Overview: Flint, MI, is currently suffering from a “perfect storm” attributable to out-of-control corrosion of its potable water distribution system. The corrosion is undermining water affordability for residents, financial viability of city government, water aesthetics, and hygiene/sanitation as revealed in local and national news reporting. We ***hypothesize*** that these circumstances will also create severe chemical/biological health risks for Flint residents, including elevated levels of lead and opportunistic premise plumbing pathogens (OPPPs) in drinking water. Preliminary data collected from a home of a lead poisoned child in Flint has revealed extraordinarily high levels of lead, with average concentrations over 20 minutes of water use exceeding 2,000 ppb (> 200 times the World Health Organization allowable levels for lead in potable water).

The main ***objectives*** of this research are to: 1) compare levels of chlorine, iron, fecal indicator bacteria, OPPPs, and corrosion-inducing bacteria present in water mains of a distribution system with uncontrolled corrosion (Flint) versus surrounding cities/counties still using non-corrosive water, 2) profile OPPPs occurrence in hot and cold potable water systems at these same locations, and 3) determine if there is evidence of elevated lead in Flint homes, and, if so, forensically determine the links to iron corrosion. Our team is uniquely qualified to do this work given our just published peer reviewed research on this subject and our extensive collaborations with key stakeholders in Flint.

Intellectual Merit: The four elements of the “perfect storm” currently undermining water quality (and possibly public health) in Flint include: a) chronic underinvestment in water infrastructure, b) under-appreciation of the role of corrosion control in sustaining urban potable water systems, c) increased corrosion due to higher chloride in Flint’s new source water, and d) failure to appropriately monitor for lead and OPPPs. The latter two factors are amongst the most important health problems arising in modern potable water systems. The high rates of corrosion occurring in Flint are releasing high levels of iron to water and consuming chlorine disinfectant, which our most recent laboratory testing has indicated will increase lead release to water and growth of OPPPs in cold and hot water plumbing systems. The unfortunate but unique opportunity offered by Flint’s current situation, provides an ideal opportunity to field test our recent discoveries regarding potentially adverse consequences of iron corrosion on chemical/microbiological water quality at field rather than laboratory scale.

Broader Impacts: This RAPID grant will directly assist residents of Flint in assessing the current safety of their potable water supply. If the results support recently issued public assurances regarding safety of water, the current problems in Flint can be considered mainly of aesthetics and perception due to very distasteful or discolored water. However, if sampling reveals widespread problems, the public will learn of the potential health threat. Since elements of the “perfect storm” afflicting Flint are occurring at some level in many other financially stressed U.S. urban centers with decaying drinking water infrastructure, this Rapid Response Research (RAPID) grant also provides an unprecedented opportunity to advance fundamental scientific and practical understanding at this emerging nexus of infrastructure-environmental engineering-public health. The general results and approach used herein can inform residents and managers of other U.S. cities, who will soon be dealing with similar problems associated with failing potable water infrastructure exacerbated by increased chloride in water due to excessive use of road salt and rising sea levels. The research also provides a compelling case study in *Citizen Science*, since the experiences of Flint parents in monitoring their children’s health and environmental exposures was a trigger for our preliminary testing, and Flint consumers will be scientifically empowered by participating in fundamental research relying on collection of samples from their homes and residences. There is also a social justice implication of the research, in that these results can help inform the current policy debate regarding strategies for dealing with cites that have gone bankrupt, as well as the discussion of access to safe and affordable drinking water as a basic human right.

RAPID: Synergistic Impacts of Corrosive Water and Interrupted Corrosion Control on Chemical/Microbiological Water Quality: Flint, MI

1. Problem Statement and Objectives

Flint, MI, is currently suffering from a "perfect storm" due to out-of-control corrosion of its potable water distribution system, undermining the well-being of the community including water affordability for residents, financial viability of city government, water aesthetics, and hygiene/sanitation.[1-13] Flint's problems began in April 2014, when emergency managers hired to deal with the city's fiscal crisis determined they could save money by switching to a local river water source as opposed to purchasing water from Detroit (Table 1). As a result of the change in source water, the Larson Iron Corrosion Index was raised from 0.54 (low corrosion) to 2.3 (very high corrosion) and the chloride to sulfate mass ratio (CSMR) index for lead corrosion increased from 0.45 (low corrosion) to 1.6 (very high corrosion). Concurrently, the managers and state primacy agency attempted to save even more money by not feeding an orthophosphate corrosion inhibitor to the water supply (Table 1).

Not surprisingly, the combined effect of more corrosive water and removal of the corrosion inhibitor unleashed unprecedented corrosion in the water main distribution system with cascading personal, economic, and public health consequences to Flint as tracked by news reports and mandatory chemical/biological monitoring of water in the distribution system mains.[1-14] ***Our recent research also predicts that these circumstances will potentially create severe chemical/biological health risks for residents, due to impacts on water within building (premise) plumbing systems that include elevated levels of lead and opportunistic premise plumbing pathogens (OPPPs).***[15-18] Because the factors impacting Flint are also occurring at some level in many other financially-stressed U.S. urban centers with decaying drinking water infrastructure, this ***Rapid Response Research (RAPID) grant provides an unprecedented opportunity to advance fundamental scientific and practical understanding at this emerging nexus of infrastructure-environmental engineering-public health.*** We view August-September 2015 as the ideal time to first sample in Flint, as more than 16 months of uncontrolled corrosion have occurred and the water remains near its seasonal peak temperature, maximizing the likelihood of serious problems with lead and OPPPs if they exist.

Table 1. Water quality parameters for drinking water supplied in Flint, MI before and after the April 2014 switch

Parameter	Before[1]	After[2]
pH	7.38	7.61
Hardness (mg/L as $CaCO_3$)	101	183
Alkalinity (mg/L as $CaCO_3$)	78	77
Chloride (mg/L)	**11.4**	**92**
Sulfate (mg/L)	25.2	41
CSMR[3]	0.45	**1.6**
Inhibitor (mg/L as P)	0.35	**NONE**
Larson Ratio[4]	0.5	**2.3**

[1]Source: City of Flint Monthly Operation Report, June 2015. Available from www.cityofflint.com
[2]Source: DWSD 2014 Water Quality Report. Available from www.dwsd.org
[3]A measure of corrosivity to lead; a value > 0.5 is a critical trigger [10]
[4]A measure of corrosivity to mild steel and iron; corrosion rate increases linearly with Larson Ratio [8]

Our key hypothesis is that the rapid corrosion of iron water mains will dramatically increase lead release to water and growth of OPPPs as measured in consumers' homes. Mechanistically, higher iron corrosion produces both higher iron in water and lower levels of free chlorine, both of which dramatically increased lead release and OPPPs regrowth in our just published laboratory research utilizing simulated distribution systems.[15-19] The ***main objectives of this research*** are to: *1) compare levels of chlorine, iron, fecal indicator bacteria, OPPPs, and corrosion-inducing bacteria present in water mains of a distribution system with uncontrolled corrosion (Flint) versus controlled corrosion in surrounding cities/counties still using non-corrosive Detroit water, 2) profile hot and cold potable water systems at the same sampling locations in #1 for OPPPs, and 3) determine if there is evidence of elevated lead in Flint homes, and, if so, forensically determine the links to iron corrosion.*[15,17-20] The unfortunate but unique opportunity offered by Flint's current situation provides an ideal opportunity to field test our recent discoveries regarding adverse consequences of iron corrosion on OPPPs and lead concentration at the tap.

2. Review of Local Events and Intellectual Merit


Figure 1. Drinking water samples collected from home of a child who was lead poisoned by Flint water.

Local Impacts. After the switch of water sources, residents of Flint were immediately subject to an outbreak of corrosion-related drinking water problems including flooding from large water main breaks and reported health ailments.[1-6] General Motors, a prime customer of the water system, reported that the new water was severely corroding auto parts on its assembly line and had to begin importing water, costing the city $400,000 in lost revenue.[9] The PI was also alerted by an Environmental Protection Agency volunteer to a case of childhood lead poisoning in a Flint home that was certified as "lead free."[4] Samples collected from the home exhibited classic "red water" that is occurring throughout the city (Figure 1), along with the highest sustained levels of lead in drinking water that we have encountered in over 25 years of research on the subject. Specifically, in 30 samples collected over a period of 25 minutes flushing at the kitchen faucet, lead concentrations averaged over 2,000 ppb and were as high as 13,000 ppb. For perspective, these levels are more than 200-1,300 times higher than World Health Organization standards (10 ppb) and several even exceeded the EPA criterion for "hazardous waste" of 5,000 ppb Pb. The city has also reported unspecified economic losses due to water main breaks and water losses through leaks.[3,7,11-12]

The corrosion problems have also had cascading impacts on health parameters monitored under federal regulations. Because the corrosion is rapidly consuming chlorine disinfectant in the water, the city violated EPA limits for *E. coli*.[5-6] The detaching iron rust also has the potential to expose consumers to other contaminants that pose a serious public health risk, including arsenic[14] and lead that have accumulated in pipes or sorbed to iron surfaces.[15-16] Health effects reported by residents since the switch include skin rashes, hair loss, vomiting, copper poisoning, and the one confirmed case of lead poisoning.[2-4,7,13] However, the relatively small number of cases reported to date almost certainly underestimates the full extent of the problem. In response to the sampling showing high lead, the authorities who made the decision to switch water sources and stop adding corrosion inhibitor publicly stated that "anyone who is concerned about lead in the drinking water in Flint can relax" and that the water is safe,[44] but refuse to sample consumers' water without pre-flushing the plumbing for at least 5 minutes the night before sampling. The latter practice is known to miss lead in water problems.

We are also concerned about possible health effects that have not yet been investigated. For example, in March 2015 Region 5 EPA was provided reports of higher incidence of Legionnaires' disease associated with bacteria growth in premise plumbing in the Flint area.[21] Legionnaires' disease has recently been acknowledged to be the primary source of waterborne disease outbreaks (and associated deaths) in the U.S.[22] Despite that acknowledged risk, there is currently no required monitoring for this important pathogen in consumers' homes, where it proliferates and can lead to human exposure and infection in showers.[22]

Intellectual Merit. The four elements of the "perfect storm" currently undermining water quality (and possibly public health) in Flint include: a) chronic underinvestment in water infrastructure, b) under-appreciation of the role of corrosion control in sustaining urban potable water systems, c) increased corrosivity of water sources nationally due to rising chloride levels from anthropogenic pollution and/or rising sea levels, and d) failure to appropriately monitor for lead and OPPPs, which are two of the most important modern-day public health problems arising in building plumbing systems.

a) **Chronic Underinvestment in Water Infrastructure**. A large fraction of the nation's potable water infrastructure is on the verge of failure, and this problem has been repeatedly voted by members of the American Society of Civil Engineers (ASCE) as the most urgent societal infrastructure challenge with an overall condition grade of "D".[23,24] Many water main distribution systems are reaching the end of their design lifetime (60-95 years), with water main breaks currently at a rate of 240,000 per year nationally and rising.[25,26] Aside from obvious public health implications associated with compromised delivery of uncontaminated drinking water to the tap, failure events can cause property damage and water loss through leaks.[27] Like many post-industrial manufacturing centers, Flint has a very large potable distribution system constructed to sustain a large consumer and industrial base that no longer exists. The projected cost to upgrade the distribution system is $1.5 billion dollars,[28] which would translate to an unbearable cost of $50,000 per existing customer in Flint.[28]

b) Under-appreciation of the role of corrosion control in sustaining potable water systems. Estimates by ASCE, the American Water Works Association (AWWA), the Environmental Protection Agency (EPA), the Water Infrastructure Network (WIN), and the National Academy of Corrosion Engineers (NACE) suggest that direct costs of water pipeline corrosion range between $8 billion - $36 billion annually and indirect costs are much higher.[27] Leaks result in 7 billion gallons of lost water each day with associated revenue losses of ≈ $3 billion per year for U.S. utilities.[29] Problems with leaking potable water plumbing systems in buildings (i.e. premise plumbing) also cost consumers billions of dollars each year.[30,31] Water utilities can reduce costs of potable water system corrosion and extend the lifetime of these invaluable assets by adding corrosion inhibitors, such as orthophosphate, to the water. Prior research using a relatively low corrosivity source water determined that each dollar invested in corrosion control produced more than $5 dollars in financial savings due to reduced corrosion damage and extended lifetime of pipeline infrastructure.[32] In Flint, the short-sighted decision to reduce chemical costs by removing the corrosion inhibitor and introducing corrosive water to the system may have produced tens if not hundreds of millions of dollars in corrosion damages to its existing potable water distribution system. We are also aware of many other utilities that are cutting back on their corrosion inhibitor doses due to cost-cutting pressures.

c) *Increased corrosivity of water sources nationally due to rising chloride levels from anthropogenic pollution and/or rising sea levels.* Chloride levels in drinking water are rising nationally in surface water due to use of road salt and seawater intrusion in coastal regions. Road salt use in winter has risen to 137 lbs per year for every American, with a doubling of salt application from 1990 to 2014 (10 vs. 22 million tons) associated with a doubling of chloride levels in northern U.S. waters as monitored by the USGS.[33,34] There is documented concern about the damage of salt application to infrastructure such as roads and bridges,[35] but rising salt levels in the Potomac (due to road salt) in 2015 also have triggered a spike in consumer complaints of red or brown water from their main distribution system.[36,37] and we are currently working with a utility in Brick, NJ that is reporting high lead in consumers' water due to higher chloride from rising sea levels near their intake as well as road salt use.[38-40] The higher corrosivity of water in Flint due to higher chloride (Table 1), therefore provides an interesting "acute" case study of higher chloride impacts that can shed light on these important national trends.

d) *Failure of utilities and regulatory agencies to take responsibility for the two most important modern day public health problems arising in building plumbing systems (i.e., lead and OPPPs).* For ten years EPA has acknowledged that utilities are collecting samples in a manner that "misses" worst case lead in water,[41-43] and to date they have not required utilities to change monitoring practices to better reveal problems. The EPA LCR sampling protocols have been under review since 2008 and the EPA is expected to issue new requirements sometime in 2016. Hence, sampling in Flint without "pre-flushing" to reduce lead, as revealed by the EPA volunteer,[4] could inform modifications to the EPA LCR. Likewise, EPA's current regulations on Legionella consider only levels that might be present in water leaving the treatment plant, where it is least likely to be present, and do not yet require monitoring at the point of entry into homes or within buildings where Legionella is most likely to be present and cause disease.[21] Our proposed sampling for Legionella at these locations can therefore inform future regulation and distribution system management policies for dealing with this emerging public health risk.[19,22]

In summary, this proposed RAPID grant characterizing the occurrence of chemical/biological problems in Flint, MI homes explores a newly emerging nexus between degrading infrastructure-environmental engineering-public health that can provide insight into problems facing many cities all over the United States.

3. Approach

The ***RAPID grant objectives*** will be achieved through three phases of sampling, using analytical methods in routine use by the project team, as follows:

Phase 1. Compare levels of chlorine, iron, fecal indicator bacteria, OPPPs, and corrosion-inducing bacteria present in water mains of a distribution system with uncontrolled corrosion (Flint) versus controlled corrosion in surrounding cities/counties still using non-corrosive Detroit water. A team including the PI and at least 3 graduate students will travel to Flint and stay 3-7 days in mid-August 2015, to collect 8 distribution system samples from surrounding cities still using Detroit water, and to also sample Flint's 8 distribution system monitoring locations (Figure 1). We will stay in two hotel rooms, one located in Flint and one in a surrounding location on Detroit water, to conveniently collect samples for free chlorine at 2 hour intervals expected to correspond to lowest and highest daily demand. All of these analyses will be conducted using standard methods with the exception of testing for corrosion-inducing bacteria which will be conducted with Biological Activity Reaction Test (BART) kits. BARTs are standardized colorimetric culture kits that are semi-quantitative and include testing for Sulfate-Reducing Bacteria (SRB), Heterotrophic Aerobic Bacteria, Heterotrophic Anaerobic Bacteria, Denitrifiers, Slime Forming Bacteria, and Acid Producing Bacteria (APB). It is hypothesized that the Flint waters will have much lower levels of free chlorine, higher levels of iron, corrosion-inducing bacteria, and fecal indicator bacteria than samples collected from locations still on Detroit water.

Phase 2. Profile building hot and cold water plumbing systems for OPPPs at the same sampling locations used in Phase 1. Protocols used previously to sample for a suite of OPPPs and two host protozoa[18,20] in hot and cold water from taps and biofilms of buildings using quantitative Polymerase Chain Reaction (q-PCR) analysis, will be used to profile the hot and cold water systems for human pathogens at the same locations tested in Phase 1. Specifically, target microbes including *Legionella pneumophila, M. avium, P. aeruginosa, Acanthamoeba and Vermamoeba vermiformis* will be quantified by qPCR, and hot water samples will be cultured for *Legionella* and

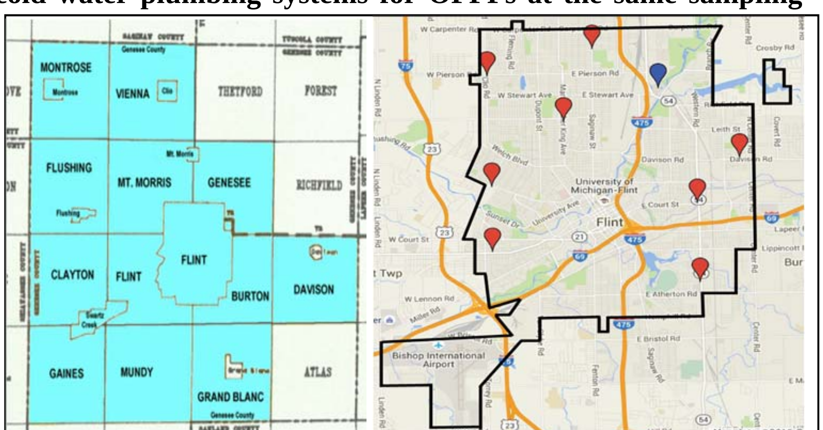

Figure 2. Blue areas indicate areas served by Detroit water before the city of Flint switched (left) and distribution of Flint monitoring stations (right).

Mycobacteria from each location. Samples collected for microbial analysis and fecal indicator bacteria (Phase 1) will be overnight shipped from Michigan via cold-pack using protocols developed by the project team on NSF Project CBET-1438328. In Flint, for comparison, at least three additional privately owned homes will be sampled for OPPPs using the same protocols as for the public buildings.

Phase 3. Determine if there is evidence of elevated lead in Flint homes. We will coordinate with several local citizen groups including the American Civil Liberties Union (ACLU), **Concerned Pastors for Social Action**, and others to sample homes in Flint for lead in water. We will prepare 300 sampling kits with instructions, to collect water samples according to standard EPA LCR protocols for shipment to community groups. Each kit will contain three bottles to sample water after standard water stagnation (> 6 hours) at typical-use flow rates, including 1) first draw standard LCR (1 liter), 2) 45 second flushing 0.5 liter sample (targeting the lead service line, if present), and 3) 5 minutes of flushing 0.25 liter sample. Each kit will have a sample form to fill out information including 1) name of person collecting sample, 2) age of home (if known), 3) mailing address of home sampled, and 4) date of sample collection. A phone number will be provided of a member of the Virginia Tech team, who can answer questions that residents have about the instructions (if any). Residents will be instructed to return the sampling kits to a centralized location according to procedures that best suit each citizen group. The sample kits will then be put into boxes provided by the project team, and shipped back to Virginia Tech with the postage paid by the RAPID grant. Assuming a response rate of 33%, 300 samples (= 0.33 X 300 X 3 bottles per kit) will be analyzed for lead, iron, copper and other constituents using the PI's Inductively Coupled Plasma Mass Spectrometer (ICP-MS). All returned kits will be analyzed, and results will be summarized in a letter to each consumer to be sent out within 1 month of receiving the samples. We will provide a phone number of a senior research scientist (Dr. Jeff Parks) that the residents can call to ask questions about their results if they have them and compile the results in a summary form for research publications and public outreach.

4. Project Management and Prior NSF Support

The senior project team (Edwards, Pruden, Falkinham) has collaborated together extensively and has a strong record of success. They will be assisted in leading the project by Dr. Brandi Clark (former NSF graduate fellow) who is a recent graduate of Virginia Tech (2015). Edwards and Clark will coordinate the Flint site visit and the lead survey. Another NSF graduate fellow (Emily Garner, formerly Emily Lipscomb) who is currently co-advised by Pruden/Edwards will assist the Flint site visit team and coordinate biological sample analysis and shipments. Pruden and Falkinham will assist in the data analysis, interpretation and write-up of the results.

5. Broader Impacts

In addition to improving practical and scientific understanding related to two of the most important problems associated with potable water and health in consumer homes (i.e., lead and OPPPs), this RAPID grant will directly assist residents of Flint in assessing the safety of their potable water supply. The results and approach used herein can inform residents and managers of other U.S. cities who will soon be dealing with similar problems associated with failing potable water infrastructure and increased corrosivity of potable water. Phase 3 of this research also provides an interesting case study in *Citizen Science* as a tool to advance scientific understanding, policy, and public health, because consumers are actively collecting samples from their homes and will be participating in National Science Foundation research. The work also has social justice implications, as the plight of Flint residents has already received national attention, and results can inform the current debate regarding access to safe, affordable water as a "right" for Americans in U.S. cities.

REFERENCES

1. Fonger, R. Flint DPW director says water use has spiked after hundreds of water main breaks. April 22, 2015. Accessed 7-26-2015 at http://www.mlive.com/news/flint/index.ssf/2015/04/flint_dpw_director_says_water.html.
2. Associated Press. Flint city councilman: 'We got bad water'. January 14, 2015. Accessed 7-24-2015 at http://www.freep.com/story/news/local/michigan/2015/01/14/flint-water-resident-complaints/21743465/.
3. Erb, R. Who wants to drink Flint's water? January 22, 2015. Accessed 7-24-2015 at http://www.freep.com/story/news/local/michigan/2015/01/22/water-woes-latest-hit-flint/22193291/.
4. Guyette, C. Scary: Leaded Water and One Flint Family's Toxic Nightmare. July 9, 2015. Accessed 7-24-2015 at http://www.deadlinedetroit.com/articles/12697/scary_leaded_water_and_one_flint_family_s_toxic_nightmare#.VbLvmvlViko.
5. Lockwood, Andrews, & Newnam Inc., Operational Evaluation Report: City of Flint (Trihalomethane Formation Concern). November 2014. Accessed 7-24-2015 at http://cityofflint.com/wp-content/uploads/Operational-Evaluation-Report.pdf
6. U.S. Environmental Protection Agency. Internal Memo: High Lead Levels in Flint, Michigan -- Interim Report. June 24, 2015. Accessed 7-24-2015 at http://www.aclumich.org/sites/default/files/file/EPAWaterReport062415.pdf.
7. Smith, M. A Water Dilemma in Michigan: Cloudy or Costly? March 25, 2015. Accessed 7-24-2015 at http://www.nytimes.com/2015/03/25/us/a-water-dilemma-in-michigan-cheaper-or-clearer.html.
8. Larson, T. E. and R.V. Skold. Laboratory Studies Relating Mineral Quality of Water to Corrosion of Steel and Cast Iron. *Corrosion* (1958). 14(6): p. 43-46.
9. Fonger, R. GM's decision to stop using Flint River water will cost Flint $400,000 per year. October 14, 2014. Accessed 7-24-2015 at http://www.mlive.com/news/flint/index.ssf/2014/10/gms_decision_to_stop_using_fli.html.
10. Nguyen, C., et al., Impact of Chloride:Sulfate Mass Ratio (CSMR) Changes on Lead Leaching in Potable Water. 2010, Denver, CO: Water Research Foundation.
11. Longley, K. Massive water leak, theft contribute to Flint water rate increases, officials say. May 10, 2012. Accessed 7-24-2015 at http://www.mlive.com/news/flint/index.ssf/2012/05/flint_officials_water_leakage.html.
12. Fonger, R., Flint's built-in water rate increase of 6 percent won't fly, say some on City Council. February 25, 2015. Accessed 7-24-2015 at http://www.mlive.com/news/flint/index.ssf/2015/02/flint_water_rates_headed_highe.html
13. Abbey-Lambertz, K. Reverend Compares Michigan City's Drinking Water Issues to the Holocaust. March 6, 2015. Accessed 7-24-2015 at http://www.huffingtonpost.com/2015/03/05/flint-water-drinking-clean-tthm_n_6810368.html
14. Lytle, D.A., T.J. Sorg, and C. Frietch, Accumulation of Arsenic in Drinking Water Distribution Systems. Environmental Science & Technology, 2004. 38(20): p. 5365-5372.
15. Masters, S., and M. Edwards. Increased Lead in Water Associated with Iron Corrosion. Environmental Engineering Science, (2015), 32 (5), 361-369.
16. Masters, S.M., Wang, H., A. Pruden and M. Edwards. Redox Gradients in Distribution Systems Influence Water Quality, Corrosion, and Microbial Ecology. Water Research, (2015), DOI: 10.1016/j.watres.2014.09.048.
17. Wang, H., Masters, S., Edwards, M.A., Falkinham, J.O. III, and A. Pruden. Effect of Disinfectant, Water Age, and Pipe Materials on Bacterial and Eukaryotic Community Structure in Drinking Water Biofilm. Environmental Science & Technology. dx.doi.org/10.1021/es402636u.
18. Wang, H., S. Masters, Y Hong, J. Stallings, J.O. Falkingham, M. Edwards and A. Pruden. Effect of disinfectant, water age, and pipe material on occurrence and persistence of Legionella, mycobacteria,

Pseudomonas aeruginosa, and two amoebas. Environmental Science & Technology 46 (21), 11566-11574 (2012).
19. Wang, H., Masters, S.; Falkinham, J.O.; Edwards, M.; and A. Pruden. Distribution System Water Quality Affects Responses of Opportunistic Pathogen Gene Markers in Household Water Heaters. Environmental Science & Technology. (2015), DOI: 10.1021/acs.est.5boa.538
20. Wang, H., M. Edwards, J. Falkinham and A. Pruden. Molecular Survey of the Occurrence of Legionella spp., Mycobacterium spp., Pseudomonas aeruginosa, and Amoeba Hosts in Two Chloraminated Drinking Water Distribution Systems. (2012), Applied and Environmental Microbiology. 78(17) 6285-6294.
21. Del Toral, Personal Communication. Timeline of Events in Flint, MI (2015).
22. Pruden A, Edwards MA, Falkinham III, JO, Arduino M, Bird J, Birdnow R, Bédard E, Camper A, Clancy J, Hilborn E, Hill V, Martin A, Masters S, Pace NR, Prevost M, Rosenblatt A, Rhoads W, Stout JE, Zhang Y. (2013) Research needs for opportunistic pathogens in premise plumbing: Methodology, microbial ecology, and epidemiology. Water Research Foundation Project 4379 Final Report. Water Research Foundation. Denver, CO, 188 pages.
23. American Society of Civil Engineers (ASCE). (2009) "Report Card for America's Infrastructure." Washington, DC. Accessed on 05/05/2010 at http://www.infrastructurereportcard.org.
24. American Society of Civil Engineers (ASCE). (2011) "Failure to Act: The Economic Impact of Current Investment Trends in Water and Wastewater Treatment Infrastructure." Washington, DC.
25. US Environmental Protection Agency (EPA). (2010) "Addressing the Challenge Through Science and Innovation." Aging Water Infrastructure Research, Office of Research and Development, Washington DC.
26. Walker, F. G. and Schaefer, G. M. (2009) "White Paper: Corrosion and Cracks in Water Pipes: Can We See Them Sooner?" Bartron Medical Imaging Inc., Largo Maryland.
27. US Environmental Protection Agency (EPA). (2002) "The Clean Water and Drinking Water Infrastructure Gap Analysis." Office of Water, Washington DC.
28. City of Flint Water System Facts. Accessed 7-26-2015 at https://www.cityofflint.com/wp-content/uploads/Water-System-Facts.pdf.
29. US Federal Highway Administration (FHWA). (2002) "Corrosion Costs and Preventive Strategies in the United States." Publication No. FHWA-RD-01-156.
30. Scardina, P. and Edwards, M. (2008) "Investigation of Copper Pipe Failures at Location I." Assessment of Non-Uniform Corrosion in Copper Piping, American Water Works Association Research Foundation, Denver, CO.
31. Bosch, D. and Sarver, E. (2007) "Economic Costs of Pinhole Leaks and Corrosion Prevention in U.S. Drinking Water Plumbing." In Proceedings of American Water Works Association Annual Conference and Exhibition, Charlotte, NC.
32. Ryder. R,A. (1980). The Costs of Internal Corrosion in Water Systems. Jour. AWWA, 72(5), pp. 267.
33. Strombert, J. What Happens to All the Salt We Dump on the Roads. Smithsonian.com. (2014). Accessed 07-26-2015 at http://www.smithsonianmag.com/ist/?next=/science-nature/what-happens-to-all-the-salt-we-dump-on-the-roads-180948079/
34. Corsi, S. R., De Ciccio, L.A., Lutz, M. A., and R. M Hirsch. River chloride trends in snow-affected urban-watersheds: increasing concentrations outpace urban growth rate and are common among all seasons. (2015), Science of the Total Environment, 508, 488-497.
35. Dindforf, C., and C. Fortin. The Real Cost of Salt Use for Winter Maintenance in the Twin Cities Metropolitan Area. Minnesota Pollution Control Agency. October 2014. Accessed 07-26-2015 at http://www.pca.state.mn.us/index.php/view-document.html?gid=21766
36. Wheeler, T. (2015), Salt Concentrations High in 2 Md. Rivers. Baltimore Sun. January 2, 2015. Accessed 07-26-2015 at http://www.baltimoresun.com/features/green/blog/bs-hs-salty-streams-20150102-story.html

37. Shaver, K. (2015), The snow brought out the salt, which caused Montgomery's brown water. Washington Post, June 17, 2015. Accessed 07-26-2015 at http://www.washingtonpost.com/local/montgomery-residents-complain-about-brown-tap-water/2015/06/17/d7910098-146c-11e5-9518-f9e0a8959f32_story.html
38. Williams, D.D.; Williams, N.E.; and Yong Cao. (1990), Road salt contamination of groundwater is a major metropolitan area, and development of a biological index to monitor its impact. Water Research, 34(1), 127-138 .
39. Penton, K. (2014). What you need to know about Brick's Water Contamination. Accessed June 26, 2015 at http://www.app.com/story/news/investigations/watchdog/government/2014/11/19/lead-bricks-drinking-water/19298753/.
40. Furlow, J.; Scheraga, J.D.; Freed, R.; and K. Rock. The vulnerability of public water systems to sea level rise. In Proceedings of the Coastal Water Resource Conference, John R. Lesnik (editor), American Water Resources Association, Middleburg, Virginia, TPS-02-1, 2002, 31-36.
41. Edwards, M.; Abhijeet, D. (2004), Role of chlorine and chloramine in corrosion of lead-bearing plumbing materials. Journal American Water Works Association. V. 96, No. 10 69-81.
42. Del Toral, M.; Porter, A.; and Schock, M. (2013). Detection and Evaluation of Elevated Lead Release from Service Lines: A Field Study. Environmental Science & Technology, 47 (16), 9300–9307
43. Gabler, E. August 5, 2011. High lead levels found in Chicago water. Accessed 7-26-2015 at http://www.chicagotribune.com/lifestyles/health/ct-met-lead-in-water-20110805-story.html.
44. Smith, L. July 13, 2015. Leaked internal memo shows federal regulator's concerns about lead in Flint's water. Accessed 7-28-2015 at http://michiganradio.org/post/leaked-internal-memo-shows-federal-regulator-s-concerns-about-lead-flint-s-water#stream/0