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ADVANCES in WATER RESEARCH

Small Systems

also in this issue

Lead and Copper

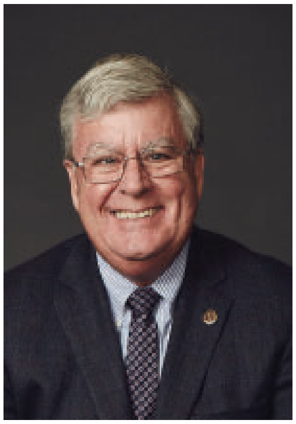
Sewer Methane

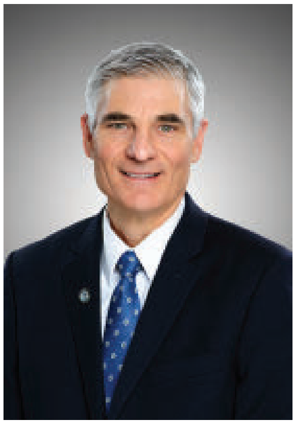
Membrane Bioreactors

THE Water Research FOUNDATION®

VIEWPOINT

Research and Innovation for All


Michael Markus


Peter Grevatt

Our core values at The Water Research Foundation (WRF) are integrity, leadership, respect, innovation, and collaboration. In line with these, we place great value on diversity, equity, and inclusion, and our goal is to always deliver the highest level of professionalism while treating all of our subscribers and partners with the utmost respect. WRF's community of subscribers and partners is highly diverse, with a wide range of water professionals providing essential water services to communities across the globe. These professionals include utility staff, consultants, manufacturers, academics, regulators, and more. They work for entities providing different types of water services, representing communities large and small and customers of varying demographics. Each of these communities is unique, with its own strengths, resources, and needs. When it comes to water services, there is no "one size fits all" model.

At WRF, we recognize and greatly value the diversity of our subscribers and partners and of the customers in the communities they serve. Our mission is to advance the science of water to improve the quality of life for all.

To ensure our subscribers have the resources they need to accomplish their goals and meet their community- and utility-specific needs, WRF research addresses a broad variety of topics in an integrated fashion. WRF's comprehensive body of One Water research and innovation covers subjects ranging from infrastructure and treatment to finance and workforce management, from energy and resource recovery to climate change and community resilience. This issue of *Advances in Water Research* highlights some of our resources geared toward small systems, which face different challenges and opportunities than larger systems due to their unique set of financial circumstances, technical resources, and community needs.

Our research and innovation priorities are driven by our subscribers and partners, who have multiple opportunities to guide our work and grow their connections with leaders across the global water sector through engagement with WRF. Subscriber and partner engagement ensures that our work continues to address the diversity of needs across the water sector.

We are proud to work with a diverse subscriber base, and to develop research and innovation projects to benefit all areas of the water sector. Whether you provide drinking water, wastewater, reuse, and/or stormwater services, we have solutions for you, and we have experts on staff to ensure you have access to the resources you need now and into the future.

Michael R. Markus, PE
Chair, Board of Directors

Peter Grevatt, PhD
Chief Executive Officer

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THE Water Research FOUNDATION®

The Water Research Foundation (WRF) is the leading research organization advancing the science of all water to meet the evolving needs of its subscribers and the water sector. WRF is a nonprofit, educational organization that funds, manages, and publishes research on the technology, operation, and management of drinking water, wastewater, reuse, and stormwater systems—all in pursuit of ensuring water quality and improving water services to the public.

ADVANCES in WATER RESEARCH

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BY THE NUMBERS

This installment of By the Numbers provides statistics on lead and copper in drinking water. For more information on this subject, see the article, Lead and Copper Rule Compliance.

Lead and copper in service lines and household plumbing are primary drinking water corrosion concerns. Lead is a toxic metal that can be harmful to human health even at low exposure levels, particularly in children. Lead is persistent and can bioaccumulate in the body over time. Drinking water containing high levels of copper may cause short-term nausea, while long-term exposure to copper can affect the liver and kidneys.

>50

Research projects related to lead and copper corrosion that WRF has funded since the late 1980s.

$20 million

Approximate value of these research projects

In 2017, WRF launched its Lead and Copper Management Research Area.

Projects funded through the Lead and Copper Management Research Area

Project Title (number)	Timeline	Total Project Value
Full Lead Service Line Replacement Guidance (4713)	2017–2020	$1,278,000
Evaluating Key Factors That Affect the Accumulation and Release of Lead from Galvanized Pipes (4910)	2018–2021	$440,000
Analysis of Corrosion Control Treatment for Lead and Copper Control (5032)	2020–2022	$486,000
Guidance for Using Pipe Loops to Inform Lead and Copper Corrosion Control Treatment Decisions (5081)	2021–2023	$402,000

Drinking water is not the only source of exposure to lead in children and adults. Lead-contaminated dust and soil and some foods can contribute significantly to lead exposure.

20%

Adult lead exposure estimated to come from drinking water

(EPA 2020)

80%

Adult lead exposure estimated to come from ingestion of food, dirt, and dust

(WHO 2011)

<10

Percentage of copper exposure estimated to come from drinking water

(HC 2018)

Due to the risks of exposure to lead and copper, various agencies have guidelines or regulations related to the levels of these metals in drinking water.

Lead regulations and guidelines from around the world

Agency	Level	Category
World Health Organization	10.0 µg/L	Provisional guideline
Commonwealth of Australia, National Health and Medical Research Council	10.0 µg/L	Health guideline
European Parliament	10.0 µg/L 5.0 µg/L	Parametric value (current) Parametric value (by January 2036)
Health Canada	5.0 µg/L	Maximum acceptable concentration
U.S. Environmental Protection Agency	15.0 µg/L 0.0	Action level Maximum contaminant level goal

Source: Data from CFR 2021, EU 2020, HC 2020, NHMRC 2011, and WHO 2017

Copper regulations and guidelines from around the world

Agency	Level	Category
World Health Organization	2.0 mg/L	Provisional guideline
Commonwealth of Australia, National Health and Medical Research Council	2.0 mg/L 1.0 mg/L	Health guideline Aesthetic guideline
European Parliament	2.0 mg/L	Parametric value
Health Canada	2.0 mg/L 1.0 mg/L	Maximum acceptable concentration Aesthetic objective
U.S. Environmental Protection Agency	1.3 mg/L 1.0 mg/L	Action level Aesthetic objective

Source: Data from CFR 2021, EU 2020, HC 2020, NHMRC 2011, and WHO 2017

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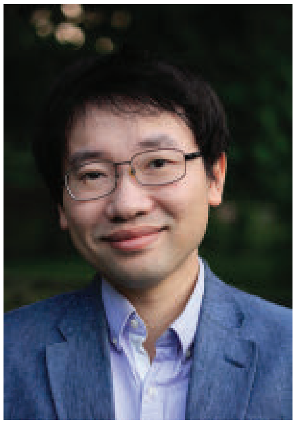
Interview with Shihong Lin

Innovations in Solute Separation



In October 2020, Dr. Shihong Lin was presented with the Paul L. Busch Award, which recognizes an individual for innovative research in the field of water quality and the water environment, with a special focus on those who show promise and make significant contributions in bridging research and its practical application. Dr. Lin is Assistant Professor in Civil and Environmental Engineering and Chemical and Biomolecular Engineering at Vanderbilt University in Nashville, TN. Dr. Lin combines both experimental and theoretical approaches to study a variety of water separation technologies, including membrane-based, electrochemical, and hybrid processes.

Congratulations on winning the Paul L. Busch Award. What does receiving this award mean to you? I am extremely honored and humbled to receive the Paul L. Busch Award and join a cohort of stellar recipients who I look up to as role models. I'm also highly inspired by learning about the life and achievements of Paul L. Busch, and I hope to follow his vision of applying innovative ideas to improve the water environment. Finally, I'm truly thankful to my students and my very supportive colleagues, mentors, and previous advisors. I would not be where I am today without their support.

How long have you been working on water separation technologies, and how did you first become interested in this topic? I have been working on water separation since 2013 when I was a postdoc at Yale University. I was working on an interesting project integrating two membrane processes to harvest waste heat using saline water as a medium, and that was when I became fascinated with membrane-based water separation.

You received the Paul L. Busch Award for your work on selective solute separation (S^3) focused on electro-regulated nanofiltration. Would you describe this work and the challenges it seeks to address? For many decades, research and development in water separation primarily focused on how to remove certain contaminants from feed water, and how to do it efficiently and robustly. Only very recently has the water community recognized the growing importance of separating solutes from each other. The major challenge is that the solutes that need to be separated are very small and similar in size. As an analogy, while separating grapes from watermelons may be relatively easy, separating grapes from cherries is much more challenging. I believe that electro-regulated nanofiltration has the potential to achieve solute-solute separation by utilizing ionic charge as an extra dimension of control.

What are the primary opportunities presented by S^3, and what applications do you anticipate for this work? The primary opportunities for S^3 are to perform separation between ions of different charges and between uncharged and charged solutes of similar size. Potential applications in the water sector include water softening, wastewater reuse, nutrient recovery, and mineral recovery from processed water. Outside of the water sector, I can envision S^3 being potentially useful in chemical and pharmaceutical manufacturing.

What other types of projects is your research team currently working on? Our research team is working on several other projects now, and they are all within the overarching theme of water separation. For example, we have projects focused on using nanofiltration and membrane distillation to recover water and other resources from various feed solutions, including treated wastewater, hypersaline brine, and source-separated urine. We also have projects where we are trying to come up with new ways to make better membranes for water separation.

Many in the water sector are exploring partnerships between universities and utilities. From the university perspective, what are your thoughts on such partnerships, and how they should be implemented? I personally feel that more could be done to promote partnerships between universities and utilities, and even industry, for water innovations. This is about more than just accelerating the adoption of the innovations coming from universities. It also helps academics in the field address research questions that are not only scientifically interesting, but also practically relevant. The Water Research Foundation has been the leader in such a mission. In addition, the U.S. Department of Energy recently funded a water hub called National Alliance for Water Innovation (NAWI), which also has a strong emphasis on partnerships between universities, national laboratories, utilities, and industries. I am excited to see more synergy between academic research, industrial development, and utility adoption.

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What do you see as the future of the water sector? From the water supply side, I envision that the water sector will continue to explore unconventional water resources to address the growing challenge of regional water scarcity. In recent years, we have witnessed the rapid growth of desalination (of both seawater and brackish water). For wastewater, whether it be municipal or industrial wastewater, we will continue to see the trends of resource recovery and wastewater reuse. The idea of viewing wastewater not as a waste but as a resource is transformative. The question is whether current technology can enable us to continue in this direction in a way that is economically viable. In all of these applications, water separation plays an important role. There is also growing attention toward distributed and modular treatment systems, and membrane processes certainly have intrinsic advantages in those areas. Lastly, I think we will see the water sector benefiting tremendously from the ongoing development of data science. The key is to apply those great tools to answer the right questions in order to achieve the greatest practical impact.

Paul L. Busch Award Celebrates 20th Anniversary

Since 2001, the Endowment for Innovation in Applied Water Quality Research has recognized outstanding achievement and creative vision through the Paul L. Busch Award. The award seeks to distinguish individuals poised for greater recognition of their innovative, ongoing contributions to water quality advancements, and has awarded $2 million in funding to up-and-coming researchers who are making major breakthroughs in the water sector.

The award was named in honor of Paul L. Busch, who embodied the spirit of creativity, visionary thinking, and practical application of scientific research — a spirit that is essential to passing a clean-water environment on to future generations. He led both private and public development of water quality technologies for more than 40 years, was passionate about education, and devoted much of his time to mentoring and promoting the next generation of environmental engineers. Dr. Busch also inspired those he worked with to examine familiar issues from new perspectives, challenging engineers and scientists to devise new technologies for addressing ongoing water quality issues, rather than relying on traditional solutions that owed more to the past than the future.

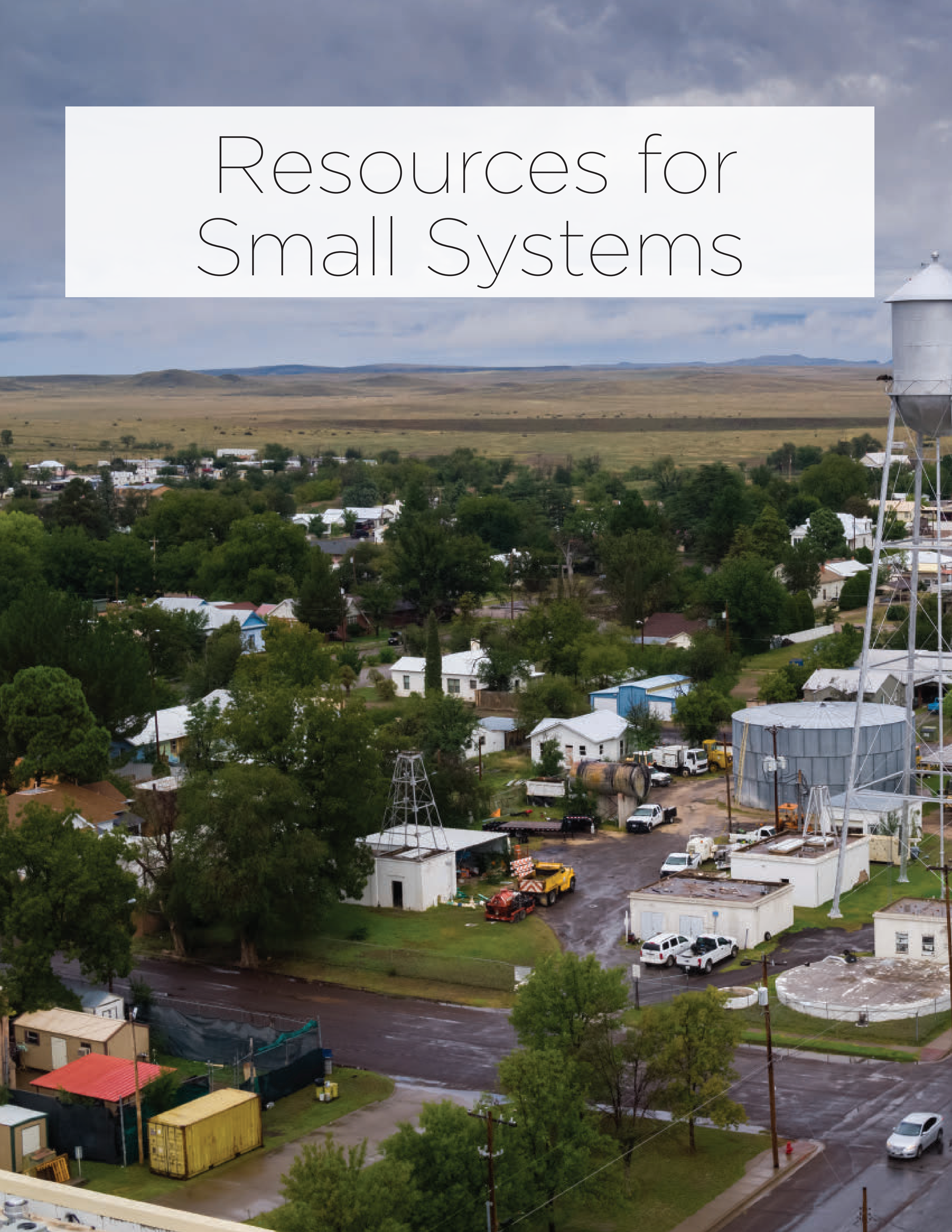
20 years Paul L. Busch Award

As we celebrate the 20th anniversary of this award, WRF thanks all of the Paul L. Busch awardees for their contributions to the water sector.

2020 - Shihong Lin
2019 - Ameet Pinto
2018 - Krista Rule Wigginton
2017 - Shaily Mahendra
2016 - Jeremy Guest
2015 - Mari Winkler
2014 - Amy Pruden
2013 - Chul Park
2012 - Robert Nerenberg
2011 - Volodymyr Tarabara
2010 - Kartik Chandran
2009 - Jaehong Kim
2008 - Andrew Schuler
2007 - Paige Novak
2006 - Paul Westerhoff
2005 - Daniel Noguera
2004 - Bruce Logan
2003 - David Sedlak
2002 - Lutgarde Raskin
2001 - Nancy Love

For more information on the award, visit www.waterrf.org/paul-busch.

Resources for Small Systems



Smaller water systems face different challenges and opportunities than larger systems due to their unique set of financial circumstances, technical resources, and community needs. But what is a small system?

By Kristin Bennett, Alyse Greenberg, and Maureen Hodgins, The Water Research Foundation

When it comes to water services, there are many definitions of small systems, varying by country, regulation, and water system type. The definitions may consider the population served, the amount of water collected or distributed, budget, or other factors. For example, the Australian Drinking Water Guidelines define small drinking water systems as those serving fewer than 1,000 people (NHMRC 2011). However, the United States' Safe Drinking Water Act defines small drinking water systems as those serving 10,000 or fewer customers (EPA 2020a). The U.S. Environmental Protection Agency defines small wastewater systems as those serving communities of 10,000 or fewer people, with an average daily wastewater flow of fewer than one million gallons (EPA 2020b).

In many ways, the definition of small system may be less important than the qualities that make these systems distinctive. No matter which definition of small system a utility meets, there are resources available to help the utility manage risks, increase efficiencies, and enhance resilience.

Risk Management

THE CHALLENGES SMALL UTILITIES face are especially difficult when considering the many risks and uncertainties that affect utility decision making, such as deteriorating infrastructure, limited financial resources, and changes in climate, population, and regulations. Risk-based planning and evaluation resources can help water utilities anticipate, evaluate, and determine how to respond to future threats and uncertainties using sustainable utility management concepts. However, most of the existing planning tools and frameworks are complex and not easily applied by smaller utilities due to constraints such as limited staff and budgets. Therefore, an approach that facilitates the use of these frameworks by small utilities and provides recommendations for tailoring them to utility-specific needs is imperative.

Obstacles and Solutions for Risk-Based Planning for Smaller Utilities and Limited Budgets (Paulson et al., forthcoming) attempts to address this need by focusing specifically on small utilities and developing a strategy to implement integrated, risk-based planning efforts that also address social equity and environmental justice. A Small Utilities Resource Framework, consisting of five modules, was developed (Table 1).

The Resource Framework (1) presents resources that can assist small drinking water and wastewater utilities in completing risk-based planning processes, (2) identifies the most useful resources for specific applications, (3) provides utilities with the information they need to select which resources are most relevant to their planning processes, and (4) explains how to use each resource. By using the Resource Framework, small utilities will be better able to tailor available guidance to their own planning processes.

Climate Change

CLIMATE CHANGE IS ONE OF MANY risks and uncertainties that the water sector must address. To increase access to key resources that will help small- and medium-sized utilities (i.e., those serving fewer than 100,000 customers) enhance their resilience to climate change, WRF partnered with the National Oceanic and Atmospheric Administration (NOAA) on a series of eight regional workshops. The workshops were geared toward water system managers, including managers of community drinking water, wastewater, and stormwater utilities; urban planners; and public works departments. An additional workshop on water equity was also held.

The workshops offered opportunities for idea sharing to identify resource needs, raise regional awareness of existing resources, increase regional connections to support decision making, and improve communication materials (NOAA 2020a).

Key lessons learned through the workshops include the following:

- A need exists for updated, local-scale information, including precipitation and flood statistics.
- Updated information needs to be incorporated into state and local codes and standards.
- Soil moisture deficits are affecting runoff, thereby increasing the need for communities to conduct vulnerability assessments and develop drought contingency plans.
- Both the desire and need exist for equity and inclusion training to help overcome barriers to equitable resilience planning.
- The staff of many small- and medium-sized water utilities do not have sufficient technical capacity, time, and resources to effectively use climate change

Table 1. Organization and major topics of the Resource Framework

Module	Resources Included in This Section	Questions Addressed in This Section
Module I: Organize and Facilitate a Planning Process	Resources to help organize and complete the following plan types: • Master plan/resilience plan • Asset management plan • America's Water Infrastructure Act–compliant plan	• Which type of plan will best address my needs? • What resources are effective for a small utility to use? • How can I use different resources together?
Module II: Identify and Evaluate Threats to Sustainability	Resources to help evaluate drinking water/wastewater system threats in the following categories: • Asset management/deteriorating infrastructure • Climate change/extreme weather • Emerging contaminants/new regulations • Financial instability	• How can I store the information gleaned when building an asset management plan? • What extreme weather events is our system exposed to, and how could that change in the future? • How can I address new changes in water quality regulations? • What tools can I use to assess utility finances to better plan for changes in revenue?
Module III: Identify and Implement Mitigation Strategies	Resources to identify and implement mitigation strategies: • Identifying potential mitigation strategies • Financing mitigation strategies • Constructing mitigation strategies	• What are some mitigation strategies other small utilities have used to address common vulnerabilities? • What resources are available to provide supplemental funding (grants/loans) for projects? • How do I manage a construction project as the owner?
Module IV: Resources for Water Systems Serving Fewer than 3,300 Persons	Resources that address the first three modules and are specific to water systems serving fewer than 3,300 persons	• What resources and tools are available for water systems serving fewer than 3,300 persons?
Module V: Social Equity and Environmental Justice in Planning	Concepts of social equity and environmental justice as they intersect drinking water/wastewater utility planning, and resources to incorporate these concepts	• What is social equity/environmental justice and how can I incorporate it into a planning process?

Source: Paulson et al., forthcoming

information and be trained on available tools.

- Climate change adaptations are more likely to be accepted when integrated into ongoing planning and operations. (NOAA 2020b)

The WRF and NOAA workshop materials are available via the 5054 project page of the WRF website.

Regulatory Compliance

MANAGERS OF SMALL SYSTEMS may also seek additional resources for addressing regulatory compliance. *Solutions for Underperforming Drinking Water Systems in California* (Feinstein et al. 2020) found that while systems of all sizes have water quality challenges, small water systems struggle the most to meet Safe Drinking Water Act standards. The most common violations found were for arsenic and total trihalomethanes. Many of these small systems primarily serve disadvantaged communities that have limited funds and resources. In addition, systems serving low-income communities of color are nearly four times as likely to have persistent water quality violations compared to systems serving white, non-Latino communities (Feinstein et al. 2020). While this project focused specifically on California, many of the findings, such as potential solutions to compliance challenges, are applicable to utilities no matter where they are located.

A diversity of solutions to regulatory compliance challenges exists, including operational solutions (e.g., remote and contract operations), treatment solutions (e.g., facility optimization and point of use/entry treatment), source water solutions (e.g., new internal and external water supplies), and partnership solutions (e.g., physical or managerial consolidation and mutual assistance). Table 2 details the characteristics and benefits of these solution types.

All four of these solution types can be effective alone or in combination; they are not mutually exclusive. However, partnership solutions are of especially high interest for many regulatory agencies. For example, 35 states in the United States provide "priority points" for partnerships when making Drinking Water State Revolving Fund awards (EPA 2017).

continued next page

Table 2. Solution types with the greatest potential value

Operational Solutions	Operational solutions are solutions that change the responsibilities of the operations staff. These can include implementing remote or contract operations, providing operators with remote access to equipment, real-time monitoring, and other smart technology options.	**Key Benefits:** Operational solutions increase efficiency and improve overall system performance by introducing remote monitoring and automation technologies that help operators focus on the most critical tasks without having to be present at each site all the time. Using both contract operators and remote monitoring technologies together can quickly provide long-term solutions to communities.
Treatment Solutions	Because many compliance problems arise from operational factors and not from the facility design, optimizing the existing facility is an effective long-term solution.	**Key Benefits:** Optimizing the existing facility is more cost effective and requires less time than building a new facility. Physical optimization can include process, mechanical, and structural improvements to provide higher quality water.
Source Water Solutions	Additional sources of water are beneficial when the existing source's operational or treatment solutions are challenging or cost prohibitive. A neighboring drinking water system can provide treated water or provide a new raw water source that may need less treatment than the original source. Recycled water or water from a nearby irrigation district could replace irrigation or non-potable needs.	**Key Benefits:** Connecting with a new source that already meets existing standards allows the system to continue to operate without having to increase operator treatment qualifications.
Partnership Solutions	Partnership opportunities include a spectrum of options, such as finding the right technical partner to assist the plant, finding the most effective mutual aid, and finding a partner for consolidation. Consolidation is when two or more utilities join together. The consolidation can be physical (such as sharing a common source water or treatment plant), or managerial (when system administration is consolidated, or via a partnership such as mutual aid). Voluntary consolidations are preferable; however, some regulatory agencies have the authority to mandate consolidation if necessary for public health.	**Key Benefits:** Technical partners can facilitate plant optimization and increase efficiency. The right mutual aid can help the plant improve operation. Consolidation provides a way for utilities to pool resources to solve common problems. Consolidation offers potential benefits in terms of finances, operations and management of the utility, and service to customers.

Source: Feinstein et al. 2020

Partnerships

UTILITY PARTNERSHIPS CAN RESULT in improved efficiencies, reduced costs, improved water supply reliability and/or water quality, and enhanced levels of service provided by the partners. For utilities interested in exploring partnership solutions, *Water Utility Partnerships: Resource Guide and Toolbox* (Henderson et al. 2019) serves as a resource for evaluating potential utility partnership or collaboration opportunities, with a focus on drinking water and wastewater utilities. The project report outlines the challenges related to developing successful water utility partnerships, and leads practitioners through the process of considering the essential elements for a partnership. These elements include partnership options, common legal structures, potential benefits, common concerns, legal issues, and communication approaches.

When considering partnerships, utilities must answer nine key questions:

1. Who should be included in the analysis of partnership options?
2. What are the objectives of a partnership? What key value(s) could serve as drivers for a partnership?
3. What are the relevant partnership options?
4. What are the legal structures under which partnerships can be formed?
5. How does a utility make the business case for a partnership?
6. What are the common concerns encountered in forming partnerships?
7. What are the legal issues a utility needs to consider?
8. How does a utility communicate about partnerships?
9. Do partnerships (and partnership options) differ between different types of water utilities?

The toolbox developed as part of this project contains eight workbooks to guide practitioners as they make their way through these questions.

It is the goal of every water utility to provide high-quality services to its customers and protect public health and the environment. Implementing strategies from the projects outlined in this article can aid utilities, especially smaller systems, in fulfilling that goal.

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INNOVATION IN ACTION

Technology Tools

The Water Research Foundation has delivered world-class, cutting-edge research to support the water sector for over 50 years. As new challenges emerge with increasing frequency, the uptake of new technologies and processes—essential extensions of research—will assist water utilities in continuing to evolve and excel. To accelerate the uptake of innovation in the water sector, WRF has a suite of tools that supports each phase of the innovation cycle (Figure 1), such as technology scans, the FAST Water Network, pilot projects, and more.

WRF's technology scan process engages with vendors and start-ups to identify new and innovative products and processes for the water sector. A panel of expert, volunteer reviewers assesses these innovations and evaluates them for their potential to provide improved performance. Those selected by the panel are included in WRF TechLink (formerly LIFT Link), an online platform that allows users to discover new technologies and research needs, connect with others with similar needs and interests, and collaborate on research and technology projects. These technologies may also be featured in technology scan webcasts.

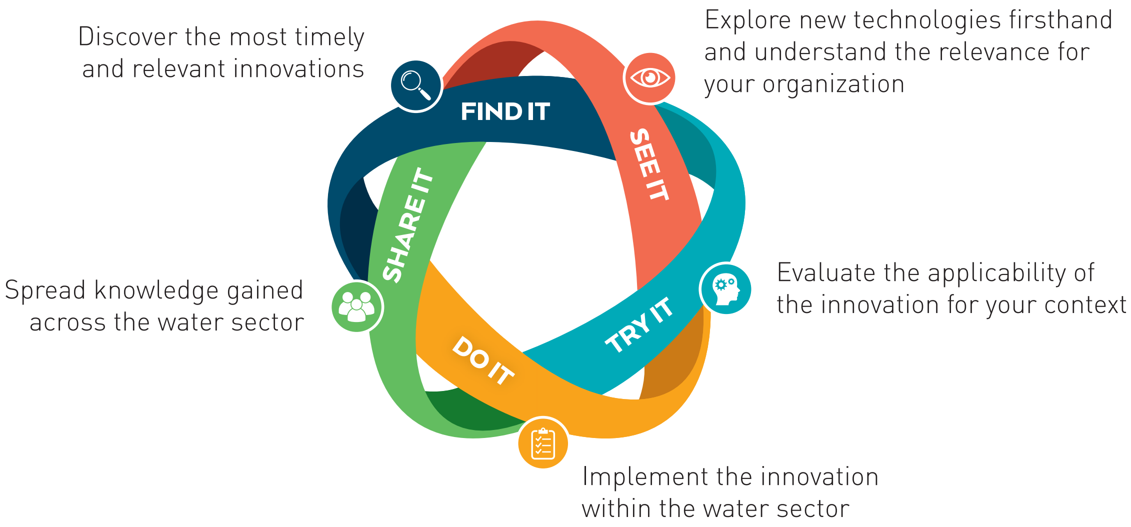
The FAST (Facilities Accelerating Science & Technology) Water Network assists in identifying facilities that are available to test innovations at the pilot scale. The Tech Trends tool identifies changes in the deployment and uptake of innovative technologies across the water sector, including at wastewater, stormwater, drinking water, desalination, and water reuse facilities. In addition to the outward-looking technology evaluations, WRF will be evaluating our own research to identify projects with innovation potential. This will enable us to create a seamless pipeline for research outcomes to be further developed, evaluated, and tested at a range of scales.

WRF is also launching a new pilot project effort to enable utilities to test promising technologies and processes at pilot and demonstration scales. A consortium of utilities, researchers, and agencies will support these projects, which will be categorized into key topics. The first four portfolios will address the following topics:

- Energy efficiency
- Water reuse
- Nitrogen reduction
- Destruction of per- and polyfluoroalkyl substances (PFAS) and perfluorooctanoic acid (PFOA)

WRF will continue to deliver two components of the innovation program in partnership with the Water Environment Federation (WEF). The Intelligent Water Systems Challenge enables students, professionals, and technologists to showcase innovations that enable utilities to leverage data to make better decisions. The Scholarship Exchange Experience for Innovation & Technology (SEE IT), supported by WRF, WEF, and the National Association of Clean Water Agencies, provides scholarships for utility personnel to visit other utilities with innovations of interest and to share experiences with their peers.

To learn more about WRF's Innovation Program, and how you can get involved, visit www.waterrf.org/innovation.



Discover the most timely and relevant innovations

Explore new technologies firsthand and understand the relevance for your organization

Evaluate the applicability of the innovation for your context

Implement the innovation within the water sector

Spread knowledge gained across the water sector

Figure 1. The innovation cycle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COMPLIANCE

Lead and Copper Rule Compliance

Utilities across the United States must be prepared to address revisions to the Lead and Copper Rule.

By Jonathan Cuppett, The Water Research Foundation; Leslie Moening and Jeff Swertfeger, Greater Cincinnati Water Works; and Steve Via, American Water Works Association

The revised Lead and Copper Rule (LCR) was published in the Federal Register (FR 2021a) on January 15, 2021. The U.S. Environmental Protection Agency (EPA) has since delayed the effective date of the revised rule to June 17, 2021, and has proposed extending the compliance date to September 2024 (FR 2021b). The current requirements of the revised rule are discussed below, but are subject to change based on additional stakeholder engagement occurring during the time extension.

There are several key areas where water utilities can focus as they prepare to comply with the rule:

- Lead service line (LSL) inventories
- Lead service line replacement plans
- Monitoring in schools and child care facilities
- Sampling tier structure
- Sampling methods
- Lead action level and trigger level
- Find and fix
- Corrosion control studies

Basic information for each of these topics is discussed in this article, but water professionals should reference the Federal Register for complete information. At this time, clarification is still needed to better understand specific details of the LCR.

Lead Service Line Inventories

SYSTEMS MUST COMPLETE AND submit inventories to their respective states to document all service lines in their systems. These inventories must contain the type of service line material:

- Lead
- Non-lead
- Galvanized requiring replacement (galvanized currently or previously preceded by a lead service line or by an unknown material)
- Lead status unknown

The service line is defined as the material connected to the main all the way into the home. If a lead connector is present (i.e., gooseneck or pigtail), that material does not need to be part of the inventory and is not considered for purposes of classifying "galvanized needing replacement." Regardless of the service line ownership scenario, the inventory must reflect materials along the entire length of the service line. The inventory should be based on documented records or other appropriate strategies as approved by the state. An accurate initial inventory of service line materials will help with related rule requirements. Systems must make the inventories available to the public. Systems serving >50,000 persons must make the inventories available online. All systems must describe inventory access options in their annual consumer confidence reports. Regular updates to the initial inventories are also required.

Lead Service Line Replacement Plans

ALL SYSTEMS WITH ANY LEAD, galvanized requiring replacement, or lead status unknown service lines must develop and submit LSL replacement plans to the state. The plans must include:

- Strategies for determining the composition of lead status unknown service lines
- Procedures for conducting full lead service line replacement (LSLR), including premise plumbing flushing instructions
- Strategies for informing customers before a full or partial LSLR
- LSLR goal rates recommended by the systems in the event of a lead trigger level exceedance

LSL Inventory and Replacement: A Case Study

GREATER CINCINNATI WATER WORKS (GCWW) HAS been actively preparing for the revised LCR and how it may impact the utility. GCWW has always met the current LCR requirements and has proactively replaced public LSLs for decades. A successful lead service line replacement program (LSLRP) was implemented in 2018 to replace private LSLs. GCWW has approximately 40,000 known private LSLs remaining, and around 8,000 water service lines of unknown material type. As a result of the revised LCR, GCWW plans to focus on reducing the number of unknown service lines in preparation for LCR implementation in 2024.

Most service lines with unknown material type are in an area that GCWW assumed operational control of in 2004, and which does not have reliable historical service line records. A tabletop research project to determine the material of these lines is being undertaken. Research includes reviewing subdivision plats and recent water main replacement record drawings to determine service line material. GCWW anticipates reducing the number of unknown material type service lines by more than 50% with this exercise. A pothole investigation project will then be conducted to determine the material of the remaining service lines. GCWW anticipates potholing enough service lines to give assurance of service line materials in an area. These efforts are in addition to the collection of information on private-side service line materials whenever GCWW or its contractors enter a home to perform work such as meter change outs or customer water quality investigations.

While GCWW's current LSLRP focuses on replacements on water main projects and those requested by property owners, a majority of the private-side LSLs are on streets where the water main was replaced prior to the LSLRP. One way to address those is to create large-scale private LSL projects. To test this approach, GCWW has identified an area where the public LSLs were replaced in a past water main project but the private side remains. GCWW plans to publicly bid this private LSLR project with over 200 LSLs to one lowest bid contractor. A project of this magnitude will include considerable coordination between the contractor, GCWW, and private homeowners. However, GCWW anticipates lower overall replacement costs due to the reduced contractor mobilization expense and concentrated project boundaries.

The revised LCR will impact many water utility resources and finances throughout the country. GCWW is being proactive in trying to reduce that burden by planning and implementing changes today that will lessen the future economic responsibility for rate payers.

- LSLR prioritization strategies
- Funding strategies for conducting LSLRs, which incorporate equity considerations

Partial replacements (e.g., leaving a customer-side LSL or leaving a galvanized service line that had been downstream of an LSL) are discouraged and do not count toward replacement goals. If a customer replaces a lead or galvanized requiring replacement service line on private property, the utility is required to replace the utility-owned portion of the service line within 45 days if it is lead or galvanized requiring replacement. If the utility-owned portion is lead status unknown, then confirmation of the material type should be evaluated to understand if replacement is required. Risk reduction steps following replacements include provision of education materials, issuing filters and replacement cartridges, and follow up sampling.

Monitoring in Schools and Child Care Facilities

A UTILITY MUST COMPILE A LIST OF all schools (elementary and secondary) and licensed child care facilities served by the system, and provide annual notification of lead health risks to these facilities. Beginning in 2024, systems must conduct sampling in at least 20% of elementary schools (typically K–8th grade) and child care facilities (built after January 1, 2014) and continue for 5 years until all elementary schools and child care facilities have been sampled. Five samples are required for schools and two samples are required for child care facilities. Beginning in 2024, secondary schools (e.g., 9th–12th grade), as well as elementary schools and child care facilities, must be sampled upon request. Information collected through this monitoring is reported back to the facilities, the primacy agency, and the relevant health department. Additional requirements regarding sampling and handling non-responsive facilities are detailed in the rule. The revision does include provisions to utilize other state or local testing programs to fulfill these monitoring requirements.

A new 90th percentile trigger level of 10 µg/L has been added

Sampling Tier Structure

AN UPDATED SAMPLE SITE selection tiering structure is incorporated into the LCR. Sample plans reflecting these new tiers must be in place when the new tiers begin to impact sampling schedules. It is likely that these changes to the tiering structure will result in additional systems exceeding the lead action level and/or trigger level. The tiering structure for community water systems is:

- Tier 1: Single-family structures (SFSs) served by LSLs. Tier 1 samples can be collected from multiple-family residences (MFRs) if they represent at least 20% of structures served by the water system.
- Tier 2: Buildings and MFRs served by LSLs.
- Tier 3: SFSs with galvanized service lines that are downstream of LSL pipes, currently or in the past, or known to be downstream of a lead connector.
- Tier 4: SFSs with copper pipes with lead solder installed before the effective date of the state's lead ban.
- Tier 5: SFSs or buildings, including MFRs, that are representative of plumbing commonly used in the service area.

If enough sites are available in Tier 1 to fulfill the number of required samples, then all samples must be Tier 1. If there are not enough Tier 1 sites to meet the sample requirement, then sites from Tier 2 can be used, then sites from Tier 3, then Tier 4, and finally Tier 5. If a utility has some LSL sample sites (Tiers 1 and 2) but not enough to reach the required number of samples, then Tier 3, 4, or 5 sites can be used; however, the highest values from these lower tiers must be used to satisfy the required number of samples.

Sampling Methods

SAMPLING AT HOME TAPS WITH A minimum 6-hour stagnation is still required under the LCR. However, additional guidance for sampling methods includes:

- No direction to flush prior to the stagnation period is permitted.
- Cleaning or removing of aerators is not allowed prior to sampling.
- Samples must be collected in 1-liter wide-mouth bottles.
- When possible, the same sample sites should be used for each monitoring period.

If samples are collected from a home with an LSL (Tier 1 or 2), then five consecutive 1-liter samples should be taken. The first liter should be analyzed for copper and the fifth liter should be analyzed for lead. If a sample is collected from a home without an LSL, then only the first liter needs to be collected and analyzed for lead and copper.

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Lead Action Level and Trigger Level

THE 90TH PERCENTILE LEAD ACTION level (AL) of 15 µg/L has been maintained, and a new 90th percentile trigger level (TL) of 10 µg/L has been added. If the AL is exceeded, more actions are required than in the previous LCR, including public notification within 24 hours. If a system is below the AL but exceeds the TL, a new suite of actions is required. The requirements for exceeding the AL and/or TL vary by system size, presence of LSLs, corrosion control study history, and water system type.

Medium systems (serving 10,000–50,000 people) and large systems (>50,000 people) without LSLs or lead status unknown service lines that exceed the TL but not the AL will be required to conduct corrosion control studies or reoptimize existing corrosion control, and are not eligible for reduced monitoring.

Medium and large systems with LSLs or lead status unknown service lines that exceed the TL but not the AL will be required to conduct corrosion control studies or reoptimize existing corrosion control, notify customers with LSLs or lead status unknown service lines, begin replacing LSLs (including galvanized lines requiring replacement), and are not eligible for reduced monitoring.

Systems exceeding the AL would be subject to additional requirements for corrosion control implementation, LSLR, public education, sampling frequency, and public notices. Small systems (<10,000 people) are allowed to use the small system flexibility provision in the rule, but must identify actions they will take if they exceed the AL.

Find and Fix

THE NEW FIND AND FIX requirement includes multiple steps:

1. Within five days of a system receiving a compliance tap sample result exceeding 15 µg/L, water quality parameter (WQP) sampling must be conducted at or near the compliance sample site with a high lead value. WQP sampling from the home that exceeded 15 µg/L does not satisfy the requirements of the rule, but can be done for informational purposes. Existing WQP and coliform sampling sites can be used for this purpose if appropriately sited.
2. Within 30 days, follow up tap sampling for lead at the site that exceeded 15 µg/L should be performed. Alternative sampling protocols are allowed to better understand the cause and source of lead. These samples are not included in compliance monitoring data used to calculate the 90th percentile lead levels for the system.
3. Analyze results from Steps 1 and 2 to determine the cause of elevated lead.
   - If the cause of elevated lead is unknown or determined to be from a source at the sampling location, then no fix is required.
   - If the cause of elevated lead is determined to be corrosive water, then additional actions are required to restore optimal water quality to that portion of the system, which could include an evaluation of the corrosion control being practiced.

In addition to the above steps, various notifications are associated with find and fix requirements. Small water systems have alternative find and fix requirements.

Corrosion Control Studies

THE REVISED RULE CONTINUES TO include several tools for evaluating corrosion control treatment, including analogous system evaluations, coupon tests, pipe rig studies, and partial system tests. If the system has LSLs, then it must conduct a pipe rig study with harvested LSLs. If the system does not have LSLs, then pipe rigs, coupon tests, partial-system tests, or analogous system evaluations can be used. When conducting corrosion control testing, the water system must evaluate each of the following corrosion control treatments:

1. Alkalinity and pH adjustment
2. The addition of an orthophosphate- or silicate-based corrosion inhibitor at a concentration sufficient to maintain an effective residual concentration in all test samples
3. The addition of an orthophosphate-based corrosion inhibitor sufficient to maintain a residual concentration of 1 mg/L (as PO_4) in all test samples
4. The addition of an orthophosphate-based corrosion inhibitor sufficient to maintain a residual concentration of 3 mg/L (as PO_4) in all test samples

While corrosion control studies are triggered by exceedance of the AL and TL, they can also be required by the primacy agency. Timelines for completion depend on system size and whether corrosion control treatment is in place.

WRF Research on Lead and Copper

WRF HAS SEVERAL ONGOING research projects related to lead and copper management. *Evaluating Key Factors That Affect the Accumulation and Release of Lead from Galvanized Pipes* (4910) will provide resources for evaluating links between galvanized iron pipe (GIP) and lead release. Figure 1 details seven scenarios of GIP corrosion related to iron, zinc, and lead leaching potential to potable water. This project will further test these preliminary leaching potential assessments and provide a final framework to better manage GIP.

Analysis of Corrosion Control Treatment for Lead and Copper Control (5032) will create guidance recommending when and how to conduct a corrosion control study (CCS) in anticipation of a treatment change, water quality change, or a requirement/desire to lower lead levels. Figure 2 shows a CCS flow diagram that could be used for an increase in oxidation reduction potential (ORP). Finalized versions of this diagram and others that focus on potential changes that impact water quality will be included in the final guidance.

Guidance for Using Pipe Loops to Inform Lead and Copper Corrosion Control Treatment Decisions (5081) will provide guidance for corrosion control pipe loop construction, operation, sampling, and data interpretation to inform pipe loop implementation for corrosion control studies. Recent changes in the LCR will require more utilities to conduct pipe loop studies to determine optimized water quality. This project will provide utilities with resources for conducting their pipe loop studies.

Development of a Community-Based Lead Risk and Mitigation Model (4965) will further the science of lead exposure risk assessment and mitigation. A risk-based computational model will be developed that predicts water and blood lead levels in order to predict lead exposure and target remediation actions. Another key component of this project is to evaluate the potential to identify the source of lead in children's blood samples (i.e., water, paint, etc.) through lead isotope analysis.

Several projects related to lead and copper corrosion have recently been completed. *Evaluation of Flushing to Reduce Lead Levels* (Cornwell et al. 2018) evaluated the impact of high-velocity flushing (HVF) on the removal of particulate lead from service lines and premise plumbing, and the subsequent impact on "at the tap" lead concentrations following full or partial LSLRs. Project results recommend conducting HVF following LSLRs to reduce lead release.

Full Lead Service Line Replacement Guidance (Brown et al. 2021) further evaluated two distinct home tap HVF techniques ("all taps at once" vs. "one tap at a time"). However, this project was focused on full LSLRs. HVF was conducted following full LSLRs at >100 homes across North America. Results indicated that both HVF techniques were successful at reducing lead at the tap following a full LSLR and should be considered as lead reduction strategies.

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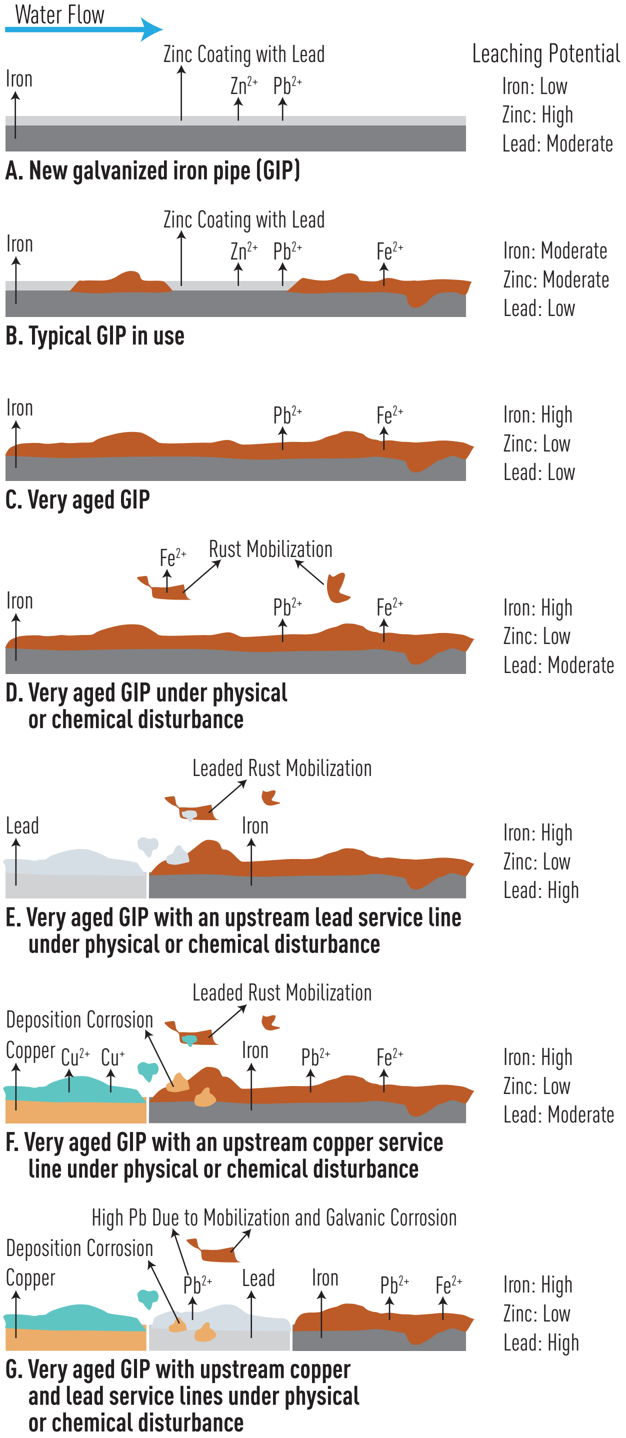

A. New galvanized iron pipe (GIP)

B. Typical GIP in use

C. Very aged GIP

D. Very aged GIP under physical or chemical disturbance

E. Very aged GIP with an upstream lead service line under physical or chemical disturbance

F. Very aged GIP with an upstream copper service line under physical or chemical disturbance

G. Very aged GIP with upstream copper and lead service lines under physical or chemical disturbance

Source: Virginia Tech 2019

Figure 1. Seven scenarios of GIP corrosion related to iron, zinc, and lead leaching potential to potable water

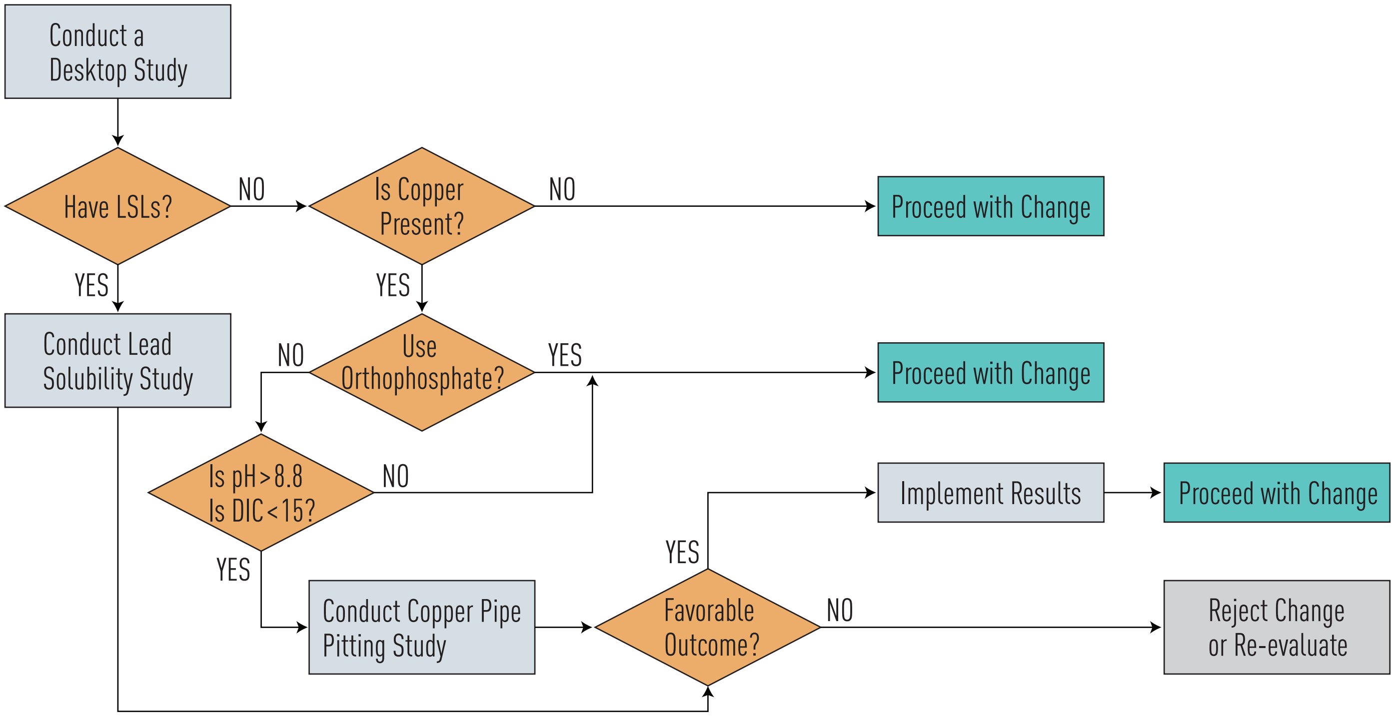

Figure 2. CCS decision diagram for an increase in ORP
(e.g., change chloramines to chlorine, or large increase in free chlorine dose)

Lead Service Line Identification Techniques (Bukhari et al. 2020) examined various prospective techniques to identify service line materials without excavation, such as metal detectors, magnetometers, ground-penetrating radar, acoustic technology, and stress wave propagation. Currently, none of these technologies have the ability to determine the service line material; however, future investment in these technologies may increase their potential.

Evaluation of Lead Pipe Detection by Electrical Resistance Measurement (Jallouli 2020) evaluated the potential for electrical resistance to determine the material composition of a service line. While initial testing showed promise, additional field testing is needed to better understand potential interferences and overcome obstacles typically encountered in the field. Figure 3 provides a schematic of the electrical resistance measurement technique. In this example, the electrical resistance between the curb stop and water meter is being measured to understand if lead is present between these two points.

Evaluation of Lead Sampling Strategies (Cornwell and Brown 2015) may be useful for addressing the sampling changes included in the LCR. This project conducted a side-by-side comparison of different water sampling strategies to determine the lead levels in the home. The different sampling methods and associated lead results could be useful for better understanding potential sources of lead and mitigation strategies.

Other Water Sector Resources

THE LEAD SERVICE LINE Replacement Collaborative is a joint effort of 27 U.S. organizations that provides resources to help accelerate full removal of lead pipes. The Collaborative's website (LSLRC, n.d.) provides resources related to LSL inventories, LSLR, and more. The Association of State Drinking Water Administrators recently released two reports related to LSLs: *Developing Lead Service Line Inventories* and *Principles of Data Science for Lead Service Line Inventories and Replacement Programs* (ASDWA, n.d.). The American Water Works Association also has a wealth of information that can assist water systems in addressing the communication, corrosion control, and lead service line replacement elements of the rule (AWWA, n.d.)

Complying with the LCR requirements will involve significant resources from utilities across the country. Utilities that prepare early will be well-positioned when compliance deadlines arrive. WRF and its partners are committed to providing resources to help the water industry address the LCR requirements.

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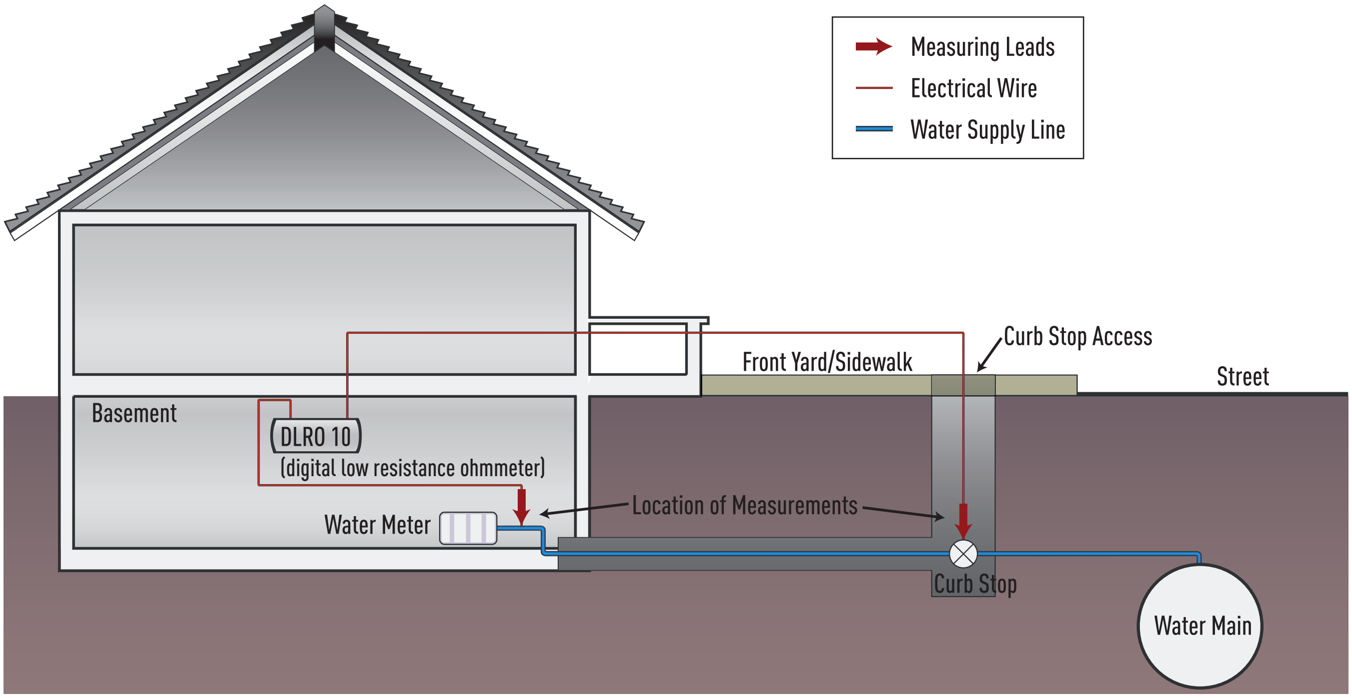

Source: Jallouli 2020

Figure 3. Schematic representation of the location of electrical resistance measurement

Estimating Sewer Methane Production

Many wastewater utilities are looking to further assess, and proactively plan for, corrosion, odor, and greenhouse gas evolution in sewer collection systems.

By John Willis, Brown and Caldwell

Conveyance Asset Prediction System (CAPS): Modeling and Mitigation (Willis et al. 2020a, b) explores the relative significance of sewer methane (CH_4) as part of the centralized wastewater treatment industry's Scope 1 greenhouse gas (GHG) emissions (direct emissions from sources controlled or owned by an entity); summarizes how the CAPS sewer CH_4 estimation methodology works; and explores factors that affect CH_4 production. Because of the emphasis many governments are placing on climate change and the desire to proactively reduce GHG emissions, local governments and utilities are strongly encouraged to develop and include their own sewer CH_4 estimates in their reporting (with opportunities for assistance discussed), or to at least be aware that sewer CH_4 likely represents the single largest vulnerability in the industry's (and an individual entity's) GHG emissions inventory.

CAPS Sewer CH_4 Estimation Methodology

THE CAPS METHODOLOGY FOR ESTIMATING SEWER CH_4 production uses a utility's collection system hydraulic model, run at average conditions, to estimate normally wetted pipe areas where biological slimes that produce CH_4 would be consistently exposed to conditions that further their growth and persistence. Model output hydraulic grades at the end of each pipe segment are compared to the pipe crown elevations. Based on those elevations, each segment (or partial segment) is classified as either "full-flowing/surcharged" or as a "gravity sewer" (with free liquid surfaces and headspace). Different equations are applied to each category, with segment CH_4 production estimates based on:

- Surcharged segments using either Equation 1 for continuous flow or Equation 2 for intermittent flow
- Gravity segments using Equation 3

$$r_{CH4\text{-}FM}=3.452\times D\times 1.06^{(T-20)} \qquad (1)$$

$$r_{CH4\text{-}FM}=3.452\times N^{(0.202)}\times D\times 0.396^{(1-N\times PT/1440)}\times 1.06^{(T-20)} \qquad (2)$$

$$r_{CH4\text{-}GS}=0.419\times 1.06^{(T-20)}\times Q^{0.26}\times D^{0.28}\times S^{-0.138} \qquad (3)$$

Where:

$r_{CH4\text{-}FM}$ = CH_4 emission rate in kg CH_4/(km*day)
D = Pipe diameter in m
T = Sewage temperature in °C
N = Number of pump cycles per day
PT = Pump time; or the duration of each pump cycle in minutes
$r_{CH4\text{-}GS}$ = CH_4 emission rate in kg CH_4/(km*day) as a function of temperature
Q = Flow in m^3/s
S = Pipe slope in m/m

Surcharged segments are estimated to produce 2 to 10 times more CH_4 than gravity segments with diameters ranging from 6 inches to 10 feet. The calculated difference in CH_4 production between categories is more extreme for larger pipe sizes, lower average flowrates, and/or greater pipe slopes.

The method ignores peak flows, which is consistent with the understanding that methanogenic slime layers do not form over the course of individual rain events and that "non-existing slime layers" would not contribute to CH_4 production. As such, CH_4 production within the modeled network is based on a static, hydraulic model output file, and only changes with sewage temperature.

All CH_4 produced is assumed to be emitted, with dissolved CH_4 in a water resource recovery facility's effluent being the only not-emitted CH_4 "sink" (based on an assumption that greater dilution in the environment only reduces the likelihood of emission). While other sinks could exist (like methanotrophic CH_4 consumption), as of the CAPS project, none had been shown to significantly reduce CH_4 concentrations or emissions, and the method accordingly assumes that produced CH_4 is emitted to the atmosphere during aeration-intensive sewage treatment.

With regard to odor-mitigating (and potentially CH_4-mitigating) chemical addition, CAPS full-scale monitoring found that summer CH_4 emissions were only barely reduced by iron-salt addition. Odor control techniques (such as caustic or nitric acid shock application) that partially or completely eliminate sewer slime layers could dramatically reduce CH_4 production. It is uncertain how effective pH-elevating or oxygenating odor control technologies are, although both are expected to exert CH_4-production-mitigating pressures.

One potential CH_4-reducing solution would involve changing collection system operation to reduce or eliminate surcharged gravity segment lengths (i.e., run downstream pumps more often/faster so that surface levels in previously surcharged segments are dropped below the pipe crown). While not broadly available in all collection systems, there are locations that might employ such pump-control solutions (e.g., like Florida, where many pumping stations "modestly relift" sewage every few miles). Running gravity sewers at lower hydraulic grades could reduce CH_4 production in affected sections by 50–90%.

Utilities in colder climates should not assume that sewer CH_4 would be irrelevant at their lower sewage temperatures, with respect to temperature effects on CH_4 production. Table 1 summarizes the modeled 10th percentile temperature parsing, with one year of measured water temperatures at DC Water's Blue Plains Advanced Wastewater Treatment Plant (AWTP), sorted in increasing order and divided into ten 36.5-day groupings with average temperatures for each 10th of the year shown. Table 1 demonstrates that, while colder sewage temperatures reduce sewer CH_4 production, they do not eliminate it. CH_4 production at 11.1°C is decreased by only half of the production at 22.6°C.

Updated Significance of Sewer CH_4

MEMBERS OF THE CAPS RESEARCH TEAM WORKED closely with researcher Kartik Chandran of Columbia University to advance the understanding of the significance of sewer CH_4 to the United States' GHGs. Specifically, a WEFTEC 2020 paper (Willis et al. 2020c) expanded upon Willis et al. (2020b) to better estimate the significance of process and effluent nitrous oxide (N_2O).

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Table 1. CAPS-methodology-estimated sewer CH_4 production rates for DC Water's collection system and 2014 sewage temperatures at 306.5 mgd average flow

10th Percentile Average Sewage Temperature (°C)	CAPS-Method-Estimated Annual Sewer CH_4 Production (metric tons of carbon-dioxide-equivalent/year)	Estimated Sewer CH_4 Production per Unit Sewage Collected (kg-CH_4/Mgal)
11.1	8,780	2.8
12.2	9,370	3.0
13.2	9,970	3.2
14.4	10,690	3.4
15.7	11,560	3.7
17.7	13,020	4.2
19.6	14,580	4.7
21.1	15,910	5.1
21.9	16,710	5.3
22.6	17,350	5.5

CAPS-reported industry-wide emissions estimates were based on GHG emissions data from Blue Plains AWTP. CAPS N_2O emissions are accordingly under-represented based on the AWTP's lowest-measured process N_2O emissions and low effluent-nitrogen discharge N_2O emissions. These accounted for only 2.1% and 7.2% of Scope-1 GHG emissions, respectively, during operation with biological nitrogen removal without digestion. Once the AWTP upgraded operation to enhanced nitrogen removal with anaerobic digestion, process and effluent N_2O represented only 1.9% and 4.5%, respectively. The updated industry-wide GHG emissions by Scope-1 emission type are presented in Figure 1 as percentages of total centralized treatment Scope-1 GHG emissions.

This updated accounting increases the estimated industry-wide Scope-1 GHG emissions from 1.9 million metric tons of carbon-dioxide-equivalent GHG per year (M-MT-CO_2e/yr) to just over 2.3 M-MT-CO_2e/yr, with the increase entirely attributable to N_2O source increases. The increase in combined N_2O emissions significance (from between 6.4% and 9.3% to 30.8%) correspondingly reduces the relative significance of sewer CH_4 and methanol carbon dioxide from 55.5% and 11.8%, respectively, to 45.3% and 9.6%. Sewer CH_4 continues to be the most significant GHG, and represents 50% more GHG emissions than process and effluent N_2O combined.

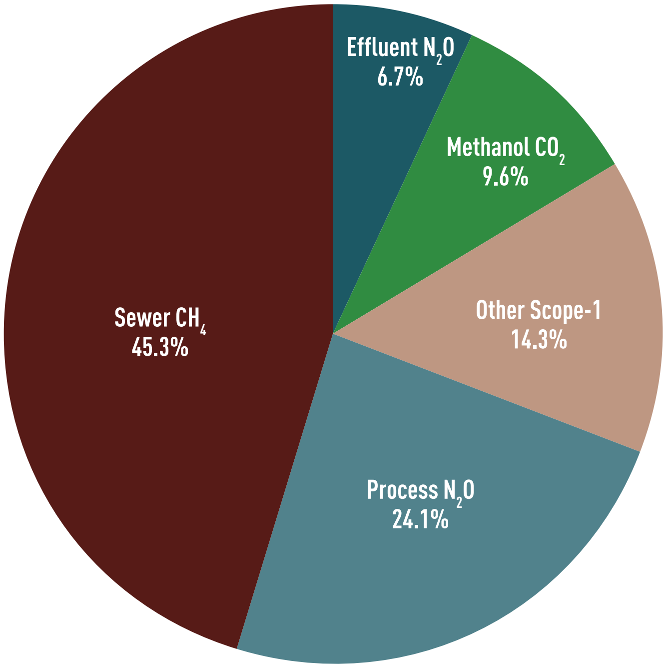

Figure 1. Updated percentages of centralized sewage treatment emissions by GHG source

Next Steps

ONLY A LIMITED NUMBER OF LARGE UTILITIES HAVE used the CAPS methodology to estimate their sewer CH_4 emissions. The research team may be able to assist agencies in developing their own estimates of local CH_4 production. The researchers are also compiling sewer CH_4 estimates, along with various operational, size, sewage temperature, and other system characterization data into a multi-collection-system database. Once the database contains enough systems with a statistically adequate diversity of size, climate, and configuration, those data would be used to develop a lower-tier, greatly simplified methodology that could be applied by any entity using readily available data. As an example, it is envisioned that a community could estimate its sewer CH_4 carbon footprint with as little information as the population served, average collection system sewage temperature, and the ratio of the collection system's lengths of surcharged pipes and force mains to free-flowing gravity sewer lengths.

This research demonstrates that sewer CH_4 is a significant Scope-1 GHG emission source for wastewater utilities, and refutes the common GHG accounting protocol assumption that no methane is generated from sewers in the developed world. By better understanding their emissions sources and their relative significance, utilities can better prepare for possible future GHG regulations.

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Membrane Bioreactors for Potable Reuse

Membrane bioreactors are increasingly being used as part of the potable reuse treatment train, and ongoing research is exploring their effectiveness at pathogen removal.

By Amos Branch, Nicola Fontaine, Stephanie Riley, Andrew Gilmore, Eva Steinle-Darling, and Andrew Salveson, Carollo Engineers, Inc.; Jim Chiasson, City of Rio Rancho Utilities Department; and Erin Partlan, The Water Research Foundation

Membrane bioreactors (MBRs) combine the processes of activated sludge treatment and suspended solids separation, fulfilling in one hybrid process the same functions as conventional activated sludge (CAS), secondary sedimentation, and tertiary filtration unit processes. Membranes inserted into activated sludge tanks retain suspended solids to efficiently achieve biological nutrient removal while treated water passes through (Figure 1). The typical advantages of an MBR, relative to CAS, are a lower footprint when treating the same nutrient load and a consistently high treated water quality that can be independent of flow within the design range.

MBR plants with capacities >10 million gallons per day (mgd) were once considered large; however, since 2016, facilities with capacities >40 mgd have been designed and installed. In the United States (U.S.), the largest operating MBR facility (Canton, OH) delivers approximately 40 mgd of annual average daily flow (AADF). Future facilities in various stages of development, including one in California, anticipate treated water delivery >200 mgd.

Connecting Wastewater and Water Reuse

MANY MBR FACILITIES ARE BEING IMPLEMENTED AS PART OF POTABLE reuse treatment trains. Because MBRs produce high-quality effluent (e.g., low nutrients, low total organic carbon [TOC], low pathogens), they can be used prior to both reverse osmosis (RO) and non-RO potable reuse schemes.

Pathogens are the primary hazards in potable reuse due to the potential for severe and acute health impacts from exposure to very low concentrations. In California, the log reduction value (LRV) (Equation 1) requirements of a treatment train for indirect potable reuse via groundwater injection are 12 for viruses and 10 for *Giardia* and *Cryptosporidium*, where an LRV of 10 equals 99.99999999% removal (CCR 2018).

$$\mathrm{LRV} = \log_{10} \frac{\textit{Concentration of Pathogen in Untreated Water}}{\textit{Concentration of Pathogen in Treated Water}} \qquad (1)$$

continued next page

The membranes used in MBRs typically have pore sizes of 0.04–0.4 µm in diameter. Protozoan pathogens are typically larger than the pore size and therefore removed by size exclusion, provided the membrane barrier is intact. Viruses of concern are typically on the smaller range (0.025–0.2 µm) of the MBR pore size, and may not be completely removed by the membrane. However, there are additional pathogen removal mechanisms within MBRs, including entrainment within, and rejection by, the dynamic membrane fouling layer; adsorption to activated sludge flocs; and biological predation (Hai et al. 2014). With these mechanisms functioning nominally, it is not uncommon to measure protozoa and virus LRVs of >6 and >5, respectively (WHO 2017).

DPR Regulation Development in CA

WRF recently completed direct potable reuse (DPR) research funded by a $1.4 million grant from the California State Water Resources Control Board (SWB) and additional funds from Metropolitan Water District of Southern California. This research will aid the SWB in the development of uniform water recycling criteria for DPR. This research can also be used by regulators, utilities, and stakeholders beyond California who are considering or implementing potable reuse.

The tools and findings from this work will enable the water sector to better address potential public health risks associated with microbial and chemical constituents of concern. Pathogen topics covered include developing additional information on pathogen concentrations in raw wastewater and the use of quantitative microbial risk assessment (QMRA) to understand microbial risk and how treatment can control risks. Chemical topics include enhanced source control, evaluation of strategies to define and control chemical contaminant peaks, and evaluation of non-targeted analysis for identifying unknown contaminants or those more likely to pass through advanced treatment.

The projects supported through the grant are:

- Tools to Evaluate Quantitative Microbial Risk and Plant Performance/Reliability (4951)
- Pathogen Monitoring in Untreated Wastewater (4989)
- Feasibility of Collecting Pathogens in Wastewater During Outbreaks (4990)
- Defining Potential Chemical Peaks and Management Options (4991)
- Evaluating Analytical Methods for Detecting Unknown Chemicals in Recycled Water (4992)

The SWB will convene an independent expert panel to review proposed DPR criteria in the second quarter of 2021. SWB's website (SWB 2020) provides information on the framework for regulating DPR and the development of DPR criteria.

WRF received an additional $3.1 million grant from the SWB to advance potable and non-potable reuse. The projects under this grant will help California and the entire water sector address technical and operational reuse challenges.

Case Studies

THE KEY INDUSTRY QUESTIONS when considering MBRs ahead of potable reuse are (1) what level of pathogen removal can be relied upon, and (2) are there any challenges associated with broken fibers and other water quality impacts to the downstream advanced treatment processes? These questions are being examined as part of *Impact of Wastewater Treatment Performance on Advanced Water Treatment Processes and Finished Water Quality* (4833), which is evaluating data from an anonymous demonstration site testing MBR ahead of RO, and from the Rio Rancho Pure facility at the City of Rio Rancho, NM, as an example of an MBR ahead of ozone and biofiltration. The flow streams for these two plants are shown in Figure 2.

MBR, RO, and UV/AOP

THE PROCESS AT THE demonstration site includes MBR, RO, and ultraviolet advanced oxidation process (UV/AOP) systems. The test plan examines MBR pathogen removal for two membrane suppliers, classifies the residual stream toxicity with implications for future scale-up, evaluates final effluent quality, and explores opportunities for public outreach. When operated in a tertiary treatment mode (i.e., post-high-purity oxygen activated sludge treatment, non-disinfected and non-nitrified), the MBR is used to nitrify, remove pathogens, and provide high-quality effluent for downstream RO treatment.

Typically, microfiltration and ultrafiltration systems (with minimal broken

Figure 1. Membranes submerged in the activated sludge of an MBR

fibers) are used to reduce organics and solids to downstream RO. MBR systems are subject to a harsh environment within the activated sludge process and, as a result, may have broken fibers. The concern specific to MBR systems upstream of RO is if, and to what extent, broken fibers result in more passage of TOC and/or particulate matter that may increase RO membrane fouling. The performance of RO downstream of MBR treatment is under investigation at the demonstration plant.

Rio Rancho Pure

IN 2015, THE CITY OF Rio Rancho built a novel advanced water purification facility to provide additional groundwater recharge. The facility consists of an MBR, an ozone/hydrogen peroxide advanced oxidation process, biological activated carbon (BAC), and chlorine disinfection. The process train removes pathogens and chemicals prior to injection into a deep aquifer for future water supply. As part of project 4833 and additional efforts, Rio Rancho is working to optimize the ozone/BAC process and document the impact of an upstream MBR.

Tiered Validation

ALTHOUGH MBRS CAN ACHIEVE high LRVs, issues such as the potential for fiber breakage make consistent pathogen removal performance uncertain. It is critical in water reuse to ensure that treatment processes consistently reduce pathogens. Consequently, credited LRVs are typically lower to provide a safety margin. Pathogen removal and the determination of pathogen log reduction credits by MBRs have been studied in Australia through the WaterVal program (WaterSecure 2017). WaterVal established a three-tiered program, and Salveson et al. (2021) re-examined and developed Tier 1 and Tier 2 concepts for MBRs in potable reuse applications in the U.S. The Tier 3 effort within the U.S. is currently under investigation as part of *Evaluation of Tier 3 Validation Protocol for Membrane Bioreactors to Achieve Higher Pathogen Credit for Potable Reuse* (4959).

The tiers are similar for both the Australian and U.S. efforts. Tier 1

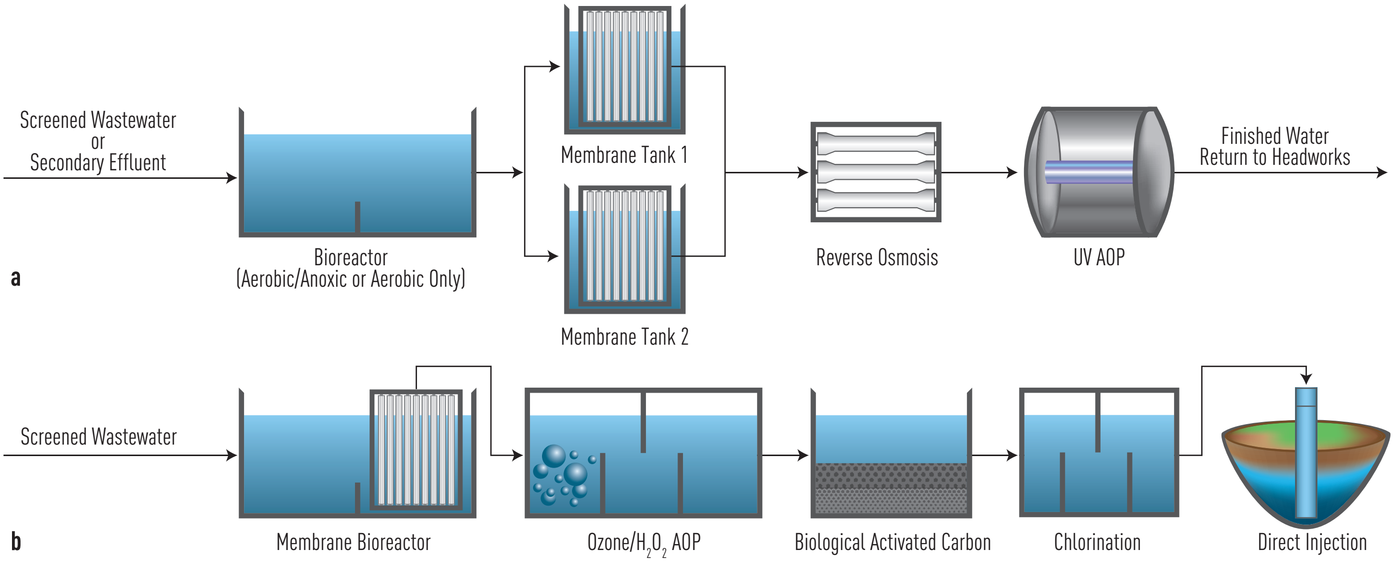

Figure 2. (a) MBR, RO, and UV/AOP demonstration plant, and (b) the MBR-based aquifer recharge scheme at Rio Rancho Pure

> Ongoing work suggests that virus LRV will be >2.0 and protozoa LRV will be >3.5

recommends conservative LRVs for protozoa, bacteria, and viruses based on a large operating data set. Tier 1 does not require demonstration of an LRV through challenge testing. Instead, operational criteria are stipulated under which the conservative LRV is valid.

Under Tier 2, MBRs undergo product- and site-specific challenge testing to demonstrate an ability to reliably achieve higher LRVs than proposed for Tier 1. The challenge testing recommends *Cryptosporidium* as the target protozoa and culturable enteroviruses as the target viruses. Salveson et al. (2021) recommends sampling during (1) precommissioning, to validate a particular membrane product; (2) commissioning, to set specific baseline LRVs at full scale and confirm surrogate limits; and (3) ongoing operation to continually confirm performance.

Tier 3 aims to provide continuous verification of pathogen removal through the correlation of LRV to monitoring techniques. Tier 3 has not yet been demonstrated; however, several studies are evaluating the feasibility of this approach.

Outlook

WORK ACROSS THE WATER SECTOR demonstrates that:

1. MBRs provide robust pathogen removal, resulting in low-pathogen-concentration feed water for subsequent purification.
2. RO performance downstream of MBRs typically exhibits no significant impact treating MBR filtrate, maintaining performance and permeability.
3. MBR filtrate provides high-quality feed water for subsequent ozone/BAC treatment, providing a low TOC effluent that allows more efficient use of ozone.

There are many efforts to better understand the performance of MBRs and support their efficient and safe application as part of potable reuse treatment trains. Ongoing work in pathogen removal validation suggests that virus LRV will be >2.0 and protozoa LRV will be >3.5 (Fontaine and Morris 2020). Even when large sample volumes of filtrate are analyzed, pathogens are often not detected after MBR treatment. The future implementation of large MBR facilities depends on ongoing research to solve design and water quality challenges, but will in turn provide operational data for further understanding of MBR performance.

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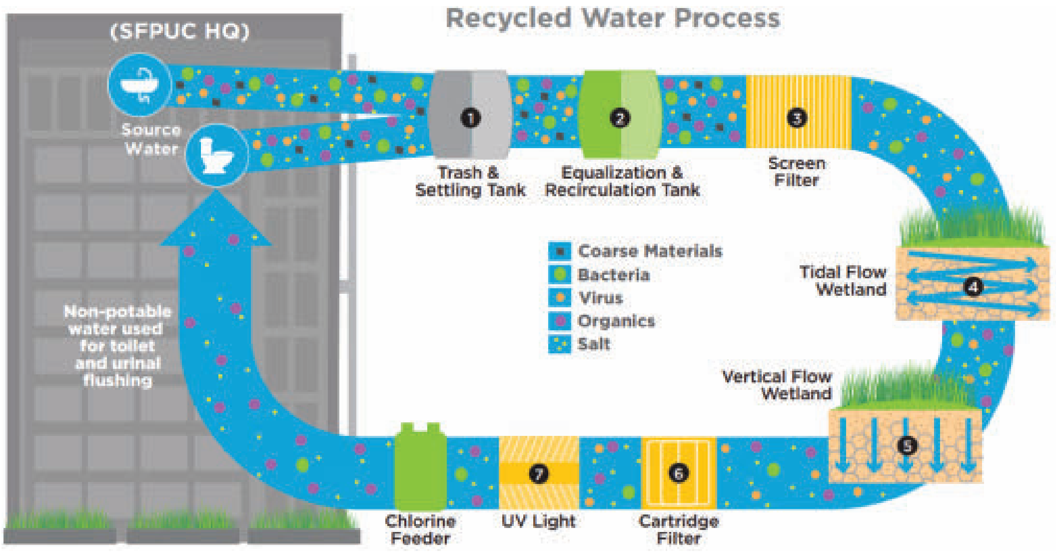
Potable Reuse Demonstration (4691)

Potable water reuse projects have been successfully implemented around the world, though most are centralized projects that source wastewater from an entire city or region. There are limited examples of small-scale, decentralized potable reuse systems, though the potential benefits and added flexibility of small-scale reuse systems are substantial. *PureWaterSF: Building-Scale Potable Water Reuse Demonstration Project* showed that building-scale wastewater can be successfully treated to potable water reuse standards. This project also addressed the challenges associated with operating and maintaining small and decentralized purification systems, performance impacts and challenges due to the strength and variability of wastewater collected from a small "sewershed," and the ability of existing online monitoring systems to accurately track a multitude of constituents in real time.



Living machine process diagram

Modeling Pump Station Vulnerability (4709)

Earthquake damage to water supply systems has profound impacts on safety and the economy that are out of proportion to pipeline repair costs. CUWNet is a model of water supply pipeline damage and restoration that can increase understanding of earthquake impacts by accounting for (1) human factors such as how repairs are slowed by electricity, mutual aid, and repair-supply limitations; (2) damage and restoration over time, considering the mainshock, aftershocks, and afterslip; and (3) service restoration as a function of completed repairs. *Seismic Fragility and Restoration of Pump Stations for Potable Water Supply* expanded CUWNet by including additional equations along with the required parameter values to add pump stations to the model. This enhancement balances simplicity with computational power: simplicity in the sense that the necessary pump station data can be easily and quickly collected, and power in the sense that the model reasonably distinguishes salient seismic features that make the pump station building and equipment more or less vulnerable to earthquakes. Taken together, these enhancements to CUWNet allow analysts to better assess the value of remediation measures as they might reduce the fragility and repair duration of the pump station.

Stormwater Best Management Practices (4968)

The International Stormwater Best Management Practices (BMP) Database is a publicly accessible repository for BMP performance data, including monitoring, design, and cost information, that provides scientifically sound information to improve the design, selection, and performance of BMPs. *International Stormwater BMP Database: 2020 Summary Statistics* includes new performance studies, along with new analysis categories for manufactured treatment devices used in stormwater management. Data summaries include basic summary statistics for BMP influent and effluent concentrations, graphical summaries of statistics, and hypothesis test results for assessing whether the BMP had an effect on influent concentrations for various pollutant-BMP combinations. Information about typical pollutant sources, dominant pollutant removal mechanisms in BMPs, and design considerations is provided. Stormwater BMPs included in the analysis include grass strips, bioswales, extended detention basins, media filters, porous pavement, retention ponds, wetland basins, manufactured treatment devices, and more. This database update will continue to support decision making for integrated stormwater management.

Constituents analyzed by pollutant category

Solids	Bacteria	Nutrients	Metals
Total suspended solids Total dissolved solids	Fecal coliform *Escherichia coli* Enterococcus	Total phosphorus Orthophosphate Dissolved phosphorus Total nitrogen Total Kjeldahl nitrogen Nitrate and nitrate plus nitrite Ammonia as N	Arsenic (total and dissolved) Cadmium (total and dissolved) Chromium (total and dissolved) Copper (total and dissolved) Iron (total and dissolved) Lead (total and dissolved) Nickel (total and dissolved) Zinc (total and dissolved)

Golf Course Best Management Practices (4746)

Golf courses use fertilizers, pesticides, and other landscape management techniques that can lead to impaired surface water and groundwater quality. Audubon International's Audubon Cooperative Sanctuary Program (ACSP) for Golf Courses can help to address these issues. As part of the ACSP, participating golf courses collect both qualitative and quantitative data about their water systems. *Analysis of Water and Landscape Best Management Practice Impacts on Water Quality on Golf Courses* is the first attempt to organize and analyze this complex and mixed-format dataset associated with U.S. golf courses. The specific research objectives were to manually extract meaningful and consistent data from the many hundreds of data files provided, analyze the data to the greatest extent possible, and make recommendations about ways to improve future ACSP data collection.

New Synthesis Reports on Key Water Topics (4949)

Through *The Water Research Foundation and One Water: Synthesis Reports on Accomplishments in the One Water Space*, WRF has been developing synthesis reports outlining the accomplishments the organization has made in the One Water space. The synthesis reports detail how WRF's prior and current research and innovation activities support all aspects of water. The latest synthesis reports in the series include Decentralized Systems, Utility Communications, Utility Finance, and Workforce.

CALENDAR

July–September

July 20–21, 2021
NACWA 2021 Utility Leadership Virtual Event
www.nacwa.org/conferences-events/event-at-a-glance/2021/07/20/nacwa-events/2021-utility-leadership-virtual-event

July 18–21, 2021
NARUC Summer Policy Summit
www.naruc.org/meetings-and-events/naruc-summer-policy-summits/2021-summer-policy-summit/

July 19–21, 2021
AWRA 2021 Virtual Summer Conference
www.awra.org/Members/Events_and_Education/Events/2021_Summer_Conference.aspx

July 19–22, 2021
AWWA 2021 Membrane Technology Conference & Exposition
West Palm Beach, FL
www.awwa.org/Events-Education/Membrane-Technology

July 27–29, 2021
Partnership for Safe Water 25th Anniversary Optimization Conference
www.ca-nv-awwa.org/canv/CNS/EventsandClasses/conf/PSW25/PSW25.aspx

August 3, 2021
AWWA/WEF Young Professionals Summit
www.awwa.org/Events-Education/Young-Professionals-Summit

August 3–6, 2021
WEF/AWWA Utility Management Conference
Atlanta, GA
www.wef.org/utilitymanagement
OR
www.awwa.org/Events-Education/Utility-Management

September 12–15, 2021
AWWA Water Infrastructure Conference
Phoenix, AZ
www.awwa.org/Events-Education/Water-Infrastructure

September 13–16, 2021
WaterJAM 2021
Virginia Beach, VA
www.vaawwa.org/Events/waterjam2021

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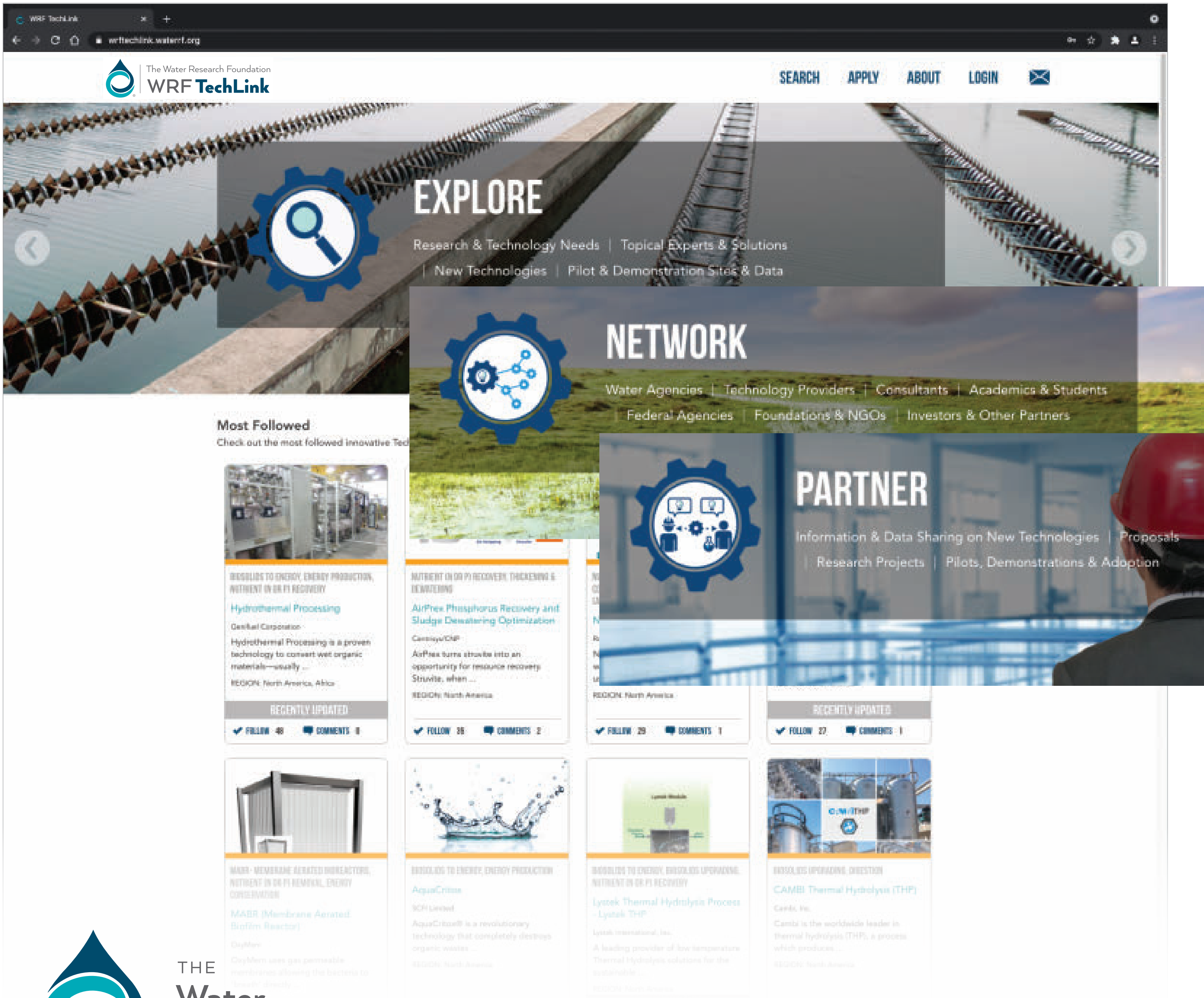

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