Missouri Water Resources Research Center Annual Technical Report FY 2012

Introduction

Water Resources Research Center Annual Technical Report FY 2012-2013

WATER PROBLEMS AND ISSUES OF MISSOURI

The water problems and issues in the State of Missouri can be separated into three general areas: 1) water quality, 2) water quantity, and 3) water policy. Each of Missouri's specific problems usually requires knowledge in these three areas.

Water Quality

New media attention to the occurrence of pesticides in drinking water in the Midwest has raised a serious public concern over the quality of Missouri's drinking water and how it can be protected. With the large agricultural activity in the state, non-point source pollution is of major interest. Because of several hazardous waste super-fund sites, hazardous waste is still of a concern to the public. The Centers' research has been to evaluate the quality of current waste sources and improve the methods to protect them. Areas of research for the past ten years have included (but are not limited to): erosion, non-point pollution reclamation of strip mine areas, hazardous waste disposal acid precipitation, anthropogenic effects on aquatic ecosystems and wetlands.

Water Quantity

Missouri has a history of either inadequate amounts of rainfall, or spring floods. Because of the 1987-89 drought years and the floods of 1993 and 1995, water quantity has become a major topic of concern. Research is needed to better understand droughts and flood conditions.

Water Policy

Policies and program need to be formulated that will ensure continued availability of water, as new demands are placed on Missouri's water. The social and economic costs may no longer be held at acceptable levels if water becomes a major issue in cities and rural areas. Past droughts and possible lowering of the Missouri River have raised serious questions over states' rights to water and priority uses. Research areas in this program have included drought planning, legal aspects, perception and values, economic analysis, recreation, land/water use policy and legislation, and long-term effects of policy decisions.

Research Program Introduction

Missouri Water Resources Research Center

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Current research activities include the following:

Stormwater Program

Federal regulations require MU, City of Columbia and Boone County to protect the quality of surface water from stormwater runoff. The Water Center has several projects to evaluate best management practices (BMPs) that will detain and filter the runoff. One project involves a diverse group from across campus working on an undergraduate research project looking into stormwater best management practices at the University of Missouri. The student team is laying groundwork to evaluate existing projects in preparation of data collection that will be used to inform future decisions. Allen Thompson, associate professor of biological engineering serves as principal investigator for the project. In addition, Bob Reed research associate professor, Enos Inniss, assistant professor and Robert Broz, extension assistant professor with agricultural engineering, round out the mentoring team.

Renewable Energy

Ground source heat pump technology is being studied with application to the agriculture sector. The constant temperature of the ground represents an incredible source of environmentally friendly, sustainable energy to heat and cool the buildings. Dr. Shawn Xu, Research Associate Professor with the Water Center, is installing ground source systems on turkey farms in Central Missouri. The energy system is part of a Department of Energy grant ($5,000,000) that Dr. Xu received to introduce the technology into agriculture applications.

Drinking Water

Mizzou Engineering's Water Resources Research Center is working with several Missouri communities to manage disinfection byproducts (DBPs) that are produced during the disinfection of drinking water. DBPs are regulated compounds and can cause cancer. Led by Assistant Professor Enos Inniss and Research Associate Professor Robert Reed, the MWRRC research teams analyze the chemical makeup of water within each community''s treatment plant, water storage towers and distribution system throughout the year. The researchers then will test how certain chemicals affect the water samples in order to identify options for complying with EPA guidelines. Funding has been available from EPA, Mo DNR, and various Missouri communities.

Wastewater Treatment

Water Center engineering researchers developed a portable wastewater treatment system for military bases that ultimately could produce water pure enough to drink. The portable treatment system treats the wastewater with advanced membranes and disinfects chemically, producing reusable water that would save what often is a scarce resource as well as provide substantial savings. Zhiqiang Hu, associate professor led the Water Center team. The Leonard Wood Institute provided the funding for this project ($832,699).

Homeland Security

The Water Center is currently working with the Department of Homeland Security on three related projects on drinking water (Best Practice protocols for Response and Recovery Operations in Contaminated Systems, Understanding Economic Impacts of Disruptions in Water Service, and Studying Distribution System Hydraulics and Flow Dynamics to Improve Water Utility Operational Decision Making). Tom Clevenger and Bob Reed, College of Engineering and Tom Johnson, Truman Center, lead the Water Center team in working with the University of Kentucky, University of Louisville and Western Kentucky University.

Urban Water Quality: Value of Green Roof Technology

Basic Information

Title:	Urban Water Quality: Value of Green Roof Technology
Project Number:	2011MO122B
Start Date:	3/1/2012
End Date:	2/28/2013
Funding Source:	104B
Congressional District:	8
Research Category:	Climate and Hydrologic Processes
Focus Category:	Water Quality, Floods, Non Point Pollution
Descriptors:	
Principal Investigators:	Joel Burken, William Eric Showalter

Publications

There are no publications.

Green Roof Technology Potential Impacts: Research Progress March 2012-Februrary 2013

PIs: JG Burken and WE Showalter

Students: Grace Harper, Lea Ahrens, Montana Puckett, Frank Allen

Abstract

Green roofs can provide energy, water management, aesthetic and ecosystems services benefits, but the magnitude and value of these benefits range greatly from location to location. This research targets evaluation of green roof stormwater runoff quantity, nutrient loading, and erosion prevention of two green roof systems in central Missouri.

During a pilot study, the runoff quantity and composition from green roof material was evaluated continuously under field conditions for two different media both tested under planted and unplanted conditions. Water quantity results show greater than 40% reduction in stormwater runoff from just the growing media and greater than 60% reduction runoff with established plants in green roof media, even though plants are just in the initial growth phases. These preliminary conclusions are conservative.

Previous studies have reported a "first flush" of excess nutrients, but these studies are without evaluating the duration and intensity of this phenomenon throughout the first year of the roof's life. This research showed total phosphorus concentrations up to 30 mg/L and nitrogen concentrations up to 60 mg/L in green roof runoff initially, with concentrations decreasing over time. Media type and age were the largest influences on phosphorus and nitrogen concentrations. Understanding and modeling runoff nutrient kinetics can better aid in developing procedures to minimize nutrient runoff.

Potential wind scour of media was evaluated through wind tunnel testing at 30 mph. As wind erosion can occur before plants are established, surface stabilizers (i.e. adhesives) have been developed to secure green roof media. Green roof adhesive and plant cover both reduced wind scour down to one-tenth of observed scour without any cover in a 30 mile/hour wind. Suspended solids in the runoff were measured to evaluate the drainage layer's ability to prevent washout during storm events. The tested green roof systems were effective, with average TSS concentrations for both below 20 mg/L.

The full-scale implementation of GAF's Gardenscapes green roofing system on the Missouri S&T campus will allow for thermal benefit studies as well as large-scale flow monitoring in ongoing research. This project allowed engagement with not only Missouri S&T but also for the Rolla community. This project will be a spotlight on green roofs technology in the area/region for years to come.

Motivation

Green roofs are increasingly becoming a preferred method of green infrastructure, green building, and city-wide stormwater planning. With incentives such as decreased taxes and expedited permits in addition to LEED certification points, green roof implementation has increased greatly and shows no indication to slow anytime soon. Green roofs have been less prevalent in Missouri and encouraging this technology in our state through demonstration and quantifying benefits on a city scale as well as for individuals. As the technology begins to be regulated in aspects such as construction, wind, and fire regulations, the "green" aspects of the green roof must be considered as well. Though past studies have shown high nutrients from new green roofs, longitudinal studies to show how the nutrients stabilize to lower levels in stormwater have yet to be done. Considering all aspects of the green roof can better assist us in determining the overall value of green roofs.

Objectives

1) Measure quantity of runoff from various green roof media and evaluate hydrographs produced from each.
2) Evaluate a green roof's effect on nutrient concentration, turbidity, and suspended solids.
3) Evaluate dissolved organic carbon concentrations and correlate to BOD added from green roof.
4) Determine impact of wind erosion on green roof systems related to media type, plants, and adhesives.
5) Evaluate cost-benefit of a roof including social benefits

Hypothesis

1) Growing media and planted conditions will reduce peak flow and total runoff.
2) Nutrients, turbidity and suspended solids will increase for all conditions when compared to control, but will show significant decrease after the first flush.
3) Green roof media will add significant organic carbon and increased BOD demands.
4) Planted and adhesive treated media will show significant reduction in wind erosion.
5) Green roofs can be cost-effective when all benefits received are considered

Pilot-Scale Tests:

Green Roof Blocks™ , 2 ft by 2 ft, are used to study the impacts of media constituents and plants on water quantity and quality of green roof runoff. Green Roof Blocks™ are aluminum trays used for modular green roofs that were designed and constructed in St. Louis (http://greenroofblocks.com/). The Green Roof Blocks™, i.e. 'trays', were donated to the project by Kelly Luckett, CEO of Green Roof Blocks.

To simulate field conditions in a controlled study, these trays were tested on top of the Butler-Carlton Civil Engineering Hall and runoff was sampled after each rain event. This set-up allowed us to test different media and planted/non-planted conditions on a smaller scale with a more controlled runoff collection system for accurate measurement of runoff as well as easy sampling for chemical analysis. Figure 1 shows the set up for each tray in the experiment and the Green Roof Blocks™. Table 1 shows the tested variable s for each tray.

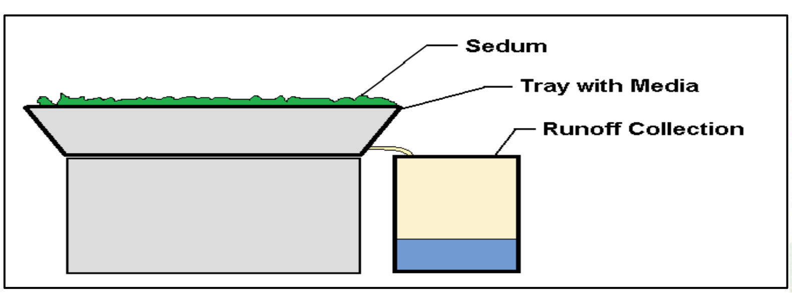


Figure 1: Pilot scale testing of media and Sedums, with schematic of test system on left and photo of Green Roof Blocks™ on right.

Table 1: Experimental Set-Up for Green Roof Blocks™ in the controlled experimental arrangement

Green Roof Trays	Number of Trays
Planted with Arkalyte	3
Unplanted with Arkalyte	3
Planted with GAF	3
Unplanted with GAF	3
Control-Empty	1
Total	13

Green Roof Media

Green roof media available for commercial use most often have proprietary compositions though they are all made up of similar components. The most common growing media used are lighter than topsoil and chosen based upon their ability to drain and support plant growth.
Green roof media is most commonly created by heating shale, slate, or clay to high temperatures causing them to expand, resulting in a lower bulk density for the mix. GAF's Start Rite growing media contains organics, a carbon compound, and inorganic media base. But more importantly, green roof media has high concentrations of nutrients.

The two media tested were an Arkalyte mix and GAF's Gardenscapes™ green roof media. The Arkalyte mix was allowed to 'age' 1 year , being excess from a past green roof research project (Luckett, 2011). The GAF gardenscapes media was delivered directly from GAF and has not been used on any previous projects. The media characteristics were characterized by the MU Agronomic Soil Testing Services (Columbia, MO) with analysis summarized below, Table 2. The Bray IP for Phosphorus of 510 and 177 lb/acre (225 and 88.5 mg/kg) respectively show high phosphorus concentrations in the media before testing. The recommended maximum P concentration in soil for agriculture is 120 lbs P/acre (about 60 ppm)

Table 2: Chemical Analysis of Green Roof Media

Lab	Sample		N.A.	O.M.	Bray I P	Ca	Mg	K	CEC
Number	Identification	pHs	meq/100g	%	lb/Ac	lb/Ac	lb/Ac	lb/Ac	meq/100 g
C1218517	GAF	8.0	0.0	8.5	510	3992	716	3944	18.0
C1218518	ARKALYSE	7.2	0.0	14.6	177	6692	400	252	18.7

Green Roof Plants

With the assistance of Jost Greenhouses (St. Louis, MO) sedum species was selected based upon their survivability in the Missouri Ozarks region. A Midwest Mix of 15 different species as well as *Sedum Kamschaticum* were chosen and planted on a 5x5 grid in the green roof blocks to aid in rapid plant coverage. The trays and plants began in our greenhouse to allow the plants to become established and due to the drought conditions of summer 2012, were not placed on the roof until late August 2012. Once the trays were moved to the roof, plants relied solely on rain water. This ensured that we could assess the plants viability before planting our full-sized green roof in the spring.

Large-Scale Implementation

As part of this overall project GAF Materials provided 3,300ft^2 of GAF Gardenscapes™ extensive vegetative roofing system and also install 6,000 ft^2 of thermoplastic polyolefin white reflective membrane (TPO) at Missouri S&T. The GAF TPO membrane is the GAF premium formulation specifically designed for high temperature /high UV applications and will allow the potential addition of other sustainable roof top systems, such as thin-film PV. In addition, monitoring the runoff from the built-in-place full scale roof will aid in our understanding of a green roof's impacts to the reduction of peak flow rates.

The installation included 4 inches of GAF gardenscapes growing media compacted 50% as specified in GAF's installation manual. Before media placement, drainage mat and metal flashing were installed. A walking path along with drain covers were installed after media compaction. Over 10,000 plants were planted on the green roof with an average of 6 inch spacing. A time-lapse video of the green roof planting can be seen at http://www.youtube.com/watch?v=fh3m9zFBur8&feature=youtu.be.

This roof will be used as a teaching tool in the Civil, Architectural, and Environmental Engineering department through classes such as Green Building and Phytoremediation and Natural Treatment Systems. In addition, this roof will be used for our full-scale thermal experiments. Thermal couples below and above the green roof in addition to the original black roof and the white TPO will be used to determine the insulation and cooling effects of the green roof. Additional research support was secured from RCI and is also supported with an REU grant from NSF for 2013 and 2014.

Results and Discussion

Green Roof Runoff Reduction

Each Green Roof Block™ tray configuration showed a reduction in runoff when compared to the control empty tray. The storage of stormwater in green roof media as well as the ET from plants allows green roofs to reduce stormwater runoff, Figure 2. The results since August 2012 show a significant reduction in green roof runoff, which can be attributed to both the plants and the growing media. Individual storms less than 6 mm resulted in 100% reduction in runoff. Sixty percent reduction in runoff by planted GAF media was the highest cumulative reduction over the past nine months of this study. Media as well as plants attributed to the runoff reduction, with media playing the largest part.

Impact of Plants

The impact of plants can be seen seasonally, as the reduction in runoff varied per season. The percent reduction varies seasonally, Table 3; and the storm size influences the reduction rate with larger storms this spring resulted in a smaller reduction in runoff on a percent basis and with wet seasons also showing a reduced overall impact on total flow. When the plants were dormant over winter, less variation between the planted and unplanted trays was observed. The plants had up to a 20% additional reduction in stormwater runoff in the fall, even though they were only months old. Greater impacts of plants are expected as they mature and increase coverage.

Variability between green roof media

Media type made the largest impact on storm water storage and storm water runoff reduction. The differences between the two unplanted media trays were constant throughout the experiment with a roughly 20% increase in water storage from the GAF tray. As the media each had different compositions and bulk density, their storm water retention is expected to vary.

Table 3: Median green roof runoff reduction for sampled storms

Months	Empty	Planted Arkalyte	Unplanted Arkalyte	Planted GAF	Unplanted GAF
Sept. - Nov.	0%	70%	49%	70%	66%
Dec. – Feb.	0%	17%	11%	29%	27%
March - May	0%	30%	22%	44%	41%

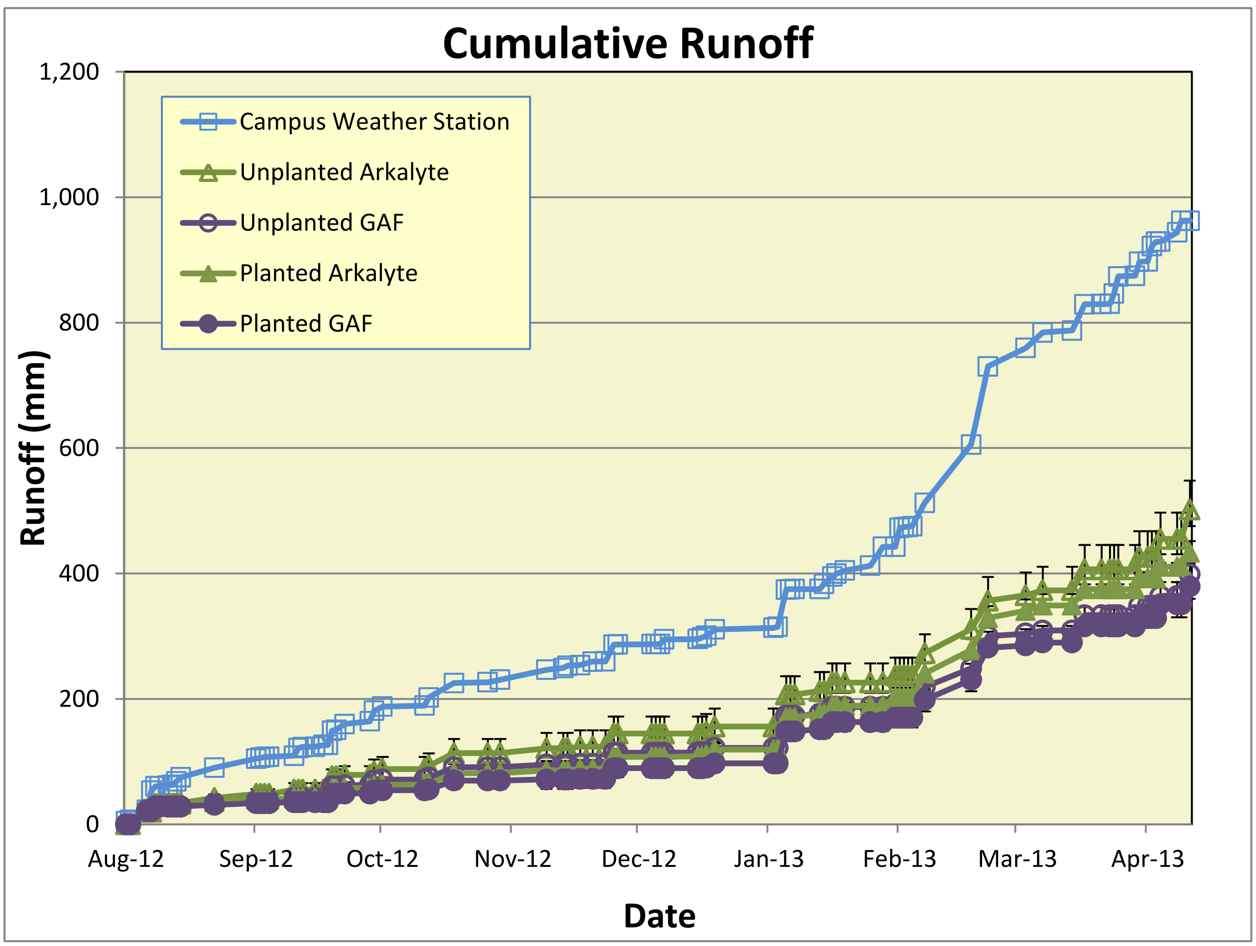


Figure 2: Cumulative runoff from pilot scale tests performed in Green Roof Blocks™

Green Roof Runoff Nutrient Loading

Green roof media available for commercial use most often have proprietary compositions most media are all made up of similar components. The most common growing media used are lighter than topsoil and chosen based upon their ability to drain and support plant growth. However, additional fertilizers are also added to the mix to sustain the green roof vegetation, which many roofing companies guarantee will keep the plants alive.

Nitrogen loading over time

Total nitrogen concentration was expected to demonstrate a “first flush” of high concentrations and then quickly lower. However, instead, a steady decrease in nitrogen concentrations has been shown, Figure 3. The TN concentration plotted as a function of time in Figure 3 also displays the total rainfall amount for the storm event as the size of each plotted data point. Storm size appears to have little impact on the concentration of TN in the runoff. Solubilities of nitrate compounds can be as high as over 40% nitrate at 25 degrees C from sodium nitrate concentrations. This dissolution of nitrogen is not limited by reaching a maximum solubility concentration. This reaction most likely comes from nitrogen moving from non-available forms to a more labile concentration and then being flushed out. Each rain event, there is less nitrogen available allowing for less of a concentration leaving each time reducing the amount of nitrogen in the runoff.

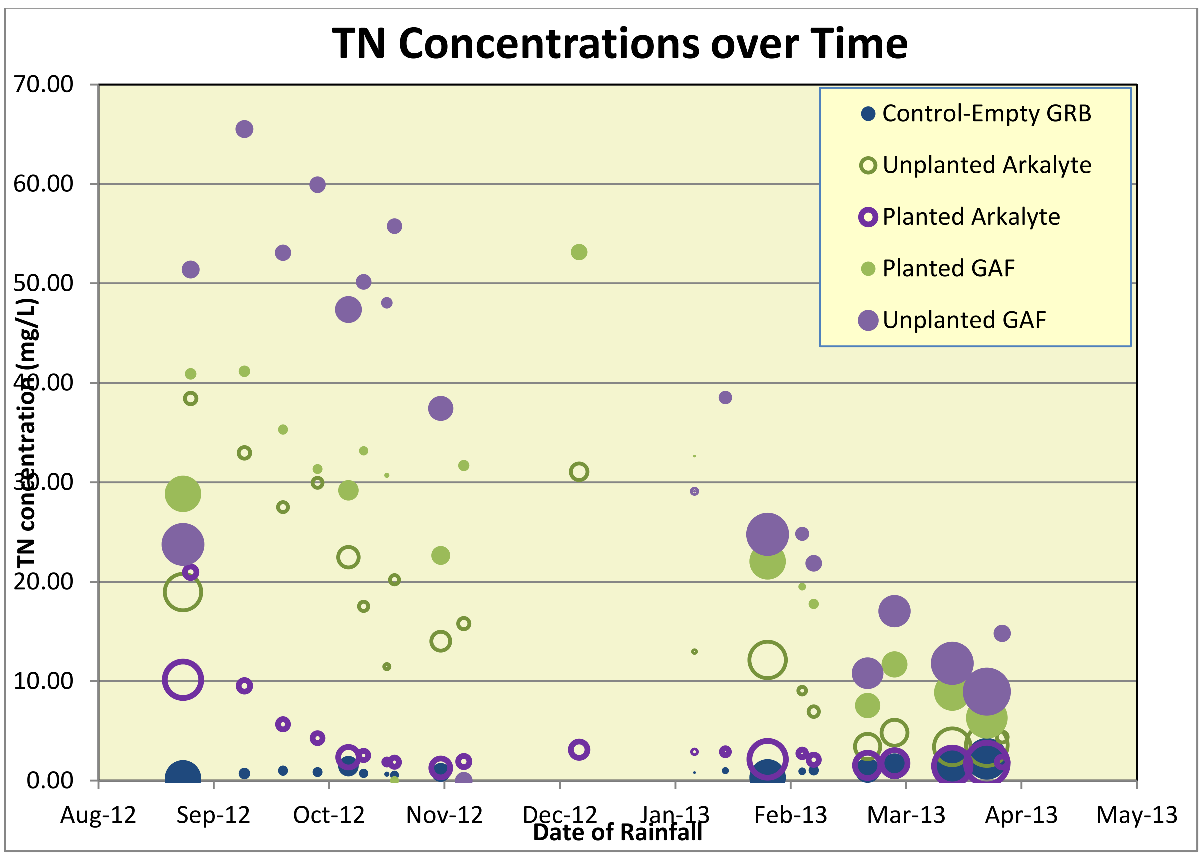


Figure 3: TN concentrations as a function of time and total rainfall amount for the sampled storm event is represented by the relative size of each plotted data point.

Phosphorus loading over time

Concentrations of total phosphate have been monitored each storm event and displayed below. Each triplicate average and the max/min concentrations are shown as error bars. The phosphate concentrations vary greatly, though the GAF media continues to be above the Arkalyte, showing media composition has the largest effect on phosphate runoff. The planted trays show lower phosphate concentrations throughout the testing. This could be due to the fact that planted roots can keep the soil stabilized and prevent erosion into the runoff. Phosphate runoff most often occurs from adsorption to soil grains which are then eroded away and into a water body. Additionally, plants uptake of phosphate could be reducing the concentrations in the soil that are capable of dissolving into the water, however the differences are seen throughout the winter which supports the explanation that plants are acting as a media stabilizer.

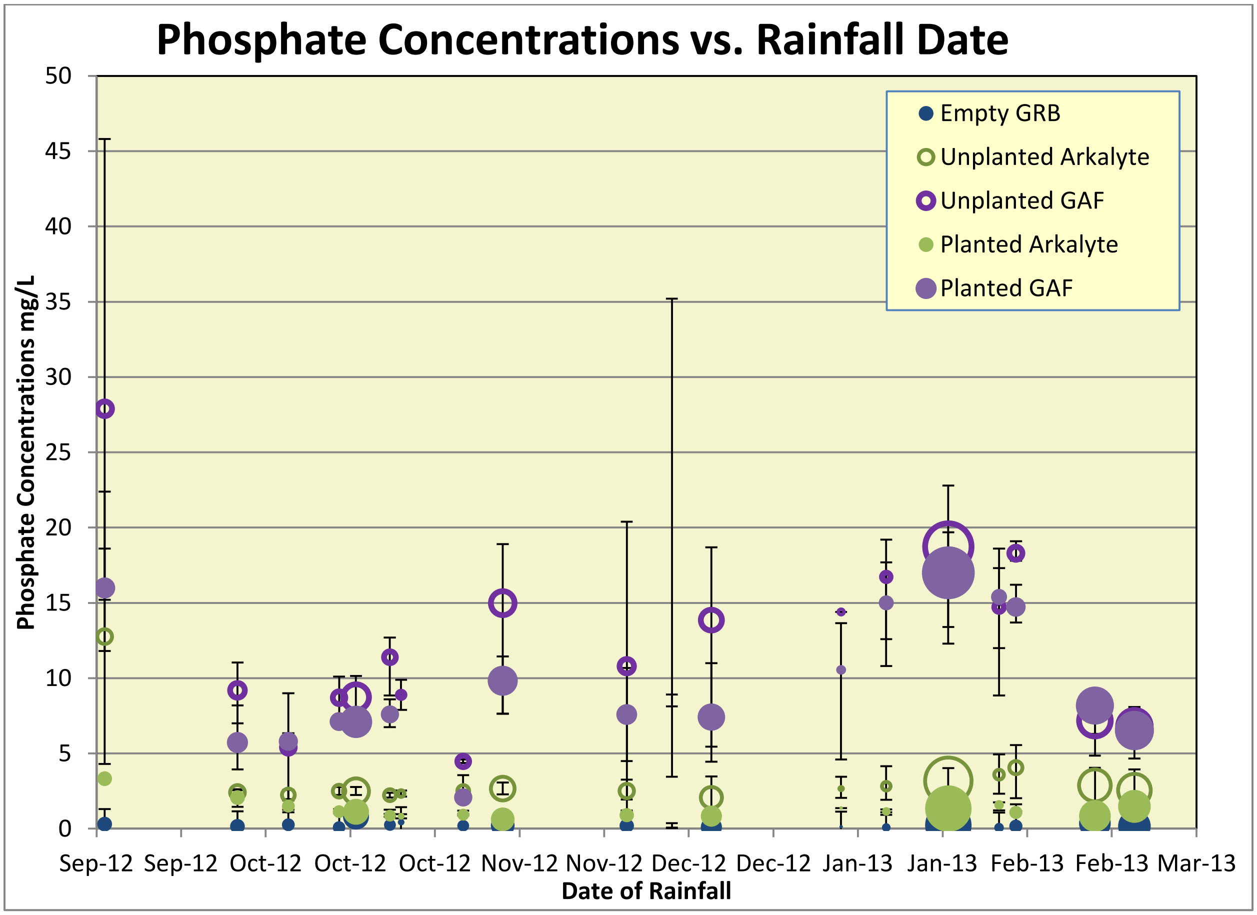


Figure 4: Phosphate concentrations over time and total rainfall amount for the sampled storm event is represented by the relative size of each plotted data point.

Green Roof Soil Erosion Control

Water Erosion Control Experiments

To determine the water quality impacts due to media particles in the runoff, total suspended solids (TSS) were measured for each rain event. TSS was measured by Method 2540 D from Standard methods for the examination of water and wastewater. TSS remained relatively unchanged over time and at acceptable concentrations. TSS concentrations from wastewater treatment plants into water bodies are often set at limits similar to 20 mg/L. All TSS values were below this standard set. This shows the effectiveness of the drainage mats designed to maintain the growing media. Figure 5 below shows the average TSS for each tested tray condition. The TSS increased for the unplanted condition supporting the theory that plants do play a role in stabilizing the media from water erosion during storm runoff.

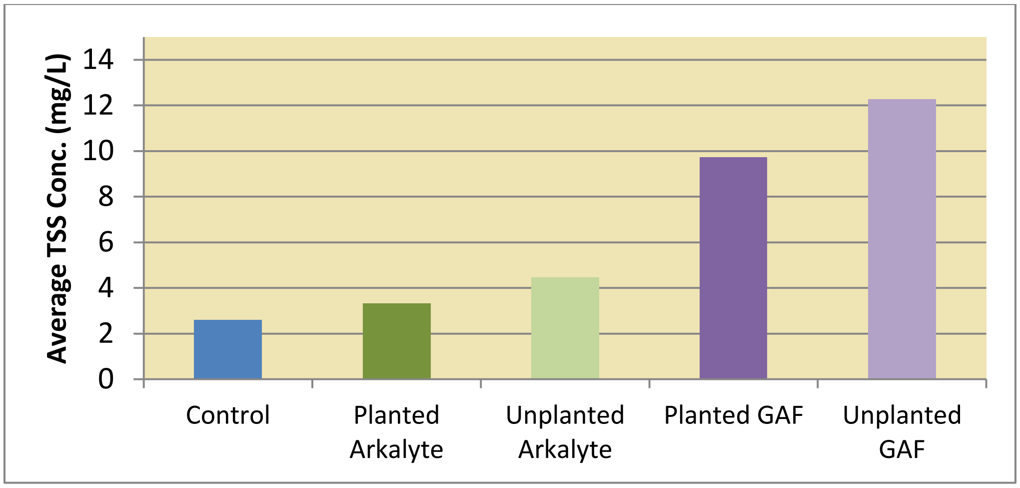


Figure 5: Total suspended solids averaged for each condition tested in Green Roof Blocks™.

Wind Erosion Control Experiments

Wind erosion is a major concern for green roofs between the time of planting and the plants reaching full coverage. Wind erosion of unplanted and planted green roof sections were tested along with, "Green Roof Glue," an adhesive to stabilize the growing media.

The eight tested trays for each medium were filled and subjected to the following treatments (each with a duplicate:

a. unplanted without green roof glue
b. unplanted with green roof glue
c. planted without green roof glue
d. planted with green roof glue

For the 4 planted trays, 3 sedum Midwest Mix plugs and 1 Sedum kamschaticum plug per tray were planted and allowed to grow for 5 weeks before testing.

The green roof glue was applied with a garden sprayer to the trays treated with glue 2 days prior to testing. For an 81 square inch (0.052m^2) pan, approximately 3.0 mL of green roof glue was applied to the growing media surface. The glue was applied evenly and sprayed from approximately 3from the surface of the trays.

The green roof blocks were last watered 2 weeks before testing. The planted green roof blocks were at approximately 50% plant coverage. The modified filter was measured before each test began. The filter support structure shown was installed in the wind tunnel and the filter was placed against the support structure. The tray holder, shown in Figure 6, was bolted into the floor of the wind tunnel and the tray being tested was secured into the tray holder. Beginning with 6 m/s and increasing by 1.5 m/s every 30 seconds, each tray was tested at increasing wind speeds up to 13 m/s. After completion of this experiment, the filter was removed and massed to determine the amount of material lost during testing.

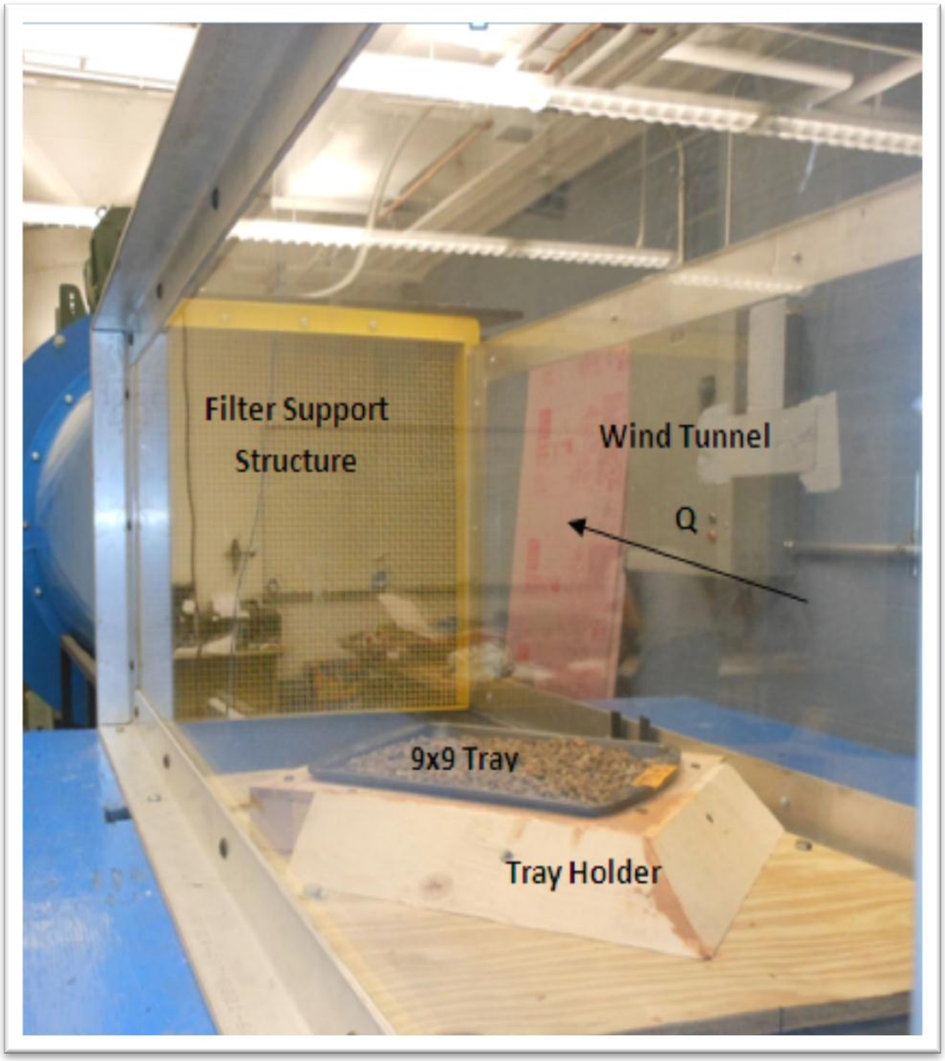
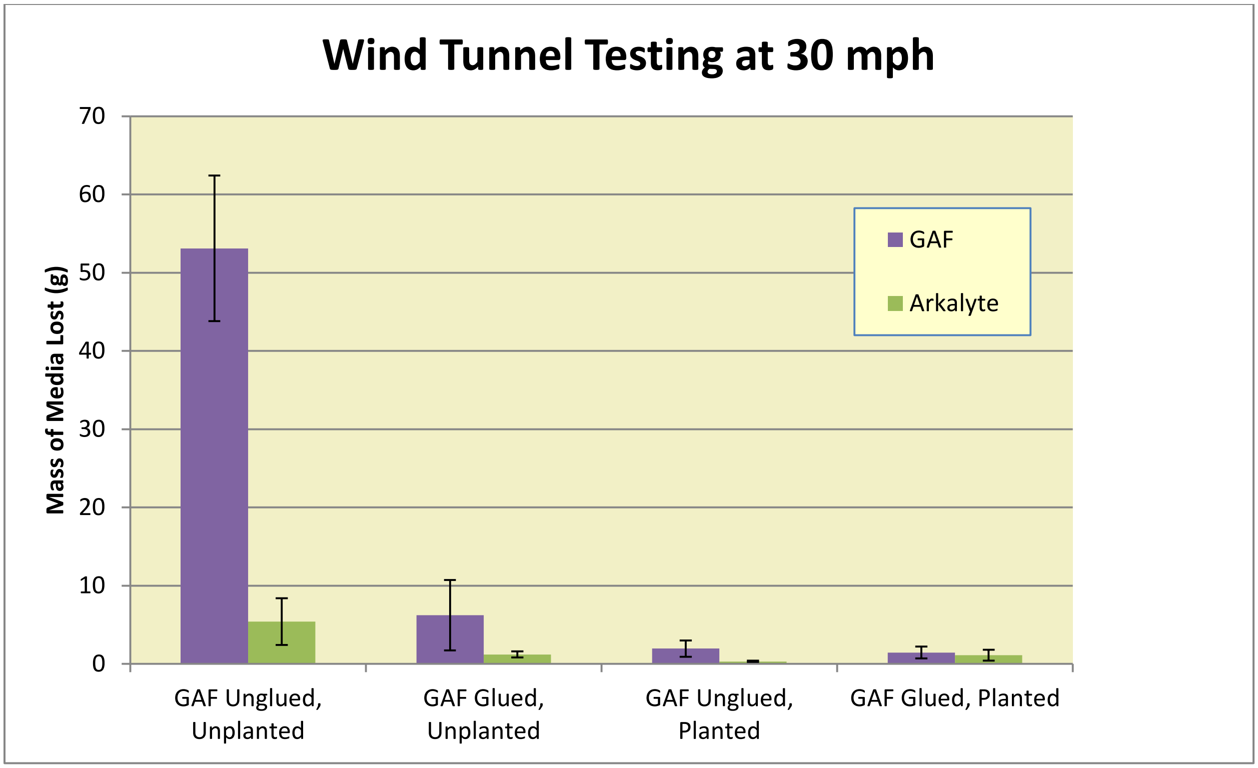


Figure 6: Wind tunnel testing apparatus

None of the tested trays experienced a substantial loss of growth media. The unplanted trays without green roof glue experienced the most material loss. A decrease was shown in material loss for the planted and glued trays with the planted trays providing a wind blanket protection for the growth media. Fines were observed to be lost around 10 m/s (30ft/s) wind speeds and pebbles were displaced. Wind scour of growth media mass for each combination tested is plotted in figure 7.

The hypothesis that both the green roof glue and planted conditions would decrease the amount of growth material lost in a windy condition was supported. The media composition impacted the amount of media lost from each tray, as GAF eroded more in all tests. This could be from the increased fines in GAF when compared to the Arkalyte mix or the aging of the Arkalyte mix (which had an entire year to erode away its finer particles).



Future Work

Now that the full-scale green roof is installed on campus, heat flux experiments can begin to analyze the energy savings due to the green roof when compared to additional roofing alternatives. Further research will include measuring runoff rates on the full-scale roof, which will validate findings in the pilot-scale study.

In addition, continued monitoring of water quality parameters will show if the system's nutrient concentrations reach steady state or continues to decrease over time. Without last summer's drought expected, impacts of the increased ET will be observed.

Publications and Presentations

Presentations of this research have been or will be made at the following conferences:

- Missouri S&T's Chancellor's Fellowship Poster Competition (March 2013)
- University of Missouri Legislative Day (April 2013)
- American Ecological Engineering Society Meeting (June 2013)
- Association of Environmental Engineering and Science Professors Conference (July 2013)
- International Phytotechnologies Conference (October 2013)

A journal publication is expected to be submitted to *Environmental Engineering and Science* in 2013 following the collection of the summer 2013 data.

In addition, this research inspired Missouri S&T to compete in the EPA Campus RainWorks Challenge focused on green infrastructure redesign for the design team's campus. The Missouri S&T team took second place for small schools with over 210 teams participating nationally, http://water.epa.gov/infrastructure/greeninfrastructure/crw_winners.cfm. The Missouri S&T RainWorks team incorporated the existing green roof research into their proposal along with plans for future green roof research and implementation. The effort also incorporated efforts from 20 students and more than 10 faculty and staff, including Chancellor Schrader. The competition video and design are posted on the EPA site http://water.epa.gov/infrastructure/greeninfrastructure/crw_missouri.cfm and http://water.epa.gov/infrastructure/greeninfrastructure/crw_winners.cfm#Missouri, respectively.

Community Involvement

The implementation of the full-scale green roof on campus drew interest from the Rolla community and was published on the front page of the Rolla Daily News (http://www.therolladailynews.com/article/20130417/NEWS/130419076/0/SEARCH). For the planting events, over 50 volunteers offered time to plant the more than 10,000 plants on the green roof. The installation was recorded on time-lapse and posted for viewing http://youtu.be/fh3m9zFBur8, and was put on the front page of the Missouri S&T website during the week before Earth Day. Educating the public about green roof benefits through this research can help encourage green infrastructure acceptance and encourage business and home owners to consider green roofs for their properties.

Conclusions

Water quantities were reduced in a similar fashion as other studies monitoring runoff reduction. The impact of plants varied seasonally and media qualities were a much larger influence on the water storage rates and thus runoff rates. As the plants reach full coverage, they may show a higher degree of influence on stormwater reduction.

The results of our nutrient monitoring shows much more than just a "first flush" of high nutrient levels from green roofs and it shows that the first year of a green roof might not be so "green." Continued monitoring will allow us to see future impacts from green roofs. This research allows us to broaden the scope to how extensive green roof applications could impair the very water bodies it is trying to improve.

The drainage materials show adequate stabilization to wind scour and with plants and/or adhesive, the green roof media can easily be maintained on top of the roof and under high wind speeds, the media is stable.

As construction and safety regulations are being developed for green roofs, initial nutrient concentrations may be regulated in the future as well due to such high mobility and high runoff concentrations of phosphorus and nitrogen observed in this study.

STUDENT SUPPORT:

Additional student support has been dedicated from RCI (formerly Roofing Contractors Institute). The grant is targeted to assess the thermal benefits of the full scale green roof. An NSF REU grant was secured on the central theme of renewable energy and energy efficiency, with Dr. Burken as a CoPI. Grace Harper was granted a Missouri S&T Chancellor's Fellowship for the duration of her MS studies on the green roof project.

Microbiological Characterization and Ecological Control of Membrane Biofouling in Side Stream Municipal Sewage Treatment Reactors Operated for Nitrification

Basic Information

Title:	Microbiological Characterization and Ecological Control of Membrane Biofouling in Side Stream Municipal Sewage Treatment Reactors Operated for Nitrification
Project Number:	2011MO125B
Start Date:	3/1/2012
End Date:	2/28/2013
Funding Source:	104B
Congressional District:	8
Research Category:	Not Applicable
Focus Category:	Wastewater, Treatment, Nitrate Contamination
Descriptors:	None
Principal Investigators:	Daniel Oether

Publications

1. G. Matar, L., Maeleb, S. Bagchi, K. Zhang, D.B. Oerther, and P.E. Saikaly, Microbial Characterization of Early and Mature Biofilms on the Membrane Surfaces of Full-Scale MBR Plants in Seattle, Washington, USA, International Water Association, 9th International Conference on Biofilm Reactors, Paris, France, May 28-30, 2013.
2. G. Matar, L., Maeleb, S. Bagchi, K. Zhang, D.B. Oerther, and P.E. Saikaly, Microbial Characterization of Early and Mature Biofilms on the Membrane Surfaces of Full-Scale MBR Plants in Seattle, Washington, USA, International Water Association, 9th International Conference on Biofilm Reactors, Paris, France, May 28-30, 2013.

Microbiological Characterization and Ecological Control of Membrane Biofouling in Side Stream Municipal Sewage Treatment Reactors Operated for Nitrification
Research Progress
March 2012-February 2013

Daniel B. Oerther, Ph.E., PE, BCEE
Mathes Chair and Director of Environmental Research Center
Missouri University of Science and Technology

Problem and Research Objectives:

Membrane bioreactors promise improved effluent water quality conditions as compared to conventional suspended growth activated sludge biological treatment systems. Membrane bioreactor systems offer the additional benefits of ease of retrofit as well as ease of operation (MBRs are a 'set it and forget it' technology). Unfortunately, the hamstring of MBR systems is the fouling of the membranes which reduces transmembrane flux and increases operating pressures and energy use. To circumvent the problem of fouling, most MBR systems are operated with regular cleaning cycles. This study aims to use an alternative, ecological approach to reduce biofouling by identifying the microbial populations responsible for the initiation of biofouling. If these 'early pioneers' can be identified, and improvements in membrane manufacturing can be developed, then cleaning and energy intensive operating conditions can be avoided.

Research Objective:

To accomplish this objective, this project examined the initiation of biofilm formation on membrane surfaces through a synergistic study of membrane properties, the chemical composition of side stream wastewater, and the ecology of nitrifying microbial communities. Four tasks were performed, namely: (T1) lab-scale membrane bioreactors were designed, constructed, and operated to treat a synthetic side stream wastewater; (T2) biofouling was characterized through evaluation of transmembrane flux, physical inspection of membrane surfaces, and chemical characterization of biofouling constituents; (T3) microbiological characterization of membrane bound and planktonic bacterial populations were performed using quantitative 16S ribosomal RNA targeted molecular signature methods; and (T4) the effectiveness of bioreactor operating conditions to control microbial community structure and therefore reduce the extent of biofouling were evaluated.

Methodology:

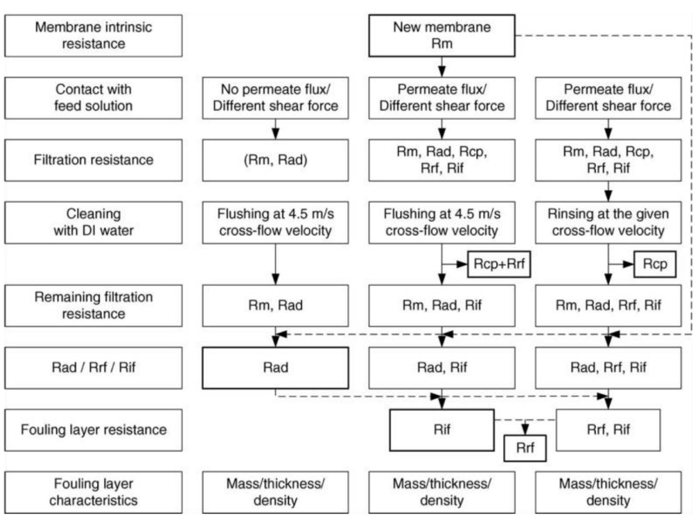
To accomplish the research objective of this proposal, four tasks were performed, namely: (T1) lab-scale membrane bioreactors were designed, constructed, and operated to treat a synthetic side stream wastewater; (T2) biofouling was characterized through evaluation of transmembrane flux, physical inspection of membrane surfaces, and chemical characterization of biofouling constituents; (T3) microbiological characterization of membrane bound and planktonic bacterial populations were performed using quantitative 16S ribosomal RNA targeted molecular signature methods; and (T4) the effectiveness of bioreactor operating conditions to control microbial community structure and therefore reduce the extent of biofouling was evaluated. Details for each task are described below.

(T1) Operate lab-scale MBRs. Prior research performed in the laboratory of the Principal Investigator (PI) has examined the role of bioreactor configuration and operating conditions on conventional chemostat-type nitrifying bioreactors treating a synthetic side stream wastewater (Smith et al, 2006; 2008; 2009). A similar approach was used for this study. Two sets of three replicate submerged configuration MBRs were operated for at least six months. Each MBR had a reaction volume of twenty-five liters. One set of reactors was operated with continuous feeding, while the second set was operated with pulse feeding to simulate a plug flow configuration. Solids separation was accomplished using a 50-micron nominal filter bag extensively tested by the PI and demonstrated to be appropriate for lab-scale MBR operation. Aeration was provided at a rate to maintain a nominal dissolved oxygen concentration set point of at least 2.0 mg/liter. Temperature was maintained at 20 C. A synthetic wastewater previously designed to test side stream nitrification contained 1,000 mg-N/L as ammonium, 50 mg-P/L, alkalinity of 7,500 mg-calcium carbonate/L, and trace micronutrients. The pH of each MBR was controlled between a set point of 7.0 and 7.2 using an automated system (Cole Parmer and Thermo Electron). Seed biomass was obtained from waste activated sludge collected at a local municipal sewage treatment plant, Rolla, MO.

Routine process parameters were measured including chemical oxygen demand (COD), pH, ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen, and phosphorus. COD, nitrate, nitrite, and phosphorous was measured colorimetrically (Hach). Ammonia and pH was measured using combination electrodes. For confirmation, nitrate was measured using ion-selective electrodes. Two types of respirometric assays were conducted to evaluate the rates of nitrification reactions. Oxygen uptake was measured using a commercial respirometer. Briefly, a sludge sample was washed with phosphate buffered saline and placed in a constant temperature reaction vessel. A concentrated solution of ammonium chloride was injected into each reaction vessel to provide an initial substrate concentration equal to 50 mg/L nitrogenous oxygen demand (NOD). The endpoint of each assay was the point at which cumulative oxygen uptake reaches the NOD of the input substrate. Replicate reaction vessels seeded with biomass but not inoculated with substrate provided controls. The result of cumulative oxygen uptake was fitted to existing differential equations describing ammonia and nitrite oxidation as previously described. A nitrogen transformation was measured using waste biomass. Briefly, a sludge sample was washed with phosphate buffered saline and placed in a constant temperature reaction vessel. Aeration was provided at a rate to maintain a nominal dissolved oxygen concentration set point of at least 2.0 mg/liter. A concentrated solution of ammonium chloride was injected into each reaction vessel to provide an initial substrate concentration equal to 50 mg/L NOD. Measurements of pH, ammonia, nitrate, and nitrite was performed continuously using combination or ion-selective electrodes, respectively. The endpoint of each assay was the point at which stoichiometric utilization of ammonia was accomplished. Replicate reaction vessels seeded with biomass but not inoculated with substrate provided controls. The results of nitrogen profiles were compared to oxygen uptake profiles.

(T2) Characterize biofouling. The PI has developed methods to evaluate reversible and irreversible membrane biofouling that are similar to 'standard' methods developed and tested in Europe. Specifically, waste biomass was removed from the lab-scale MBRs described in T1, above. The biomass was characterized for total and suspended solids and volatile solids as well as mean particle size and standard deviation of particle size. Samples were brought to a standard suspended solids concentration of 5,000 mg/L and placed in a temperature controlled storage vessel. Cross-flow membrane test cells consisting of two parallel stainless steel plates were used as a membrane test chamber. With an adjustable surface height of 0.4 cm and a constant filtration area of 72 square cm, the system was tested under tangential surface velocities of 0.1, 1.0, 2.0, 3.5, or 4.5 m/s. A constant transmembrane pressure of either 100 kPa or 0 kPa was used to evaluate flux. The use of a cross flow velocity of 0.1 m/s is used in place of a dead-end filtration test. Although dead-end filtration theoretically has no continuous shear force due to the absence of cross flow, a cross flow velocity of 0.1 m/s was used to prevent loose precipitants from settling on the membrane surface.

As previously described, a resistance in series model was used to evaluate the results of the proposed flux test. Figure two (top of next page) outlines the relationship between the resistance in series model and the experimental measurements performed during the flux test. Columns II, III, and IV that include static, dynamic, and sacrificial mode, respectively, represent three phases of operation. Parameters evaluated include: permeate flux (J), trans-membrane pressure (P), adsorption resistance (Rad), concentration polarization (Rcp), fouling resistance (Rf), irreversible fouling resistance (Rif), membrane intrinsic resistance (Rm), reversible fouling resistance (Rrf), total filtration resistance (Rt), resistance after four hours of filtration (Rt240), resistance after flushing (Rtf), resistance after rinsing (Rtr), and viscosity of permeate.



Since MBR systems include both submerged membrane systems (also known as internal membrane systems) and external membrane systems, it is important for this study to specify that only low pressure membranes examined including microfiltration and nanofiltration membranes operated at a transmembrane pressure of less than one bar. In these systems, the primary fouling mechanisms include pore blockage and cake formation above the membrane surface. By excluding high-pressure membranes from this study, fouling associated with pore fouling or plugging were excluded. The selection of these experimental parameters is based upon the typical configurations used for MBRs operated for the treatment of ammonia rich side streams at municipal sewage treatment plants and to simplify the mechanisms responsible for fouling.

Since the specific composition and fabrication technique are critical for determining the characteristics of membrane selectivity, permeability, chemical and thermal stability, and mechanical robustness, this study examined a subset of available membranes including specimens from the following part numbers: GE Osmonics (DS-J); G-10; G-20; G-50; G-80 and GE Zenon Environmental KO1-X, TECH-SEP KERASEP composite Al2O3/TiO2-ZrO2 (effective pore size 20-30 nm; molecular weight cut-off ~ 300,000 dalton).

Prior to their evaluation in the flow cell, membrane samples were characterized using scanning electron microscopy, X-ray photoelectron spectroscopy, transmission electron microscopy, Fourier Transform Infrared spectroscopy, and secondary ion mass spectrometry. Contact angle measurements for the membrane-water-air interface were also performed to determine the degree of surface hydrophobicity. After operating the flow cell, membrane samples were analyzed using the same tools. The instruments necessary to conduct these tests are available in the Materials Research Center at the Missouri University of Science and Technology. The PI has performed these tests previously in a related study.

(T3) Microbiological characterization. In previous studies of MBRs treating pulp and paper wastewater and an extra planetary wastewater, the PI has employed a suite of 16S rRNA targeted molecular signature methods to characterize the microbial community structure. A similar approach was used for this study.

Briefly, a 2 mL sample of mixed liquor was collected weekly and before each filtration test, centrifuged at 10,000 xg, and the biomass pellets were stored at -80 C for DNA extraction. The membranes with sessile (irreversibly attached) biomass after the filtration tests were also collected, cut into small pieces aseptically, and stored at -80 C. Genomic DNA from the cell pellets were extracted using the Ultraclean soil DNA extraction kit (MoBio Laboratories, Inc., Carlsbad, California) according to the manufacturer's instructions. Genomic DNA of the sessile biomass were extracted by submerging the membrane samples into 0.5 mL deionized water and heated at 95 C for 15 minutes in 2-mL sterile microcentrifuge tubes. Isolated genomic DNA was used as a template for polymerase chain reaction (PCR).

At least three alternative methods were used to evaluate the composition of the nitrifying microbial communities. First denaturing gradient gel electrophoresis (DGGE) were performed using primers
S-D-Bact-341f-a-S-57 (59-CGCCCGCCGCGCGCGGCGGGCGGGGCGGGGGCACGG GGGGCCTACGGGAGGCAGCAG-39) and S-D-Bact-534R-a-S-17 (59-ATTACCGCGGCTGCTGG-39). An existing D-code system (BioRad) was used according to the manufacturer's instructions. Equal amounts of PCR products (approximately 500 ng) were loaded onto 8% polyacrylamide gels (37.5:1, acrylamide: bisacrylamide) with a 30 to 60% linear gradient of denaturant (100% denaturant contains 7M urea and 40% [v/v] formamide). Gels were run for 20 hours at 35 V in 0.5 3 TAE buffer (20-mM tris-acetate and 0.5-mM EDTA at pH 8.0)

maintained at 60 C. Following electrophoresis, the gel was stained for 20 minutes with SYBR Green I (Molecular Probes, Eugene, Oregon) and visualized by UV illumination.

The second molecular signature method tested denatured high performance liquid chromatography (DHPLC) using an existing WAVE instrument (Transgenomics). Equal amounts of PCR products (approximately 300 ng) were analyzed using a DNASep cartridge and a two buffer system. Buffer A consisted of an aqueous solution of 0.1 M triethylammonium acetate (TEAA), pH 7.0; and buffer B consisted of an aqueous solution of 0.1 M TEAA, pH 7.0, with 25% (v/v) acetonitrile. Chromatograms were recorded at a wavelength of 260 nm.

The third molecular signature method tested was direct cloning and sequencing. PCR products were cloned using the TOPO TA Cloning Kit (TOPO10 Electrocomp Cells, Invitrogen Corporation, Carlsbad, California). Ampicillin and x-gal were used to screen for transformed cells containing recombinant plasmids. Approximately 500 clones were selected for each sample. Plasmid inserts were amplified using commercially available primers [M13 (TGTAAAACGACGGCCAGT) and M13 Reverse (CAGGAAACAGCTATGACC)]. Sequences were obtained from the University of Missouri Genome Center and analyzed by BLAST to identify individual operational taxonomic units (a.k.a., microbial populations).

Collectively, these three assays allowed the identification of specific microbial populations attached to the membrane as well as present in the mixed liquor. Given the limited duration of exposure in the flow cell (i.e., four hours), prior experience strongly suggests that populations found in increased relative abundance in the membrane bound fraction are likely responsible for the initiation of biofouling. This information was coupled with microbial ecology theory to evaluate control measures described below in T4.

(T4) Evaluate control measures. Research by the PI and others have begun to show a link between bioreactor operating conditions and theoretical concepts from microbial ecology. For example, competition among similar microbial populations for limiting resources is related to the mean cell residence time (a.k.a., solids retention time) of suspended growth bioreactors where specific operating conditions can induce greater diversity within the microbial community. Furthermore, diversity within the microbial community is correlated with resistance to perturbation. For a professional engineer, this translates into design decisions (i.e., SRT can now be used to select for microbial communities that are resistant to industrial discharges to municipal sewage collection systems). The PI has demonstrated this approach for suspended growth nitrifying microbial communities previously where completely mixed side stream bioreactor configurations selected for different predominant ammonia oxidizers as compared to plug flow configurations. A similar relationship among influent configurations and the identity of the predominant bacterial populations in MBRs treating pulp and paper wastewater has also been demonstrated by the PI and co-workers). In this study, the prior research of the PI in three separate areas, namely: (1) ecological theory and bioreactor configuration; (2) side stream nitrification; and (3) MBRs were integrated to achieve the research objective of preventing the initiation of membrane biofouling.

Principal Findings and Significance:

Our results show that: (a) the microbial communities in the five plants were different; (b) the microbial communities on the membrane were different from the microbial communities in suspension (i.e., early pioneer biofilm was different from the mixed liquor and the mature biofilm); (c) the mixed liquor and mature biofilm were very similar microbial communities; and (d) there was not a common core of bacterial populations that composed an 'early pioneer' microbial community. Hence, our results suggest (1) the results of lab scale studies where a common core of bacterial populations that compose an 'early pioneer' microbial community needs to be more carefully re-evaluated; and (2) our initial hypothesis that an ecological strategy might be employed to reduce membrane biofouling is unlikely to yield a net positive result.

Student Support:

PI Daniel Oerther
Co-I's Pascal Saikaly, King Abudullah University of Science and Technology, Saudi Arabia
Co-I's Kai Zhang, Senior Engineer, Ovivo Water
Doctoral students
Mikhel Shetty, Missouri S&T
Gerard Matar, KAUST

MS students
Lilian Malaeb, KAUST
Samik Bagchi, KAUST

BS students
Tommy Goodwin, Alex Korf, Melissa Buechlein, Katie Kuehn, Missouri S&T

Publications:

G. Matar, L., Maeleb, S. Bagchi, K. Zhang, D.B. Oerther, and P.E. Saikaly, Microbial Characterization of Early and Mature Biofilms on the Membrane Surfaces of Full-Scale MBR Plants in Seattle, Washington, USA, International Water Association, 9th International Conference on Biofilm Reactors, Paris, France, May 28-30, 2013.

G. Matar, L., Maeleb, S. Bagchi, K. Zhang, D.B. Oerther, and P.E. Saikaly, Microbial Characterization of Primary Colonizers on the Membrane Surfaces of Full-Scale MBR Plants, International Water Association, Leading Edge Technology, Bordeaux, France, June 3-6, 2013.

Information Transfer Program Introduction

The Missouri Water Resources Research Center's objectives are: 1) to establish active research programs to aid in understanding and solving Missouri's and the Nation's water problems, 2) to provide education opportunities in research for students with an interest in water resources and related fields, and 3) to be actively dedicated to the dissemination of information through all aspects of the media.

The technology assistance program goal is to meet objective 3, dissemination of information through all aspects of the media.

The Center continues to maintain an active information transfer program through:

- coordination of local seminar program
- publication of Water Center newsletter
- interaction with state and federal water agencies
- Director serves on various national and local water related boards, organizations and committees
- continued cooperation with district USGS office (representative on advisory committee)
- maintenance and expansion of comprehensive web site
- making available of Center's publications
- responding to public requests and questions
- meeting with advisory committee to improve information transfer activities

Technology Transfer

Basic Information

Title:	Technology Transfer
Project Number:	2011MO123B
Start Date:	3/1/2012
End Date:	2/28/2013
Funding Source:	104B
Congressional District:	9
Research Category:	Not Applicable
Focus Category:	Education, None, None
Descriptors:	None
Principal Investigators:	Thomas E. Clevenger

Publications

There are no publications.

INFORMATION TRANSFER

The Center maintained an active information transfer program that included:

1) Coordination of local seminar program:

The Environmental Engineering and Water Resources Research Center hosted an active local seminar series throughout the year. In addition, other special seminars included speakers from out of state and internationally to speak on a variety of topics:

Dr.Jianzhong Sun, Jianshu University, China, "Breaking the biomass recalcitrance for fuels and chemicals: current challenges and our opportunities and strategies."

Dr. Fuzhong Zhang, Washington University, "Dynamic sensor-regulator systems for the microbial production of advanced biofuels."

Dr. Barth F. Smets, Technical University of Denmark, "Redox stratified biofilms to support completely autotrophic nitrogen removal: Principles and results."

Wen-Tso Liu, University of Illinois, "Drinking water distribution system biofilms: from sampling to microbial ecology."

2) Publication of Water Center newsletter:

The Water Center newsletter is a yearly publication. The purpose of the Center's newsletter is to inform the scientific community as well as the public, of the activities of the Center, i.e., new research projects funded, and upcoming conferences. The Center's primary focus is on its own information transfer activities and the general scope of the projects that were funded.

3) Interaction with state and federal water agencies:

Cooperating agencies associated with the Water Center include:

Universities:

- University of Missouri
- University of Missouri-Rolla, Missouri State University
- University of Alaska Southeast
- University of Illinois
- Western Kentucky University
- Mississippi State University
- University of Montana
- University of New Hampshire
- Penn State University

State Agencies:

- Department of Natural Resources

- Missouri Department of Economic Development
- Department of Conservation

Federal Agencies:
- USGS/US Department of Interior
- Environmental Protection Agency
- Department of Commerce
- Department of Energy

Local Agencies:

Cities of
- Booneville
- Columbia
- Marceline
- Marshfield
- Monroe City
- Trenton

Private Organizations:
- BioMicrobics
- CST
- Environmental Dynamics, Inc.
- International Heat Pump Association
- John Deere
- Leggett & Platt
- Leonardwood Institute
- Sprayroc

4) Director served on various national and local water related boards, organizations and committees

5) Continued cooperation with district USGS office (representative on advisory committee)

6) Maintenance and expansion of website http://water.missouri.eduu

The Water Center website highlights information regarding the USGS Program including currently funded projects through USGS, Call for New Proposals, yearly newsletter and publications archive. The website also highlights news articles regarding research and student involvement within the Center and College of Engineering and laboratory facilities available.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	3	0	0	0	3
Masters	3	0	0	0	3
Ph.D.	2	0	0	0	2
Post-Doc.	0	0	0	0	0
Total	8	0	0	0	8

Notable Awards and Achievements

The implementation of the full-scale green roof on campus drew interest from the Rolla community and was published on the front page of the Rolla Daily News (http://www.therolladailynews.com/article/20130417/NEWS/130419076/0/SEARCH. For the planting events, over 50 volunteers offered time to plant the more than 10,000 plants on the green roof. The installation was recorded on time-lapse and posted for viewing http://youtu.be/fh3m9zFBur8, and was put on the front page of the Missouri S&T website during the week before Earth Day. Educating the public about green roof benefits through this research can help encourage green infrastructure acceptance and encourage business and home owners to consider green roofs for their properties.

This research inspired Missouri S&T to compete in the EPA Campus RainWorks Challenge focused on green infrastructure redesign for the design team's campus. The Missouri S&T team took second place for small schools with over 210 teams participating nationally, http://water.epa.gov/infrastructure/greeninfrastructure/crw_winners.cfm. The Missouri S&T RainWorks team incorporated the existing green roof research into their proposal along with plans for future green roof research and implementation. The effort also incorporated efforts from 20 students and more than 10 faculty and staff, including Chancellor Schrader. The competition video and design are posted on the EPA site http://water.epa.gov/infrastructure/greeninfrastructure/crw_missouri.cfm and http://water.epa.gov/infrastructure/greeninfrastructure/crw_winners.cfm#Missouri, respectively.

Publications from Prior Years

1. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Lee, S.S., C.J. Gantzer, A.L. Thompson, S.H. Anderson, and R.A. Ketcham. 2008. Using high-resolution computed tomography analysis to characterize soil-surface seals. Soil Sci. Soc. Am. J. 72:1478-1485.
2. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Lee, S.S., C.J. Gantzer, A.L. Thompson, S.H. Anderson. 2010. Polyacrylamide and gypsum amendments for erosion and runoff control on two soil series. J. Soil Water Conserv. 65(4):233-242.
3. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Lee, S.S., C.J. Gantzer, A.L. Thompson, and S.H. Anderson. 2011. Polyacrylamide efficacy for reducing soil erosion and runoff as influenced by slope. J. Soil Water Conserv. 66 (3): 172-177.
4. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Blanco-Canqui, H., C.J. Gantzer, and S.H. Anderson. 2006. Performance of grass barriers and filter strips under interrill and concentrated flow. J. Env. Qual. 35: 1969-1974.
5. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Blanco-Canqui, H., C.J. Gantzer, S.H. Anderson, E.E. Alberts, and A.L. Thompson. 2004. Grass barrier and vegetative filter strip effectiveness in reducing runoff, sediment, nitrogen, and phosphorous loss. Soil Sci. Soc. Am. J. 68:1670-1678.
6. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Blanco-Canqui, H., C.J. Gantzer, S.H. Anderson, and E.E. Alberts. 2004. Grass barriers for reduced concentrated flow induced soil and nutrient loss. Soil Sci. Soc. Am. J. 68:1963-1972.
7. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Blanco-Canqui, H., C.J. Gantzer, S.H. Anderson, and A.L. Thompson. 2004. Soil berms as an alternative to steel plate borders for runoff plots. Soil Sci. Soc. Am. J. 68:1689-1694.
8. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Blanco-Canqui, H. C.J. Gantzer, S.H. Anderson, E.E. Alberts, and F. Ghidey. 2002. Saturated hydraulic conductivity and its impact on simulated runoff for claypan soils. Soil Sci. Soc. Am. J. 66:1596-1602.
9. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Kazemi, H.V., S.H. Anderson, K.W. Goyne, and C.J. Gantzer. 2009. Aldicarb and carbofuran transport in a Hapludalf influenced by differential antecedent soil water content and irrigation delay. Chemosphere 74:265-273.
10. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Kazemi, H.V., S.H. Anderson, K.W. Goyne, and C.J. Gantzer. 2008. Atrazine and alachlor transport in claypan soils as influenced by differential antecedent soil water content. J. Environ. Qual. 37:1599-1607.
11. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Kazemi, H.V., S.H. Anderson, K.W. Goyne, and C.J. Gantzer. 2008. Spatial variability of bromide and atrazine transport parameters for a Udipsamment. Geoderma 144:545-556.
12. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Rachman, A., S.H. Anderson, C.J. Gantzer, and E.E. Alberts. 2004. Soil hydraulic properties influenced by stiff-stemmed grass hedge systems. Soil Sci. Soc. Am. J. 68:1386-1393.

13. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Los, P., S.H. Anderson, and C.J. Gantzer. 2001. Vegetative barriers for erosion control. 4 pp., MU Extention Guide (G 1653).
14. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Conference Proceedings - Gantzer, Clark J., Allen L. Thompson, and Stephen H. Anderson. 2011. Guidelines for polyacrylamide use for erosion control from soils of differing texture, pH, and clay mineralogy. p. 28. Conservation Science and Policy: Global Perspectives and Applications. 66th Soil and Water Conservation Society International Annual Conference, Washington DC, July 17-20.
15. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Conference Proceedings - Lee, S.S., C.J. Gantzer, S.H. Anderson, and. A.L. Thompson. 2010. Saturated hydraulic conductivity of surface seals estimated from computed-tomography-measured porosity 2010 SWCS Annual Conference July 18-21, 2010. St. Louis, MO. (non-refereed- abstract).
16. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Conference Proceedings - Wu, Si-Hyun, K.W. Goyne, R. N. Lerch, C.-H Lin, and S. H. Anderson. 2006. Adsorption of isoxaflutole degradates to aluminum and iron hydrous oxides. CD-ROM. Indianapolis, IN. 12-16 Nov. 2006. ASA, CSSA, SSSA International Meetings.
17. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Other Publications - Mattingly, Christina A. 2004. Influence Of Raindrop Energy On Polyacrylamide Effectiveness. MS Thesis. University of Missouri-Columbia, Columbia, MO.
18. 2002MO5B ("Microbial Influences on Geophysical Signatures: A Proxy for the Understanding and the Monitoring") - Conference Proceedings - Abdel Aal, G.Z., Atekwana, E.A., Slater L.D., 2004, Effect of different phases of diesel biodegradation on low frequency electrical properties of unconsolidated sediments, Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP 04), Colorado Springs, CO, 386-395.
19. 2002MO5B ("Microbial Influences on Geophysical Signatures: A Proxy for the Understanding and the Monitoring") - Conference Proceedings - Abdel Aal, G.Z., Atekwana, E.A., Slater, L.D., and Ulrich, C. 2003, Induced Polarization (IP) measurements of soils from an aged hydrocarbon contaminated site: Symposium on the Application of Geophysics to Environmental and Engineering Problems (SAGEEP 03), San Antonio, TX, 190-201.
20. 2002MO5B ("Microbial Influences on Geophysical Signatures: A Proxy for the Understanding and the Monitoring") - Other Publications - Abdel Aal, G.Z., Atekwana, E.Al, Slater, L.D., Effect of hydrocarbon biodegradation on the low-frequency electrical properties of unconsolidated sediments: AGU Fall 03.
21. 2005MO53B ("Fate and Transport of Heavy Metals in Artificial Soil") - Other Publications - Bergsten, J., 2006, Sorption and transport of heavy metals in artificial soil, M.S. Thesis, University of Missouri Fall 2006.
22. 2005MO53B ("Fate and Transport of Heavy Metals in Artificial Soil") - Conference Proceedings - Wayllace, A., and Likos, W.J., 2006, Numerical modeling of artificial soil as an evapotranspirative cover, Proceedings of 4th International Conference on Unsaturated Soils, Carefree, AZ, April 2006.
23. 2004MO31B ("Use of Excitation/Emission Matrix Fluorescence") - Conference Proceedings - Conference Proceedings: B. Hua and B. Deng. Water source characterization and classification with fluorescence EEM spectroscopy: PARAFAC analysis. 34th Annual waste management conference, Missouri Waste Control Coalition, Lake Ozark, MO, June 25-27, 2006.
24. 2004MO31B ("Use of Excitation/Emission Matrix Fluorescence") - Other Publications - Masters Thesis: Koirala, Amod; "Use of Fluorescence Excitation Emission Matrix Spectroscopy for Water and Waste Water Characterization."
25. 2009MO99B ("Visible Light-activated Titanium Dioxide-based Photocatalysts: Synthesis and Potential Environmental Applications ") - Articles in Refereed Scientific Journals - Hua, B., F. Dolan, C. McGhee, T. Clevenger, B. Deng, 2007, Water−source characterization and classification with fluorescence EEM spectroscopy: PARAFAC analysis, International Journal of Environmental Analytical Chemistry, 87(2), 135−147.

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27. 2006MO61B ("EEM Fluorescence Spectroscopy Fingerprints and Monitoring of NDMA and TTHM Formation Potentials") - Articles in Refereed Scientific Journals - Hua, B., F. Dolan, C. McGhee, T. Clevenger, B. Deng, 2007, Water−source characterization and classification with fluorescence EEM spectroscopy: PARAFAC analysis, International Journal of Environmental Analytical Chemistry, 87(2), 135−147.
28. 2006MO61B ("EEM Fluorescence Spectroscopy Fingerprints and Monitoring of NDMA and TTHM Formation Potentials") - Articles in Refereed Scientific Journals - Hua B, A. Koirala, K. Veum, J. Jones, T. Clevenger, B. Deng, 2007, Fluorescence fingerprints and total trihalomethanes and N-nitrosodimethylamine formation potentials, Environmental Chemistry Letters, 5(2), 73-77.
29. 2006MO61B ("EEM Fluorescence Spectroscopy Fingerprints and Monitoring of NDMA and TTHM Formation Potentials") - Conference Proceedings - Conference Proceedings: B. Hua and B. Deng. Water source characterization and classification with fluorescence EEM spectroscopy: PARAFAC analysis. 34th Annual waste management conference, Missouri Waste Control Coalition, Lake Ozark, MO, June 25-27, 2006.
30. 2004MO31B ("Use of Excitation/Emission Matrix Fluorescence") - Other Publications - Masters Thesis: Koirala, Amod; "Use of Fluorescence Excitation Emission Matrix Spectroscopy for Water and Waste Water Characterization."
31. 2000MO3B ("Development of a Simple Combustion Process for Disposal of Waste from LIvestock Operations") - Conference Proceedings - Flanigan, V.J., S. Shi, N.P. Nateri, P. Nam, K. Kittiratanpiboom and S. Kapila, 2003, A Fluidized Bed Combustor for Treatment of Farm Wastes presented at the IV International Conference on Value Added recovery and Recycling of Industrial and Agricultural Waste (Varirie 2003) L Aquila, Italy.
32. 2009MO100B ("Developing Guidelines for Polyacrylamide Use for Erosion and Runoff Reduction") - Articles in Refereed Scientific Journals - Mattingly, C.A., A.L. Thompson, C.J. Gantzer. 2010. Polyacrylamide influence on runoff and sediment detachment from a silt loam soil. Trans. ASABE Vol 53(1):31-38.
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