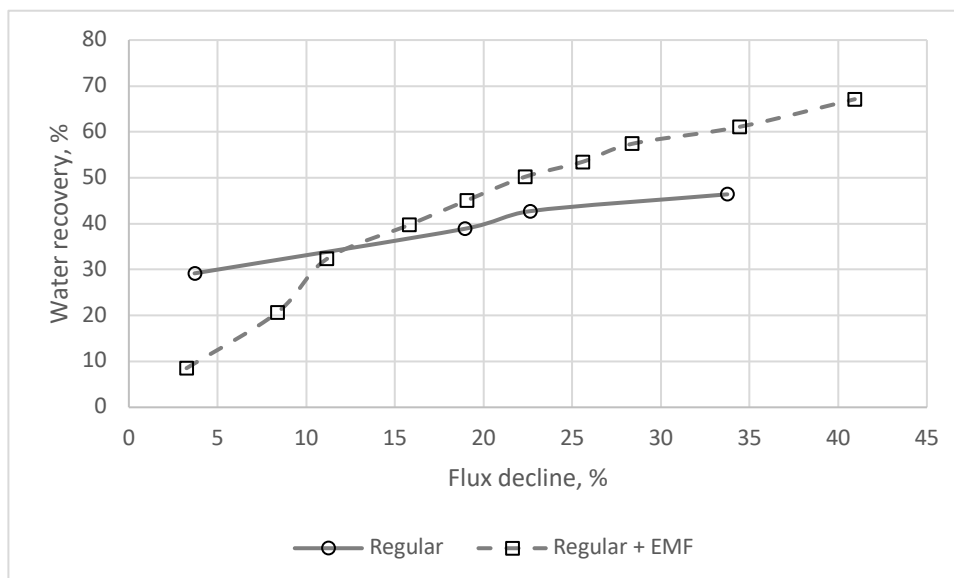


Figure 11. Water recovery *versus* flux decline during desalination of brackish groundwater

FINDINGS

EMF was demonstrated effectively as a pretreatment to control membrane fouling and scaling, and reduced the amount of chemicals needed to treat brackish water. 3D printed membranes provide a viable solution to reduce fouling and scaling, increasing the lifetime of the elements.



Figure 12. Comparison of RO membranes with conventional mesh spacer (left) and 3D printed spacer technology (right). Source: Aquamembranes.com

The 3D printed membranes, working with EMF, had 53% lower specific permeate flux than the flat sheet membranes with mesh spacers used in the bench scale study. During full scale applications using spiral wound elements, 3D printed spacers could be thinner than mesh spacers, as shown in Figure 12. Then, 3D printed spacers can increase the membrane packing density in a standard pressure vessel, thereby increasing water production per membrane element.

CONCLUSIONS

The primary conclusions about the bench scale study are summarized below:

- i. The EMF remarkably enhanced water recovery from 50% to 70% during desalination of the challenging brackish groundwater.
- ii. For regular membranes, the EMF reduced the water flux decline rate and significantly improved membrane performance by 57%.
- iii. PWP and salt rejection tests did not show significant difference between striped and dotted membranes.
- iv. Regular membranes exhibited better PWP and salt rejection than 3D printed membranes.
- v. For the striped membranes, EMF did not have significant impact due to a higher standard deviation obtained in the experiments.

The bench-scale testing demonstrated the EMF provides an effective pretreatment to control membrane scaling during desalination of brackish groundwater. The proposed technology can significantly reduce operational costs, energy, and negative environmental impacts of desalination technologies.

6. Provide a paragraph on who will benefit from your research results. Include any water agency that could use your results.

This research will benefit water industry and communities in the world that need to treat impaired waters such as brackish water, wastewater, and seawater. It has the potential to provide water security all around the globe and minimize the operational costs, energy demand, and negative environmental impacts of desalination technologies. It helps municipalities, communities, industry, and agriculture to address the challenge of water security, allowing economic development.

7. Describe how you have spent your grant funds. Also provide your budget balance and how you will use any remaining funds.

My grant is being spent to pay my tuition and international student health insurance at NMSU, as shown in Table 2.

Table 2. Grant funds and budget balance

Date	Description	Received	Spent	Balance
6/01/2019	Total grant	6,500.00		6,500.00
9/11/2019	Tuition – Fall Semester 2019		3,069.00	3,431.00
10/09/2019	International Student Health Insurance		660.00	2,771.00
1/06/2020	Tuition – Spring Semester 2020		2,771.00	0.00
TOTAL BALANCE				0.00

The budget was spent in totally.

8. List presentations you have made related to the project.

Some of the presentation and conferences I was planning to attend were impacted for the COVID-19 pandemic. Then, the due date to submit abstracts were postponed. Below is a list of presentations I attended and one that I will attend:

- i. Juliano Penteadó de Almeida, Xuesong Xu, Wenbin Jiang, Huiyao Wang, Phil King, Pei Xu. HRRO with innovative 3D printed open flow channel spacers and electromagnetic field. 2020 ReNUWIt Annual Meeting, Stanford University. September 8-10, 2020. San Francisco, CA.
- ii. Pei Xu, Wenbin Jiang, Xuesong Xu, Juliano Almeida, Huiyao Wang, Lu Lin, Randy Shaw. The Opportunities and Limitations of Electromagnetic Field for Scaling Control. 2020 Multi-State Salinity Coalition Annual Salinity Summit, Las Vegas, NV. February 26-28, 2020. (Invited talk).
- iii. Wenbin Jiang, Xuesong Xu, Juliano Penteadó de Almeida, David Johnson, Lu Lin, Huiyao Wang, Pei Xu. Electromagnetic Field Devices for Prevention of Membrane Fouling and Scaling. 2nd Annual WIN Workshop, BGNDRF, Alamogordo, NM. Oct 28 – 29, 2019. (Invited talk)
- iv. Juliano Penteadó de Almeida, Xuesong Xu, Wenbin Jiang, Huiyao Wang, Lu Lin, Pei Xu. Increasing Water Recovery and Reducing Membrane Scaling Using Innovative Electromagnetic Field (EMF) and 3D Printed Membranes. 64th Annual New Mexico Water Conference. November 6-8, 2019. Pojoaque, NM.

9. List publications or reports, if any, that you are preparing. For all publications/reports and posters resulting from this award, please attribute the funding to NM WRRI and the New Mexico State Legislature by including the account number: NMWRRI-SG-2019.

I am preparing a paper to publish in a high quality journal.

10. List any other students or faculty members who have assisted you with your project.

Dr. Xuesong Xu, Dr. Wenbin Jiang, Dr. Huiyao Wang and Dr. David C. Johnson.

11. Provide special recognition awards or notable achievements as a result of the research including any publicity such as newspaper articles, or similar.

An eNews article about this research was published in: <https://nmwrri.nmsu.edu/9392-2/>

12. Provide information on degree completion and future career plans. Funding for student grants comes from the New Mexico Legislature and legislators are interested in whether recipients of these grants go on to complete academic degrees and work in a water-related field in New Mexico or elsewhere.

My future plan, after completing my PhD degree, is to continue researching about water desalination and its applications to solve a world problem that is becoming more and more complicated, especially in arid and semi-arid regions. Water security is essential to sustainability worldwide and I would like to give my contribution on it.