Impact of coagulation on biofiltration: removal of trace organic contaminants to mitigate the effects of wastewater reuse on drinking water treatment

By Ricardo Lugo, The University of Texas at Austin

1. Title. Impact of coagulation on biofiltration: removal of trace organic contaminants to mitigate the effects of wastewater reuse on drinking water treatment

2. Project Type. Research

3. Focus Categories. Treatment (TRT), water quality (WQL), Drought (DROU)

4. Research Category. Engineering

5. Keywords. Trace organics, coagulation, biofiltration, water reuse

6. Start Date. 3/1/2016

7. End Date. 2/28/2017

8. Principal Investigators.

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Co-Principal Investigator: Mary Jo Kirisits, Associate Professor, Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin, 301 E Dean Keeton St, Stop C1786, Austin, TX 78712. E-mail: kirisits@utexas.edu. Phone: 512.232.7120

9. Congressional District. 21st District

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10. Abstract.

Direct and indirect potable reuse is an increasingly attractive option to mitigate the effects of water scarcity in the state of Texas. A key problem in water reuse is to find effective treatment processes to remove an increasing variety and concentration of trace organic contaminants (TrOCs) such as endocrine disruptors, pharmaceuticals, and personal care products. **The benefits of biofiltration, including particle removal, biodegradation, and adsorption, make it an attractive process for addressing this problem.** For optimum treatment, biofiltration must be studied holistically within the treatment train. For instance, biofiltration is often preceded by coagulation, which impacts the type and amount of organic matter entering the biofilter; this could influence microbial activity in the biofilter, with implications for the biodegradation of TrOCs.

The goal of the work is to develop a holistic understanding of coagulation-biofiltration. The specific objective of the work is to examine the impact of coagulant type/dose and pH on the removal of multiple TrOC by biofiltration. To meet this objective, a 12-month project is proposed, which will be divided into two tasks. Task 1 (completed Fall 2015) is to prepare key materials for the project, including choosing a suite of TrOCs and to concentrate natural organic matter for preparing synthetic water. The use of synthetic water precludes natural season variations in water quality from complicating data interpretation. Task 2 is to examine the impact of two coagulants (ferric chloride and alum) and pH on the removal of the TrOCs by biofiltration.

11. Budget Breakdown.
See attachment A.

12. Budget Justification.
See attachment B.

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Attachment A –BUDGET BREAKDOWN

Cost Category	Federal	Non-Federal	Total
1. Salaries and Wages			
- Principal Investigator(s)		$5,206	$5,206
- Graduate Student(s)	$3,146		$3,146
- Undergraduate Student(s)			
- Others			
Total Salaries and Wages	$3,146	$5,206	$8,352
2. Fringe Benefits			
- Principal Investigator(s)		$1,246	$1,246
- Graduate Student(s)			
- Undergraduate Student(s)	$849		$849
- Others			
Total Fringe Benefits			$2,095
3. Tuition			
- Graduate Student(s)			
- Undergraduate Student(s)			
Total Tuition			
4. Supplies	$1,005		$1,005
5. Equipment			
6. Services or Consultants			
7. Travel			
8. Other direct costs			
9. Total direct costs	$5,000	$6,452	$11,452
10a. Indirect costs on federal share	XXXXXX XXXXXX		
10b. Indirect costs on non-federal share	XXXXXX XXXXXX	$3,548	$3,548
11. Total estimated costs	$5,000	$10,000	$15,000

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Total Costs at Campus of the University on which the Institute or Center is located.	$5,000	$10,000	$15,000
Total Costs at other University Campus Name of University:	$	$	$

Attachment B – BUDGET JUSTIFICATION

Salaries and Wages for PIs. Provide personnel, title/position, estimated hours and the rate of compensation proposed for each individual.
Professor Kirisits (institutional PI) will contribute effort equal to 44.6% of one month's salary.
Salaries and Wages for Graduate Students. Provide personnel, title/position, estimated hours and the rate of compensation proposed for each individual. (Other forms of compensation paid as or in lieu of wages to students performing necessary work are allowable provided that the other payments are reasonable compensation for the work performed and are conditioned explicitly upon the performance of necessary work. Also, note that tuition has its own category below and that health insurance, if provided, is to be included under fringe benefits.)
Graduate student Lugo (PI of record) will work 143 hours on the grant at a rate of $22/hour.
Salaries and Wages for Undergraduate Students. Provide personnel, title/position, estimated hours and the rate of compensation proposed for each individual. (Other forms of compensation paid as or in lieu of wages to students performing necessary work are allowable provided that the other payments are reasonable compensation for the work performed and are conditioned explicitly upon the performance of necessary work. Also, note that tuition has its own category below and that health insurance, if provided, is to be included under fringe benefits.)
Salaries and Wages for Others. Provide personnel, title/position, estimated hours and the rate of compensation proposed for each individual.
Fringe Benefits for PIs. Provide the overall fringe benefit rate applicable to each category of employee proposed in the project. . Note: include health insurance here, if applicable.
The fringe benefit rate for Professor Kirisits is 23.9% of wages.
Fringe Benefits for Graduate Students. Provide the overall fringe benefit rate applicable to each category of employee proposed in the project. Note: include health insurance here, if applicable.
The fringe benefit rate for graduate student Lugo is 27% of wages.
Fringe Benefits for Undergraduate Students. Provide the overall fringe benefit rate applicable to each category of employee proposed in the project. Note: include health insurance here, if applicable
Fringe Benefits for Others. Provide the overall fringe benefit rate applicable to each category of employee proposed in the project. . Note: include health insurance here, if applicable.
Tuition for Graduate Students.
Tuition for Undergraduate Students
Supplies. Indicate separately the amounts proposed for office, laboratory, computing, and field supplies. Provide a breakdown of the supplies in each category.
Funding to support analysis of trace organic compounds (sample vials, syringes, standards, and equipment usage costs) and consumable supplies for routine analyses (chemicals, plates, pipet tips, gloves, centrifuge tubes) is requested.
Equipment. Identify non-expendable personal property having a useful life of more than one (1) year and an acquisition cost of more than $5,000 per unit. If fabrication of equipment is proposed, list parts and materials required for each, and show costs separately from the other items. A detailed breakdown is required.
Services or Consultants. Identify the specific tasks for which these services, consultants, or subcontracts would be used. Provide a detailed breakdown of the services or consultants to include personnel, time, salary, supplies, travel, etc.
Travel. Provide purpose and estimated costs for all travel. A breakdown should be provided to include location, number of personnel, number of days, per diem rate, lodging rate, mileage and mileage rate, airfare (whatever is applicable).
Other Direct Costs. Itemize costs not included elsewhere, including publication costs. Costs for services and consultants should be included and justified under "Services or Consultants (above). Please provide a breakdown for costs listed under this category.
Indirect Costs. Provide negotiated indirect ("Facilities and Administration") cost rate.

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The indirect cost rate is 55% of modified total direct costs.

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14. Statement of Critical Regional Water Problems.

As water scarcity continues, the number of wastewater-impacted drinking water treatment plants likewise will increase. Thus, indirect and direct potable reuse will become more commonplace. The 2012 Texas State Water Plan predicts that water reuse will provide approximately 1.53 million acre-feet per year of water supply statewide by 2060 and will meet 18% of the projected water needs. Under low-flow conditions, there are many Texas cities where the influent to the drinking water treatment plant consists mainly, if not 100 percent, of wastewater from upstream cities (Rice et al., 2015). The increase in reuse, application of more conservation measures, and longer drought periods means that drinking water treatment plants will see both a greater variety and increasing concentration of trace organic contaminants (TrOCs), including endocrine-disrupting compounds (EDCs) and pharmaceuticals and personal care products (PPCPs). **Therefore, the drinking-water industry needs to find effective treatment processes to remove an increasing variety and concentration of TrOCs.** The multi-barrier benefits of biofiltration, including particle removal, biodegradation, and adsorption, make this an attractive process for addressing the TrOC problem.

Biofiltration has been assessed for the removal of several types of TrOC, including EDCs such as bisphenol A (Zearley & Summers, 2012); PPCPs such as analgesics, antibiotics, anti-inflammatory agents, and stimulants (Zearley & Summers, 2012); and taste and odor compounds such as 2-methylisoborneol (MIB) and geosmin (Nerenberg et al., 2000). Biofiltration is often preceded by coagulation, flocculation, and sedimentation. Maximizing the simultaneous removal of multiple TrOC via independent optimization of each unit process in a treatment train ignores synergism and antagonism among the processes. As a result a holistic consideration of contaminant removal by biofiltration must include examination of common upstream processes, such as coagulation. Therefore, in this work, I will study the impact of coagulation on biofiltration for the simultaneous removal of multiple TrOC. **Overall, this study will result in practical guidance for drinking water treatment plants to maximize the removal of multiple TrOCs, as well as total organic carbon (TOC) and trihalomethane formation potential (THMFP), using the coagulation-biofiltration treatment train.**

15. Statement of Results.

The results of this project will show if coagulation can be tailored to maximize the removal of TrOCs by biofiltration; these data will be disseminated to the drinking water industry and academics at conferences (e.g., American Water Works Association conferences) and in journals (e.g., *Journal of the American Water Works Association* and *Water Research*).

16. Nature, Scope, and Objectives.

The objective of the work is to develop a holistic understanding of the combination of coagulation-biofiltration, such that the removal of TrOCs can be maximized. I will examine the impact of coagulant type (ferric chloride and alum) and dose as well as the impact of pH on the removal of a suite of TrOCs by biofiltration.

Task 1: Design and prepare synthetic water. This task, which has been completed in Fall 2015, involved choosing a suite of diverse TrOCs (Table 1) and concentrating natural organic matter (NOM) for preparing synthetic water. The use of synthetic water precludes natural season variations in water quality from complicating data interpretation. The ten chosen TrOC will each have a concentration of 0.5 μg/L in the synthetic water. They were selected based on a range of chemical classes and applications, ubiquity in natural waters, and biodegradability. Samples for TrOC analysis will be collected in acid-washed glass vials and manually concentrated on solid phase micro extraction fibers with a polydimethylsiloxane divinylbenzene coating. TrOCs will be analyzed with an Agilent 5977A gas chromatograph/mass spectrometer (GC-MS) or a TS Ultimate 3000 liquid chromatograph connected to a TSQ Quantiva mass spectrometer (LC-MS). NOM has been concentrated from Lake Austin (Austin, TX) using an ion-exchange/reverse osmosis system. The process includes filtration through three progressively smaller filters (last one is 0.45-μm), followed by cation exchange with the Ambersorb 200H resin (a strong-acid cation-exchange resin) and reverse osmosis with a Dow Filmtec spiral-wound TW30 membrane (Barrett et al., 2014.)

Table 1. Suite of diverse TrOC and their associated analytical methods

Compound	*TrOC category*	*Chemical class*	*Method*
2-MIB	Microbial derived odor	borneo	GC-MS Martínez (2013)
geosmin	Microbial derived odor	bicyclic alcohol	
diclofenac	pharmaceutical/ Nonsteroidal anti-inflammatory drugs (NSAID)	phenylacetic acid	LC-MS Vanderford et al. (2012)
naproxen	pharmaceutical/NSAID	propionic acid	
gemfibrozil	pharmaceutical/ anti-convulsant	fibric acid derivative	
atenolol	pharmaceutical/ cardiovascular	isopropylamino-propanol derivative	
estrone	pharmaceutical/hormone	aromatic C18 steroid	
caffeine	food product	xanthines	
thiabendazole	pesticide/fungicide	benzimidazole	
N,N-Diethyl-meta-toluamide (DEET)	pesticide	aromatic amide	

Task 2: Impact of coagulation type/dose. Using the jar-test procedure, an optimum coagulant dose and pH will be determined for maximum TOC removal in the synthetic water (alkalinity: 100 mg/L as $CaCO_3$, pH: 7.8, TOC 5 mg/l, hardness: 20 mg/L as $CaCO_3$). These optimized conditions will be compared to non-optimized conditions. The non-optimized conditions will still have the same coagulant doses but the pH will not be controlled, such that it reaches the natural pH after coagulant addition. The purpose of examining non-optimized conditions is to avoid lowering the pH further than that naturally produced due to coagulant addition; this is important because many plants will raise the pH before or after biofiltration, so the cost of caustic will be reduced in this fashion. The synthetic water will be coagulated in large batches, and uncoagulated synthetic water will be used for control studies. The synthetic waters will be supplemented with nitrogen (NH_4Cl) and phosphorus (KH_2PO_4) to prevent nutrient limitations, and the pH of the biofilter influent will be adjusted to 8.2 to prevent phosphate adsorption in case of floc carryover to the biofilters.

Biofiltration. Three parallel, 1-in inner-diameter, bench-scale filter trains (each consisting of two columns in series) have been set up using granular activated carbon (GAC) media from existing biofilters (Arlington, TX). Each train will be run for 1 week with raw Lake Austin water to seed the filters with microorganisms. Then, the first train will be operated as the control with uncoagulated synthetic water (6 mos); the second train will be run sequentially using synthetic water coagulated under the optimized conditions (6 mos) and non-optimized conditions (6 mos) for ferric chloride; the third biofilter train will be run sequentially using synthetic water coagulated under the optimized conditions (6 mos) and non-optimized conditions (6 mos) for alum. The GAC media will be changed out between the optimized and non-optimized coagulation experiments to prevent filter history from complicating data interpretation, and raw Lake Austin water will be run through each new filter for 1 week to seed the microbial community.

The suite of TrOCs will be spiked to the synthetic water after coagulation, and then the biofilter influent will be housed in a headspace-free tank to minimize loss of volatile components. The influent, columns, and tubing will be covered with foil to prevent photodegradation of contaminants and algal growth. The columns will be run upflow via peristaltic pumps, and the total empty bed contact time (EBCT) of each train will be 6 min to simulate a 20-min full-scale EBCT (Manem and Rittmann, 1990). The flow rate, pH and dissolved oxygen will be measured daily in the influent and effluent. Once per week, samples will be analyzed for turbidity, heterotrophic plate counts (HPC), TOC, dissolved organic carbon (DOC), and assimilable organic carbon (AOC) per standard methods already used in the lab. Twice per month, THMFP and the suite of TrOCs will be measured. The effluent HPC will be used as a surrogate for biofilter biomass, such that the correlation between TrOC removal and biomass can be tested.

17. Methods, Procedures and Facilities.

The Environmental and Water Resources Engineering program labs contain all of the necessary equipment to perform the methods highlighted in the previous section. This includes a pH meter, organic carbon analyzer, ion chromatograph, LC-MS, GC-MS, autoclave, incubators, UV/Vis spectrophotometer, refrigerator, -20/-80^{o}C freezers, and luminometer, as well as columns, tubing, and pumps for the biofilters.

18. Related Research.

Biofiltration. The primary goal of a rapid-rate filter in drinking water treatment is the removal of particles. When no disinfectant residual (e.g., chlorine) is applied to a filter, biofilm growth occurs more easily, and the filter becomes a biofilter. Particle removal is still an important goal in biofiltration, but the microorganisms present in the biofilter also can effect removal of multiple inorganic and organic contaminants (Lauderdale et al., 2012). Biofiltration can reduce the concentration of biodegradable dissolved organic carbon (BDOC) in the plant effluent, which has a variety of benefits such as increasing the biological stability of the water and reducing the concentration of biofilm bacteria in the distribution system (Volk & LeChevallier, 1999) as well as reducing THMFP.

Coagulation. Coagulation, flocculation, and sedimentation reduce particle loading to the biofilter and can remove a portion of NOM from the water (reviewed by Matilainen et al., 2010). To help minimize disinfectant byproduct (DBP) concentrations in finished drinking water, U.S. Environmental Protection Agency regulations specify the removal of TOC (which includes DBP precursors) by enhanced coagulation, where the required TOC removal depends on the TOC and alkalinity of the source water.

Coagulation and biofiltration should be used in concert with one another to minimize effluent organic carbon and THMFP. Lauderdale and Brown (2013) examined one way of doing this; they demonstrated that purposefully decreasing TOC removal via coagulation (by halving the coagulant dose) could be offset by increased TOC removal via biofiltration, resulting in very similar overall TOC removals by coagulation/biofiltration under both coagulant conditions. These results suggests that shifting greater burden for TOC removal to the biofilters, which are operationally less expensive than is coagulation, could provide cost-savings to a utility.

Studies have noted greater NOM removal with ferric- as compared to aluminum-based coagulants (e.g., Bell-Ajy et al., 2000). The hydrophilic neutral fraction of NOM, which strongly contributes to BDOC, tends to remain in the water after alum coagulation (Soh et al., 2008). Volk et al. (2000) found that ferric coagulants generally removed up to 20% more BDOC than did aluminum coagulants. Hence, when coagulation occurs upstream of biofiltration, the choice of coagulant must be made in light of how that coagulant will impact the overall removal of NOM and TrOCs. In particular, the concentration of BDOC influent to the biofilter must be sufficient to sustain the biomass needed for TrOC removal. Given that TrOC in drinking water are likely to be secondary microbial substrates due to their low concentrations, such as 10-1000 ng/L, sufficient primary substrate (e.g., BDOC) is necessary to support the biomass; for instance, Westerhoff et al. (2005) found greater removal of MIB under biofilter conditions with higher BDOC.

Several studies have suggested that the amount of biomass in a biofilter, as long as it is above some critical minimum amount, does not impact the overall removal of biodegradable organic matter in a biofilter (e.g., Urfer et al., 1997). However, Urfer et al. (1997) also suggest that the critical minimum amount of biomass might be higher for more slowly biodegradable components as compared to the amount of biomass necessary for more easily biodegradable components; thus, the poor biodegradation of some TrOC (e.g., sulfamethoxazole) could have much to gain by increased biomass concentrations in the biofilter. Overall, coagulation will impact the amount and composition of NOM in the biofilter influent; this could influence microbial community structure and biodegradation capability, with implications for the removal of TrOCs, TOC/DOC, BDOC, AOC, and THMFP.

TrOCs. Drinking-water biofilters have been shown to biodegrade EDCs and PPCPs (Zuehlke et al., 2007), as well as the algal metabolites 2-MIB and geosmin (Elhadi et al., 2006, McDowall et al., 2007), at micropollutant concentrations. Additionally the removal of EDCs and PPCPs by bank filtration has been attributed to biodegradation (Hoppe-Jones et al., 2010). However, few data are available for the removal of TrOCs by biofilters under controlled operational conditions (Zhu et al. 2010).

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Westerhoff, P., Yoon, Y., Snyder, S., Wert, E. 2005. *Environ Sci Technol* 39(17), 6649-6663.

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Zhu, X.I., Getting, T., and Bruce, D., 2010. *JAWWA* 102(12), 67-77.

Zuehlke, S., Duennbier, U., Heberer, T., 2007. *Chemosphere* 69(11), 1673-1680.

19. Training potential.

It is estimated that this project will train one M.S. student (PI Lugo), one Ph.D. student (Williams) and one undergraduate student (to be recruited in Spring 2016).

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20. Investigator's qualifications.

Ricardo Lugo

Skill Highlights

- Agilent QQQ 6460 LCMS experience
- Immunoassay experience
- Wet lab experience
- Native fluency: Spanish & English

Education

University of Texas at Austin, U.S.A. MSC Environmental and water resource engineering Present

- Physical and chemical treatment
- Water pollution chemistry
- Design of wastewater and water treatment facilities
- Hydrology

University of Texas at Austin, U.S.A. BSC marine & fresh water biology 2008

- Organic chemistry
- Biostatistics
- Oceanography
- PCR experience
- Chemistry
- Field biology
- Coastal science
- Wet lab experience
- Microbial ecology
- Microbiology

National University of Ireland Galway, Ireland. Study abroad semester 2008

- Aquatic plant science
- Coastal dynamics
- History
- Creative writing

Professional Experience

Toxicorp, Davenport Fl Contract work

Consultant

Responsibilities

- Data analysis relating to environmental contaminants

Advanced Pain Care, Austin TX Jan 2013-Jan 2014

Associate Scientist

Responsibilities

- Run and maintain Olympus AU400 Immunoassay
- Agilent QQQ 6460 LC-MS experience preparing and running samples, QCs, internal standard, mobile phases
- Interpret data and report results
- Order supplies and reagents
- Perform daily, weekly and monthly maintenance

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Amazon.co.uk Cork City, Cork, Ireland Sept 2010–Nov 2012

Digital/Project Specialist

Responsibilities

- Technical support
- Open new lines
- Business process re-engineering

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Mary Jo Kirisits

A. Professional Preparation

State Univ. of New York at Buffalo	(Buffalo, NY)	Civil Engin.	B.S. (1995)
Univ. of Illinois at Urbana-Champaign	(Urbana, IL)	Environmental Engin.	M.S. (1997)
Univ. of Illinois at Urbana-Champaign	(Urbana, IL)	Environmental Engin.	Ph.D. (2000)
Northwestern Univ.	(Evanston, IL)	Environmental Engin.	Postdoc (2000-2003)

B. Appointments

9/12 - present	Associate professor; University of Texas at Austin; Austin, TX
1/04 - 8/12	Assistant professor; University of Texas at Austin; Austin, TX
9/00 - 12/03	Postdoctoral research fellow; Northwestern University; Evanston, IL
8/95 - 5/00	NSF graduate research fellow; University of Illinois at Urbana-Champaign; Urbana, IL

C. Peer-Reviewed Products

(i) Products most relevant to proposed project

1. Chambers, B., A.R.M.N. Afrooz, S. Bae, N. Aich, L. Katz, N. Saleh, and **M.J. Kirisits**. 2014. Effects of Chloride and Ionic Strength on Physical Morphology, Dissolution, and Bacterial Toxicity of Silver Nanoparticles. *Environ Sci Technol.* 48:1:761-769. doi: 10.1021/es403969x
2. Marsolek, M.D., **M.J. Kirisits,** K.A. Gray, and B.E. Rittmann. 2014. Coupled Photocatalytic-Biodegradation of 2,4,5-Trichlorophenol: Effects of Photolytic and Photocatalytic Effluent Composition on Bioreactor Process Performance, Community Diversity, and Resistance and Resilience to Perturbation. *Water Res.* 50:59-69. doi: 10.1016/j.watres.2013.11.043
3. Davidson, A. N., J. C. Chee-Sanford, H. Y. (M.) Lai, C.-h. Ho, J. B. Klenzendorf, and **M. J. Kirisits**. 2011. Characterization of Bromate-Reducing Bacterial Isolates and their Potential for Drinking Water Treatment. *Water Res.* 45:18:6051-6062. doi: 10.1016/j.watres.2011.09.001
4. De Long, S.K., K.A. Kinney, and **M.J. Kirisits**. 2008. Prokaryotic Suppression Subtractive Hybridization PCR cDNA Subtraction, a Targeted Method to Identify Differentially Expressed Genes. *Appl Environ Microbiol.* 74:1:225. doi: 10.1128/AEM.01647-07
5. **Kirisits, M.J.**, L. Prost, M. Starkey, and M.R. Parsek. 2005. Characterization of Colony Morphology Variants Isolated from *Pseudomonas aeruginosa* Biofilms. *Appl Environ Microbiol*. 71:8:4809-4821. doi: 10.1128/AEM.71.8.4809-4821.2005

(ii) Other significant products

1. De Long, S.K., X. Li, S. Bae, J.C. Brown, L. Raskin, K.A. Kinney, and **M.J. Kirisits**. 2012. Quantification of Genes and Gene Transcripts for Microbial Perchlorate Reduction in Fixed-Bed Bioreactors. *J Appl Microbiol.* 112:3:579-592. doi: 10.1111/j.1365-2672.2011.05225.x
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3. Wahman, D.G., **M.J. Kirisits**, L.E. Katz, and G.E. Speitel, Jr. 2011. Ammonia-Oxidizing Bacteria in Biofilters Removing Trihalomethanes are Related to *Nitrosomonas oligotropha*. *Appl Environ Microbiol.* 77:7:2537-2540. doi: 10.1128/AEM.02464-10
4. Mendez, C.B., J.B. Klenzendorf, B.R. Afshar, M.T. Simmons, M.E. Barrett, K.A. Kinney, and **M.J. Kirisits**. 2011. The Effect of Roofing Material on the Quality of Harvested Rainwater. *Water Res*. 45:5:2049-2059. doi: 10.1016/j.watres.2010.12.015
5. De Long, S.K., K.A. Kinney, and **M.J. Kirisits**. 2010. qPCR Assays to Quantify Genes and Gene Expression Associated with Microbial Perchlorate Reduction. *J Microbiol Methods* 83:2:270-274. doi: 10.1016/j.mimet.2010.09.002

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D. Synergistic Activities

1. Selected professional societies
   - American Water Works Association
     - Chair, University Student Activities Committee (2014-present)
     - Member, Biological Drinking Water Treatment Symposium Planning Committee (2015-present)
2. Selected professional reviews
   - *Applied and Environmental Microbiology*, *Biodegradation*, *Environmental Science and Technology*, *Journal of the American Water Works Association,* and *Water Research*
3. Outreach activities
   - Outreach program: San Juan Diego Catholic High School (85% Hispanic, 50% from families where no member has gone to college), Austin, TX (2010-present)
   - Trained 40 undergraduate researchers (23 female or minority) in the laboratory

E. Collaborators and Other Affiliations

(i) Collaborators and Co-Editors

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(iii) Thesis Advisor and Postgraduate-Scholar Sponsor (* woman or minority)

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Number of graduate students advised: 8 in-progress/25 total (18 women or minorities)
Number of postdoctoral scholars sponsored: 1 in-progress/3 total (2 women)