Final Abstract

Final Report Approved on January 23, 2025

M.L. 2020 Project Abstract

For the Period Ending June 30, 2024

Project Title: Managing Highly Saline Waste From Municipal Water Treatment

Project Manager: Natasha Wright

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Funding Source:

Fiscal Year:

Legal Citation: M.L. 2021, First Special Session, Chp. 6, Art. 5, Sec. 2, Subd. 04a

Appropriation Amount: $250,000

Amount Spent: $250,000

Amount Remaining: -

Sound bite of Project Outcomes and Results

Our research project advanced the development of a cost- and energy-efficient method of managing the brine (concentrated salt-laden liquid waste) from desalination-based water treatment facilities. This will increase the economic feasibility of utilizing reverse osmosis for treatment, thereby reducing the addition of chloride, sulfate, and other contaminants to Minnesota waterways.

Overall Project Outcome and Results

Chloride and sulfate levels in Minnesota waterways is a growing concern due to the potential for harm to aquatic life (chloride) and the quality of water used for growing wild rice (sulfate). Because wastewater treatment plants are not currently equipped with the technology to remove dissolved salts, chloride and sulfate that enter these facilities end up back in waterways. An opportunity exists to reduce the chloride and sulfate discharge to waterways by installing desalination technology at industrial point sources, or possibly at the municipal scale. Doing so, however, results in a liquid waste stream that contains all the removed contaminants in highly concentrated form. This waste stream (brine) has to be properly disposed of, the cost of which is directly related to the brine's volume.

Our project focused on convection-enhanced evaporation (CEE) to reduce the volume of this salt-laden brine. The proposed CEE system utilizes a series of stacked evaporation trays, increasing the surface area available for evaporation unit of land area by approximately 30x versus a standard evaporation pond. We developed a model to predict the evaporative behavior of the proposed CEE system and to predict the levelized capital and operational cost of the system depending on the operating parameters and geographic location. We then used the model to explore different design configurations, where vertical surfaces were shown to reduce the overall footprint area by up to 77%. Through the development of an optimization framework and novel control method, annual operating costs in Minnesota were reduced to an estimated $6.63/m^3 of brine.

Our research project advanced the development of a cost- and energy-efficient method of managing the brine from desalination-based water treatment facilities. This will increase the economic feasibility of utilizing reverse osmosis for treatment, thereby reducing the addition of chloride and sulfate to Minnesota waterways.

Project Results Use and Dissemination

Results from this research project were disseminated through four scholarly publications in peer-reviewed journals, as well as via conference presentations at the UCOWR Annual Water Resources Conference, the European Desalination Society, and the International Desalination Association World Congress.

Environment and Natural Resources Trust Fund

M.L. 2020 Approved Final Report

General Information

Date: January 24, 2025

ID Number: 2020-037

Staff Lead: Mike Campana

Project Title: Managing Highly Saline Waste From Municipal Water Treatment

Project Budget: $250,000

Project Manager Information

Name: Natasha Wright

Organization: U of MN - College of Science and Engineering

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Project Reporting

Final Report Approved: January 23, 2025

Reporting Status: Project Completed

Date of Last Action: January 23, 2025

Project Completion: June 30, 2024

Legal Information

Legal Citation: M.L. 2021, First Special Session, Chp. 6, Art. 5, Sec. 2, Subd. 04a

Appropriation Language: $250,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota to develop a cost- and energy-efficient method of managing the concentrated saline waste from a municipal water treatment plant to increase the feasibility of using reverse osmosis for centralized water softening and sulfate removal. This appropriation is subject to Minnesota Statutes, section 116P.10.

Appropriation End Date: June 30, 2024

Narrative

Project Summary: We will develop a cost- and energy-efficient method of managing the concentrated saline waste from a municipal desalination plant, increasing the economic feasibility of centralized water softening and sulfate removal.

Describe the opportunity or problem your proposal seeks to address. Include any relevant background information.

Levels of chloride and sulfate (both salts) in Minnesota waterways is a growing concern due to the potential for harm to aquatic life (chloride) and the quality of water used for growing wild rice (sulfate). Increased chloride comes from multiple sources including salt used for winter road maintenance, residential and commercial water softeners, industry, and agriculture. Sulfate also has multiple sources to surface water, including industrial waste, domestic waste, and use of groundwater for agricultural, industrial, and domestic needs. Because WWTPs are not equipped with the technology to remove dissolved salts, chloride and sulfate that enter these facilities end up back in waterways.

An opportunity exists to reduce this discharge to waterways by installing centralized water softening and desalination technology (such as reverse osmosis, RO) at the municipal scale. Doing so, however, results in a liquid waste stream that contains all the removed contaminants in highly concentrated form; this waste stream has to be treated and properly disposed of, which is expensive. A recent ENTRF-funded report to analyze sulfate treatment options indicates that brine management would represent >46% of the total capital cost and >81% of the operational cost of a newly installed RO system at sample POTWs (MPCA, 2018).

What is your proposed solution to the problem or opportunity discussed above? Introduce us to the work you are seeking funding to do. You will be asked to expand on this proposed solution in Activities & Milestones.

While inland treatment plants using RO typically inject this concentrated waste into deep wells, evaporate the remaining water in large evaporation ponds, or use an evaporative crystallizer, none of these methods are viable for treatment plants in Minnesota. All three are far too expensive and standard evaporation ponds require too much land area, especially given the seasonal climate variation (temperature and humidity) in Minnesota.

One method that could be used to reduce the capital and energetic cost of brine management is convection enhanced evaporation (CEE). An example of CEE is Wind Aided Intensified eVaporation (WAIV), a system that utilizes hanging vertical sheets to increase the evaporative surface area for a given area of land (Gilron, 2003). Initial calculations show that WAIV could reduce the land area required by at least 30 times versus standard evaporation ponds, while avoiding the high capital cost and fuel required for a crystallizer. However, a number of questions remain about the optimal physical design, ideal material properties for the hanging sheets, and how precipitated salts could be removed from the sheets. Our goal is to answer those questions – and in the future, be able to reuse the precipitated salts for practical purposes.

What are the specific project outcomes as they relate to the public purpose of protection, conservation, preservation, and enhancement of the state's natural resources?

The target project outcome of our research will be a cost- and energy-efficient system for managing the brine (concentrated salt-laden liquid waste) from membrane-based water treatment plants at the municipal scale. This will increase the economic feasibility of utilizing reverse osmosis for centralized water softening and treatment, thereby substantially reducing the addition of chloride, sulfate, and other contaminants to Minnesota waterways.

Project Location

What is the best scale for describing where your work will take place?

Statewide

What is the best scale to describe the area impacted by your work?

Statewide

When will the work impact occur?

During the Project and In the Future

Activities and Milestones

Activity 1: Develop model for how the highly concentrated salt brine evaporates from vertical and horizontal surfaces

Activity Budget: $121,242

Activity Description:
Our current model for evaporation from horizontal surfaces will be extended to predict the evaporative behavior from vertical surfaces. This model will capture the interaction between the concentrated brine and the evaporative material. Modeling will include natural (wind), forced, and mixed convection scenarios as well as both vertical sheets and horizontal trays. The modeled results will be compared to data from an in-lab single surface system. The existing model will be also be extended to include expected performance in cold weather (e.g. Minnesota winters). Finally, all results will be synthesized in the form of peer-reviewed journal publication and a public facing summary.

Activity Milestones:

Description	Approximate Completion Date
1. Understand the fundamental equations governing evaporation of highly saline brines from vertical surfaces	September 30, 2021
2. Develop integrated model of enhanced evaporation from vertical and horizontal surfaces	May 31, 2022
3. Compare modeled results with experimental data from in-lab single surface system	September 30, 2022
4. Synthesize results in the form of peer-reviewed journal publication and public facing summary.	December 31, 2022

Activity 2: System optimization and piloting

Activity Budget: $128,758

Activity Description:
Once we have a predictive model, we will analyze the parametric relationships between various variables (for example water composition, ambient temperature and humidity, brine temperature, air speed, surface material). We will use this understanding to perform multi-objective design optimization, focused on reducing cost and energy consumption. A case study using a local wastewater composition (selected in partnership with our collaborators) and ambient weather conditions will be used to develop a MN-specific case study and techno-economic assessment. A small pilot-system will be prototyped and tested under simulated conditions in the lab.

Activity Milestones:

Description	Approximate Completion Date
1. Understanding of parametric relationships between system variables in vertical configuration	June 30, 2023
2. Develop theory for an optimized system design	December 31, 2023
3. Pilot system tested under simulated conditions and techno-economic assessment for a MN WWTP prepared.	May 31, 2024
4. Synthesize results in the form of peer-reviewed journal publication and public facing summary.	June 30, 2024

Project Partners and Collaborators

Name	Organization	Role	Receiving Funds
Catherine Neuschler	Minnesota Pollution Control Agency	The MPCA continues to be interested in centralized water softening and treatment. Their staff will help us understand cost barriers and determine common operating points (flow rates, water quality parameters), enabling us to optimize and provide case studies on benefits achieved through this technology.	No

Dissemination

Describe your plans for dissemination, presentation, documentation, or sharing of data, results, samples, physical collections, and other products and how they will follow ENRTF Acknowledgement Requirements and Guidelines.
The target audience for results from this research will be engineers and scientists in academia, professionals in the area of desalination and water treatment, city managers and other local government officials, industry and trade organization personnel (for example, the Minnesota Pollution Control Agency and Metropolitan Council Environmental Services (MCES). Results will be disseminated through scholarly publications in peer-reviewed journals. Funds have been allotted in the budget such that results can be published in open access journals whenever possible, maximizing data availability and dissemination. Results from the research project will also be presented at regional conferences such as the Conference on the Environment or the American Water Works Association: Minnesota Section Annual Conference.

The Minnesota Environment and Natural Resources Trust Fund (ENRTF) will be acknowledged through use of the trust fund logo or attribution language on project print and electronic media, publications, signage, and other communications per the ENRTF Acknowledgement Guidelines.

Long-Term Implementation and Funding

Describe how the results will be implemented and how any ongoing effort will be funded. If not already addressed as part of the project, how will findings, results, and products developed be implemented after project completion? If additional work is needed, how will this work be funded?
We have been awarded federal funding for a project that complements the proposed research, leveraging LCCMR dollars. The federal grant will facilitate complementary experimental work for CEE systems that use the horizontal tray orientation with a focus on a larger-scale experiment in the hot and dry climate of New Mexico. This is in contrast to the predominately model-based/optimization work that is the focus of this study, with application to MN local climate. We also hope to work with a team at the Carlson School of Management to determine realistic value propositions for the technology as part of Activity 2.

Budget Summary

Category / Name	Subcategory or Type	Description	Purpose	Gen. Ineli gible	% Bene fits	# FTE	Class ified Staff?	$ Amount	$ Amount Spent	$ Amount Remaining
Personnel										
Project Manager		Project coordination, guide development of model extension, supervise graduate students. 1 month/year, 3 years, including UMN rate of 36.5% benefits.			27%	0.24		$45,486	-	-
Graduate Research Assistant		Analytical model extension, prototype design, fabrication, and testing. Includes UMN rate of 19.9% benefits plus tuition.			43%	1.5		$160,546	-	-
Undergraduate Researcher		Assist with prototyping and data collection system. 2 students for 10 hours/wk at $12/hr.			0%	0.5		$12,480	-	-
							Sub Total	**$218,512**	**$218,512**	**-**
Contracts and Services										
							Sub Total	**-**	**-**	**-**
Equipment, Tools, and Supplies										
	Tools and Supplies	Prototyping materials, consumable supplies, labortary notebooks, sensors and data aquisition equipment, operating costs for laboratory instruments required for analyses and experiments	Tools and supplies required to prototype the brine evaporation system and to collect the data necessary for data validation.					$31,226	$31,226	-
							Sub Total	**$31,226**	**$31,226**	**-**
Capital Expenditures										
							Sub Total	**-**	**-**	**-**
Acquisitions and Stewardship										

							Sub Total	**-**	**-**	**-**
Travel In Minnesota										
	Miles/ Meals/ Lodging	University vehicle rental, hotel/meal charges	Site visits with WWTPs and other local stakeholders					$262	$262	-
							Sub Total	**$262**	**$262**	**-**
Travel Outside Minnesota										
							Sub Total	**-**	**-**	**-**
Printing and Publication										
							Sub Total	**-**	**-**	**-**
Other Expenses										
							Sub Total	**-**	**-**	**-**
							Grand Total	**$250,000**	**$250,000**	**-**

Classified Staff or Generally Ineligible Expenses

Category/Name	Subcategory or Type	Description	Justification Ineligible Expense or Classified Staff Request

Non ENRTF Funds

Category	Specific Source	Use	Status	$ Amount	$ Amount Spent	$ Amount Remaining
State						
			State Sub Total	**-**	**-**	**-**
Non-State						
In-Kind	University of Minnesota	Because the project is overhead free, laboratory space, electricity, and other facilities/administrative costs (54% of direct costs excluding permanent equipment and graduate student tuition benefits) are provided in-kind.	Secured	$109,000	$109,000	-
			Non State Sub Total	**$109,000**	**$109,000**	**-**
			Funds Total	**$109,000**	**$109,000**	**-**

Attachments

Required Attachments

Visual Component

File: 47e038f8-07e.pdf

Alternate Text for Visual Component

Image shows current option for concentrate management from municipal treatment is prohibitively cost and energy intensive. Diagram of alternative treatment method....

Supplemental Attachments

Capital Project Questionnaire, Budget Supplements, Support Letter, Photos, Media, Other

Title	File
Letter of Support - MPCA	4071bb42-39f.pdf
Background Check Certification	da140a2d-207.pdf
Journal Article Describing the Horizontal Tray Configuration	87565ebe-57c.pdf
Journal Article Describing System Optimization Framework	69431721-e56.pdf
Journal Article Describing Vertical Surface Configuration	c14cd3a7-3af.pdf
Exp – Model Comparison, Pure Water	e4e27bd1-e39.jpe
Lab-Scale CEE Experimental Setup Update Sept 2023	dc3c9e44-66b.pdf
Journal Article - Real Time Controller	8068af81-197.pdf
Thesis - Trenton Brown - Lab Scale Validation	b8017736-f0d.pdf
Lab-Scale CEE Experimental Update 2	862ac413-bf0.pdf
Summary of Results	d07df3a3-98d.pdf

Difference between Proposal and Work Plan

Describe changes from Proposal to Work Plan Stage

Due to the delay in project start date, some milestone work from the originally proposed first Activity has already been completed. Edits were thus made to the project milestones to clarify the specific work yet to be completed. A fourth milestone was also added to each activity to indicate results synthesis and publication.

The proposed budget total was $262,000; the budget was adjusted to match the recommended amount of $250,000. This adjustment came from a re-evaluation of the funds to be used for supplies and prototyping and is not expected to impact the team's ability to complete the project milestones.

Additional Acknowledgements and Conditions:

The following are acknowledgements and conditions beyond those already included in the above workplan:

Do you understand and acknowledge the ENRTF repayment requirements if the use of capital equipment changes?

N/A

Do you understand that travel expenses are only approved if they follow the "Commissioner's Plan" promulgated by the Commissioner of Management of Budget or, for University of Minnesota projects, the University of Minnesota plan?

Yes, I understand the UMN Policy on travel applies.

Does your project have potential for royalties, copyrights, patents, sale of products and assets, or revenue generation?

Yes

Do you understand and acknowledge IP and revenue-return and sharing requirements in 116P.10?

Yes

Do you wish to request reinvestment of any revenues into your project instead of returning revenue to the ENRTF?

No

Does your project include original, hypothesis-driven research?

Yes

Does the organization have a fiscal agent for this project?

Yes, Sponsored Projects Administration

Work Plan Amendments

Amendment ID	Request Type	Changes made on the following pages	Explanation & justification for Amendment Request (word limit 75)	Date Submitted	Approved	Date of LCCMR Action
1	Amendment Request	• Budget • Other • Budget - Travel and Conferences • Budget - Printing and Publication • Budget - Personnel • Budget - Capital, Equipment, Tools, and Supplies • Attachments	A 2.1% increase ($4525) in personnel budget accounts for the actual annual increase in salary and fringe over the project period as compared to the estimate prior to project start. An 11% increase ($3213) in the Supplies budget was due to an increase in product costs over the project period and a slight underestimate in the use of consumables. Conference and paper publications fees were paid from other funds available to our research lab.	January 7, 2025	Yes	January 8, 2025

Status Update Reporting

Final Status Update August 14, 2024

Date Submitted: January 7, 2025

Date Approved: January 8, 2025

Overall Update
The target project outcome of this research project is a cost- and energy-efficient system for managing the brine (concentrated salt-laden liquid waste) from membrane-based water treatment plants. Over the project period, we developed a model to predict the evaporative behavior of the proposed convection-enhanced evaporation system and predict the levelized capital and operational cost of the system depending on the operating parameters and geographic location. We have used this model to develop a control logic that determines how the system should operate given real-time ambient weather conditions. The controller is expected to lead to significant operational cost savings of >20%. We have implemented a lab-scale prototype to validate the modeled results and have updated this lab-scale prototype to work with the real-time controller.

Activity 1
Tasks 1-3 are complete as of the last update.

Task 4: "Synthesize results" – The results of this activity have been published in the two journal publications attached with the previous update. The final component which compares the modeling work to the bench-scale testing is summarized in the MS Thesis work of student Trenton Brown (see attachment).
(This activity marked as complete as of this status update)

Activity 2
Task 1: Complete as of the last update.

Task 2: Complete as of the last update.

Task 3: We have updated the bench-scale system in lab to allow for real-time control of the primary operating variables (wind speed, brine temperature, and injection rate); this will allow us to test the system under unique ambient conditions. A description of the setup was included in the previous update. This system was tested in ambient conditions with initial results summarized in the "Lab-Scale CEE Experimental Update 2" attachment.

Task 4: Complete as of the last update.
(This activity marked as complete as of this status update)

Dissemination
Four journal articles have now been published, with one more remaining for submission. No additional conference presentations have been made since the previous update. The innovations in patent application US 2023/0082501 A1 were funded in part by the present award.

Status Update Reporting

Status Update March 1, 2024

Date Submitted: March 11, 2024

Date Approved: May 8, 2024

Overall Update
The target project outcome of our research will be a cost- and energy-efficient system for managing the brine (concentrated salt-laden liquid waste) from membrane-based water treatment plants. To date, we have developed a model to predict the evaporative behavior of the proposed convection-enhanced evaporation system and predict the levelized capital and operational cost of the system depending on the operating parameters and geographic location. We have used this model to develop a control logic that determines how the system should operate given real-time ambient weather conditions. We have implemented a lab-scale prototype to validate the modeled results and since the last update, have updated this lab-scale prototype to work with the real-time controller.

Activity 1
Tasks 1-3 are complete as of the last update.

Task 4: "Synthesize results" – The results of this work have been published in the two journal publications attached with the previous update. The final paper which compares the modeling work to the bench-scale testing is drafted and undergoing final revisions.

Activity 2
Task 1: Complete as of the last update.

Task 2: Complete as of the last update. Published version of the final findings in is attached.

Task 3: We have updated the bench-scale system in lab to allow for real-time control of the primary operating variables (wind speed, brine temperature, and injection rate); this will allow us to test the system under unique ambient conditions. A brief two page description of the setup was included in the previous update. This system is being currently being testing in ambient conditions with results to be included in the final report.

Task 4: Intermediary results have been published as described above.

Dissemination
Four journal articles have now been published, with one more remaining for submission. No additional conference presentations have been made since the previous update.

Status Update Reporting

Status Update September 1, 2023

Date Submitted: November 19, 2023

Date Approved: February 23, 2024

Overall Update
The target project outcome of our research will be a cost- and energy-efficient system for managing the brine (concentrated salt-laden liquid waste) from membrane-based water treatment plants. To date, we have developed a model to predict the evaporative behavior of the proposed convection-enhanced evaporation system and predict the levelized capital and operational cost of the system depending on the operating parameters and geographic location. We have used this model to develop a control logic that determines how the system should operate given real-time ambient weather conditions. We have implemented a lab-scale prototype to validate the modeled results and since the last update, have updated this lab-scale prototype to work with the real-time controller.

Activity 1
Tasks 1-3 are complete as of the last update.
Task 4 - “Synthesize results” – The results of Activity 1 have been published in the two journal publications attached with the previous update. The final paper which compares the modeling work to the bench-scale testing is drafted and we hope to submit by the end of the year.

Activity 2
Task 1: Complete as of the last update.
Task 2: We had developed the general optimization theory as of the last update. This optimization theory has now been extended to an optimized control theory. The relevant paper manuscript is attached (confidential, since not yet published). This paper includes a case study for MN weather conditions.
Task 3: We have updated the bench-scale system in lab to allow for real-time control of the primary operating variables (wind speed, brine temperature, and injection rate); this will allow us to test the system under unique ambient conditions. Included in the attachments is a brief two page description of the setup, including schematics.
Task 4: Intermediary results have been published as described above.

Dissemination
Dissemination of this work has begun via academic publications and presentations at the Universities Council on Water Resources (UCOWR), European Desalination Society (EDS), and the International Desalination Association (IDA) conferences. We have also presented this work to at the UMN Mechanical Engineering Golden Medallion (Alumni) Event.

Status Update Reporting

Status Update March 1, 2023

Date Submitted: March 27, 2023

Date Approved: March 27, 2023

Overall Update
The target project outcome of our research will be a cost- and energy-efficient system for managing the brine (concentrated salt-laden liquid waste) from membrane-based water treatment plants at the municipal scale. To date, we have developed a model to predict the evaporative behavior of the proposed system and predict the levelized capital and operational cost of the system depending on the operating parameters. We have implemented a lab-scale prototype to validate the modeled results.

Activity 1
Tasks 1 and 2:
We have developed a model for evaporation from horizontal and vertical surfaces to predict evaporation behavior and energy demand. The model has been extended to include wind, forced, and mixed convection scenarios in co-flow and cross-flow (vertical) configurations. The results of these modeling efforts have been summarized in two journal manuscripts. The first article summarizes the horizontal tray model (Kaddoura, Chosa, Wright, Desalination, 2021, see attachment). The second article summarizes the vertical configuration (Kaddoura, Wright, Applied Thermal Engineering, 2023, see attachment).

Task 3:
We have constructed and instrumented a single tray, horizontal evaporation setup for collection of experimental results. We have completed all pure water evaporation tests (see attached figure "Exp – Model Comparison, Pure Water.")

Task 4:
The results of this work have been published in the two aforementioned journal publications. The final papers related the experimental work on the bench-scale testing is currently being drafted and with expected submission by 6/30/2023.

Activity 2
Task 1:
The parametric relationships were described in (Kaddoura, Chosa, Wright, Desalination, 2021) article. Key highlights include a deeper understand of optimal spacing between evaporation surfaces, and the relative gain of adding thermal energy (to heat the brine) versus electric energy (to increase the fan speed).

Task 2: We are ahead of schedule on this task having developed a general optimization theory. The results of this work were published in (Kaddoura and Wright, Water Research, 2022, see attachment). We are currently working on extending this optimization theory to an optimized control theory and expect to have the results of this study summarized and published in 2023. This work includes a case study for MN weather conditions.

Task 3: We are begun the design work necessary to update the bench-scale system in lab to allow for real-time control of the primary operating variables (wind speed, brine temperature, and injection rate); this will allow us to test the system under unique ambient conditions.

Task 4: Intermediary results have been published as described above.

Dissemination

Dissemination of this work has begun via academic publications and presentations at the Universities Council on Water Resources (UCOWR), European Desalination Society (EDS), and the International Desalination Association (IDA) conferences.

Status Update Reporting

Status Update September 1, 2022

Date Submitted: September 1, 2022

Date Approved: September 7, 2022

Overall Update
The target project outcome of our research will be a cost- and energy-efficient system for managing the brine (concentrated salt-laden liquid waste) from membrane-based water treatment plants at the municipal scale. To date, we have developed a model to predict the evaporative behavior of the proposed system and predict the levelized capital and operational cost of the system depending on the operating parameters.

Activity 1
Tasks 1 and 2:
We have developed a model for evaporation from horizontal and vertical surfaces to predict both evaporation behavior and energy demand. The model has been extended to include wind, forced, and mixed convection scenarios in co-flow and cross-flow configurations. The results of these modeling efforts have been summarized in two journal manuscripts. The first article summarizes the horizontal tray model (Kaddoura, Chosa, Wright, Desalination, 2021, see attachment). The second article is currently under review at Applied Thermal Energy and describes the alternate configurations (vertical, cross-flow, wind-based convection).

Task 3:
We have constructed and instrumented a single tray, horizontal evaporation setup for collection of experimental results. We are currently comparing experimental results to the modeled results and expect to meet the Sept 30, 2022 milestone.

Activity 2
We are ahead of schedule on this activity having developed a general optimization theory. We are currently working on extending this optimization theory to an optimized control theory and expect to have the results of this study summarized and published in 2023.

Dissemination
Dissemination of this work has begun via academic publications and presentations at the Universities Council on Water Resources (UCOWR) conference and European Desalination Society conference. We plan to schedule a meeting with the MPCA before the next reporting period to update them on our progress.