Right Sizing Tomorrow's Water Systems for Efficiency, Sustainability, and Public Health

FINAL REPORT

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Executive Summary

Period Covered by the Report: October 1, 2016 through March 29, 2022

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Title: Right Sizing Tomorrow's Water Systems for Efficiency, Sustainability, and Public Health

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Research Category: Water

Project Period: October 1, 2016 through March 29, 2022

Objective of Research: The project goal was to better understand and predict water quality and health risks posed by declining water usage and low flows. Our hypotheses focused on (i) testing the predictability of integrated water distribution system-plumbing models the project team developed and calibrated for residential and commercial buildings; (ii) identifying the most significant determinant(s) of water quality in these systems; and (iii) identifying water system design and operational conditions that pose increased human health risks. Project objectives were to: (1) Improve the public's understanding of decreased flow and establish a range of theoretical plumbing flow demands from the scientific literature and expert elicitation with our strategic partners; (2) Elucidate the factors and their interactions that affect water quality through fate and transport simulation models for residential and commercial buildings; and (3) Create a risk-based decision support tool to help guide decision makers through the identification of plumbing characteristics, operations and maintenance practices that minimize health risks to building inhabitants.

Summary of Findings (Outputs/Outcomes):

With strategic partnerships, collaborations, workshops, field and bench-scale testing efforts, the team developed new knowledge that provides a better understanding of building water quality and health risks posed by low flows. Through full-scale testing of a state-of-the-art, continuously monitored, residential home, eight predictive water quality plumbing models were developed and calibrated. Developed models can be scaled for other plumbing designs, operational conditions, and water distribution inputs. Simulations and scenario testing were used to predict microbial concentrations for human health risk assessment. A multi-tiered, web-based decision support system that integrated the literature review, testing, and modeling was created and made publicly available online. Chemical and microbiological behavior of commercial and institutional building water systems were examined through full- and pilot-scale testing. Some outcomes of each research objective are described below.

Objective 1: Substantial public engagement and outreach was accomplished during this study with a focus on public understanding of plumbing, water quality, and its role in protecting public health. Tens of thousands of page views were cataloged for the www.PlumbingSafety.org website setup in response to this study. Educational videos as well as lists of resources, frequently asked questions, guidance documents, and OpEds were made publicly available. Team members responded to questions from the general public that were received in person, by email and telephone. These individual questions ranged from water testing practices, plumbing material selection considerations, and troubleshooting. Notably, a public education and support effort was conducted in response to several wildfires, where homeowner plumbing received or were suspected to have received chemically contaminated drinking water. In all, more than 100 presentations were delivered by project team members across the public health, water utility, product manufacturer, and building design sectors. Results were formally shared through events held in the U.S., Canada, the United Kingdom, and also through an international water association webinar and webinars with key stakeholders in the USEPA Office of Water. Support was also provided to the American Water Works Association (AWWA) in developing a building water system guidance document in response to the COVID-19 pandemic.

Objective 2: Content within the 25 peer-reviewed scientific journal publications developed forms the foundation of this study's discoveries and products developed in Objective 3. Knowledge-gaps and resources to predict and reduce cold and hot water building plumbing health risks were identified. New health risk models and assessments were developed for *Pseudomonas aeruginosa*, *Acanthamoeba,* and *Naegleria fowleri.* Microbiological testing of cooling towers revealed new water quality-plumbing interaction discoveries. Commercial and institutional building testing revealed novel discoveries important to plumbing design, operation, in-building sampling, and exposure. Water quality in many of the buildings tested had never been previously examined. Weekend stagnation (Friday to Monday) in an office building revealed water quality building issues and minor to serious widespread microbiological and chemical contamination was found in other buildings, including at a school. Schools and childcare centers were identified as specifically needing attention in future building water quality efforts.

The overwhelming majority of the study effort was dedicated to water quality, pressure, flow, and temperature testing of a single family home located next to Purdue University's campus in West Lafayette, Indiana. Data from this home was used to develop integrative hydraulic-water quality models for residential buildings (Objective 3). Intensive water testing was conducted in the 'Most Monitored Home in America' for one year. Approximately 2.64 billion online monitoring data points were collected. More than 222,200 labor hours were conducted. Testing revealed that water quality delivered to homes is not consistent in chemical quality, and water without disinfectant residual was sometimes delivered to the home. Several bench-scale experiments were conducted to help describe water quality observations in commercial, institutional, and residential buildings. Because plastic materials are increasingly replacing metal counterparts, the interaction of water with plastic materials was investigated. Some key discoveries included: (1) Plastic plumbing pipes accumulate heavy metal and sediment scales during their service-life; (2) polyethylene pipes are chemically attacked by copper species leached from brass valves and pipes; (3) significant variability in organic carbon leaching at different temperatures, water pH, and brands was observed for plastic pipes certified for drinking water use; and (4) a variety of plastic pipes generated volatile organic compounds when exposed to high heat, and these chemicals were leached into water when they came into contact. Discovery about materials underscored an important need for future efforts to focus on understanding how plastics are influencing water quality at fixtures (i.e., organic carbon, chemical levels, disinfectant residual, microbial growth/biofilms, disinfectant byproducts).

Objective 3: A series of calibrated plumbing hydraulic-water quality models were developed for the extensively monitored single-family residential home. Results can be used to support better planning, design, analysis, and operational decision-making for building water systems design, operation, and investigations. The integrative hydraulic water quality models were developed using EPANET and EPANET-MSX. The eight models predict the level of free chlorine, total trihalomethanes (TTHM), Cu, Fe, Pb, NO_3^-, heterotrophic plate count (HPC), and *Legionella spp.* concentration at each fixture for plumbing use, operational characteristics, and design layouts. Reducing building water use in the model by 25% prompted increased concentrations of HPC and Legionella, each increasing by a factor of about 10^5. When the service line length was increased, *Legionella spp.* concentrations increased by up to 10^6 gene copies /L in the Summer season. Two decision support tools (*The Plumbing Water Quality Tool* and *QMRA Decision Support Tool*) can now be used by building designers, owners, public health officials, regulators, policymakers, utility staff, and other professionals for predicting chemical and microbiological water quality and health risks at building fixtures. These tools are publicly available online. These are the only two tools currently available and study results provide insights into future development challenges.

Publications/Presentations: More than 100

Supplemental Keywords: Residual, Hydraulic residence times, EPANET, Water demand, Plastic Pipes, Pathogens, QMRA

Relevant Websites: The following websites were created: www.PlumbingSafety.org, https://engineering.purdue.edu/PlumbingSafety, Plumbing Water Quality Tool (https://dsiweb.cse.msu.edu/waterquality/water-quality), and QMRA Decision Support Tool (https://dsiweb.cse.msu.edu/waterquality/qmra).

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1. Background and Approach

1.1 Research goal and objectives

The project goal was to better understand and predict water quality and health risks posed by declining water usage and low flows. This effort focused on (i) testing the predictability of integrated water distribution system- plumbing models the project team develops and calibrates for residential and commercial buildings; (ii) identifying the most significant determinant(s) of tap water quality in these systems; and (iii) identifying water system design and operational conditions that pose increased human health risks.

Project objectives were to:

(1) Improve the public's understanding of decreased flow and establish a range of theoretical plumbing flow demands from the scientific literature and expert elicitation with our strategic Partners;

(2) Elucidate the factors and their interactions that affect water quality through fate and transport simulation models for residential and commercial buildings; and

(3) Create a risk-based decision support tool to help guide decision makers through the identification of plumbing characteristics, operations and maintenance practices that minimize health risks to building inhabitants.

1.2 Approach

This study was a collaboration between several academic institutions, as well as the plumbing, building design and construction, and public health sectors **(Figure 1).** During the study, the team sought and received feedback from practicing architects and engineers, state drinking water primacy agency and public health agency representatives, members of the public, building owners, managers, and experts at US EPA Office of Research and Development, plumbing manufacturers, among other organizations. The purpose of this feedback was to better inform experimental design, data analysis, interpretation, and reporting. A secondary goal of this project was also to be responsive to water quality and health risks raised publicly during this study.

Figure 1. List of some partnering, supporting, and participating organizations who participated in this study

2. Summary of Findings

Objective 1. Improve the public's understanding of decreased flow and establish a range of theoretical plumbing flow demands from the scientific literature and expert elicitation with our strategic partners

Highlights

- Substantial public engagement and outreach was accomplished during this study with a focus on public understanding of plumbing, water quality, and its role in protecting public health.
- Tens of thousands of page views were cataloged for the www.PlumbingSafety.org website setup in response to this study. Educational videos as well as lists of resources, and frequently asked questions were made publicly available.
- Team members responded to questions from the general public that were received by email and telephone. These individual questions ranged from water testing practices, plumbing material selection advice, and troubleshooting.
- A public education and support effort was conducted in response to several wildfires, where homeowner plumbing systems had received or were suspected to have received contaminated drinking water.
- More than 100 presentations were delivered by project team members across the public health, water utility, product manufacturer, and building design sectors. Results were shared through events held in the U.S., Canada, the United Kingdom, and also through an international water association webinar. Support was also provided to the American Water Works Association (AWWA) in developing a building water system guidance document in response to the COVID-19 pandemic.
- A peer-reviewed literature review established a range of theoretical plumbing flow demands.

Education and engagement was a core component of this study. Team activities have resulted in study results being widely shared with the public and through various sectors. Members of the public in and outside the U.S. have learned about the study though popular press reports on newspaper, radio, tens of thousands of page loads were registered through the website (www.PlumbingSafety.org) that was catalyzed by this study. The website included tutorials about plumbing basics and links to brief videos, and links to presentations.

During the conduct of the study team members received direct questions from various building owners and inhabitants by email and telephone. In these cases, the team worked to help these individuals seek guidance from their local health departments or simply provided feedback on the information provided. Some, but not all, topics included how to test drinking water wells after sitting stagnant for greater than 1 year, how to determine what the black slime was coming out of their plumbing fixtures and coating their pipes, where to take samples if the plumbing is thought to be contaminated with lead, how can 9 mg/L of toluene of contaminated drinking water be removed from a newly plumbed residential crosslinked polyethylene (PEX) system, and where to send lead samples for drinking water analysis. Other questions related to the health risks analyses included which fixture types are associated with the safest drinking water quality.

Direct engagement was conducted in response to several wildfires where residential and commercial buildings either received chemically contaminated drinking water from an affected utility or the plumbing was thought to be contaminated due to the fire's proximity. After the 2018 Camp Fire disaster, team members supported community recovery by designing and conducting a hands-on public education event in partnership with multiple institutions and a local community-based group. A local community group penned a summary of the event (Jenks 2019) and a peer-reviewed journal publication by Odimayomi et al. (2021) described the results, so the event could be replicated by others. This training was in response to the mental health and infrastructure damage challenges. In short, the 2018 Camp Fire in Butte County, California, was the state's most destructive wildfire in history, destroying more than 14,600 homes. The wildfire caused widespread drinking water system chemical contamination resulting in acute and chronic health risks, requiring water use restrictions. Six months after the fire, the community were still receiving chemically contaminated water to their homes and businesses. Amid the disaster response, 54% of the author's survey respondents self-reported that at least one member in their household had anxiety, stress, or depression directly related to the water contamination issues. Uncertainty about water and plumbing safety prompted respondents to alter water use in the home (83%), install in-home water treatment technologies (47%), and/or seek alternate water sources (85%). To provide affected households with answers to plumbing testing and safety questions, the research team designed and conducted a community education event June 27, 2019 at the Paradise Alliance Church in Paradise, California. Many community members had technical questions about how to conduct water testing to determine whether their plumbing was safe. The research team identified several significant public health information gaps and a need for clear recommendations.

Public health and technology pieces were also published in trade magazines and presentations from this project in part or in full were presented at the following events one or more times:

1. American Chemical Society (ACS) Spring and Fall Meetings
2. American Council for an Energy-Efficient Economy (ACEEE) Hot Water Forum
3. American Water Works Association (AWWA) Annual Conference and Exposition
4. American Water Works Association (AWWA) Virtual Summit
5. American Water Works Association (AWWA) Florida Section Webinar
6. American Water Works Association (AWWA) Kentucky-Tennessee Section Webinar
7. American Water Works Association (AWWA) Distribution Systems Subcommittee 'Beyond the Meter' Meeting
8. American Society of Civil Engineers (ASCE) Environmental Water Resources Institute (EWRI) Congress
9. American Society of Civil Engineers (ASCE) EWRI Premise Plumbing Modeling Webinar
10. American Society of Plumbing Engineers (ASPE) Webinar

11. Association of Environmental Engineering and Science Professors AEESP Research and Education Conference
12. Association of State and Territorial Health Officials (ASTHO) Annual Meeting
13. Camp Fire Response and Recovery Support Event in Paradise, California
14. Christopher Burke Engineering, Ltd. Webinar
15. Community Forum on Wildfires and Health in Eugene, Oregon
16. Environmental Operators Certification Program Annual Meeting
17. Institute for Journalism and Natural Resources Workshop
18. India-Canada Centre for Innovative Multidisciplinary Partnerships to Accelerate Community Transformation and Sustainability (IMPACTS) Water and Environment Student Talks (WESTalks)
19. Indiana Facilities Management Association Webinar
20. Indiana Rural Water Association Water Institute Annual Meeting
21. Indiana State Department of Health Webinar: Building Water Safety for Schools
22. Indiana Water Environment Association Annual Conference
23. International Association of Plumbing and Mechanical Officials Emerging Water Technology Symposium
24. International Water Association (IWA) Webinar
25. IWA 20th International Symposium on Health-Related Water Microbiology. Vienna, Austria.
26. National Environmental Health Association (NEHA) Private Water Network Meeting
27. National Environmental Health Association (NEHA) Annual Exposition and Conference
28. Society of Risk Analysis (SRA) Annual Meeting
29. PHCPPros COVID and Building Water System Webinar
30. Plumbing Industry Leadership Coalition Annual Meeting
31. Plumbing Manufacturers International Annual Meeting
32. Purdue University’s Building Water SLAM Event
33. Royal Society of Public Health Webinar
34. US EPA Annual Drinking Water Workshop
35. US EPA Source Water Leadership Forum
36. US Green Building Council Greebuild Conference
37. US National Academies of Science, Engineering, and Medicine (NASEM) Water Science and Technology Board Meeting
38. US National Academies of Science, Engineering, and Medicine (NASEM) Workshop, Implications of the California Wildfires for Health, Communities, and Preparedness

39. Water Quality Association (WQA) Annual Meeting
40. Water Research Foundation (WaterRF) Webinar
41. Watersmart Innovations Conference & Exposition
42. University of Alaska FIREWALL Workshop
43. University of California Riverside Public Policy Seminar
44. University of New Mexico Distinguished Lecture Series
45. UNC (University of North Carolina at Chapel Hill) Water Microbiology Conference

In response to the COVID-19 pandemic, team members were asked to contribute to a best practice guide for building managers. Part of their effort included sharing insights from the present study with co-developers in an effort to produce this guidance document:

Responding to Water Stagnation in Buildings with Reduced or No Water Use: A Framework for Building Managers. Published by: American Water Works Association (AWWA), Denver, CO. 2020.

Objective 2. Elucidate the factors and their interactions that affect water quality through fate and transport simulation models for residential and commercial buildings

Highlights

- 25 peer-reviewed scientific journal publications were developed and their content forms the foundation of this study's discoveries and products developed in Objective 3.

- Knowledge-gaps and resources to predict and reduce cold and hot water building plumbing health risks were identified. New health risk models and assessments were developed for *Pseudomonas aeruginosa, Acanthamoeba,* and *Naegleria fowleri.* Microbiological testing of cooling towers revealed new discoveries.

- Commercial and institutional building testing revealed discoveries important to plumbing design, operation, in-building sampling, and exposure. Water quality in many buildings tested had never been examined. Weekend stagnation (Friday to Monday) prompted water quality issues and minor to serious widespread microbiological and chemical contamination was found in some buildings. Schools and childcare centers were identified as specifically needing attention in future work.

- An overwhelming majority of the study effort was dedicated to water quality, pressure, flow, and temperature testing of a single family home located next to Purdue University's campus. Data from this home was used to develop integrative hydraulic-water quality models for residential buildings and decision support tools (Objective 3). Intensive water testing was conducted in the Most Monitored Home in America for one year. Approximately 2.64 billion online monitoring data points were collected. More than 222,200 labor hours were conducted. Testing revealed that water quality delivered to homes is not consistent in chemical quality, and water without disinfectant residual was sometimes delivered to the home.

- Several bench-scale experiments were conducted to help describe water quality observations in commercial, institutional, and residential buildings. Because plastic materials are increasingly replacing metal counterparts, the interaction of water with plastic materials was investigated. Key discoveries included: (1) Plastic plumbing pipes accumulate heavy metal and sediment scales, (2) Polyethylene pipes are chemically attacked by copper species leached from brass valves and pipes, (3) For certified products massive variability in organic carbon leaching at different temperatures, water pH, and brands was observed, (4) A variety of plastic pipes generate volatile organic compounds with drinking water limits when exposed to high heat. Results underscored an urgent need to understand how plastics are influencing water quality at fixtures (i.e., organic carbon, chemical levels, microbial growth/biofilms).

Bench-, pilot- and field-scale studies were conducted involving residential and commercial buildings in response to this objective. Efforts were directed at understanding what water quality conditions existed at fixtures and then why. While decades of research have been conducted on this topic, this study focused on gaps identified through proposal development and with participating organizations during the present study. **Table 1** lists the published studies. Several of the cross-study topics will be highlighted below.

2.1 Knowledge-gaps, risks, and resources identified

An important task in the overall project was to identify knowledge gaps associated with plumbing safety (chemical and microbiological exposures). Julien et al. (2020) explored the current state of the science on plumbing safety through a literature review and stakeholder workshop with representatives from the public and private sectors. Study results revealed that links between water usage, design, and material selection and water quality must be established with data-driven methods to support risk assessment and risk management decisions. Of particular interest was a better understanding of the contribution of water usage and piping materials to the proliferation of opportunistic pathogens especially *Legionella* which was quantified in this study. Because of the significance of this study, the abstract and link is posted below:

> *Sustainability, water conservation, water efficiency, and green infrastructure have led to significant decreases in the quantity of water used in buildings. In addition, changes in water usage, building design, plumbing material selection, and high-efficiency fixtures contribute to water age and potential chemical and microbiological contamination. Through a literature review and stakeholder workshop with representatives from the public and private sectors, this article explores the current state of the science on plumbing safety. Results indicate that links between water usage, design, and material selection and water quality must be established with data-driven methods to support risk assessment and risk management decisions. Of particular interest is a better understanding of the contribution of water usage and piping materials to the proliferation of opportunistic pathogens. This article will help further efforts to evaluate these pathogenic risks, a critical need as drinking water regulations have primarily focused on exposure through ingestion. – Water Science, 2020*

Near the end of the overall study the COVID-19 pandemic occurred. In response to health concerns by building owners, managers, inhabitants, and health officials where concern was on the health risk of exposure to stagnation water, another literature review was conducted. This study was partially funded by the present US EPA National Priorities study. This 2021 literature review examined considerations for large building water quality after extended stagnation (Proctor et al. 2021). Here, a primer of large building water system preventative and remedial strategies, peer-reviewed, government, industry, and nonprofit literature relevant to water stagnation and decontamination practices for plumbing was synthesized. Preventative practices to help avoid the need for recommissioning (e.g., routine flushing) and specific actions, challenges, and limitations associated with recommissioning were identified and characterized. Considerations for worker and occupant safety were also indicated.

2.2 New health risk models and assessments for *Pseudomonas aeruginosa* and *Naegleria fowleri*

Several health risk models and assessments were completed to assist officials interpret water testing results for *Pseudomonas aeruginosa, Acanthamoeba,* and *Naegleria fowleri. Pseudomonas aeruginosa* is an opportunistic pathogen that can grow and proliferate in biofilms in plumbing systems and is capable of causing infections through the ocular, inhalation, and dermal routes of exposure. When the pathogen colonizes showerheads and faucets, there is risk of exposure to contaminated water through the ocular route during hand and face-washing events and the inhalation route during showering events. *P. aeruginosa* can cause an infection of the lungs, a more severe risk for immunocompromised individuals, and is one of the main causes of bacterial keratitis. A reverse quantitative microbial risk assessment (QMRA) was completed to determine the threshold concentrations of *P. aeruginosa* associated with the US Environmental Protection Agency's maximum acceptable health risk guideline for waterborne pathogens of 1 infection in 10,000 persons per year (Dean and Mitchell 2020). The ocular exposure route poses a more significant risk of infection to the average user at the tap, as indicated by the median threshold concentrations of 6.04×10^{11}, 0.92, and 37 colony forming units (CFU) per liter for the showering, face-washing, and handwashing events, respectively. The reverse QMRA methodology followed in this analysis provides distributions of concentrations of concern that will aid decision makers in prioritizing mitigation strategies and monitoring plans for plumbing systems.

A follow-up study developed a dose response model for *Pseudomonas aeruginosa* for the inhalation route of exposure using pre-existing data (Dean and Mitchell 2020). A dose response model for this route of exposure is needed to assess risks posed by the inhalation of aerosols from showers, humidifiers, or hot tubs contaminated with *P. aeruginosa*. Single-hit theory models traditionally used for dose response modeling did not provide significant fits to the limited available data. The multi-hit dose response model operates under the cooperativity theory and did provide a significant fit, suggesting that a single *P. aeruginosa* bacterium is not sufficient to initiate a pulmonary infection in an immunocompetent host. A hierarchical Bayesian analysis was used to benchmark this model against additional dose response experiments and results further suggested that the multi-hit model may better represent the dose response behavior for this exposure route. The best fitting model has an LD_{50} of 2,588,047 Colony Forming Units. This model can be used to quantify risk in inhalation exposure scenarios, however, due to the limited amount of primary data, it is especially important for any future risk assessment to analyze the impact that using different dose response models may have on the final risk estimates and recommended control measures.

A separate study developed novel dose–response models for *Naegleria fowleri* from selected peer-reviewed experiments on the virulence based on the intranasal exposure pathway (Dean et al. 2019). One data set measured the response of mice intranasally inoculated with the amebae and the other study addressed the response of mice swimming in *N. fowleri* infected water. The measured response for both studies was death. All experimental data were best fit by the beta-Poisson dose–response model. The three swimming experiments could be pooled, and this is the final recommended model with an LD_{50} of 13,257 amebae. The results of this study provide a better estimate of the probability of the risk to *N. fowleri* exposure than the previous models developed based on an intravenous exposure. An accurate dose–response model is the first step in quantifying the risk of free-living amebae like *N. fowleri*, which pose risks in recreational environments and have been detected in drinking water and plumbing systems. A better understanding of this risk will allow for risk management that limits the ability for pathogen growth, proliferation, and exposure.

The focus on eye infections caused by contaminated water use prompted a study to developed dose response models for determining the probability of eye or central nervous system infections from previously conducted studies using different strains of *Acanthamoeba spp.* (Dean et al. 2021). The data were a result of animal experiments using mice and rats exposed corneally and intranasally to the pathogens. The corneal inoculations of *Acanthamoeba* isolate Ac 118 included varied amounts of *Corynebacterium xerosis* and were best fit by the exponential model. Virulence increased with higher levels of *C. xerosis.* The *Acanthamoeba culbertsoni* intranasal study with death as an endpoint of response was best fit by the beta-Poisson model. The HN-3 strain of *A. castellanii* was studied with an intranasal exposure and three different endpoints of response. For all three studies, the exponential model was the best fit. A model based on pooling data sets of the intranasal exposure and death endpoint resulted in an LD_{50} of 19,357 amebae. The dose response models developed in this study are an important step towards characterizing the risk associated with free-living amoeba like *Acanthamoeba* in drinking water distribution systems. Understanding the human health risk posed by free-living amoeba will allow for quantitative microbial risk assessments that support building design decisions to minimize opportunities for pathogen growth and survival.

2.3 Water testing discoveries in commercial and institutional buildings

A variety of field studies were conducted which revealed previously unknown phenomena as well as confirmed prior observations by other investigators. For example, Ra et al. (2020) found a variety of widespread chemical and microbiological drinking water problems at a 7 year old LEED certified school including copper and legionella contamination. In this Summer and Fall season study, 65% of the building water samples collected (*n* = 74 out of 114) had no detectable disinfectant residual, heterotrophic plate count ranged from 11 to 400 CFU/100 mL, and no copper action level (AL) exceedances were found; the AL is a health-based threshold. But - *inside the building* - almost 70% of first draw cold samples exceeded the AL during summer, while 37% of samples exceeded the AL after classes resumed. Total copper concentration in the building was related to the distance from the building entry point. The softener was an incubator for bacterial growth and nitrification was detected throughout the plumbing (*n* = 29 out of 29 for hot, *n* = 17 out of 22 for cold). The state's recommended spot flushing remediation strategy for reducing copper concentration was found to be ineffective. Water delivered to the building from a regulated public water system met all federal drinking water standards. As a result, water chemical and microbiological testing of the building entry point and stagnated water outlets was recommended before new schools are placed into service and during the life of new and existing buildings.

At the same time (Aw et al. 2022) conducted enhanced microbiological monitoring of the school building. This study was conducted to better understand microbial water quality changes in a LEED-certified school building during low water use (Summer) and normal water use (Autumn). The copper plumbed building contained water saving devices, a hot water recirculation system, and received chloraminated drinking water from a public water system. Three separate sampling events were conducted during the summer break inside the building and another three sampling events were conducted after the school returned to session. Using quantitative PCR, *Legionella spp.* were detected in all water samples, followed by *Mycobacterium spp.* (99%). *Mycobacterium avium* (75%) and *Acanthamoeba spp.* (17.5%) throughout the building water system. *Legionella pneumophila* and *Naegleria fowleri* were not detected in any of the samples. The mean concentrations of *Legionella spp., Mycobacterium spp., Mycobacterium avium*, and *Acanthamoeba spp.* detected in water samples were 3.9, 5.7, 4.7, and 2.8 $\log_{10}$ gene copies per 100 mL, respectively. There was a statistically significantly difference in the mean concentrations of *Legionella spp., Mycobacterium spp.* and *M. avium* gene markers in water samples between school breaks and when school was in session. Cultivable Legionella were also detected in water samples collected during periods of low water use. This study highlights the need for routine proactive water quality testing in school buildings to determine the extent of drinking water quality problems associated with plumbing and direct action to remediate microbial colonization.

Another notable study was conducted by Logan-Jackson et al. (2021) who investigated microbiological quality at institutional drinking water and cooling tower water. *Legionella pneumophila* is the species that is most often cultured from the natural environment, while disease-relevant *Legionella* species, such as *Legionella micdadei*, *Legionella bozemanii*, *Legionella anisa*, and *Legionella longbeachae* have yet to be extensively explored in plumbing. This study examined the concentrations of five pathogenic *Legionella* species (listed previously) in the influent and the taps of five different large buildings (BPS, ERC, F, FH, and M), undertaken during the start of two semesters (late summer/fall (August–September) and early winter/spring (January)). A total of 37 large-volume samples to examine building water quality (influents to the buildings and exposure sites (taps)) were collected and analyzed using droplet digital™ PCR. *Legionella* spp. (23S rRNA) were present in all water samples during both seasons. The majority (66%) of the exposure sites (bathroom taps) were positive for at least one target *Legionella* species (listed above). Results showed that pathogenic *Legionella* species were most often detected during the winter/spring sampling event – the percent positives for any one of the pathogenic *Legionella* species at the hot-water taps was 80% in building F and 40% in BPS, M, FH, and ERC. *Legionella pneumophila* and *L. longbeachae* were found in the highest concentrations (2.0 $\log_{10}$ gene copies (GC)/100 mL) at the hot-water taps in buildings F and ERC, respectively. No strong relationships were found with the physical–chemical parameters. Overall, general *Legionella* spp. concentrations increased in the winter/spring samples due possibly to lower water usage (lower occupancy and no use of cooling towers, which led to more water stagnation or time in the system).

As part of this study, to understand microbiological abundance of pathogens in building plumbing, Logan-Jackson and colleagues also investigated pathogenic *Legionella spp.* and free-living amoebae species in a drinking water system and cooling towers. Pathogenic Legionella species grow optimally inside free-living amoebae to concentrations that increase risks to those who are exposed. The aim of this study was to screen a complete drinking water system and cooling towers for the occurrence of *Acanthamoeba spp.* and *Naegleria fowleri* and their co-occurrence with *Legionella pneumophila, Legionella anisa, Legionella micdadei, Legionella bozemanii,* and *Legionella longbeachae*. A total of 42 large-volume water samples, including 12 from the reservoir (water source), 24 from two buildings (influents to the buildings and exposure sites (taps)), and six cooling towers were collected and analyzed using droplet digital PCR (ddPCR). *N. fowleri* co-occurred with *L. micdadei* in 76 (32/42) of the water samples. In the building water system, the concentrations of *N. fowleri* and *L. micdadei* ranged from 1.5 to 1.6 Log_{10} gene copies (GC)/100 mL, but the concentrations of species increased in the cooling towers. The data obtained in this study illustrate the ecology of pathogenic Legionella species in taps and cooling towers. Investigating Legionella's ecology in drinking and industrial waters will hopefully lead to better control of these pathogenic species in drinking water supply systems and cooling towers.

Further work was dedicated by Logan-Jackson and Rose (2021) to using droplet digital PCR^{TM} (ddPCR) to characterize total *Legionella spp.* and five specific *Legionella* species from source (groundwater) to exposure sites (taps and cooling towers). A total of 42–10 L volume water samples were analyzed during this study: 12 from a reservoir (untreated groundwater and treated water storage tanks), 24 from two buildings (influents and taps), and six from cooling towers, all part of the same water system. The approximate water age (time in the system) for all sample locations are as follows: ~4.5, 3.4, 9.2, 20.8, and 23.2 h for the groundwater to the reservoir influent, reservoir influent to the reservoir effluent, reservoir effluent to building Fa (building names are abbreviated to protect the privacy of site location), building ERC and the cooling towers, respectively. Results demonstrated that gene copies of *Legionella spp.* (23S rRNA) were significantly higher in the cooling towers and ERC building ($p < 0.05$) relative to the reservoir and building Fa (closest to reservoir). *Legionella spp.* (23S rRNA) were found in 100% (42 out of 42) of water samples at concentrations ranging from 2.2 to 4.5 Log_{10} GC/100 mL. More specifically, *L. pneumophila* was found in 57% (24 out of 42) of the water samples, followed by *L. bozemanii* 52% (22 out of 42), *L. longbeachae* 36% (15 out of 42), *L. micdadei* 23% (10 out of 42) and *L. anisa* 21% (9 out of 42) with geometric mean concentrations of 1.7, 1.7, 1.4, 1.6 and 1.7 Log_{10} GC/100 mL, respectively. Based on this study, it is hypothesized that water age in the distribution system and the plumbing as well as building management plays a major role in the increase of *Legionella* spp., (23S rRNA) and the diversity of pathogenic species found as seen in the influent, and at the taps in the ERC building—where the building water quality was most comparable to the industrial cooling towers. Other pathogenic *Legionella* species besides *L. pneumophila* are also likely amplifying in the system; thus, it is important to consider other disease relevant species in the whole water supply system—to subsequently control the growth of pathogenic *Legionella* in the built water environment.

Another study focused on water quality changes due to weekend stagnation in a LEED office building (Montagnino et al. 2022). Specifically, the role of water stagnation (~60 hours) in a 2-story commercial office building on building water quality was studied (January to February 2020) for three weekends. Chemical and biological parameters including pH, total chlorine, metals concentrations, *Legionella spp.* and total cell count were analyzed to understand the differences in water quality at the building entry point, and at eleven fixtures within the building's copper plumbing. Consistently, the total chlorine concentration decreased over the weekend ($p < 0.05$), was greatest at the building entry point (maximum 0.8 mg/L), and was lowest within the plumbing (maximum 0.28 mg/L). As expected, total cell count levels were much greater on Monday compared to Friday ($p < 0.05$) at every sampling point. *Legionella spp*. was found to be highest at the fixture with no use recorded during sampling. Throughout the building, copper and lead levels increased over the weekend ($p < 0.05$). Copper exceedances above the federal health-based drinking water limit (1.3 mg/L) were localized to four fixtures, branched from the same riser, that shared a pattern of variable use. Flushing was conducted at one location with consistent copper exceedances but 54 minutes were required to reach the public water supply. Flushing was not a viable copper remediation method as it would need to be repeated every 19 hours or require discarding more than 50 gallons before use. No prior water testing was conducted in the buildings' life. The results suggest that water quality varies significantly over the week. This has implications for water testing plans and interpretation of data collected from buildings.

Because of the discovery that school buildings had copper that exceeded the action levels but this finding was not known until our team conducted the testing, a follow-up study was conducted. The study goal was to better understand the risks of elevated copper levels at U.S. schools and childcare centers (Montagnino et al. 2022). Copper health effects, chemistry, occurrence, and remediation actions were reviewed. Of the more than 98,000 schools and 500,000 childcare centers in the U.S., only about 0.2% (17,653) had copper water testing data in the federal Safe Drinking Water Information System (SDWIS) database. Of the facilities designated public water systems, about 13% (2,332 of 6,419) had reported a copper exceedance. Studies of schools that were not designed a PWS also had exceedances. Few studies have been conducted to document levels in schools and childcare centers. Widely different sampling protocols and remedial actions have been reported. Flushing contaminated water from plumbing was the most evaluated remedial action but was not found to be reliable because copper quickly rebounded when flushing stopped. In–building water treatment systems have been used, but some are not capable of making the water safe. Health risk was difficult to determine due to the limited occurrence data and lack of studies on best management practices.

2.4 Water testing discoveries in residential buildings

A central focus of the present study was to develop integrative hydraulic-water quality models for residential buildings so that the models could be used for health risk assessments and plumbing design evaluations. As part of this effort, several studies were conducted to monitor water flow, temperature, chemical and microbiological quality in the study site home. This building was called the Retrofitted Net-zero Energy, Water & Waste (ReNEWW) home and was a collaboration between Purdue University and Whirlpool Corporation. This home was extensively monitored and a focus of the overall study. This home was referred to as "The Most Monitored Home in America."

In 2018, a case study was conducted to understand fixture water use, drinking water quality and their possible link, in the newly plumbed ReNEWW home (Salehi et al. 2018). Water use and water quality were monitored at four in-building locations from September 2015 through December 2015. Once the home was fully inhabited average water stagnation periods were shortest at the 2nd floor hot fixture (90 percentile of 0.6–1.2 h). The maximum water stagnation time was 72.0 h. Bacteria and organic carbon levels increased inside the plumbing system compared to the municipal tap water entering the building. A greater number of bacteria was detected in hot water samples (6–74,002 gene copy number/mL) compared to cold water (2–597 gene copy number/mL). This suggested that hot water plumbing promoted greater microbial growth. The basement fixture brass needle valve may have caused maximum Zn (5.9 mg/L), Fe (4.1 mg/L), and Pb (23 μg/L) levels compared to other fixture water samples (Zn ≤ 2.1 mg/L, Fe ≤ 0.5 mg/L and Pb ≤ 8 μg/L). At the basement fixture, where the least amount of water use events occurred (cold: 60–105, hot: 21–69 event/month) compared to the other fixtures in the building (cold: 145–856, hot: 326–2230 event/month), greater organic carbon, bacteria, and heavy metal levels were detected. Different fixture use patterns resulted in disparate water quality within a single-family home. The greatest drinking water quality changes were detected at the least frequently used fixture.

A more intensive water testing effort was conducted from October 2017 to November 2018. Testing involved continuous monitoring of water flow, air and water temperature at service line and all plumbing components. Approximately 2.64 billion online monitoring data points were collected. Pressure monitoring was conducted at the service line during water sampling for periodic 2-3 week periods. Over the 1 year period, 58 discrete sampling events were conducted at the home at 5 locations for both cold and hot water systems and the service line. Samples were collected either at 7am, 12pm, or 3pm depending on the day. Additional details about the parameters characterized, sampling, and data analysis activities are described below. Roughly 40 people (faculty, staff, students) at multiple institutions were working on this ReNEWW home testing effort. More than 222,223 labor hours were conducted for water sampling and analysis, and this time duration does not include data interpretation, reporting and other activities needed for reporting the results. To help interpret water quality results from the home, several bench-scale experiments were also conducted.

To collect the microbiological data necessary for developing the models in Objective 3, microbial dynamics at the ReNEWW Home were monitored over the course of one year (58 sampling events) and examined the effects of water stagnation, season, and changes in physicochemical properties on the occurrence of opportunistic pathogen markers (Ley et al. 2020). Mean heterotrophic plate counts (HPC) were typically lowest upon entering the building at the service line, but increased by several orders of magnitude at the furthest location in the building plumbing. *Legionella spp.* and *Mycobacterium spp.* were detected in the plumbing, with the highest detection occurring in the summer months. Log-transformed HPC were significantly correlated with total cell counts (TCC) ($r_s = 0.714$, $p < 0.01$), *Legionella spp.* ($r_s = 0.534$, $p < 0.01$), and *Mycobacterium spp.* occurrence ($r_s = 0.458$, $p < 0.01$). Reduced water usage induced longer stagnation times and longer stagnation times were weakly correlated with an increase in *Legionella spp.* ($r_s = 0.356$, $p < 0.001$), *Mycobacterium spp.* ($r_s = 0.287$, $p < 0.001$), TCC ($r_s = 0.216$, $p < 0.001$) and HPC ($r_s = 0.395$, $p < 0.001$). Interrelationships between seasonal shifts in water chemistry and genus-level genetic markers for opportunistic pathogens were revealed. This study highlights how drinking water microbiology varies seasonally and spatially throughout a low-flow plumbing building and highlights the possible unintended consequences associated with reduced water usage and increases in stagnation.

At the same time microbiology was being measured during the 1 year study of the ReNEWW home, chemical characteristics of the water were also being examined (Salehi et al. 2020). A study was conducted to better understand seasonal and spatial water quality differences in that building. Water flow rate and temperature were monitored for one year at the service line and at every fixture throughout the crosslinked polyethylene plumbing. Discrete water sampling events (58) were conducted at the service line, 1st floor kitchen sink, 2nd floor bathroom sink, the water heater, and 2nd floor shower. More than 2.4 billion online monitoring records were collected for fixture flow and temperature. In-building water stagnation time varied seasonally and across fixtures. Significant spatial and temporal water chemical quality variations were found. Average seasonal variability was found for service line temperature (15–23 °C) for the total chlorine residual (0.4–0.9 mg/L as Cl_2), NH_3 (<0.01–0.4 mg/L as N), NO_3^- (0.1–0.8 mg/L as N), and Cu (32–81 μg/L) concentrations. For 10.3% of the discrete water sampling events, service line water did not contain a detectable total chlorine residual. Water pH consistently and significantly increased in the plumbing system from 7.5 to 9.4, and total trihalomethane (TTHM) levels increased up to 89%. The service line total organic carbon level (0.5–0.6 mg/L) was consistent, but much greater in-building variability was found for cold (0.4–61.0 mg/L) and hot water (0.5–4.7 mg/L). Models are needed to predict chemical water quality at the faucet using service line water quality results and plumbing design and operational information. Building water sensor technology innovations are also needed.

After the 1 year water quality and flow monitoring effort was complete, the ReNEWW home was switched to receiving water from rainwater (Ley et al. 2021). Very little information exists about how switching water sources for plumbing influence water safety. When rainwater harvesting is utilized as an alternative water resource in buildings, a combination of municipal water and rainwater is typically required to meet water demands. Altering source water chemistry can disrupt pipe scale and biofilm and negatively impact water quality at the distribution level. Still, it is unknown if similar reactions occur within building plumbing following a transition in source water quality. The goal of this study was to investigate changes in water chemistry and microbiology at a green building following a transition between municipal water and rainwater. We monitored water chemistry (metals, alkalinity, and disinfectant byproducts) and microbiology (total cell counts, plate counts, and opportunistic pathogen gene markers) throughout two source water transitions. Several constituents including alkalinity and disinfectant byproducts served as indicators of municipal water remaining in the system since the rainwater source does not contain these constituents. In the treated rainwater, microbial proliferation and *Legionella spp.* gene copy numbers were often three logs higher than those in municipal water. Because of differences in source water chemistry, rainwater and municipal water uniquely interacted with building plumbing and generated distinctively different drinking water chemical and microbial quality profiles.

Table 1. List of Published Peer-Reviewed Studies Partially or Fully Supported by this Project

Lead Institutions: PU = Purdue University; MSU = Michigan State University; TU = Tulane University; MC = Manhattan College; UM = University of Memphis; Collaborating Authors: AZU = Arizona State University; BC = Butte College; CSUS; California State University at Chico; MP = Montreal Polytechnique; NU = Northeastern University; UCB = University California Berkeley; UI = University of Iowa; VT = Virginia Tech.

Initiative	Lead
Knowledge-Gap and Synthesis Investigations	
Knowledge gaps and risks associated with premise plumbing drinking water quality: https://doi.org/10.1002/aws2.1177	MSU-PU-MC
Considerations for large building water quality after extended stagnation: https://doi.org/10.1002/aws2.1186	PU-UM-MP-VT-NU-UI-AZU
New Health Risk Assessments	
Development of a dose–response model for *Naegleria fowleri*: https://doi.org/10.2166/wh.2018.181	MSU
A dose response model for the inhalation route of exposure to *P. aeruginosa:* https://doi.org/10.1016/j.mran.2020.100115	MSU
Reverse QMRA for Pseudomonas aeruginosa in Premise Plumbing to Inform Risk Management: https://doi.org/10.1061/(ASCE)EE.1943-7870.0001641	MSU
Modeling the dose response relationship of waterborne Acanthamoeba: https://doi.org/10.1111/risa.13603	MSU

New Commercial and Institutional Building Investigations	
Finding building water quality challenges in a 7 year old green school: implications for building design, sampling, and remediation: https://doi.org/10.1039/D0EW00520G	PU -TU
The Occurrence of 5 Pathogenic Legionella species from Source (Groundwater) to Exposure (Taps and Cooling Towers) In a Complex Water System: https://doi.org/10.1039/D0EW00893A	MSU
Cooccurrence of Five Pathogenic Legionella spp. and Two Free-Living Amoebae Species in a Complete Drinking Water System and Cooling Towers: https://doi.org/10.3390/pathogens10111407	MSU
Over the weekend: Water stagnation and contaminant exceedances in a green office building: https://doi.org/10.1371/journal.pwat.0000006	PU-TU
Water Age Effects on the Occurrence and Concentration of Legionella Species in the Distribution System, Premise Plumbing, and the Cooling Towers: https://doi.org/10.3390/microorganisms10010081	MSU
Prevalence of opportunistic pathogens in a school building plumbing during periods of low water use and a transition to normal use: https://doi.org/10.1016/j.ijheh.2022.113945	TU-PU
School and childcare center drinking water: copper chemistry, health effects, occurrence, and remediation: https://doi.org/10.1002/aws2.1270	PU-MSU-UI-EPA

New Residential Building Investigations	
Case study: Fixture water use and drinking water quality in a new residential green building: https://doi.org/10.1016/j.chemosphere.2017.11.070	PU-MSU
An investigation of spatial and temporal drinking water quality variation in green residential plumbing: https://doi.org/10.1016/j.buildenv.2019.106566	PU-MSU-UM
Drinking water microbiology in a water-efficient building: stagnation, seasonality, and physicochemical effects on opportunistic pathogen and total bacteria proliferation: https://doi.org/10.1039/D0EW00334D	TU-PU-MSU
Impacts of Municipal Water–Rainwater Source Transitions on Microbial and Chemical Water Quality Dynamics at the Tap: https://10.1021/acs.est.0c03641	PU-TU-MSU
Water safety attitudes, risk perception, experiences, and education for households impacted by the 2018 Camp Fire, California: https://doi.org/10.1007/s11069-021-04714-9	PU-UCB-BC-CSUS
New Plumbing Material Discoveries	
Metal Accumulation in Representative Plastic Drinking Water Plumbing Systems: https://doi.org/10.5942/jawwa.2017.109.0117	PU
Competitive heavy metal adsorption onto new and aged polyethylene under various drinking water conditions: https://doi.org/10.1016/j.jhazmat.2019.121585	PU
Corrosion of upstream metal plumbing components impact downstream PEX pipe surface deposits and degradation: https://doi.org/10.1016/j.chemosphere.2019.07.060	PU
Formation and sorption of trihalomethanes from cross-linked polyethylene pipes following chlorinated water exposure: https://doi.org/10.1039/D0EW00262C	PU
Drinking water contamination from the thermal degradation of plastics: implications for wildfire and structure fire response: https://doi.org/10.1039/D0EW00836B	PU

New Modeling and Decision Support Tools	
Identifying water quality variables most strongly influencing Legionella concentrations in building plumbing https://doi-org.proxy1.cl.msu.edu/10.1002/aws2.1267)	MSU-PU-TU
New models for predicting chemical and biological quality at residential fixtures https://doi.org/10.1002/aws2.1280	MC-PU-MSU

2.5 Plumbing material discoveries

2.5.1 Heavy metal interactions with plastic drinking water plumbing materials

Because of the growing use of plastics in building water systems and continuing corrosion of existing and new metal components, several bench-scale studies were conducted to better understand water quality in plastic plumbing. In some studies, materials were exhumed from the field and characterized.

Follow-up work by Huang et al. (2019) for PEX pipes revealed calcium, iron, manganese, phosphorous, and zinc were the most abundant elements on residential plumbing pipe surfaces. Black and yellow deposits were found on some of the exhumed PEX pipe's inner walls, which were mainly Cu, Fe, and Mn oxides (CuO, $Cu(OH)_2$, Fe_2O_3, $FeOOH$ and MnO_2). Follow-up bench-scale experiments revealed that metal levels in the drinking water did not always predict metal loadings on plastic pipe surfaces. The pH 4 water resulted in a greater amount of metals released into the bulk water, but the pH 7.5 water resulted in a greater amount of metals deposited on the PEX pipe surfaces. Hot water (55 °C) induced a greater amount of organics released and higher metal loadings on PEX pipe surfaces at pH 7.5. ATR-FTIR analysis showed that at 55 °C, PEX pipes connected to copper and brass components had the greatest oxidation functional group peak intensity (>COOC<, >CO, and >COC<).

A follow-up study was conducted by Huang et al. (2020) to identify factors that influence Cu, Fe, Pb, Mn, and Zn loading on new and aged low-density polyethylene (LDPE) under various drinking water conditions. Polyethylene materials are some of the most common plastics used in plumbing to include service lines, well supply water lines, water distribution pipes, faucet connectors, and appliance lines. The applied aging procedure increased LDPE surface area, hydrophilicity and the number of oxygen containing functional groups. Aged LDPE adsorbed up to a 5 fold greater metals than the new LDPE: Cu > Pb, Zn > Mn. Water pH (5.5 to 10.5) significantly altered LDPE surface metal loading. The organic carbon leached from plastic pipes inhibited Cu adsorption (−43.8%), but other metals were less impacted (−5.7% to −9.1%). The addition of free chlorine and corrosion inhibitor retarded metal adsorption to suspended LDPE materials. Overall, by changing water conditions total metal loadings (i.e., Cu, Mn, Pb and Zn) were altered 20.1 to 35.4%. When Fe was present, Cu (−4.0%) and Pb (−4.5%) loadings were reduced, while lesser impacts were found for Mn and Zn. Cu^{2+}, Pb^{2+} and Zn^{2+} hydroxides and oxides were identified as the major metal deposit forms on the LDPE surface by XPS. To better predict metal fate in plastic piping systems, plastic surface characteristics, dissolved organics, water pH, hydraulic conditions and microbial growth should be considered.

To further understand how Pb interacts with polyethylene surfaces a series of bench-scale experiments were conducted by Salehi et al. (2019). Specifically, the influence of polymer aging, water pH, and aqueous Pb concentration on Pb deposition onto low density polyethylene (LDPE) was investigated. LDPE pellets were aged by ozonation at 85 °C. ATR-FTIR and X-ray photoelectron spectroscopy (XPS) analysis of aged LDPE surfaces showed that a variety of polar functional groups (>CO<, >CO, >COO) were formed during aging. These functional groups likely provided better nucleation sites for $Pb(OH)_2$ deposition compared to new LDPE, which did not have these oxygen-containing functional groups. The type and amount of Pb species present on these surfaces were evaluated through XPS. The influence of exposure duration on Pb deposition onto LDPE was modeled using the pseudo-first-order equation. Distribution ratios of 251.5 for aged LDPE and 69.3 for new LDPE showed that Pb precipitates had greater affinity for the surface of aged LDPE compared to new LDPE. Aged LDPE had less Pb surface loading at pH 11 compared to loading at pH 7.8. Pb surface loading for aged LDPE changed linearly with aging duration (from 0.5-7.5 h). Pb surface loading on both new and aged LDPE increased linearly with increasing Pb initial concentration. Greater Pb precipitation rates were found for aged LDPE compared to new LDPE at both tested pH values.

2.5.2 Organic compound leaching and sorption with plastic drinking water materials

Because PEX pipes are being used, and had been reported leach chemicals into water, a series of experiments were conducted within larger studies as well as separate studies. For the materials tested, all had been previously certified by NSF International Standard 61 Health Effects testing. In the residential study by Salehi et al. (2020), bench-scale experiments were conducted to better understand the magnitude of synthetic organic matter (SOM) leaching from PEX pipes. This experiment involved two brands of new PEX pipes and a series of water changes from pipe sections over a 30 day period (**Table 2**). Before experiments, the pipes were prepared including disinfected. High SOM leaching was observed for the new materials, and this differed by brand and water temperature.

Table 2. Total Organic Carbon Concentration (mg/L) during the 30 Day Exposure Period

Water pH and Exposure Time		PEX-a Pipe		PEX-b Pipe	
		23°C	50°C	23°C	50°C
pH 7	Day 3	13.09 ± 7.43	41.29 ± 0.50	16.66 ± 11.21	58.92 ± 38.70
	Day 15	3.33 ± 0.11	5.71 ± 0.42	0.89 ± 0.13	12.88 ± 0.35
	Day 30	5.07 ± 0.51	3.44 ± 1.35	1.08 ± 0.21	10.77 ± 0.26
pH 10	Day 3	-	77.69 ± 16.44	-	39.95 ± 6.01
	Day 15	-	5.64 ± 0.10	-	7.26 ± 0.55
	Day 30	-	1.55 ± 0.10	-	5.25 ± 0.46

This is Table SI-5 from Salehi et al. (2020).

To further understand the role of PEX pipes on fixture water quality, a study by Cao et al. (2020) was conducted. This study assessed how these processes could further impact concentrations of disinfection by-products (DBPs) and specifically trihalomethanes (THMs) when exposed to chlorinated water. One brand of three different PEX types (PEX-a, PEX-b, and PEX-c) were exposed to synthetic water, which was subsequently chlorinated over 120 h under varying water quality conditions (e.g. temperature, pH, bromide concentration, and free chlorine dose). Results indicated that THM formation was fairly modest for all three PEX types at 22 °C but increased by a factor of ~2 at 55 °C for the PEX-a pipe. Other water quality conditions exhibited more limited effects. Pipe-storage time strongly affected leached organic carbon levels but did not affect THM formation. THM sorption also occurred for all three PEX types and was similarly controlled by temperature. Sorption data fit well to a kinetic adsorption model. Combined effects of THM formation and sorption at 22 °C generated no aqueous phase THMs, although this effect was not similarly examined at 55 °C. These results suggest that sorption may mitigate the effects of THM formation if PEX pipes continue to reside downstream of where formation occurred, but this may not be the case if other pipe types (e.g. metal pipes) are present. Overall, these findings have important regulatory consequences since current THM monitoring may or may not account for building PEX plumbing.

In response to wildfire caused drinking water contamination caused and discovered since 2017, a study by Isaacson et al. (2020) was conducted to determine if the thermal degradation of common plastic drinking water pipes (*i.e.*, PEX, HDPE, PP, PVC, and CPVC) may be a source of drinking water contamination. Widespread volatile organic compound (VOC) contamination was found in water distribution systems following three wildfires in California. A potential source of this contamination was thought to be due to the degradation of plastic components in drinking water distribution systems. Eleven plastic drinking water pipes, across eight brands, were exposed to elevated temperatures (200 °C to 400 °C), and subsequently submerged in water or in *n*-hexane to observe the extent of VOC leaching. Results indicated that thermally damaged drinking water pipes can be sources of VOC leaching, with ten of the eleven materials leaching benzene, a carcinogen, into water. As exposure temperature increased, an increase in VOC leaching was observed in the polyethylene materials. Conversely, in the vinyl materials the significant mass loss associated with high exposure temperature was inversely proportional to the amount of BTEX leaching that was observed. Additional tentatively identified compounds (TICs), consisting primarily of aliphatic hydrocarbons, saturated ketones, or aromatic compounds, were found in the water (22 TICs) and *n*-hexane (134 TICs) leachate of burned plastics. This study has significant implications for both wildfire and structure fire recovery as plastic materials are increasingly being used in buried and building plumbing, and visual inspection is not a sufficient indicator of contamination risk.

Objective 3. Create a risk-based decision support tool to help guide decision makers through the identification of plumbing characteristics, operations and maintenance practices that minimize health risks to building inhabitants.

Highlights

- ❖ A series of calibrated plumbing hydraulic-water quality models were developed for the extensively monitored single-family residential home. Results can be used to support better planning, design, analysis, and operational decision-making for building water systems design, operation, and investigations.
- ❖ The integrative hydraulic water quality models were developed using EPANET and EPANET-MSX, and the eight models predict the level of free chlorine, total trihalomethanes (TTHM), Cu, Fe, Pb, NO_3^-, heterotrophic plate count (HPC), and *Legionella spp.* concentration at each fixture for plumbing use, operational characteristics, and design layouts.
- ❖ Reducing building water use in the model by 25% prompted increased concentrations of HPC and Legionella, each increasing by a factor of about 10^5. When the service line length was increased, *Legionella spp.* concentrations increased by up to 10^6 gene copies /L in the Summer season.
- ❖ Two decision support tools (The Plumbing Water Quality Tool and QMRA Decision Support Tool) can now be used by building designers, owners, public health officials, regulators, policymakers, utility staff, and other professionals for predicting chemical and microbiological water quality and health risks at building fixtures. These tools are publicly available online. These are the only two tools currently available and study results provide insights into future development challenges.

An ultimate goal of the present study was to create a risk-based decision support tool to help guide decision makers through the identification of plumbing characteristics, operations, and maintenance practices that minimize health risks to building inhabitants. This study developed a multi-tiered, web-based decision support system publicly available online. This tool is based on the significant residential plumbing investigations as well as myriad studies conducted in and for commercial and institutional buildings. Feedback from practicing plumbing engineers, architects, building owners, and health officials was received and incorporated into the ultimate products.

3.1 Critical water quality relationships for predicting legionella in residential buildings were discovered

Plumbing design guidance has not been updated to reflect changes in use, leading to increased hydraulic retention time and exacerbating pathogen risks. While the effects of several water quality variables on *Legionella spp.* concentrations are well-studied at bench-scale, little is known about the strength of, or interactions between, these relationships in full-scale plumbing. The influence of water quality variables and water use metrics on *Legionella spp.* concentrations was evaluated with several statistical tools from a data-driven perspective (Julien et al. 2022). The results add to the weight of evidence required to develop systematic risk management strategies like monitoring. Variables related to Legionella and logistically more feasible to measure in full scale buildings, such as dissolved oxygen, heterotrophic plate count, total organic carbon, and water age, were identified.

3.2 Eight integrative hydraulic-water quality models were developed

A series of calibrated plumbing hydraulic-water quality models were developed for the extensively monitored ReNEWW house (Palmegiani et al. 2022). A comprehensive literature review was performed to identify a set of kinetic or equilibrium equations governing each of the water quality parameters present within residential plumbing. The developed model incorporated complete hydraulics and water quality data at the internal and external boundaries of the residential building. To observe any abnormal pressure/ hydraulic transient behavior at the service line, continuous pressure data was also utilized. The integrative hydraulic water quality models were developed using EPANET and EPANET-MSX, and the eight models predict the level of free chlorine, total trihalomethanes (TTHM), Cu, Fe, Pb, NO_3^-, heterotrophic plate count (HPC), and *Legionella spp.* concentration at each fixture for plumbing use, operational characteristics, and design layouts. Model development revealed that the carrying capacity to describe *Legionella spp.* growth (and other organisms) under water usage and plumbing design conditions is lacking in the literature. This information is needed for higher resolution modeling. Reducing building water use by 25% prompted increased concentrations of HPC and Legionella, each increasing by a factor of about 10^5. When the service line length was increased, *Legionella spp.* concentrations increased by up to 10^6 gene copies /L in the Summer season. The proposed new modeling framework can be used to support better planning, design, analysis, and operational decision-making.

3.3 Two plumbing decision support tools were created and are now publicly available

To develop the decision support tools, results from prior objectives and the integrative hydraulic- water quality models were brought into this effort. Boundaries for the DST development were established (i.e., a range of theoretical plumbing flow demands) from the scientific literature and expert elicitation with our strategic partners.

We have developed two plumbing decision support tools (DSTs): *The Plumbing Water Quality Tool* (https://dsiweb.cse.msu.edu/waterquality/water-quality) and *The QMRA Decision Support Tool* (https://dsiweb.cse.msu.edu/waterquality/qmra). *The Plumbing Water Quality Tool* presents various water quality scenarios in a simulated version of the Whirlpool/Perdue ReNEWW house using EPANET. *The QMRA Decision Support Tool* assesses the relative risks of various hazards under different use scenarios. The audience of both tools are (1) citizens who are interested in learning about water quality in homes and (2) practitioners who want to compare concentration and/or risk of hazards in a model home. Users can simulate the hazard and/or risk of hazard under two scenarios, and which are presented in written and graphical formats. Here, we provide examples of the DST outputs for two distinct scenarios for the *Plumbing Water Quality Tool* (**Figure** 2) and the *QMRA Decision Support Tool* scenarios (**Figure 3**).

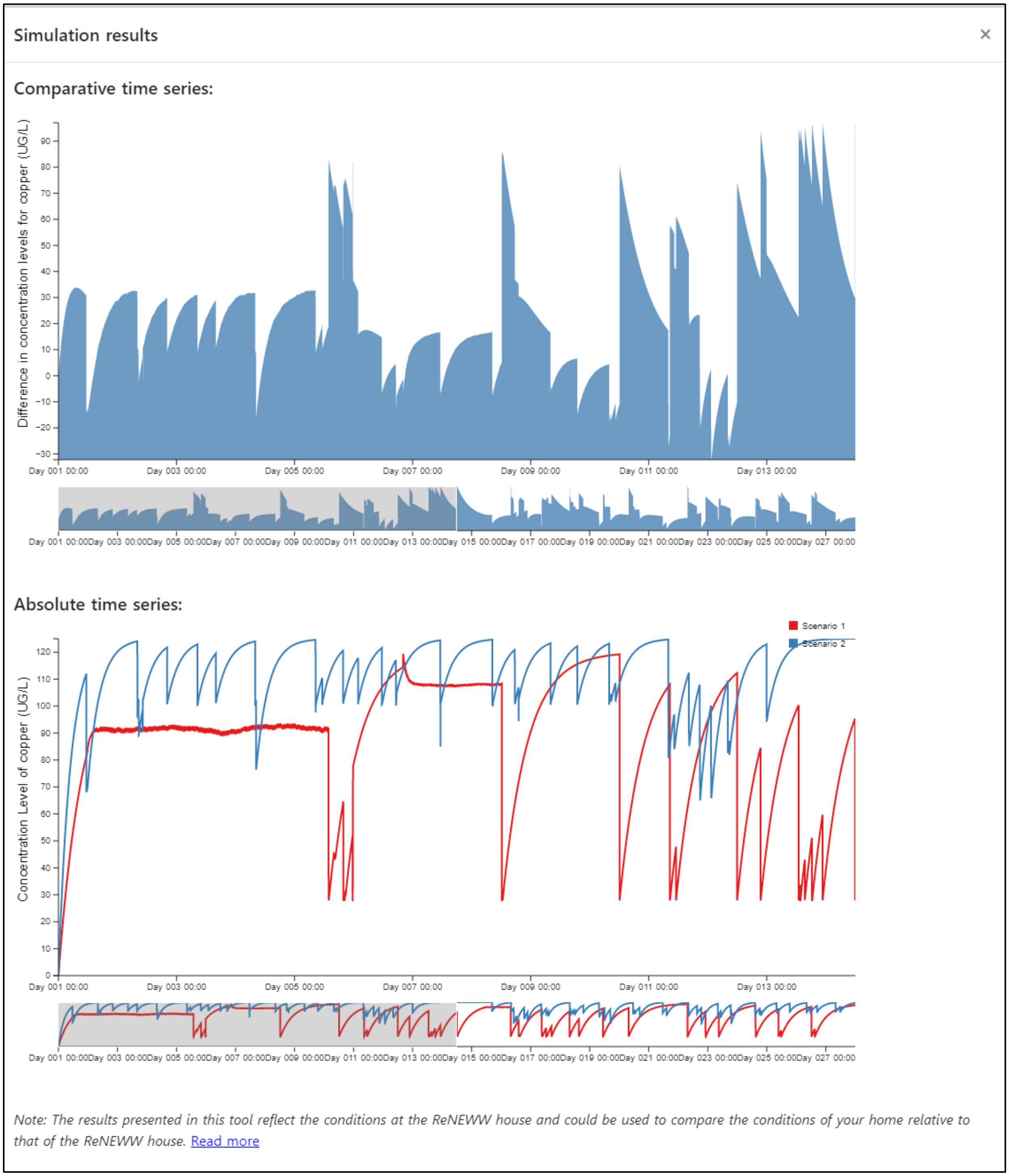


Figure 2. An example of *Plumbing Water Quality Tool* output comparing the relative levels of simulated copper concentrations under two different plumbing scenarios

Step 5: Risk characterization ×

The annual risk of scenario 1 is 10 times less risky than scenario 2

Scenario 1 results in a **one-in-one-hundred-thousand** risk of infection per year. This is below the EPA threshold of acceptable annual risk.

Scenario 2 results in a **one-in-one-million** risk of infection per year. This is below the EPA threshold of acceptable annual risk.

Click here for advanced results

For *Scenario 1*, the person would be exposed to a median dose of **3.4898e-8 CFU** of leg per exposure

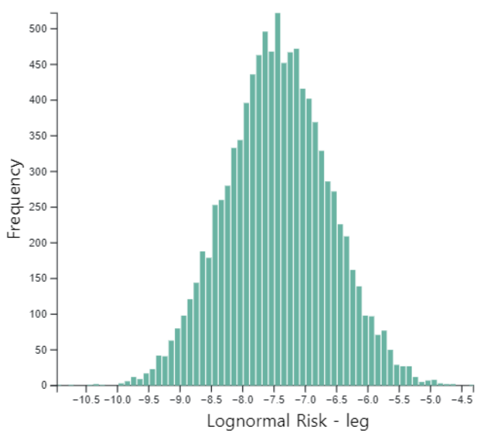
The median lognormal risk per dose for *Scenario 1* is -7.4572

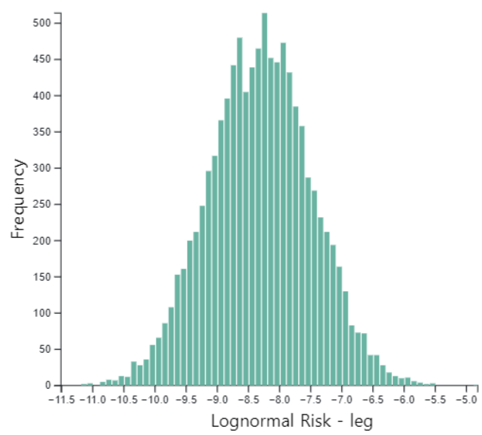
For *Scenario 2*, the person would be exposed to a median dose of **4.9153e-9 CFU** of leg per exposure

The median lognormal risk per dose for *Scenario 2* is -8.3085

Summary Statistics per usage

Scenario	Min Log Risk	Median Log Risk	Mean Log Risk	Max Log Risk
Scenario 1	-10.96	-7.457	-6.675	-4.314
Scenario 2	-11.51	-8.308	-7.537	-4.818





Note: This tool is indended for educational purposes, and its default parameters do not reflect pathogen levels in any particular building. It's primary purpose is to demonstrate the relative effects of water use management on microbial risk. Read more

Figure 3. An example of *QMRA Decision Support Tool* output for two different exposure scenarios involve Legionella

3. Ongoing Work

Several studies partly funded by the US EPA grant were not described above because parts of them were ongoing at the time this final report was submitted. These studies are either being prepared for publication, undergoing peer-review, or are still in data the gathering phase (**Table 3**). The topics involved include better understanding in-building water treatment devices, new plumbing startup, predicting fixture water quality, and others.

Table 3. Ongoing Studies Partially Supported by this Project not Published when this Report was Submitted

Initiative	Lead
Water quality observations when new softeners and copper plumbing commissioned for residential buildings	PU
Hydrocarbon contamination and decontamination of building water treatment devices by flushing	PU
Machine learning framework for predicting downstream water end-use events with upstream sensors	MSU-PU
Water age and modeling in a residential home	MSU-MC-PU

4. Relevant Websites

Both Purdue University and Michigan State University established websites to disseminate findings and resources from this study and provide access to the Plumbing Decision Support Tools developed through this project.

Purdue University websites

www.PlumbingSafety.org

https://engineering.purdue.edu/PlumbingSafety

Michigan State University websites

Decision Support Tool - Plumbing Water Quality Tool (https://dsiweb.cse.msu.edu/waterquality/water-quality)

Decision Support Tool - QMRA Decision Support Tool (https://dsiweb.cse.msu.edu/waterquality/qmra)

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- And many more…

6. Subaward Monitoring

Purdue University approved invoices for subawardees on a periodic basis. The PI checked with each subaward PI in person and through electronic communications to confirm adequate progress throughout the effort. No deficiencies were identified. Results from the subawardees were integrated into the overall deliverables and products resulting from project.

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Appendix A – Copies of Publications

Appendix B – Model, Codes, and Materials