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

Date of Report: January 15, 2016

Date of Next Status Update Report: December 31, 2016

Date of Work Plan Approval:

Project Completion Date: June 30, 2019

Does this submission include an amendment request? No

PROJECT TITLE: Development of Innovative Sensor Technologies for Water Monitoring

Project Manager: Tianhong Cui

Organization: University of Minnesota

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Web Address:

Location: Minneapolis, MN

Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$509,000**
	Amount Spent:	**$0**
	Balance:	**$509,000**

Legal Citation: M.L. 2016, Chp. xx, Sec. 116P.10., Subd. 04k

Appropriation Language:

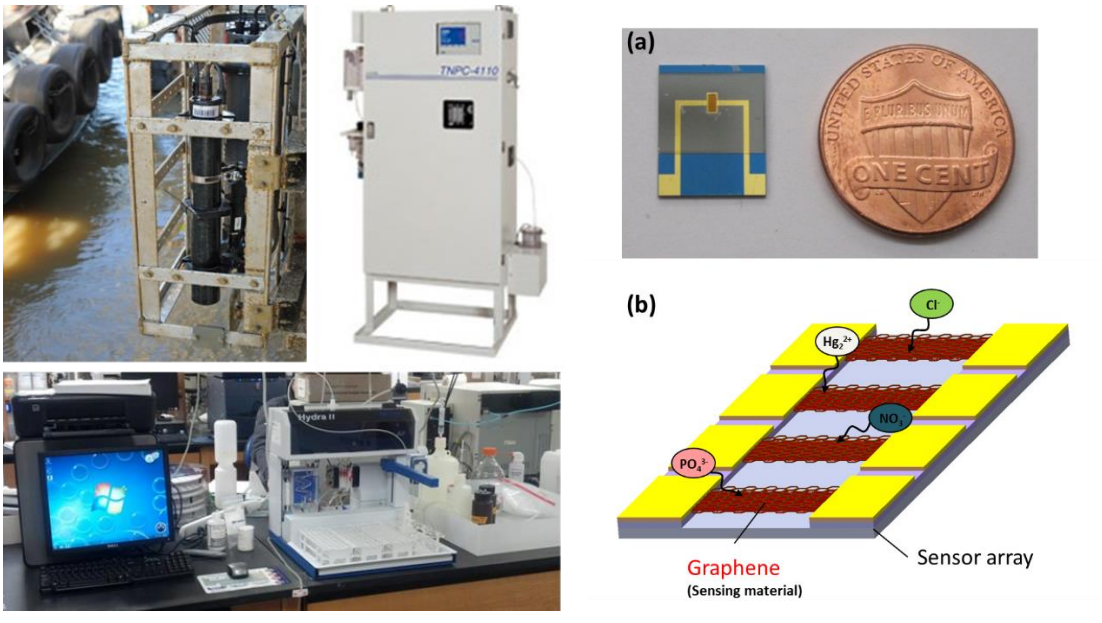
(k) Development of Innovative Sensor Technologies for Water Monitoring

$509,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota to develop inexpensive and efficient sensitive sensors and wireless sensor networks for continuous monitoring of contaminants in lakes and rivers in Minnesota. 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: Development of Innovative Sensor Technologies for Water Monitoring

II. PROJECT STATEMENT:

The objective of this project is to develop very tiny, cheap, fast, accurate sensors to continuously monitor pollutants including phosphate, nitrate, mercury, and chlorine in Minnesota's waters (Figure 1). This is a new testing and monitoring technique, which can provide remote sensing capability to accurately assess the conditions of Minnesota's waters at very low cost. The proposed new technology is to manufacture graphene micro sensors using the micro-manufacturing capability available in Minnesota, and to build wireless sensing networks based on the sensors. Graphene is a monolayer of carbon atoms with outstanding material properties, a newly developed material very sensitive to molecules in liquids. This will enable the tiny sensors to detect pollutants in lakes and rivers with very high sensitivity and super short response time to pollutants in waters. In contrast, currently environmental control agencies have to rely on bulky and expensive equipment to conduct off-line detections and analyses. The advanced manufacturing techniques at the University of Minnesota allow us to develop the sensors in a very high quantity at a super low cost, while surmounting the performance of pollutants detection using large equipment or devices. In addition, the sensors can be further developed into sensing networks so that we can form wireless detection for continuous monitoring of water quality in Minnesota. This will help the end-users including clear water agencies, researchers, and advocacy groups for continuous detection and analyses of Minnesota waters and prevent from ecological contaminations. This project is intended to develop the tiny cheap sensors, to prove its feasibility, and to provide foundational knowledge of the technique. In the next phase of the research, we will closely collaborate with state agencies, water researchers, and industry to develop an implementation plan for pollutants monitoring in broader water regions in Minnesota.



Current Technology **New Technology Proposed**

Figure 1. A comparison of pollutants monitoring in waters between the current and proposed new technologies.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of December 31, 2016:

Project Status as of June 30, 2017:

Project Status as of December 31, 2017:

Project Status as of June 30, 2018:

Project Status as of December 31, 2018:

Overall Project Outcomes and Results as of June 30, 2019

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Development of tiny cheap sensors and sensor arrays
Description: The objective of this activity is to develop tiny sensors using graphene, which is very tiny, cheap, fast, accurate, sensitive, and durable for pollutants monitoring in lakes and rivers in Minnesota. Multiple sensors as a sensor array will be designed and fabricated for continuous monitoring of phosphate, nitrate, mercury, and chlorine in waters. The size of a single sensor or a sensor array will be as small as a rice grain. The sensor network system together with the sensors will be at least 10,000 times smaller than the current existing equipment, while the cost is at least 1,000 times lower than the bulky machine currently used for water quality detection, overrunning performance of the bulky equipment being used.

We propose a new sensor that promises to be an alternative to conventional sensors. Graphene, known as a one-atom-thickness carbon material, is used as a sensing material in our sensors. Graphene exhibits following excellent characteristics: (1) ease of being used in current microfabrication technology, (2) high sensitivity due to exposure of species to every single carbon atom, (3) low inherent electrical noise, (4) capability of being integrated in tiny sensors, and (4) high carrier mobility. Due to its simplicity, low cost, and high performance, graphene sensors solve major problems with the current sensors, and empower the water monitoring system for environmental protection.

Specific tasks will be:
1. Single and multi-array sensors hardware will be developed for testing and continuous monitoring of water quality indicators including phosphate, nitrate, mercury, and chlorine. Initial testing results of tiny sensors in response to pollutants in lab.
    a. Design, simulation, and optimization of single sensor and sensor array structures.
    b. Design of fabrication flow chart of single sensor and sensor array.
    c. Fabrication of sensor and sensor array using the micro- and nano-fabrication technology.
    d. Lab test of single sensor and sensor array in phosphate, nitrate, mercury, and chlorine.

2. Software for signal process and data display will be developed
    a. Develop and optimize program codes for signal process from the sensor and sensor array.
    b. Develop and optimize program codes for data display for the sensor and sensor array.

3. Tiny sensors will be tested in comparison with conventional results in lab; Improved sensors with optimized design, fabrication, and testing; Sensors testing of pollutants monitoring of waters sampled from lakes and rivers in Minnesota.

a. Lab test single sensor and sensor array together with experiments based on conventional tests of pollutants.
b. Analyze and compare the results from the sensors developed and the conventional approaches.
c. Improve and optimize the design, fabrication, and testing of single sensor and sensor array.
d. Field test single sensor and sensor array from selected lakes and rivers in Minnesota.

4. Comprehensive assessment of the techniques will be completed.

a. Assess the design of the structures of single sensor and sensor array.
b. Assess the fabrication techniques of single sensor and sensor array.
c. Assess the sensor performance including selectivity, sensitivity, detection limit, and response time of single sensors and sensor array in lab.
d. Assess the sensor performance including selectivity, sensitivity, detection limit, response time, and life time of single sensors and sensor array in field tests of lakes and rivers.

Summary Budget Information for Activity 1: **ENRTF Budget: $ 333,005**
Amount Spent: $ 0
Balance: $ 333,005

Outcomes	Completion Date	Budget
1. Single and multi-array sensors hardware will be developed for testing and continuous monitoring of water quality indicators including phosphate, nitrate, mercury, and chlorine; Initial testing results of tiny sensors in response to pollutants in lab	*6/30/2017*	*$110,000*
2. Software for signal process and data display will be developed	*6/30/2017*	*$80,000*
3. Tiny sensors will be tested in comparison with conventional results in lab; Improved sensors with optimized design, fabrication, and testing; Sensors testing of pollutants monitoring of waters sampled from lakes and rivers in Minnesota	*6/30/2018*	*$123,005*
4. Comprehensive assessment of the techniques will be completed	*6/30/2018*	*$20,000*

Project Status as of December 31, 2016:

Project Status as of June 30, 2017:

Project Status as of December 31, 2017:

Project Status as of June 30, 2018:

Project Status (Integration Work with Activity 2) as of December 31, 2018:

Final Report Summary (Integration Work with Activity 2) as of June 30, 2019:

ACTIVITY 2: Development of wireless sensing networks and field testing
Description: A prototype unit will be designed and constructed to demonstrate the feasibility. Data networking protocol and hardware will be developed and tested. Field testing will include setting up a

test site and three data relay stations. Upon completion of the project, we will demonstrate the integrated system to the stakeholders and LCCMR committee members and officials.

We will develop data networking protocol and hardware in order to send and receive signals from the graphene sensors wirelessly. This enables us to visualize pollutant levels at a monitoring station (Figure 2). The new technology will make great impacts on easy and low-cost monitoring of waters, promising that it advances monitoring a large number of lakes and rivers in Minnesota for environmental protection and human health safety.

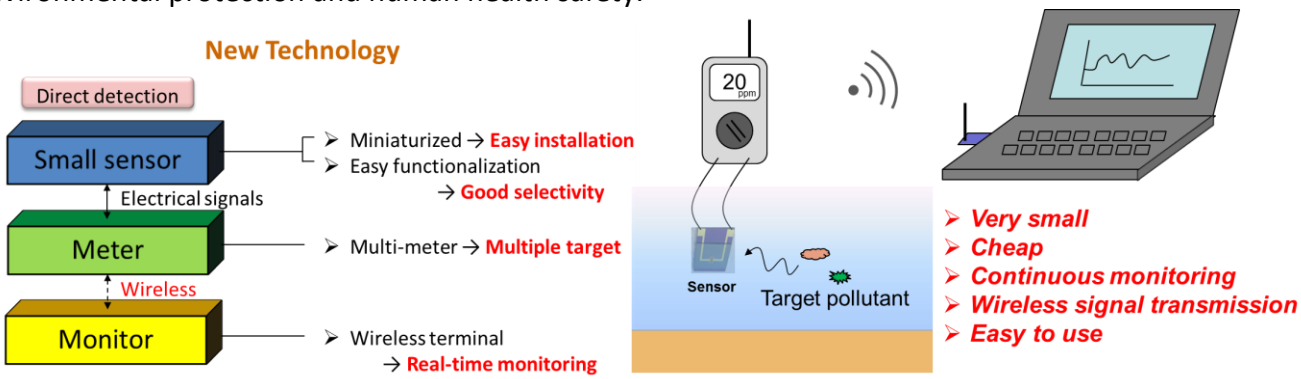


Figure 2. Sensor network proposed in this project for monitoring pollutants in waters

Specific tasks will be:

1. A prototype of sensing network with tiny sensors unit will be developed.
   a. Design, simulate, and optimize sensing network with tiny sensors.
   b. Assemble and test electrical signal process of sensing network.
   c. Lab test sensing network in solutions of phosphate, nitrate, mercury, and chlorine.

2. Data networking protocol and hardware will be developed.
   a. Develop and optimize data networking protocols.
   b. Develop and optimize sensing network hardware.

3. The prototype unit will be set up on a water site and data transmission through relay will be tested.
   a. Lab test sensing networks with experiments based on conventional tests of pollutants.
   b. Analyze and compare the results from the sensing networks and the conventional approaches.
   c. Improve and optimize the design, assembly, and testing of sensing networks.
   d. Field test sensing networks from lakes and rivers in Minnesota.

Summary Budget Information for Activity 2:

ENRTF Budget: **$ 175,995**
Amount Spent: **$ 0**
Balance: **$ 175,995**

Outcomes	Completion Date	Budget
1. A prototype of sensing network with tiny sensors unit will be developed	*6/30/2019*	*$60,000*
2. Data networking protocol and hardware will be developed	*6/30/2019*	*$60,000*
3. The prototype unit will be set up on a water site and data transmission through relay will be tested	*6/30/2019*	*$55,995*

Project Status as of December 31, 2016:

Project Status as of June 30, 2017:

Project Status as of December 31, 2017:

Project Status as of June 30, 2018:

Project Status as of December 31, 2018:

Final Report Summary as of June 30, 2019:

V. DISSEMINATION:

Description:

The findings will be disseminated through:

(1) On site demonstration as described in the activities
(2) Public seminars
(3) Progress update on biorefining.cfans.umn.edu and www.me.umn.edu
(4) Presentations at national and international technical conferences
(5) Communications with interested entrepreneurs
(6) Peer reviewed papers
(7) Collaboration with MPCA

The technologies, if demonstrated successfully, may be implemented to many lakes and rivers in the State of Minnesota and beyond. Any intellectual properties and related revenues as a result of the program will be shared between UMN and LCCMR.

Project Status as of December 31, 2016:

Project Status as of June 30, 2017:

Project Status as of December 31, 2017:

Project Status as of June 30, 2018:

Project Status as of December 31, 2018:

Final Report Summary as of June 30, 2019

VI. PROJECT BUDGET SUMMARY:
A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$ 423,132	• Dr. Tianhong Cui PI (4.3 weeks (.11FTE) + fringe 33.7% fringe) for 3 years. 9 months appointment • Dr. Roger Ruan (3.12 weeks (.08FTE) + fringe 33.7% fringe) for 3 years. 9 months appointment • Dr. Paul Chen (14.5 weeks (.28FTE) + fringe 33.7% fringe) for 3 years. 12 months appointment • Post-Doc (Ruan and Chen) (6 months + 22.4% fringe) for 3 years • Graduate Research Assistant 50% FTE (fall & spring include 17.6% fringe plus $18.29/hour tuition, summer 17.6% fringe only) for 3 years
Professional/Technical/Service Contracts:	$37,500	Scientific Services (Cui): User fees at Minnesota Nano Center and Characterization Facility at the University of Minnesota. The cost is about $541 per month for the Post-Doc, and $500 per month for the graduate research assistant for 3 years.
Equipment/Tools/Supplies:	$39,368	Lab Supplies (Cui): fabrication materials & supplies including silicon wafers ($3,413), polymer substrates ($4,000), chemicals ($6,000), graphene substrate and solutions ($5,000), carbon based gases ($3,000), bottles, gloves, other electronics for testing, etc. ($2,500) Lab Materials & Supplies (Ruan & Chen): Purchase of chemical reagents ($3,000), analytical kits ($2,500), compressed gases ($500), glassware ($855), consumable supplies (standards and columns) for analytical instruments ($5,000), instrument maintenance and repair ($3,600)
Travel Expenses in MN:	$9,000	Ruan & Chen domestic travel (year 2 &3): Mileage, lodging, and meals for travel between the sensor testing sites and the university; Cui, Ruan, and Chen need work together on the testing. This cost is based on the university compensation policy.
TOTAL ENRTF BUDGET:	**$509,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: N/A

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 4.41 FTE

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: 0

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-State			
Mocon Inc.	$173,199	$50,000	Developing graphene gas sensors
State			
The university overhead unpaid	$237,500	$0	Developing tiny sensors for pollutants monitoring in waters
TOTAL OTHER FUNDS:	**$410,699**	**$50,000**	

VII. PROJECT STRATEGY:

A. Project Partners:

Tianhong Cui, professor in Mechanical Engineering, will serve as PI and project manager. He will be responsible for overseeing the project, all reports, and deliverables. He will also develop the tiny sensors, portable sensor network units, and data transfer protocols. Roger Ruan, professor in Bioproducts and Biosystems, will be a collaborator responsible for setting up field testing of the proposed techniques. Paul Chen, associate professor in Bioproducts and Biosystems, will be another collaborator responsible for lab analysis of water quality using conventional and the proposed techniques.

B. Project Impact and Long-term Strategy:

Minnesota Pollution Control Agency (MPCA) works together with other agencies and advocacy groups in developing strategy to prevent, control, and abate discharges that cause water pollution and violate water quality standards. The first task in the strategy is testing and assessment to provide information on the conditions of the waters. Currently, many of our water bodies are unmonitored despite the requirement of the federal 1972 Clean Water Act. The proposed tiny sensors will provide low-cost, but high-performance techniques and infrastructure, i.e. unique sensors and sensing networks, for assessment of Minnesota's waters in much greater geographic area. Upon completion this project will realize economical and high-performance tiny sensing technique for continuous monitoring of water conditions. The knowledge learned throughout the project will provide a solid foundation for further research and development efforts that would lead to eventual implementation of the novel technique practically enabling broader monitoring of Minnesota's waters with remote sensing and data transmission via wireless capability. This will provide a solution to current resources strapped monitoring programs in Minnesota, ultimately help implement the MPCA's clear water strategy, and thus enhance the ecological benefits of Minnesota waters.

In addition, we will plan to file patents on the proposed sensors and sensor networks for commercialization in the future. We can also use the sensors or sensor networks for monitoring and detection of drinking water, juice, liquid food, etc. As a result, the innovative technology can also benefit the local industry by developing new products in Minnesota including new graphene tiny sensors and sensor networks for broader applications.

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
Mocon Inc., Graphene gas sensors	Nov. 2014 - July 2016	$173,199
Alexandria Extrusion Inc., Microstructures for Heat Transfer	Nov. 2011 - Dec. 2015	$165,516
DARPA, MEMS-Based Active Heat Sink Technology	Jan. 2009 - Sept. 2013	$2,579,025
MN Partnership, Nano-Sensors	Jan. 2010 – Dec. 2012	$637,500

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

IX. VISUAL COMPONENT or MAP(S):

X. RESEARCH ADDENDUM:

Enclosed

XI. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted no later than September 2016, March 2017, September 2017, March 2018, September 2018, and March 2019. A final report and associated products will be submitted on June 30, 2019.

Environment and Natural Resources Trust Fund

M.L. 2016 Project Budget

Project Title: Development of Innovative Sensor Technologies for Water Monitoring

Legal Citation: M.L 2016, Sec. 116P.10., Subd. 04k

Project Manager: Tianhong Cui

Organization: Univeristy of Minnesota

M.L. 2016 ENRTF Appropriation: $ 509,000

Project Length and Completion Date: 3 Years, June 30, 2019

Date of Report: January 15, 2016

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Budget	Amount Spent	Activity 1 Balance	Activity 2 Budget	Amount Spent	Activity 2 Balance	Activity 3 Budget	Amount Spent	Activity 3 Balance	TOTAL BUDGET	TOTAL BALANCE
BUDGET ITEM	***Development of tiny cheap sensors and sensor arrays***			***Development of wireless sensing networks and field testing***							
Personnel (Wages and Benefits)	$278,364		$278,364	$144,768		$144,768				$423,132	$423,132
Tianhong Cui, PI: $21,909 (75% salary, 25% benefits); 11% FTE each year for 3 years, 3% increase years 2-3. $67,720 fo 3 years in total.											
Ruan, Co-PI: $10,252 (75% salary, 25% benefits): 8% FTE each year for 3 years, 3% increase years 2-3. $31,688 for 3 years in total.											
Chen, Co-PI: $32,183 (75% salary, 25% benefits): 28% FTE each year for 3 years, 3% increase years 2-3. $99,474 for 3 years in total.											
PostDoc: $27,315 (82% salary, 18% benefits): 50% FTE each year for 3 years, 3% increase years 2-3. $84,428 for 3 years in total.											
1 RA's at 50%: $45,736 (58% salary, 24% benefits); 50% FTE each year for 3 years, 3% increase years 2-3. $139,822 in tota											
Equipment/Tools/Supplies	$25,641		$25,641	$13,727		$13,727				$39,368	$39,368
Lab Supplies (Cui): fabrication materials & supplies including silicon wafers ($3,413), polymer substrates ($4,000), chemicals ($6,000), graphene substrate and solutions ($5,000), carbon based gases ($3,000), bottles, gloves, other electronics for testing, etc. ($2,500)											
Lab Materials & Supplies (Ruan & Chen): Purchase of chemical reagents ($3,000), analytical kits ($2,500), compressed gases ($500), glassware ($855), consumable supplies (standards and columns) for analytical instruments ($5,000), instrument maintenance and repair ($3,600)											
Travel expenses in Minnesota	$4,500		$4,500	$4,500		$4,500				$9,000	$9,000
Ruan & Chen domestic travel (year 2 &3): Mileage, lodging, and meals for travel between the sensor testing sites and the university; Cui, Ruan, and Chen need work together on the testing. This cost is based on the university compensation policy.											
Other	$24,500		$24,500	$13,000		$13,000				$37,500	$37,500
Scientific Services (Cui): User fees at Minnesota Nano Center and Characterization Facility at the University of Minnesota. The cost is about $541 per month for the Post-Doc, and $500 per month for the graduate research assistant for 3 years.											
COLUMN TOTAL	**$333,005**		**$333,005**	**$175,995**		**$175,995**				**$509,000**	**$509,000**