Environment and Natural Resources Trust Fund
2016 Request for Proposals (RFP)

Project Title: **ENRTF ID: 066-B**

Virtual Bioreactor for Improving Treatment of Minnesotas Wastewaters

Category: B. Water Resources

Total Project Budget: $ 536,916

Proposed Project Time Period for the Funding Requested: 3 years, July 2016 to June 2019

Summary:

A virtual bioreactor, to accurately simulate activated sludge wastewater treatment processes, will be created. Engineers will use this powerful tool to optimize treatment plant performance and improve Minnesota's water quality.

Name: Henry Mott

Sponsoring Organization: U of MN

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Location

Region: Statewide

County Name: Statewide

City / Township:

Alternate Text for Visual:

Map showing locations of 216 activated sludge based MN wastewater plants; schematic illustrating flow path of wastewater through a conventional (aka plug-flow-like) activated sludge reactor; plot showing smooth profile generated by segregated flow modeling approach in contrast to stepped profile generated by tanks in series modeling approach.

_____ Funding Priorities _____ Multiple Benefits _____ Outcomes _____ Knowledge Base

_____ Extent of Impact _____ Innovation _____ Scientific/Tech Basis _____ Urgency

_____ Capacity Readiness _____ Leverage _______ TOTAL ______%

PROJECT TITLE: ***Virtual Bioreactor for Improving Treatment of Minnesota's Wastewaters***

I. PROJECT STATEMENT

Each day upwards of a half billion gallons of wastewater, the vast majority of Minnesota's municipal and industrial wastewater discharges, are treated and discharged into Minnesota's waters by 216 plants that use activated sludge technology. We demand a great deal from activated sludge processes and our demands are escalating – lowered levels of nitrogen and phosphorus and removal of specific trace organic pollutants prior to discharge. Highly accurate modeling of wastewater processes will be essential to realizing these objectives. Unfortunately, current models employ inaccurate approximations of high-performance, high-efficiency reactors and cannot take full advantage of the detailed characterizations of activated sludge microbial communities available in the scientific literature. The overarching goals of this project are as follows.

- to create and make available for general use a "virtual bioreactor", that employs a next generation, highly representative reactor modelling approach and quantitative knowledge of key microbial populations, for use by process engineers to optimize performance of and design more effective activated sludge processes.
- to connect the body of scientific understanding of microbes responsible for specific treatment processes with process engineering in order to improve design and operation of wastewater plants to reduce discharges of phosphorus, nitrogen and specific pollutant and improve energy efficiency.

Scientists use polymerase chain reaction (PCR) technology to replicate genes and, thus, to count and aid in identification of specific microbes responsible for biochemical processes. Generally, it is these counts that are reported in the literature. Unfortunately, process models require microbial abundances in mass concentration units. This disconnect hinders beneficial use of a huge body of microbiological understanding. Means to convert microbial counts to mass concentrations are vital to effective future process modeling and control efforts.

Highly efficient activated sludge bioreactors are most often configured to mimic the "plug-flow" hydrodynamic condition – wherein elements of fluid entering the reactor are considered to pass through the reactor in the exact order of entry. In real reactors, mixing of fluid elements with those ahead and behind does occur, rendering the hydrodynamic system highly complex. Many process engineers simply do not attempt to model these reactors, opting to work from "experience" and empiricism. Others employ what is called the reactors-in-series model, which envisions the real reactor as a series of completely mixed reactors, greatly simplifying the mathematics. Unfortunately this approach yields a "stepped" rather than a smooth profile of reactant and product abundances and of process reaction rates with position in the reactor. The segregated flow model, which captures the plug-flow concept while also accounting for mixing among fluid elements is the heart of the cutting edge wastewater modeling approach the principal investigator has devised and shown to realistically simulate key activated sludge processes. The current developers' platform version will be extended to general-use executable form and hydraulically and microbially calibrated to produce a valuable analytical tool for use by process and design engineers to optimize existing and design better-performing new bioreactors.

II. PROJECT ACTIVITIES AND OUTCOMES

Activity 1: *Produce a virtual bioreactor for use in simulating performance of activated sludge processes and make it available for use by process and design engineers* **Budget: $176916**

Given the risks associated with non-compliance with discharge limitations, process engineers and operators are highly reluctant to "experiment" with their processes to identify more efficient operational practices. The virtual bioreactor will enable risk-free process experimentation. Design engineers will have the ability to more accurately simulate activated sludge performance, leading to more robust designs and improved performance.

Outcome	Completion Date
1. convert existing computational model from developers' platform to executable form	*06/30/2017*
2. calibrate virtual bioreactor using project-derived hydrodynamic and microbial data	*06/30/2019*

Activity 2: *Calibrate reactor hydrodynamics (dispersion) through conduct of tracer tests* **Budget: $150000**

Tracer tests employing project-developed standard protocols will be conducted on operating bioreactors to characterize hydraulics leading to determination of dispersion coefficients. Dispersion coefficients will be correlated with reactor geometry, wastewater flow, aeration system configuration and air delivery to produce a general correlation so that reactor hydrodynamics can be accurately predicted for virtually any bioreactor of "conventional" design. When combined with geometry and flow information, the dispersion coefficient yields the residence time density distribution that lies at the heart of the segregated flow modeling approach.

Outcome	**Completion Date**
1. develop detailed protocols for conduct and analysis of tracer tests	*12/31/2016*
2. conduct tracer tests at operating bioreactors and analyze resulting data	*12/31/2017*
3. produce a correlation relating dispersion to geometric and operational parameters	*06/30/2018*

Activity 3: *Quantitatively characterize key microbial populations in activated sludge* **Budget: $180000**
Activated sludge from operating plants will be sampled to quantify heterotrophic bacteria, ammonia oxidizing archaea and bacteria, phosphorus accumulating bacteria, and denitrifying bacteria. Protocols will be developed and implemented to convert qPCR microbe counts to mass concentrations for calibrating the virtual bioreactor.

Outcome	**Completion Date**
1. enumerate key microbial populations using qPCR enumeration techniques	*06/30/2017*
2. develop detailed protocols for converting qPCR counts to mass concentrations	*12/31/2018*
3. generalize experimental and analytical procedures for broad-based implementation	*06/30/2019*

Activity 4: *Outreach and dissemination of research products* **Budget: $30000**

Outcome	**Completion Date**
1. create a web page about the virtual bioreactor project hosted on the U of MN website	*06/30/2017*
2. inform potential users about and educate users to employ the virtual bioreactor	*06/30/2019*
3. release fully calibrated virtual bioreactor for use in bioreactor optimization and design	*06/30/2019*

III. PROJECT STRATEGY

A. Project Team/Partners

Henry Mott, PhD, PE, Visiting Professor, Civil, Environmental, and Geo-Engineering, University of Minnesota, and Professor Emeritus, Civil and Environmental Engineering, SD School of Mines and Technology. *Responsible for directly overseeing all project activities including report preparation, outreach and dissemination of results.*
Raymond Hozalski, PhD, PE, Professor, Civil, Environmental, and Geo-Engineering, University of Minnesota. *Responsible for qPCR to enumerate microbes and technical input on all other project activities.*
Metropolitan Council Environmental Services. *Responsible for facilitating access to MCES wastewater plants and technical assistance in conduct of tracer tests, microbial sampling, and data collection for model calibration.*

B. Project Impact and Long-Term Strategy

The overarching impact of this project will be the reduction of the quantities of nitrogen, phosphorus and other specific emerging contaminants to the waters of Minnesota. A side benefit will be improved efficiency of energy utilization for wastewater treatment, reducing Minnesota's overall carbon footprint. The virtual bioreactor will be hosted on the U of MN website and made available free of charge to all who desire to employ it. Outreach activities will inform the engineering and plant operator communities about the virtual bioreactor and provide opportunities for potential users to become educated in its use for simulation of plant processes.

C. Timeline Requirements

This project will be completed in three years. Conversion of the segregated flow modeling approach from a MathCAD 15 developers' platform to a downloadable, executable program will be completed in the first year. Tracer testing and microbial sampling at Twin Cities metro wastewater plants will be completed in the first two years. Correlation of tracer test results with reactor geometry and operational parameters and development of methods to convert microbial counts to mass concentrations will be completed in year 3. Calibration of the virtual bioreactor to the actual plant performance data will be completed by the end of year 3.

2016 Detailed Project Budget

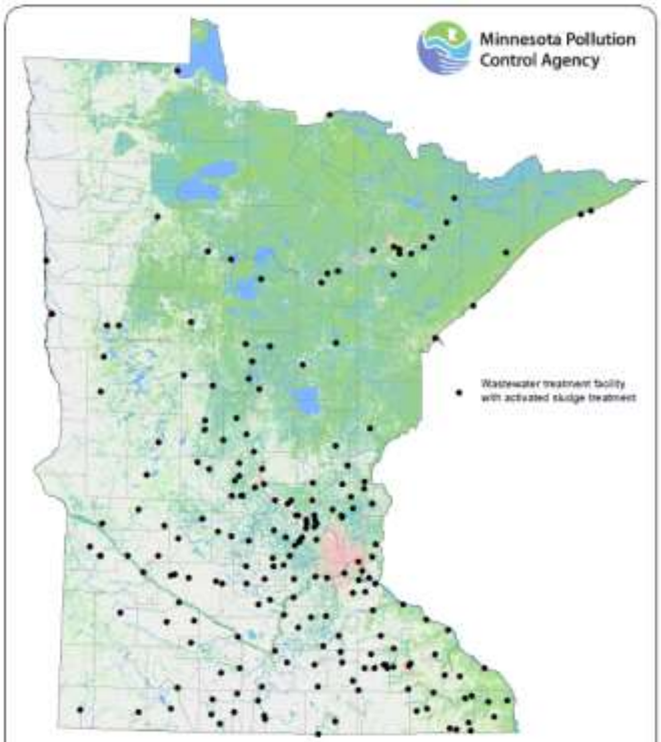
Project Title: Virtual Bioreactor for Improving Treatment of Minnesota's Wastewaters

IV. TOTAL ENRTF REQUEST BUDGET *[3]* years

BUDGET ITEM	AMOUNT
Personnel:	
Henry V. Mott, Principal Investigator - Engage directly in virtual bioreactor development from current developer's platform, perform direct oversight of all project activities	$ 127,140
Direct Salary (25% of full-time, 12-month basis) - $95094	
Fringe benefits (33.7% of direct salary) - $32046	
Raymond M. Hozalski, Co-investigator - Provide technical assistance for hydraulic and microbial characterizations	$ 56,731
Direct Salary (33% of full-time, 3-month, summer, basis) - $42432	
Fringe benefits (33.7% of direct salary) - $14299	
Graduate Research Assistants (yet to be named) - Perform hydraulic and microbial characterizations, analyze and interpret acquired data, perform hands-on programming work for virtual bioreactor development	$ 271,125
Direct Salary (100% of full-time graduate student effort, 12-month basis) - 157006	
Fringe benefits (17.6 % of direct salary + tuition reimbursement) - $114119	
Undergraduate Research Assistants (yet to be named) - Perform routine laboratory work based on project-developed protocols, direct salaries only (33% of full-time effort)	$ 31,920
Equipment/Tools/Supplies:	
Automatic sampling devices for hydraulic and microbial characterizations 10 ea @ $1500	$ 15,000
Laboratory supplies in support of hydraulic and microbial characterizations:	$ 30,000
DNA extration kits ($10000); reagents and standards for qPCR ($10000); glassware for sample collection and storage ($2000); media and supplies for culturing bacteria; chemicals and supplies for conduct of tracer analyses	
Travel:	$ 5,000
In-state travel to attend wastewater operators' meetings, visit wastewater plants, and meet with engineers for project outreach activities. ($4500)	
Attend Central States Water Association, MN Section, Conference on the Environment (in Minneapolis or St. Paul) in 2017 and 2018 to present project findings to enhance outreach activities. ($500)	
TOTAL ENVIRONMENT AND NATURAL RESOURCES TRUST FUND $ REQUEST =	$ 536,916

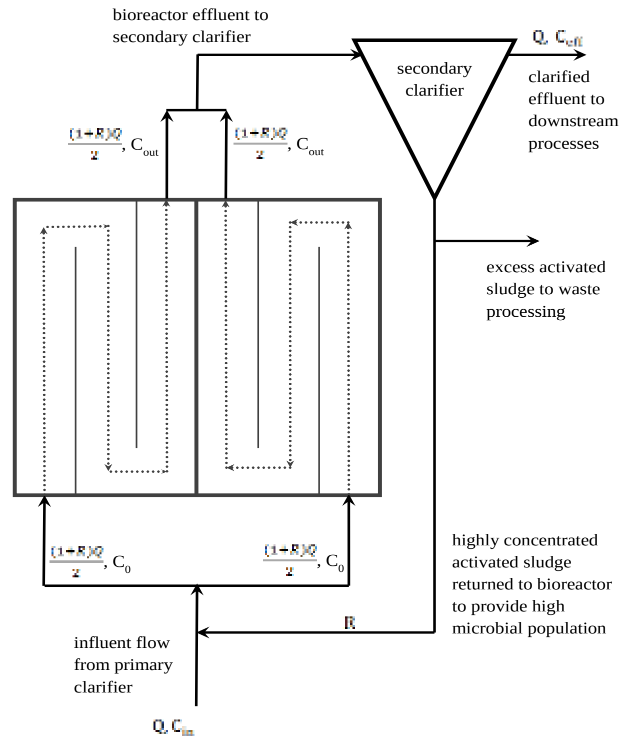
V. OTHER FUNDS

SOURCE OF FUNDS	AMOUNT	Status
Other Non-State $ To Be Applied To Project During Project Period:	N/A	
Other State $ To Be Applied To Project During Project Period: *Indirect costs normally charged to projects by the U of MN that cannot be included with this funding requests.*	$ 223,445	*pending*
In-kind Services To Be Applied To Project During Project Period: *Metropolitan Council Environmental Services - facilitation of acess and provision of technical and facilitation assistance in conduct of hydraulic testing, microbial sampling and process investigations at MCES-operated wastewater plants.*	not determined	*pending*
Funding History: *preliminary work, non-externally funded, 2005-2008, (1 MS thesis produced at the SD School of Mines) to explore applicability of segregated flow model to improve modeling accuracy; independent non-externally funded work by H. Mott in 2012-2015 to extend preliminary work to nutrient removal systems.*	not determined	secured
Remaining $ From Current ENRTF Appropriation:	N/A	

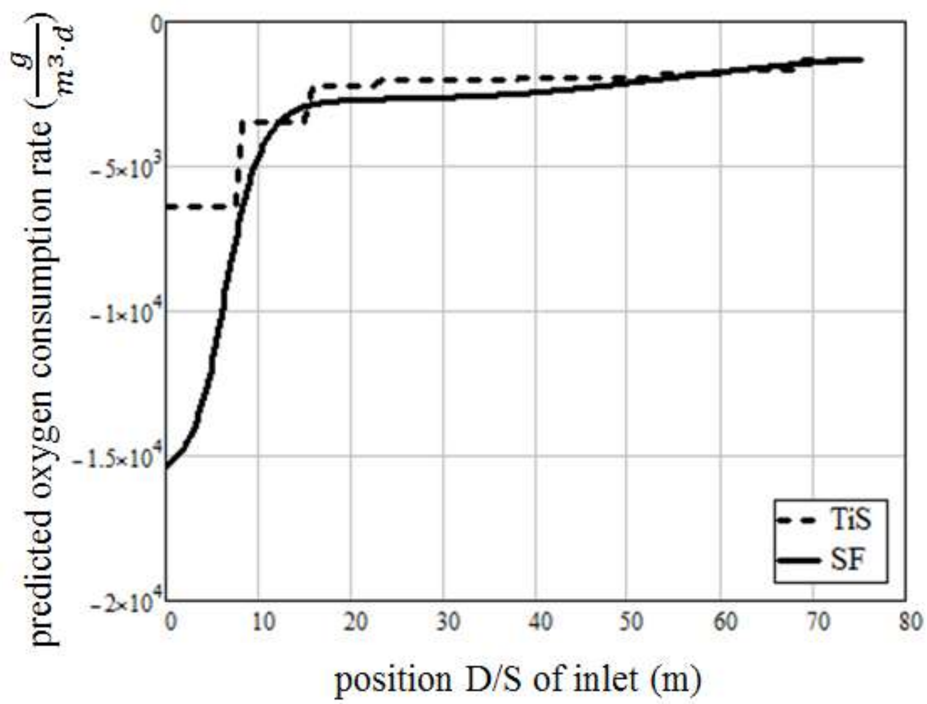


Courtesy of MN Pollution Control Agency

Wastewater treatment facilities utilizing activated sludge treatment technology as of April 24, 2015.



Schematic of a typical conventional (aka plug-flow like) activated sludge bioreactor system.



Selected output from simulations of the performance of a plug-flow like bioreactor using the complete-mix reactors (tanks) in series (TiS) and segregated flow (SF) models. The actual operating profile for the oxygen consumption rate should be smooth, declining from inlet to outlet along the flow path of the reactor, rather than stepped as that resulting from the TiS model. The SF model provides a result that is consistent with the expected behavior of the process within the reactor.

Project Manager Qualifications and Organization Description

Project Manager

Dr. Henry V. Mott, PhD, PE, Principal Investigator

Visiting Professor, Civil, Environmental, and Geo-Engineering (CEGE), University of Minnesota, Twin Cities; Professor Emeritus, Civil/Environmental Engineering, SD School of Mines and Technology (SDSM&T); BS (Civil Engineering), 1973, SD School of Mines and Technology; MSE (Environmental Engineering), 1984, Washington State University; PhD (Environmental Engineering), 1989, University of Michigan.

Dr. Mott has ten years engineering practice experience as a foundation for his twenty-four year tenure with SDSM&T. From both formal training and a passion for connecting knowledge "silos", he is extremely well versed in physical/chemical and microbial processes. He has authored a textbook (*Environmental Process Analysis: Principles and Modeling*, Wiley, 2014), authored or co-authored 15 peer-reviewed articles on a wide variety of topics, and guided 24 MS-level students in completion of thesis projects. He has developed and delivered more than twenty distinct named courses addressing topics ranging from undergraduate engineering computing, fluid mechanics and environmental process analysis and lab, to graduate-level biological process design and lab, environmental systems analysis, and environmental contaminant fate and transport. Coupling of mathematics with conceptual physical, chemical and microbial models is one of Dr. Mott's career-long passions. He is an intensely practical engineer who is very capable with mathematics, numerical methods, basic and environmental sciences, and hands-on investigations.

Dr. Mott has studied the segregated flow model off and on for 30 years, more recently realizing its applicability to modeling processes carried out in conventional (aka, plug-flow-like) activated sludge reactors. In his textbook he has documented the applicability of the segregated flow modeling approach to modeling heterotrophic processes in conventional activated sludge reactors. At the 28th CSWEA Conference on the Environment, Dr. Mott detailed the applicability of the segregated flow modeling approach to the carbonaceous BOD/nitrification process carried out in a conventional bioreactor. This work has since been incorporated into a manuscript submitted to ASCE's *Journal of Environmental Engineering*. He has successfully incorporated the activated sludge model ASM2D, addressing microbially-enhanced nutrient removal from wastewater, into the segregated flow modeling approach. To date he has performed all modeling using MathCAD 15, a powerful developers' tool, and is eager to produce a user-friendly, general use virtual bioreactor for use by process engineers.

Dr. Raymond M. Hozalski, PhD, PE, Co-Investigator

Professor, Department of Civil, Environmental, and Geo- Engineering, University of Minnesota; B.ChE (Chemical Engineering), 1990, Villanova University; MS (Environmental Engineering), 1992, Johns Hopkins University; PhD (Environmental Engineering), 1996, Johns Hopkins University.

Dr Hozalski has authored or co-authored 61 peer reviewed articles and three book chapters on a wide variety of topics and has guided ten doctoral dissertations and twenty four master's thesis projects. His research focuses on water treatment systems including filtration, biofiltration, sorption, and chemical oxidation as well as water distribution system issues. His research has recently produced some of the first detailed characterizations of bacterial communities in biofilms on the insides of water distribution system pipes and in tap water. His investigations span the full spectrum from basic research to applied research done in collaboration with water utilities in Minnesota and beyond. He is experienced in the application of molecular or DNA-based methods for enumerating and characterizing bacterial populations.

Organization

Research will be conducted through the Civil, Environmental, and Geo-Engineering Department of the University of Minnesota employing available world class laboratory and computational facilities. The mission of the U of MN includes conduct of world-class research and service to the State of Minnesota. Wastewater treatment plants operated by the Metropolitan Council Environmental Services Division will be subjects for significant portions of the work. MCES' Process and Research/Development groups, whose missions are to develop effective and efficient strategies to treat wastewaters generated in the Twin Cities' Metro area, will lend their hands-on, practical knowledge and wealth of process experience to the project where applicable.