M.L. 2016, Chp. 186, Sec. 2, Subd. 04l Project Abstract
For the Period Ending September 30, 2018

PROJECT TITLE: Membrane-Based Process for Decentralized Drinking Water Production
PROJECT MANAGER: Santiago Romero-Vargas Castrillón
AFFILIATION: UMN, Dept. Civil, Environmental, and Geo- Engineering
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2016, Chp. 186, Sec. 2, Subd. 04l

APPROPRIATION AMOUNT: $190,000
AMOUNT SPENT: $70,540.53
AMOUNT REMAINING: $120,459.47

<u>Overall Project Outcome and Results</u>

The main outcome of this project is a novel surface modification protocol for water treatment membranes. We showed that graphene oxide coatings, known to exhibit antibacterial properties, improve the efficiency with which the membranes remove micropollutants, such as N-nitrosodimethylamine (NDMA), which are common in Minnesota surface waters. Additional outcomes of this project were promotion of Minnesota's human capital through training of graduate and undergraduate students (2 graduate and one undergraduate student where supported at various points of the project), a M. S. thesis completed by Henry Croll (one of the graduate students supported by the project), a conference presentation (at the Annual Meeting of the American Institute of Chemical Engineers, AIChE 2017), and a recent publication in Separation and Purification Technology, a peer-reviewed international journal.

<u>Project Results Use and Dissemination</u>

This project accomplished the following dissemination outcomes

Pee-reviewed publications (1): H. Croll, A. Soroush, M. Pillsbury, and SRVC. "Graphene oxide surface modification of polyamide reverse osmosis membranes for improved N-nitrosodimethylamine (NDMA) removal". Separation and Purification Technology 210 (2019) 973–980

The article is available from the following link without a subscription until November 2, 2018:
https://authors.elsevier.com/a/1XjGX4wbrSvhOh

Conference papers (1): A. Soroush, H. Croll, and SRVC. "N-Nitrosodimethylamine (NDMA) Removal by Thin Film Composite Polyamide Reverse Osmosis Membranes". 2017 AIChE National Meeting, Minneapolis, MN. November 1st, 2017.

Dissertations (1): H. Croll. "Improvements to Polyamide Reverse Osmosis Membranes for Removal of Small, Uncharged, Hydrophilic Solutes". MS Thesis, University of Minnesota, 2018 (available from the UMN Libraries).

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2016 Work Plan

Date of Report: September 30, 2018

Final Report

Date of Work Plan Approval: June 7, 2016

Project Completion Date: September 30, 2018

Does this submission include an amendment request? no

PROJECT TITLE: Membrane-Based Process for Decentralized Drinking Water Production

Project Manager: Santiago Romero-Vargas Castrillón, Ph. D.

Organization: University of Minnesota, Department of Civil, Environmental, and Geo- Engineering

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Location: Statewide

Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$191,000**
	Amount Spent:	**$70,540.53**
	Balance:	**$120,459.47**

Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 04l

Appropriation Language:

$191,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota to develop a low-energy use, membrane-based treatment technology to produce drinking water locally from surface waters by removing heavy metals and contaminants of emerging concern, including pesticides and pharmaceuticals. This appropriation is subject to Minnesota Statutes, section 116P.10. This appropriation is available until June 30, 2019, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Membrane-based Process for Decentralized Drinking Water Production

II. PROJECT STATEMENT: Water pollution and water scarcity are two of the central problems of our time, even in regions such as Minnesota and the Upper Midwest, rich in water resources. Ensuring that sufficient water supplies are available to meet human and ecological needs will demand sustainable water management, and novel technologies to treat water bodies impacted by contamination. In Minnesota, our ground and surface waters (i.e., rivers and lakes) exhibit increasing levels of contaminants such as heavy metals, pharmaceuticals, hormones, and personal care products, which are removed to an insufficient extent by conventional water treatment processes. There is thus a clear need to develop water treatment processes that minimize the potential for human exposure to these emerging contaminants. The objective of the proposed work is to develop a membrane-based water treatment process capable of producing potable water from untreated surface, well or ground water impacted by contaminants of emerging concern. The concept proposed combines two emerging membrane processes, forward osmosis (FO) and membrane distillation (MD), which can leverage solar thermal energy, geothermal energy, or industrial waste heat as energy sources. Therefore, the proposed process has the potential to be less energy intensive than reverse osmosis (RO) water treatment processes, while exhibiting comparable, if not higher, contaminant removal. Moreover, given that both FO and MD operate at around ambient pressures, the hybrid FO-MD process proposed will also show lower capital costs compared to RO; lower capital costs make the proposed technology an attractive option for decentralized water treatment in virtually any small community in Minnesota. The proposed effort is structured along the following objectives:

- Development of membrane distillation and forward osmosis membrane materials exhibiting high flux (>12 gal ft^{-2} day^{-1}) and high removal (>90%) of contaminants commonly found in Minnesota surface and groundwater.
- Proof of concept demonstration of a hybrid FO-MD pilot-scale unit to produce drinking water from untreated surface or groundwater. The process developed will be scalable and its MD stage will operate at temperatures < 80 °C (< 176 °F), such that low-grade heat may be used as the main energy supply for the process.

Amendment request (6/30/2018)

The project manager (PM) will be resigning from his position on the faculty at the University of Minnesota on September 30th, 2018. On consultation with Becca Nash, LCCMR director, it was recommended that the project completion date be changed to September 30th, 2018, upon which a final report will be submitted with the project findings. Further, it was recommended that student support be terminated at the end of the summer term (August 26th, 2018); this will allow the graduate student funded by this project to complete his research and manuscript submitted for publication. To reflect the changes to the project duration, the PM requests that the project completion date be changed to September 30th, 2018. Further, given that an alternate project manager could not be found, the PM requests that Activity 2 outcomes not be achieved and the funds remaining for that activity be returned to the ENRTF. The dataset for this project will remain at the University of Minnesota and will be included as an addendum to the dissertation and stored in the UMN library system. All capital equipment acquired through this project will be transferred to the Department of Civil, Environmental, and Geo-Engineering at the University of Minnesota in order to meet LCCMR requirements related to purchase of capital equipment. Further, the PM requests approval to transfer $503 from personnel wages and benefits to supplies and services, given that the latter category was slightly overspent.

Amendment Approved by LCCMR 7/26/2018

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of January 30, 2017:

Work in the fall of 2016 focused on graduate student training, FO membrane development and the construction of a membrane testing apparatus. Details are provided in the status update of activity 1.

Project Status as of June, 30 2017:

Work in the spring of 2017 continued to focus on graduate student training, membrane synthesis, and troubleshooting of the membrane testing apparatus (which became fully operational in March of 2017).

Project Status as of January 30, 2018:

A membrane modification protocol was developed to improve the rejection of nitrosamines by water treatment membranes. A conference paper was presented reporting the results (see Dissemination). Note: expenses are reported in the appended spreadsheet through 12/31/17.

Project Status as of June 30, 2018:

We are currently developing membrane surface modification strategies to improve removal of urea, a contaminant that is commonly found in domestic wastewater. A manuscript reporting improved removal of NDMA by GO-modified membranes will be submitted shortly.

Overall Project Outcomes and Results:

The main outcome of this project is a novel surface modification protocol for water treatment membranes. We showed that graphene oxide coatings, known to exhibit antibacterial properties, improve the efficiency with which the membranes remove micropollutants, such as N-nitrosodimethylamine (NDMA), which are common in Minnesota surface waters. Additional outcomes of this project were promotion of Minnesota's human capital through training of graduate and undergraduate students (2 graduate and one undergraduate student where supported at various points of the project), a M. S. thesis completed by Henry Croll (one of the graduate students supported by the project), a conference presentation (at the Annual Meeting of the American Institute of Chemical Engineers, AIChE 2017), and a recent publication in *Separation and Purification Technology*, a peer-reviewed international journal.
Note: the student salary budget in activity 1 was slightly overspent by $1882.46; to make up for this shortfall, $1882.46 were moved from the student support budget of activity 2 to activity 1.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Development of membrane materials for filtration by forward osmosis and membrane distillation
Forward osmosis is an emerging membrane process in which permeation is driven by osmotic pressure, i.e., the tendency of water to migrate across a selective membrane from a low-salinity solution to one of higher salinity. In the first stage of the proposed process, FO will be used to extract water from untreated surface waters into a synthetic salt solution known as draw solution. To achieve this goal, we will develop aromatic polyamide forward osmosis (FO) membranes. The FO membranes will be prepared by molecular layer-by-layer (mLBL) deposition, which will allow us to optimize the permeate water flux and the efficiency with which the membranes reject organic contaminants and heavy metals. The mLBL technique will also allow us to control the surface chemistry of the membrane, thereby enabling chemical modification with fouling-resistant coatings. Surface modification is essential to prevent membrane fouling (i.e., clogging) with natural organic matter and other compounds abundant in surface and ground waters.

The second stage of the proposed process leverages membrane distillation to separate purified water from the draw solution. In MD, thermal energy is supplied to the draw solution in order to drive pure water vapor across a microporous hydrophobic membrane. Because temperatures around 60-80 °C suffice to drive permeation, low grade heat from solar, geothermal, or industrial sources can be used as energy supply for the separation process.

The FO and MD membrane materials will be characterized in terms of their water transport properties and solute rejection (using heavy metals such as Cd, and small organic molecules as model contaminants of emerging concern) using RO, FO and MD experimental setups. After optimization of the membrane materials with respect to water permeability, salt rejection, and fouling resistance, we will construct a lab-scale apparatus (membrane area approximately 20 cm^2) to provide a proof-of-concept demonstration of a hybrid FO-MD water treatment process. The lab-scale prototype will be evaluated with a "synthetic" feed water with a composition representative of river and lake waters, as well as with feed waters sampled from the Mississippi River, Upper Red Lake, and Lake Superior.

Summary Budget Information for Activity 1: **ENRTF Budget: $108,818.46**
Amount Spent: $70,540.53
Balance: $38,277.93

Outcome	Completion Date
1. Personnel training and construction of lab-scale FO, RO and MD filtration setups	December 31, 2016
2. Initial FO membranes prepared by mLBL deposition	June 30, 2017
3. Initial MD membranes fabricated by phase inversion	June 30, 2017
4. Characterization and optimization of FO and MD membrane transport and selectivity properties	October 31, 2017
5. Characterization of FO and MD membrane fouling resistance	December 31, 2017
6. Proof-of-concept demonstration of a lab-scale hybrid FO-MD process, operating at < 80 °C, water flux of 20 L m^{-2} h^{-1} (12 gal ft^{-2} day^{-1}), and showing >90% rejection of contaminants.	April 30, 2018

Activity Status as of January 30, 2017:

A laboratory-scale reverse osmosis (RO) setup was constructed in the lab of the PI. A graduate student is undergoing training in the synthesis of thin film composite forward osmosis membranes. Membrane synthesis by molecular layer-by-layer deposition has begun. The graduate student has also been trained in various experimental techniques required for materials characterization (atomic force microscopy, electron microscopy, zeta potential, IR spectroscopy, contact angle goniometry).

Activity Status as of June 30, 2017:

Work in the spring semester focused on Activity 1, specifically the development of FO membranes for drinking water treatment. The graduate student continued to be trained in membrane fabrication by non-solvent induced phase inversion (a technique that will also be used in the fabrication of distillation membranes), molecular layer-by-layer deposition, interfacial polymerization, and layered interfacial polymerization. In addition, an analysis protocol to measure the concentration of contaminants present in drinking water by LC-MS-MS was developed. This protocol is currently being used to measure the removal of contaminants with the fabricated membranes. In addition, we are exploring the fabrication of membranes with novel monomers to improve the removal of drinking water contaminants.

Activity Status as of January 30, 2018:

We modified polyamide membranes for water treatment with graphene oxide (GO), a carbon-based nanomaterial. GO is usually added to membrane surfaces to improve their resistance to biofouling. However, we found that, in addition to this, GO improves the removal of NDMA, a carcinogenic disinfection byproduct common in drinking water sources. The rejection of NDMA by GO-modified membranes was found to be 5% higher than that of unmodified membranes (i.e., 82.5% compared to 77.1%). In addition, the permselectivity of the membranes, defined as the ratio of the water permeability to that of NDMA, was also found to be higher after modification of the membranes with GO: for GO-modified membranes it was found to be 492, whereas for GO-free membranes a permselectivity of 370 was found.

These results were presented during a national chemical engineering conference (see Dissemination). A manuscript reporting these findings will also be prepared for submission to a scholarly journal.

Activity Status as of June 30, 2018:

We are currently developing membrane surface modification protocols for removal of low-molecular weight contaminants, such as urea. The surface modification currently being investigated consists of grafting fluorinated alkylamines to the membrane surface using EDC-NHS coupling chemistry.

A manuscript reporting the improved removal of NDMA by GO-functionalized membranes (see 1/30/18 status update) was written and will be submitted shortly.

Project Outcomes and Results: As explained below, a novel functionalization of the membrane surface improved the rejection of nitrosamines, which are carcinogenic compounds generated during disinfection of water and wastewater.

Final Report Summary: In the growing area of membrane-based water treatment, the performance of reverse osmosis (RO) is limited by poor membrane selectivity towards nitrosamines and other low-molecular weight, neutral contaminants, some of which affect Minnesota's rivers and lakes. This study aimed to increase RO membrane rejection of N-nitrosodimethylamine (NDMA), a carcinogenic nitrosamine that is produced during chlorination and chloramination of secondary wastewater effluent. Toward this goal, we modified commercial polyamide RO membranes with graphene oxide (GO) nanosheets, and demonstrated that GO functionalization can decrease the NDMA permeability coefficient by 31%, while only decreasing water permeability by 13%. The improved selectivity is likely due to additional steric exclusion derived from the GO nanosheet coating. Moreover, membrane characterization indicated that the GO modification does not change the hydrophilicity or roughness of the interface. The latter interfacial characteristics, combined with the well-established biocidal properties of graphenic nanomaterials, render GO functionalization a promising strategy for the development of highly selective membranes for water treatment and wastewater reclamation.

Activity 2: Development of a pilot-scale hybrid FO-MD water purification process. The prototype developed in Activity 1 will be scaled up to a membrane area of 150 cm^2 (0.16 ft^2). The performance metrics that will be considered to assess the success of the pilot-scale unit are a production rate of 2 gal/day with < 10% flux decrease due to fouling over 24 hours of operation, and >90% removal of organic contaminants and heavy metals. In addition, the MD stage of the pilot will operate a temperatures < 80 °C. Experiments will be conducted with feed waters collected from the Mississippi River, Upper Red Lake, and Lake Superior.

Summary Budget Information for Activity 2: **ENRTF Budget: $82,181.54**
Amount Spent: $ 0
Balance: $82,181.54

Outcome	Completion Date
1. Pilot-scale construction	April 30, 2018
2. Initial characterization of water flux and contaminant rejection in pilot-scale unit	December 31, 2018
3. Demonstration of pilot-scale unit showing >90% contaminant rejection at temperatures < 80 °C	June 30, 2019

Activity Status as of January 30, 2017: no activity to report

Activity Status as of June 30, 2017: no activity to report

Activity Status as of January 30, 2018: no activity to report

Activity Status as of June 30, 2018: no activity to report. Due to the circumstances discussed in the June 30, 2018 amendment request, this activity will not continue and the funds will be returned to the ENRTF after project close-out.

Project Outcomes and Results: no activity to report

Final Report Summary: no activity to report

V. DISSEMINATION:

Description: Results will be disseminated via publication in peer-reviewed journals such as The Journal of Membrane Science, Water Research, and Environmental Science & Technology. Results will also be communicated through oral and poster presentations at local, regional and national conferences on water technology.

Status as of January 30, 2017: no activity to report

Status as of June 30, 2017: no activity to report

Status as of January 30, 2018: the graduate student presented a paper at the 2017 AIChE National Meeting in Minneapolis, on November 1st, 2017. The title of the presentation was:
"N-Nitrosodimethylamine (NDMA) Removal by Thin Film Composite Polyamide Reverse Osmosis Membranes"

Status as of June 30 2018: no activity to report

Final Report Summary: This project accomplished the following dissemination outcomes

Pee-reviewed publications (1): H. Croll, A. Soroush, M. Pillsbury, and SRVC. "Graphene oxide surface modification of polyamide reverse osmosis membranes for improved N-nitrosodimethylamine (NDMA) removal". Separation and Purification Technology 210 (2019) 973–980

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Conference papers (1): A. Soroush, H. Croll, and SRVC. "N-Nitrosodimethylamine (NDMA) Removal by Thin Film Composite Polyamide Reverse Osmosis Membranes". 2017 AIChE National Meeting, Minneapolis, MN. November 1st, 2017.

Dissertations (1): H. Croll. "Improvements to Polyamide Reverse Osmosis Membranes for Removal of Small, Uncharged, Hydrophilic Solutes". MS Thesis, University of Minnesota, 2018. (available from the UMN Libraries)

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$86,892	Graduate research assistant (50% time per year for two years, salary 57% of cost, tuition 33% of cost, fringe benefits 10% of cost)
Professional/Technical/Service Contracts:	$N/A	
Equipment/Tools/Supplies:	$21,767	Laboratory equipment and supplies ($21,264) including, but not limited to: chemicals for membrane fabrication and characterization (polysulfone, poly(ether sulfone), poly(vinyl pyrrolidone) and poly(vinylidene fluoride), polyethylene glycol, dopamine hydrochloride, Tris HCl buffer, ethylenediamine, m-phenylene diamine, trimesoyl chloride, n-hydroxysuccinimide, EDC carbodiimide), alginate, bovine serum albumin, Suwanee River natural organic matter, organic solvents for membrane fabrication (dimethylformamide, n-methyl-pyrrolidinone, acetone, ethanol, isopropanol, iso-par-g, hexane), membrane casting equipment (casting blade, non-woven fabric, glass plates), supplies for membrane characterization (microscopy sample holders and cantilevers for force spectroscopy), characterization facility user fees (for use of analytical instrumentation in the Characterization Facility at UMN).
Capital Expenditures over $5,000:	$81,341	Spin coater for membrane fabrication ($8,000), lab-scale forward osmosis (FO) apparatus ($15,000), lab-scale membrane distillation (MD) apparatus ($15,000), lab-scale reverse osmosis (RO) apparatus ($15,041), pilot-scale hybrid FO-MD unit ($28,300).
Travel Expenses in MN:	$ 1,000	Travel in Minnesota for surface water collection such as Lake Superior and Upper Red Lake. Mileage will be reimbursed at $0.55 per mile or current UMN compensation plan.
TOTAL ENRTF BUDGET:	**$ 191,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000:

Spin coater for forward osmosis membrane fabrication ($8,000): a spin coater is necessary for the fabrication of forward osmosis membranes using the molecular layer-by-layer deposition technique.

Lab-scale forward osmosis (FO, $15,000), membrane distillation (MD, $15,000) and reverse osmosis (RO, $15,041) units: one lab-scale FO and one lab-scale MD unit are required to characterize the water transport properties (i.e., water permeability) of the FO and MD membrane materials developed in activity 1, as well as the fouling resistance of the materials. A RO lab-scale unit is needed to determine the solute permeability coefficient of the membranes developed in activity 1. Components for the construction of 1 lab-scale forward osmosis and 1 membrane distillation system: Gear pumps, heads and water heater/chiller (8 pumps, 2 heaters/chillers, total: $17,000), custom-made flow cells for forward osmosis and membrane distillation (2 cells, total: $2,000), unit instrumentation (2 computers, 2 conductivity meters, 4 stirring plates, 8 flowmeters, valves, fittings, water reservoirs, total: $11,000). Components for the RO setup: high pressure pump ($10,641), filtration cell ($1,000), valves, tubing, fittings, flowmeters ($3400).

Fabrication of a pilot-scale FO-MD water purification system as part of activity 2 ($28,300): filtration cells (2 @ $2500 each), 1 heater unit ($4300), 1 chiller ($3000), 4 gear pumps and 4 pump drives ($6,000), tubing, valves, instrumentation ($10,000).

Per the June 30, 2018 amendment request, all capital equipment will be transferred to the Department of Civil, Environmental, and Geo- Engineering at the University of Minnesota so it can continue to be used for its useful life for the intended purpose or, if the use changes, to pay back the Environment and Natural Resources Trust Fund an amount equal to either the cash value received or a residual value approved by the LCCMR director if it is sold.

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: A full-time graduate student researcher will be employed with this appropriation for 2 years (for 2 FTE over the entire 3-year project period). This results in a total of 1 FTE for the total project.

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: N/A

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
N/A	N/A	N/A	N/A
State	N/A	N/A	N/A
	$	$	
TOTAL OTHER FUNDS:	**$N/A**	**$N/A**	

VII. PROJECT STRATEGY:

A. Project Partners:

The project manager will be Professor Santiago Romero-Vargas Castrillón (U. of Minnesota), who will supervise a graduate student in the execution of the proposed work. Romero-Vargas has expertise in the development, characterization, and testing of membrane materials for water purification, and membrane-based processes for water production.

B. Project Impact and Long-Term Strategy:

The proposed work will result in membrane materials and low-energy processes for the removal of heavy metals and organic contaminants of emerging concern from untreated surface waters in Minnesota. We expect this project to lead to further applications in municipal wastewater treatment (e.g., the direct, decentralized treatment of sewage) and, also, to patentable technology.

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
United States Geological Survey. Project title: “Improving the (Bio)fouling and Mechanical Resistance of Ultrafiltration Membranes for Drinking Water Production”. The project proposed in this work plan partially builds on results and expertise developed during the USGS-sponsored project.	3/1/2015 – 2/28/2016	$ 30,000

Matching funds from UMN for the abovementioned USGS project.	3/1/2015 – 2/28/2016	$60,000

VIII. FEE TITLE ACQUISITION/CONSERVATION EASEMENT/RESTORATION REQUIREMENTS:

A. Parcel List: N/A

B. Acquisition/Restoration Information: N/A

IX. VISUAL COMPONENT or MAP(S):
See attached.

X. RESEARCH ADDENDUM:
See attached.

XI. REPORTING REQUIREMENTS:
Periodic work plan status update reports will be submitted no later than January 30, 2017, June 30, 2017, January 30, 2018, and June 30, 2018. A final report and associated products will be submitted by September 30th, 2018.

Environment and Natural Resources Trust Fund
M.L. 2016 Project Budget

Project Title: Membrane-Based Process for Decentralized Drinking Water Production
Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 04l
Project Manager: Santiago Romero-Vargas Castrillón
Organization: University of Minnesota - Twin Cities
M.L. 2016 ENRTF Appropriation: $191,000
Project Length and Completion Date: September 30th, 2018 (figures as of 8/30/18)

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Budget (7/26/2018)	Amount Spent	Activity 1 Balance	Activity 2 Budget	Amount Spent	Activity 2 Balance	Revised TOTAL BUDGET	Revised TOTAL BALANCE
BUDGET ITEM				***Development of a Forward Osmosis-Membrane Distillation Pilot Scale Unit***				
Personnel (Wages and Benefits)								
Graduate research assistant (50% time per year for two years, salary 57% of cost, tuition 33% of cost, fringe benefits 10% of cost)	$44,642.46	$44,642.46	$0.00	$42,249.54	$0.00	$42,249.54	$86,892.00	$42,249.54
Professional/Technical/Service Contracts								
Equipment/Tools/Supplies								
Laboratory equipment and supplies ($21264) including, but not limited to: chemicals for membrane fabrication and characterization (polysulfone, poly(ether sulfone), poly(vinyl pyrrolidone) and poly(vinylidene fluoride), polyethylene glycol, dopamine hydrochloride, Tris HCl buffer, ethylenediamine, m-phenylene diamine, trimesoyl chloride, n-hydroxysuccinimide, EDC carbodiimide), alginate, bovine serum albumin, Suwanee River natural organic matter, organic solvents for membrane fabrication (dimethylformamide, n-methyl-pyrrolidinone, acetone, ethanol, isopropanol, iso-par-g, hexane), membrane casting equipment (casting blade, non-woven fabric, glass plates), supplies for membrane characterization (microscopy sample holders and cantilevers for force spectroscopy), characterization facility user fees (for use of analytical instrumentation in the Characterization Facility at UMN).	$11,135.00	$11,135.00	$0.00	$10,632.00	$0.00	$10,632.00	$21,767.00	$10,632.00
Capital Expenditures Over $5,000								

Spin coater for forward osmosis membrane fabrication: a spin coater is necessary for the fabrication of membranes using the molecular layer-by-layer technique	$8,000.00	$0.00	$8,000.00	$0.00	$0.00	$0.00	$8,000.00	$8,000.00
Fabrication of one bench-scale forward osmosis experimental setup and one membrane distillation experimental setup: a bench-scale setup to be used for membrane characterization and fouling experiments during activity 1 of the project. Components for the construction of 1 lab-scale forward osmosis and 1 membrane distillation system: Gear pumps, heads and water heater/chiller (8 pumps, 2 heaters/chillers, total: $17000), custom-made flow cells for forward osmosis and membrane distillation (2 cells, total: $2000), unit instrumentation (2 computers, 2 conductivity meters, 4 stirring plates, 8 flowmeters, 8 3-way valves, 2 10-packs of fittings, 4 water reservoirs, total: $11000).	$30,000.00	$0.00	$30,000.00	$0.00	$0.00	$0.00	$30,000.00	$30,000.00
Fabrication of a reverse osmosis experimental setup for the characterization of membranes: high pressure pump ($10,641), filtration cell ($1,000), valves, tubing, fittings, flowmeters ($3400).	$15,041.00	$14,763.07	$277.93	$0.00	$0.00	$0.00	$15,041.00	$277.93
Fabrication of a pilot-scale FO-MD water purification system as part of activity 2: filtration cells (2 @ $2500 each, 1 heater unit @ $4300, 1 chiller @ $3000, 4 gear pumps and 4 pump drives @ $6,000, tubing, valves, instrumentation @ $10,000)	$0.00	$0.00	$0.00	$28,300.00	$0.00	$28,300.00	$28,300.00	$28,300.00
Travel expenses in Minnesota								
Mileage and lodging. To collect water samples within Minnesota (Lake Superior, Upper Red Lake, Mississippi River). Mileage will be reimbursed @ $0.55 per mile or current U of M compensation plan.		$0.00	$0.00	$1,000.00	$0.00	$1,000.00	$1,000.00	$1,000.00
COLUMN TOTAL	**$108,818.46**	***$70,540.53***	**$38,277.93**	**$82,181.54**	***$0.00***	**$82,181.54**	**$191,000.00**	***$120,459.47***

Membrane-based process for decentralized drinking water production.